**REMOTE SENSING BASED ASSESSMENT OF SOIL DEGRADATION UNDER CLIMATE CHANGE: A CONTEMPORARY REVIEW**

**ABSTRACT**

Soil degradation, driven by both natural and anthropogenic forces, poses a serious threat to agricultural productivity, ecosystem health, and global food security challenges that are increasingly intensified by climate change. This paper explores the complex interplay between climate change and soil degradation processes, including erosion, compaction, salinization, chemical contamination, and biological decline. It highlights how altered precipitation patterns, rising temperatures, and sea-level rise exacerbate soil deterioration by affecting soil properties, vegetation cover, and microbial communities. The study emphasizes the critical role of remote sensing technologies, particularly satellite imagery and UAV-based platforms integrated with artificial intelligence, in monitoring soil health and detecting degradation patterns at various scales. Despite the advantages of remote sensing in providing timely, spatially extensive data, challenges such as data resolution, atmospheric interference, and integration with field data remain. The paper also discusses the potential of emerging technologies and interdisciplinary approaches to support decision-making and sustainable land management. It concludes with a call for improved data infrastructure, capacity-building, and policy support to enable more effective use of remote sensing in combating soil degradation under changing climatic conditions.

**Keywords:** Remote Sensing; Soil Degradation; Climate Change, Sustainable land management

**INTRODUCTION**

Soil, a vital natural resource, is indispensable for agriculture, ecosystem functioning, and human well-being, playing a pivotal role in food production, water regulation, carbon sequestration, and nutrient cycling. However, soil resources are increasingly threatened by degradation processes, encompassing physical, chemical, and biological decline, with profound implications for environmental sustainability and human livelihoods (Fall et al., 2022). Climate change, characterized by altered temperature and precipitation patterns, extreme weather events, and rising atmospheric CO2 concentrations, exacerbates soil degradation by influencing soil properties, vegetation cover, and land use practices (Begum et al., 2019). The increase in global population, rising per capita income, and changes in dietary preferences are projected to drive a 70% increase in global agricultural production by 2050 (Loveland & DeFries, 2004). Agriculture has substantial impacts on the environment, contributing significantly to greenhouse gas emissions, land degradation, water pollution, and biodiversity loss. Intact ecosystems are being converted to agricultural lands, further exacerbating environmental problems. Currently, soil degradation impacts an estimated 33% of global land resources, posing a significant threat to food security, water availability, and climate change mitigation (McGreevy et al., 2022; Kassam & Friedrich, 2012). The convergence of climate change and soil degradation necessitates a comprehensive understanding of the underlying mechanisms, spatial patterns, and temporal dynamics of soil degradation, as well as the development and implementation of effective mitigation strategies.

**OVERVIEW OF SOIL DEGRADATION PROCESSES AND THEIR DRIVERS**

Soil degradation manifests through various processes, each characterized by distinct mechanisms and impacts on soil functionality (Stavi et al., 2021). Erosion, the detachment and transport of soil particles by wind or water, represents a primary form of degradation, leading to topsoil loss, reduced soil fertility, and sedimentation of waterways (Smith et al., 2024). Climate change-induced alterations in rainfall intensity and frequency can exacerbate erosion rates, particularly in vulnerable landscapes with steep slopes or sparse vegetation cover. Compaction, recognized as another critical facet of soil degradation, arises from the imposition of excessive mechanical stresses, frequently stemming from the operation of heavy agricultural machinery or the concentrated grazing of livestock, which induces a reduction in soil pore space, thereby impeding water infiltration, root penetration, and gas exchange (Batey, 2009). Soil sealing, which is the covering of soil with impervious materials such as concrete and asphalt, is a significant concern in urban and industrial areas, leading to the loss of valuable agricultural land and disrupting hydrological cycles. Salinization, characterized by the excessive accumulation of soluble salts in the soil profile, poses a significant threat to agricultural productivity, particularly in arid and semi-arid regions, with high evaporation rates exacerbating the upward movement and deposition of salts near the soil surface (Evelin et al., 2019; Oñate-Valdivieso et al., 2024). Chemical degradation, encompassing processes such as acidification, contamination, and nutrient depletion, further impairs soil quality and ecosystem health (Richmond, 2015). The excessive use of chemical fertilizers and pesticides, as well as the deposition of atmospheric pollutants, can disrupt soil nutrient cycles, alter soil pH, and introduce toxic substances into the soil environment (Raghavendra & Venkatesha, 2020).

