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# Advancing Environmental Sustainability Through Remote Sensing: A Review of Applications, Limitations, and Emerging Solutions

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*Review*

# Advancing Environmental Sustainability through Remote Sensing: A Review of Applications, Limitations, and Emerging Solutions

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**Abstract:** Remote sensing and Geographic Information Systems (GIS) have emerged as indispensable tools for sustainable environmental management, enabling efficient monitoring, analysis, and decision-making across various ecological domains. This work employs a systematic literature review approach using the PRISMA framework, synthesizing existing studies on the applications of remote sensing in key areas such as forest management, desertification control, water resource monitoring, and biodiversity conservation. It examines the effectiveness of different remote sensing techniques, including multispectral and hyperspectral imaging, LiDAR, and thermal infrared sensing, in tracking environmental changes over large spatial scales. The review highlights critical challenges such as data accessibility, sensor limitations, and the need for advanced analytical skills while exploring emerging solutions like machine learning integration and data fusion techniques. By providing a comprehensive analysis of remote sensing applications, this study offers valuable insights for policymakers, researchers, and environmental managers, advocating for the integration of geospatial technologies in sustainable resource governance. The research recommends interdisciplinary collaborations to leverage technological advancements to improve environmental monitoring and conservation efforts.

**Keywords:** geographic; environment; remote sensing; water; desert

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## 1. Introduction

Sustainable environmental management is essential for balancing present resource needs while safeguarding the well-being of future generations (Abdul–Wahab and Takase, 2019 ; Gifty et al., 2024). According to the U.S. Environmental Protection Agency (EPA), sustainable management requires the integration of environmental, economic, and social considerations to protect natural resources. However, human-induced environmental changes, including climate change (SDG 13: Climate Action), desertification (SDG 15: Life on Land), and biodiversity loss (SDG 14 – Life Below Water & SDG 15 – Life on Land), pose major global challenges (Ci, 2011; Cracknel & Varotsos, 2011; Li et al., 2011: Alorki et al., 2024; Tahiru et al 2024c; Tahiru et al., 2024d). Addressing these complex issues demands accurate identification, monitoring, and assessment to understand underlying processes, predict future trends, and develop effective policies (Gong, 2012).

Traditional environmental monitoring techniques face several limitations. Before the advent of computer-based methods, spatial analyses relied on manual data collection, which was often error-prone, inconsistent, and regionally fragmented. Furthermore, variations in measurement standards and equipment across different regions hindered large-scale, uniform data collection, limiting the accuracy, reliability, and efficiency of environmental assessments. These challenges underscore the

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need for innovative and scalable solutions to support sustainable development and environmental governance.

The emergence of Remote Sensing (RS) and Geographic Information Systems (GIS) has revolutionized environmental monitoring, enabling efficient data collection, processing, and analysis over vast geographical areas. Remote sensing provides a cost-effective, timely, and reliable approach to tracking environmental changes in real-time (Nemani et al., 2003; Berenfeld et al., 2006). To ensure that remote sensing data translates into actionable solutions, it must be precise, timely, and capable of supporting informed decision-making in key sustainability sectors (McGowen et al., 2001; Ticehurst et al., 2003).

Since the release of the Millennium Ecosystem Assessment (MEA) in 2005, there has been a surge in research utilizing remote sensing for environmental monitoring (Egoh et al., 2007; Skourtos et al., 2010; White et al., 2010; Costanza & Kubiszewski, 2012). Previous studies highlight the strong interconnection between social and environmental systems, emphasizing how ecosystem services such as provisioning, regulating, supporting, and cultural functions contribute to sustainable development (Costanza et al., 1997; Imhoff et al., 2004; de Groot, 2006; Reid et al., 2006; Deegan et al., 2012; Porras, 2012). By linking remote sensing data with SDG-driven policies, environmental managers can enhance decision-making, improve resilience to climate change, and foster biodiversity conservation.