**ROLE OF CLIMATE CHANGE IN ACCELERATING SOIL DEGRADATION**

Climate change serves as a major catalyst for soil degradation, amplifying the severity and extent of various degradation processes across diverse ecosystems. Changing temperature and precipitation patterns can disrupt soil hydrological balance, leading to prolonged drought periods and/or intense rainfall events that accelerate soil erosion, nutrient leaching, and desertification (Mihi et al., 2022). Specifically, increased temperatures can accelerate the decomposition of organic matter, releasing carbon dioxide into the atmosphere and reducing the soil's capacity to store carbon and regulate nutrient cycles (Guo et al., 2013). Alterations in rainfall patterns, characterized by more frequent and intense storms, can overwhelm the soil's infiltration capacity, resulting in increased surface runoff, soil erosion, and sedimentation of waterways (Chalise et al., 2019). Moreover, climate change-induced sea level rise can lead to saltwater intrusion into coastal aquifers and agricultural lands, exacerbating soil salinization and rendering vast areas unsuitable for crop production (Ilangumaran & Smith, 2017). Changing climate conditions also promote the spread of invasive plant species and alter the composition and function of soil microbial communities, further disrupting ecosystem processes and accelerating soil degradation rates (Malambane et al., 2023). The intricate interplay between climate change and human activities, such as deforestation, unsustainable agriculture, and urbanization, further complicates the challenge of mitigating soil degradation and ensuring long-term soil health. Extreme weather conditions linked to climate change can lead to serious soil degradation that accelerates soil erosion (Ch. et al., 2020). The deterioration of soil quality encompasses a range of factors such as decreased fertility, biological degradation, increased susceptibility to erosion, elevated acidity and salinity, and the exposure of subsoil with poor physicochemical characteristics (Saha et al., 2012).

**REMOTE SENSING TECHNIQUES FOR SOIL DEGRADATION ASSESSMENT**

Remote sensing technologies provide a versatile toolkit for assessing soil degradation, offering capabilities for monitoring soil properties, land cover changes, and vegetation health across broad spatial and temporal scales. Remote sensing data, acquired from satellite-based or airborne sensors, can be used to derive various indicators of soil degradation, including vegetation indices, soil moisture content, surface roughness, and salinity levels (Rubio-Aliaga et al., 2019). Vegetation indices, such as the Normalized Difference Vegetation Index, provide insights into vegetation cover and plant health, which are often indicative of soil quality and land degradation status (Shoshany et al., 2013). Bare Soil Index is a spectral index which utilizes the reflectance values in the red, blue, and shortwave infrared portions of the electromagnetic spectrum (Al‐Bakri et al., 2012). Soil moisture content can be estimated using microwave remote sensing techniques, which are sensitive to the dielectric properties of soil and can provide information on water availability for plant growth (Zhang et al., 2019). Surface roughness, which is indicative of soil erosion and land surface stability, can be assessed using radar remote sensing techniques that measure the backscattering of microwave radiation from the soil surface. Furthermore, remote sensing data can be used to map land cover changes, such as deforestation, urbanization, and agricultural expansion, which are major drivers of soil degradation (Loveland & DeFries, 2004). By integrating remote sensing data with field observations, soil models, and geographic information systems, researchers can develop comprehensive assessments of soil degradation patterns and identify areas at high risk of further degradation (Xie, 2013). Geographical information system technologies have great potentials in the field of soil and has opened newer possibilities of improving soil statistic system as it offers accelerated, repetitive, spatial and temporal synoptic view (Rao et al., 2019).