The integration of remote sensing, GIS, and Global Positioning Systems (GPS) has empowered governments, private organizations, and research institutions, including those in Ghana, to implement effective environmental management strategies. These technologies facilitate the monitoring of coastal morphology, watersheds (SDG 6 – Clean Water and Sanitation), land cover, forest density (SDG 15 – Life on Land), and biodiversity (SDG 14 – Life Below Water & SDG 15 – Life on Land), particularly in remote and ecologically sensitive areas (Kumar et al., 2015). Given the growing role of remote sensing in environmental sustainability, this review aims to synthesize current applications, highlight key challenges, and explore future directions for improving environmental management practices through remote sensing technologies. By aligning geospatial innovations with the Sustainable Development Goals (SDGs), this study contributes to the advancement of data-driven sustainability solutions that promote climate resilience, biodiversity conservation, and responsible resource management.

## 2. Problem Statement

Environmental monitoring is essential for sustainable resource management; however, traditional methods face significant limitations in accuracy, efficiency, and scalability. Conventional approaches, such as ground-based surveys and manual data collection, are often labor-intensive, prone to inconsistencies, and inadequate for capturing large-scale environmental changes. Additionally, variations in measurement standards across regions create challenges in obtaining uniform and comparable datasets, hindering effective policy formulation and resource management strategies.

Remote sensing technology has emerged as a powerful tool to address these challenges, offering cost-effective, timely, and comprehensive data collection over vast geographical areas. Its applications align with Sustainable Development Goal (SDG) 15: Life on Land, which emphasizes protecting, restoring, and promoting sustainable use of terrestrial ecosystems, managing forests, combating desertification, and halting biodiversity loss. However, despite its advantages, barriers such as data accessibility, the need for advanced analytical skills, and technological infrastructure gaps—especially in developing countries—continue to hinder its widespread adoption.

This review seeks to address these gaps by critically examining the role of remote sensing in key environmental domains, including water resource management (SDG 6 – Clean Water and Sanitation), land-use changes (SDG 11: Sustainable Cities and Communities), and biodiversity conservation (SDG 13: Climate Action). It explores how remote sensing can enhance data-driven decision-making for sustainable development while identifying key challenges and opportunities for

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its effective implementation. By providing an in-depth analysis of current trends, methodologies, and case studies, this review contributes to the broader discourse on leveraging geospatial technologies for achieving the SDGs and promoting sustainable environmental governance.

## 3. Methodology

This review adopts a systematic literature review approach to synthesize existing research on remote sensing applications in environmental management (Takal et al., 2025, Tahiru et al., 2024a, Tahiru et al.,2024b). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was utilized to ensure a structured and transparent selection of relevant studies.

**Data Sources and Search Strategy:** Relevant peer-reviewed articles, conference proceedings, and reports were retrieved from major academic databases, including Web of Science, Scopus, Google Scholar, and ScienceDirect. The search terms used included "remote sensing for environmental management," "GIS and sustainability," "satellite-based environmental monitoring," and "applications of remote sensing in biodiversity conservation."

Inclusion and Exclusion Criteria: Studies were included if they:

- Focused on remote sensing applications in environmental sustainability, land-use change, water resource management, or biodiversity conservation.
- Were published in English between 2000 and 2024 to capture recent developments and trends.
- Provided empirical evidence, methodological advancements, or case studies relevant to the scope of this review.

Studies were excluded if they:

- Did not explicitly discuss remote sensing or GIS applications.
- Were purely theoretical without empirical validation.
- Had limited relevance to sustainable environmental management.

**Data Extraction and Analysis:** Selected studies were systematically analyzed based on their research objectives, methodologies, key findings, and contributions to environmental management. Themes such as water quality monitoring, vegetation assessment, and land-use planning were identified and categorized to highlight the various applications of remote sensing. Additionally, critical gaps in research, technological limitations, and policy implications were examined.

By employing a structured review methodology, this study ensures a comprehensive and objective synthesis of literature, facilitating a better understanding of the role of remote sensing in sustainable environmental governance.

## 4. Results and Discussion

*Key Themes in Remote Sensing Applications*

This section categorizes the major applications of remote sensing in environmental management based on a systematic analysis of existing literature. The review identifies key thematic areas where remote sensing technologies have been extensively applied and evaluates their contributions, limitations, and future potential. This review effectively discusses various applications of remote sensing in environmental management. However, some sections could be more structured and synthesized to avoid redundancy. Below are detailed observations for each thematic area:

**a. Water Quality Monitoring**

Water quality monitoring using remote sensing has become an essential tool for assessing water bodies at various spatial and temporal scales (Takal et al 2023). This section explores the application of remote sensing technologies, such as hyperspectral and multispectral imaging, in detecting water quality parameters like turbidity, chlorophyll concentration, total suspended solids, and dissolved organic matter. Remote sensing has enabled large-scale and real-time assessments of water pollution,

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eutrophication, and algal blooms, particularly in areas where in-situ measurements are costly and time-consuming (Tahiru et al., 2023).

The integration of GIS further enhances the visualization and analysis of water quality trends, supporting decision-making processes for water resource management. This review synthesizes findings from various studies that demonstrate the effectiveness of satellite-based and airborne remote sensing in assessing water pollution. Key remote sensing sensors used in water quality monitoring include MODIS, Landsat, Sentinel-2, and MERIS, which offer different spectral resolutions suitable for monitoring different water quality parameters. Additionally, the application of machine learning algorithms and data fusion techniques has improved the accuracy and reliability of remotely sensed water quality data.

However, despite the advantages, challenges such as atmospheric interference, cloud cover, and spectral mixing limit the accuracy of remote sensing-based water quality assessments. The review discusses potential solutions, including calibration with ground-truth data, advanced algorithmic corrections, and the integration of multiple remote sensing platforms to enhance the reliability of water quality monitoring. Further research is needed to improve retrieval algorithms and validate remotely sensed data with in-situ measurements for more precise and actionable insights.

This theme explores how remote sensing technologies, such as hyperspectral and multispectral imaging, have been used to monitor water quality parameters like turbidity, chlorophyll concentration, and suspended sediments.

**b. Crop Irrigation Demand Monitoring**

Remote sensing plays a crucial role in optimizing agricultural water use by assessing evapotranspiration rates, soil moisture content, and crop health. This section explores the application of remote sensing technologies, such as thermal infrared sensors and multispectral imaging, in monitoring irrigation demand. Key satellite sensors, including MODIS, Landsat, and Sentinel-2, have been widely employed in assessing irrigation requirements, enabling precision agriculture and efficient water resource management.

The integration of GIS further enhances spatial analysis, allowing for the identification of areas experiencing water stress and the development of targeted irrigation strategies. Case studies illustrating the application of remote sensing in drought risk management and irrigation scheduling highlight the effectiveness of these technologies in reducing water wastage and improving crop yield. Despite its advantages, challenges such as cloud cover interference, sensor resolution limitations, and the need for ground-truth validation persist. The study discusses solutions, including data fusion techniques, machine learning algorithms for predictive modeling, and the integration of remote sensing data with Internet of Things (IoT)-based soil moisture sensors to improve irrigation efficiency. However, further research is recommended to refine retrieval models and enhance the accuracy of irrigation demand assessments.

**c. Remote sensing in vegetation assessment**

Remote sensing offers significant advantages over ground based methods of mapping vegetation cover and discriminating species (Underwood et al.,2003; Mcgowen et al.,2001; Safiso et al., 2018) . Howbeit, it is a challenge to monitor vegetation using remote sensing because of the variations in vegetation radiation with respect to view zynell angle, terrain slope and sun zynell angle (Dymond et al.,2001; Tahiru et al., 2024e; Bishop and Congalton, 2006), atmospheric noise contributions, soil, humidity and shadow, variation in leaf area index, orientation of leaves and age difference of plants (Joshi et al.,2004; Tahiru et al., 2024f).

Landsat thematic mapper (TM) and other broadband satellite data are used in identifying vegetation patterns including weed infestations especially when they are widespread and dense (Underwood et al.,2003; Safiso et al., 2018) but its application is limited in identifying weed interspersed with other vegetation and small weed infestation (Lass et al.,2005).