**APPLICATIONS OF UAVS AND AI IN MONITORING SOIL HEALTH**

Unmanned Aerial Vehicles are now critical for high resolution remote sensing because of their capacity to collect data with exceptional spectral, spatial, and temporal resolutions, together with precise data on plant height and multi-angular observations (Maes & Steppe, 2018). Early remote sensing applications involved broad land and agriculture monitoring via satellite, along with crop yield monitoring, and plant disease and invasive species detection (Chauvin et al., 2021). The fusion of UAV-based remote sensing with artificial intelligence algorithms has revolutionized the field of soil monitoring, enabling rapid and accurate assessment of soil properties and land degradation indicators at unprecedented scales (Sankey et al., 2020). UAVs can be equipped with a variety of sensors, including multispectral, hyperspectral, and thermal cameras, to capture detailed information on soil conditions and vegetation health (Zhang & Zhu, 2023). These aerial platforms allow one to raise different data gathering sensors or devices , including commercial digital cameras , and even to view these data in real time (Sastre et al., 2020). Data from UAVs can provide detailed visual data and detect potential problems or damage (Islam, 2023). When paired with remote sensing techniques, UAVs offer a flexible method of acquiring three-dimensional optical data at high resolution through overlapping images (Dupuis et al., 2020). AI algorithms, such as machine learning and deep learning, can be trained to analyze UAV-based remote sensing data and extract valuable insights into soil properties, such as soil moisture content, organic matter content, and nutrient levels (Yao et al., 2019). These algorithms can also be used to detect and map areas of soil erosion, salinization, and contamination, providing valuable information for targeted soil conservation and remediation efforts. Furthermore, AI can be used to automate the processing and analysis of UAV-based remote sensing data, reducing the time and cost associated with traditional soil surveys and laboratory analyses (Hassler & Baysal-Gurel, 2019). UAVs offer other advantages, such as flexibility in collecting images, improved spatial resolution, and control over temporal resolution (Santana et al., 2021). By integrating UAV-based remote sensing with AI algorithms, researchers and land managers can gain a more comprehensive understanding of soil health and land degradation dynamics, enabling more effective decision-making for sustainable land management.

**CHALLENGES IN REMOTE SENSING-BASED SOIL MONITORING**

Despite the numerous advantages of remote sensing techniques for soil degradation assessment, several challenges remain that need to be addressed to improve the accuracy, reliability, and applicability of these methods. One major challenge is the complexity of soil properties and processes, which can be difficult to capture using remote sensing data alone. Another challenge is the influence of atmospheric conditions, such as clouds, haze, and aerosols, on the quality of remote sensing data. Additionally, the availability of high-quality, high-resolution remote sensing data can be limited, particularly in developing countries and remote regions. Moreover, the interpretation of remote sensing data requires specialized expertise and knowledge of soil science, remote sensing principles, and image processing techniques. The data processing could be time-consuming and can involve complex software. Therefore, effective methods need to be developed to manage and fully utilize the vast amounts of data produced. Furthermore, the integration of remote sensing data with other data sources, such as field observations, soil maps, and climate data, can be challenging due to differences in spatial and temporal scales, data formats, and data quality. Moreover, the validation of remote sensing-based soil degradation assessments requires extensive field sampling and laboratory analyses, which can be costly and time-consuming.

**FUTURE PERSPECTIVES AND MITIGATION STRATEGIES**

Future research should focus on developing more robust and accurate remote sensing techniques for assessing soil degradation under climate change, integrating remote sensing data with other data sources, and developing decision support tools for sustainable land management. There is a need to promote the adoption of remote sensing technologies in agriculture by addressing challenges related to data access, reliability, and privacy (Abiri et al., 2023). Further research is needed to develop innovative mitigation strategies that can enhance soil resilience to climate change and reduce the impacts of soil degradation on agricultural productivity and ecosystem services. Arbuscular mycorrhizal fungi and their interactions with soil microorganisms improve soil fertility, but their interaction with free native nematode and their impact on soil structure under drought stress needs further research (Fall et al., 2022).

It is also important to consider the role of policy and governance in promoting sustainable land management practices and ensuring the long-term health and productivity of soil resources (Fall et al., 2022). Moreover, the transfer of imagery and its management need efficient infrastructure.

**CONCLUSION**

Remote sensing techniques offer a powerful tool for assessing soil degradation under climate change, providing valuable information for sustainable land management and ecosystem conservation (Robert, 2004). The utilization of remote sensing technologies can provide a broad scope and the ability to collect sequential imagery to estimate trends and patterns of alternative tillage practices (Zheng et al., 2014). Despite the challenges, advancements in remote sensing technologies, data analysis techniques, and mitigation strategies hold great promise for improving our understanding of soil degradation processes and promoting sustainable land management practices. By integrating remote sensing data with other data sources and developing decision support tools, researchers and land managers can make more informed decisions about land use planning, soil conservation, and climate change adaptation. It is important to address the technical and managerial requirements for the application of remote sensing to soil and crop management (Robert, 2004; Zheng et al., 2014).

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