In Ghana, Vorzdorgbe (2011) used Landsat ETM+ DECEMBER 2000 satellite imagery to transform analogue map of portions of kabo river forest reserve in the kajebi district of oti region to digital spatial data, the resultant vegetation type maps derived is used to provide spectral guide on potential ground areas likely to suffer forest fires in the dry season. Mensah et al (2018) applied supervised classification to detect land use cover and land cover changes in the bosomtwe forest reserve, spanning 1991, 2002 and 2017 using sentinel – 2 satellite imagery, landsat 4 – TM and Landsat 7 - ETM. It was concluded on the basis of the results obtained that land cover/use of bosomtwe range forest reserve have undergone significant change in the last 26years (Mensah et al., 2018). Tagoe and Mantey (2017) employed landsat images of years 1991, 2003 and 2017 for the classification of land cover / use impacted by anthropogenic activities, the results from the study indicated 18% increase in built up areas from 1991 – 2017 around weija reservoir.

**d. Application of GIS Data in Biodiversity and Watershed Management**

Remote sensing and GIS technologies are instrumental in biodiversity conservation and watershed management. These tools facilitate large-scale monitoring, habitat mapping, species distribution modeling, and ecosystem health assessments. Key satellite-based sensors such as Landsat, MODIS, and Sentinel-2 provide high-resolution imagery that supports conservation initiatives and watershed management strategies.

GIS enables spatial analysis of species richness, fragmentation patterns, and habitat connectivity, helping conservationists identify priority areas for intervention. Remote sensing also plays a critical role in tracking deforestation, land degradation, and the effects of climate change on biodiversity and water resources. Additionally, GIS applications in watershed management involve hydrological modeling, flood risk assessment, and water quality monitoring, ensuring sustainable management of freshwater resources.

Advanced methodologies, including drone-based monitoring, LiDAR, and AI-powered image classification, further enhance biodiversity and watershed assessments by offering detailed insights into ecosystem dynamics and hydrological processes. Despite these advancements, challenges such as data accessibility, resolution limitations, and the need for ground-truth validation persist.

While this section discusses potential solutions, including integrating multiple remote sensing datasets, leveraging machine learning algorithms, and adopting community-driven monitoring approaches. Future research should focus on improving data harmonization techniques and strengthening collaboration between conservation agencies, water resource managers, and remote sensing experts to enhance biodiversity and watershed management efforts.

Remote sensing and GIS technologies have become essential tools in biodiversity conservation, offering large-scale and real-time monitoring capabilities. These technologies facilitate habitat mapping, species distribution modeling, and ecosystem health assessments. Key satellite-based sensors such as Landsat, MODIS, and Sentinel-2 provide high-resolution imagery that supports biodiversity conservation initiatives.

GIS enables spatial analysis of species richness, fragmentation patterns, and changes in habitat connectivity, allowing conservationists to identify priority areas for intervention. Additionally, remote sensing helps track deforestation, land degradation, and the impacts of climate change on biodiversity. Advanced methodologies, such as drone-based monitoring, LiDAR, and AI-powered image classification, further enhance biodiversity assessments by providing detailed insights into ecosystem dynamics.

Despite significant advancements, challenges such as limited data accessibility, resolution constraints, and the necessity for ground-truth validation continue to hinder remote sensing applications. However, integrating multiple remote sensing datasets, utilizing machine learning algorithms, and implementing community-driven monitoring approaches have emerged as effective and sustainable solutions. Future research should prioritize refining data harmonization techniques and fostering stronger collaboration between conservation agencies and remote sensing experts to enhance the accuracy and impact of biodiversity management efforts.

**e. Forest Management Using Remote Sensing and GIS**

Forests play an essential role in regulating global climate, maintaining biodiversity, and providing ecosystem services. Effective forest management requires accurate and timely data to monitor changes in forest cover, assess forest health, and track deforestation and afforestation trends.

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Remote sensing and GIS technologies provide a robust framework for achieving these objectives, enabling large-scale analysis and long-term monitoring of forest ecosystems.

One of the primary applications of remote sensing in forest management is forest cover change detection. Multispectral and hyperspectral satellite sensors, such as Landsat, Sentinel-2, and MODIS, facilitate the classification of forest types, the detection of illegal logging activities, and the monitoring of reforestation efforts. LiDAR and RADAR technologies further enhance forest assessments by providing three-dimensional data on canopy structure and biomass estimation. This is particularly crucial for carbon sequestration studies and climate change mitigation strategies.

In addition to monitoring forest cover, remote sensing plays a vital role in wildfire detection and management. Thermal infrared sensors help identify active fires, assess burn severity, and predict fire-prone areas based on vegetation dryness and fuel load assessments. GIS-based spatial modeling assists in fire risk mapping, enabling policymakers to implement preventive measures and allocate resources effectively.

Despite these advancements, challenges such as cloud cover interference, sensor limitations, and data processing complexities remain. The integration of machine learning algorithms and data fusion techniques is increasingly being explored to enhance the accuracy and reliability of forest monitoring efforts.

**f. Combating Desertification Using Remote Sensing and GIS**

Desertification poses a significant environmental challenge, particularly in arid and semi-arid regions where unsustainable land use and climate change exacerbate land degradation. Remote sensing and GIS provide essential tools for assessing desertification trends, monitoring vegetation cover loss, and implementing sustainable land management strategies.

Satellite-derived vegetation indices, such as the Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI), are widely used to evaluate vegetation health and detect early signs of desertification. Time-series analysis of satellite imagery allows researchers to track long-term changes in land cover and assess the effectiveness of afforestation and soil conservation initiatives.

Furthermore, remote sensing plays a crucial role in drought monitoring and early warning systems. By analyzing soil moisture levels, precipitation patterns, and temperature anomalies, remote sensing data helps predict drought conditions and inform proactive mitigation strategies. GIS-based spatial analysis enables the mapping of high-risk areas, guiding policymakers in prioritizing resource allocation and intervention efforts.

Restoration efforts, such as afforestation and sustainable land management practices, benefit from remote sensing technologies that assess the suitability of degraded lands for rehabilitation. By integrating remote sensing data with field-based assessments, land managers can develop targeted interventions that maximize ecological restoration outcomes.

While remote sensing provides invaluable insights into combating desertification, challenges such as data accessibility, resolution constraints, and the need for localized calibration of satellite data persist. Advancements in remote sensing sensor technology and the increasing availability of high-resolution datasets are expected to enhance the effectiveness of remote sensing applications in desertification control.

## 5. Remote Sensing and Policy Integration in Ghana

Remote sensing findings play a crucial role in informing policy decisions related to environmental sustainability, land management, and disaster response (Tahiru et al., 2024e). By providing accurate, real-time data on deforestation, land degradation, water quality, and urban expansion, remote sensing enables policymakers to design evidence-based interventions that enhance resource governance. For instance, in forest conservation, satellite imagery can help enforce protected area regulations by detecting illegal logging activities and guiding reforestation efforts. Similarly, policymakers can use drought monitoring data to implement targeted water conservation strategies, ensuring resilience against climate change impacts.

*Case Studies in Ghana*

In Ghana, remote sensing technologies have been instrumental in tracking deforestation trends, particularly in the Atewa Range Forest Reserve and Kakum National Park. A study by Asante et al. (2020) utilized Landsat and Sentinel-2 satellite imagery to monitor deforestation rates in these regions, revealing significant forest loss due to illegal mining (galamsey) and agricultural expansion. The findings led to increased governmental action, including stricter enforcement of mining regulations and community-led afforestation initiatives.

Another significant application of remote sensing in Ghana is in monitoring the degradation of Lake Bosomtwe, the country's largest natural lake. Research conducted by Mensah et al. (2019) used satellite-derived vegetation indices (NDVI) and water quality assessments to identify the impact of land-use changes on the lake's ecosystem. The study provided valuable data for conservation efforts, prompting local authorities to implement policies restricting land encroachment and unsustainable fishing practices.

Remote sensing has also played a vital role in urban planning, particularly in managing urban sprawl in Accra and Kumasi. A study by Tagoe and Mantey (2017) analyzed Landsat images from 1991, 2003, and 2017 to assess the expansion of built-up areas around the Weija Reservoir. The results indicated an 18% increase in urban development over 26 years, leading to concerns over water resource management. In response, policymakers introduced stricter zoning laws and enhanced monitoring using GIS-based spatial planning tools.

Governments and regulatory bodies increasingly rely on remote sensing-derived data for urban planning, agricultural policy, and climate mitigation programs. The integration of geospatial intelligence into decision-making processes enhances transparency, accountability, and efficiency. In Ghana, for example, remote sensing is being utilized to track the impact of afforestation programs such as the Ghana Forest Plantation Strategy, which aims to restore degraded forest landscapes (Tahiru et al., 2024e). Satellite imagery has been used to assess the survival rates of newly planted trees and detect areas requiring additional intervention. Furthermore, remote sensing data support international environmental agreements by providing standardized monitoring mechanisms for commitments such as the Paris Agreement and the Convention on Biological Diversity.

To maximize the policy impact of remote sensing applications, it is essential to foster collaboration between scientists, government agencies, and local communities. Capacity-building initiatives should be prioritized to equip policymakers with the technical skills required to interpret geospatial data effectively. Additionally, frameworks for integrating remote sensing outputs into national environmental policies should be strengthened, ensuring that data-driven insights translate into actionable measures for sustainable resource management.

**Table 1.** Policy, Remote Sensing Applications, Limitations, and Solutions.

| Policy Target | Remote Sensing Application | Limitations | Emerging Trends and Solutions |
|---|---|---|---|
| **Forest Conservation** | Satellite imagery for deforestation monitoring | Cloud cover interference, limited temporal resolution | AI-driven image analysis, LiDAR for forest biomass estimation |

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|---|---|---|---|
| **Water Resource Management** | Remote sensing for water quality assessment | Spectral confusion, low spatial resolution in some sensors | Hyperspectral imaging, machine learning for water quality prediction |
| **Urban Planning** | GIS for land-use mapping and urban sprawl detection | Data inconsistency across regions, difficulty in real-time analysis | Smart city frameworks, integration of IoT with remote sensing |
| **Climate Change Mitigation** | Remote sensing for greenhouse gas emissions tracking | Sensor calibration issues, high cost of real-time monitoring | Use of drones and high-resolution sensors for localized monitoring |
| **Disaster Risk Reduction** | Satellite-based early warning systems for floods, wildfires | Delayed data processing, inaccuracies in extreme weather prediction | AI-enhanced forecasting models, real-time satellite data fusion |
| **Agricultural Policy** | Remote sensing for crop monitoring and precision farming | Limited access to high-resolution imagery, technical expertise gap | Open-source satellite data, increased farmer training in remote sensing |

The table above provides a structured overview of how remote sensing applications inform policy decisions, the limitations associated with their implementation, and potential solutions to improve efficiency and effectiveness.

## 6. Conclusion

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Remote sensing and GIS have revolutionized environmental monitoring by providing cost-effective, scalable, and reliable tools for assessing ecological changes over time. This review has highlighted their critical applications in forest management, combating desertification, monitoring water resources, and preserving biodiversity. Despite the significant progress made, challenges such as data accessibility, sensor limitations, and the need for specialized analytical skills continue to hinder their full potential. However, advancements in artificial intelligence, data fusion techniques, and improved sensor technologies offer promising solutions to overcome these barriers. Moving forward, greater emphasis should be placed on interdisciplinary collaborations, policy integration, and capacity-building efforts to ensure that remote sensing technologies are effectively utilized for sustainable environmental management. By fostering research and development in this field, policymakers and environmental managers can leverage remote sensing to make informed decisions that enhance ecological resilience and promote long-term sustainability

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