

The Role of Remote Sensing in Monitoring Deforestation and Land Cover Change

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Abstract

Deforestation and land cover change represent some of the most pressing environmental challenges of the 21st century, with far-reaching consequences for biodiversity, climate regulation, and sustainable development. Remote sensing has emerged as a powerful and indispensable tool in detecting, quantifying, and analyzing these changes at multiple spatial and temporal scales. By employing satellite imagery, aerial photography, and advanced geospatial techniques, remote sensing enables researchers to monitor deforestation patterns, identify drivers of land cover transformation, and assess the ecological impacts of human activities with high precision. The integration of Geographic Information Systems (GIS) with remote sensing further enhances the ability to model land use dynamics, forecast future scenarios, and support evidence-based policy formulation. Case studies from tropical forests, urban expansion zones, and agricultural frontiers illustrate how remote sensing provides consistent, repeatable, and cost-effective data critical for conservation planning and sustainable resource management. Moreover, advancements in machine learning and cloud-based platforms such as Google Earth Engine have revolutionized large-scale monitoring, enabling near real-time detection of forest loss. This paper argues that remote sensing is not only a scientific tool but also a strategic instrument for governments, NGOs, and international organizations in designing climate mitigation strategies, combating illegal logging, and achieving global sustainability goals.

Keywords: Remote Sensing, Deforestation, Land Cover Change, GIS (Geographic Information Systems), Satellite Imagery

Introduction

Deforestation and land cover change have emerged as critical global environmental concerns due to their profound impacts on climate regulation, biodiversity conservation, hydrological cycles, and sustainable livelihoods. With rapid urbanization, agricultural expansion, mining, and infrastructure development, vast areas of forests and natural landscapes are being degraded or converted, leading to ecosystem imbalances and accelerating global warming. Traditional ground-based methods of monitoring such changes, although valuable, are often limited in scope, time-consuming, and resource-intensive, particularly when applied to large and inaccessible regions. In this context, remote sensing has become an indispensable technological

advancement, offering a cost-effective, reliable, and comprehensive means to observe, analyze, and quantify deforestation and land cover change over time and space. By utilizing satellite imagery, aerial photography, and advanced geospatial analysis, remote sensing provides consistent and repetitive coverage that enables researchers, policymakers, and conservationists to detect patterns of forest loss, understand land use transitions, and assess the drivers and consequences of environmental change. The integration of Geographic Information Systems (GIS) with remote sensing further enhances spatial modeling and predictive capabilities, making it possible to map hotspots of deforestation, evaluate ecological risks, and design targeted interventions for conservation and sustainable resource management. Furthermore, advancements in cloud-based platforms and artificial intelligence have revolutionized real-time monitoring, empowering international organizations and governments to enforce regulations, mitigate illegal logging, and align with global climate agreements such as the Paris Accord and Sustainable Development Goals (SDGs). Thus, the role of remote sensing extends beyond academic inquiry to practical applications in environmental governance, positioning it as a vital tool in addressing the multifaceted challenges posed by deforestation and land cover change in the 21st century. Deforestation and land cover change are among the most pressing environmental issues of our time, driving biodiversity loss, altering atmospheric carbon balance, and threatening ecological sustainability. Forests, which serve as vital carbon sinks and habitats for countless species, are being cleared at unprecedented rates due to agricultural expansion, logging, urbanization, and infrastructure development. Monitoring these changes is essential to understanding their scale and impacts, yet traditional field-based surveys are constrained by cost, time, and geographic limitations. Remote sensing has revolutionized this process by providing accurate, large-scale, and repeatable data across different time periods and regions. Through satellite imagery and aerial observations, remote sensing enables detailed assessment of forest cover, land use dynamics, and environmental degradation. Its integration with Geographic Information Systems (GIS) allows for advanced spatial analysis and predictive modeling, making it possible to detect deforestation hotspots, evaluate risks, and support sustainable resource management. Technological advancements such as machine learning algorithms, cloud computing platforms like Google Earth Engine, and high-resolution imagery have further enhanced the capacity for real-time monitoring. This positions remote sensing not only as a scientific tool but also as a critical instrument for global policy implementation, environmental conservation, and climate change mitigation.

Optical imagery (Landsat, Sentinel, MODIS) for vegetation mapping

Monitoring deforestation and land cover change has become a global priority as forest ecosystems continue to be degraded by human and natural forces, leading to biodiversity loss, carbon emissions, and climate instability. Remote sensing, particularly through optical imagery, provides one of the most reliable and comprehensive approaches to detect, quantify, and analyze these changes across temporal and spatial scales. Satellite missions such as Landsat, with its decades-long archive, have enabled consistent long-term monitoring of forest cover change, making it possible to track gradual deforestation patterns and land use conversions over nearly five decades. Sentinel satellites, launched by the European Space

Agency, have enhanced this capacity with higher temporal frequency and finer spatial resolution, allowing for near real-time monitoring and better detection of small-scale deforestation events. Similarly, the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor has played a critical role in generating daily, large-scale imagery that is vital for global vegetation monitoring and early warning systems. These optical datasets, when processed using vegetation indices such as the Normalized Difference Vegetation Index (NDVI), provide valuable insights into vegetation health, biomass loss, and land degradation trends. The integration of such imagery with Geographic Information Systems (GIS) and advanced analytical techniques further allows researchers and policymakers to map deforestation hotspots, evaluate ecological impacts, and design targeted conservation interventions. By making environmental data accessible, consistent, and scalable, optical remote sensing imagery has transformed the way scientists, governments, and NGOs address deforestation challenges and land cover change, highlighting its indispensable role in advancing sustainable forest management and global climate action. The challenge of accurately monitoring deforestation and land cover change has long required tools capable of providing consistent, repeatable, and large-scale observations, a need fulfilled by remote sensing technologies such as the Landsat program. Since its inception in 1972, Landsat has offered the world's longest continuous record of Earth observation, enabling researchers to trace forest cover changes over nearly five decades. Its multispectral imagery allows for detailed vegetation mapping, forest health assessments, and the detection of land use transformations such as agricultural expansion, urban growth, and logging activities. By applying vegetation indices like NDVI and change detection algorithms, Landsat imagery has been instrumental in identifying long-term patterns of forest degradation and regeneration across diverse ecosystems. This historical continuity is particularly important in understanding cumulative impacts, validating climate models, and guiding sustainable forest management policies. As one of the most accessible and widely used optical datasets, Landsat continues to be a cornerstone in deforestation monitoring, bridging the gap between scientific research and environmental decision-making.

Sentinel's High-Resolution Contribution

Recent advancements in remote sensing, particularly with the launch of the European Space Agency's Sentinel satellites, have significantly enhanced the ability to monitor deforestation and land cover change in near real-time. Sentinel-2, with its high-resolution multispectral sensors, provides detailed imagery at 10–20 meter spatial resolution and frequent revisit times, making it possible to detect even small-scale deforestation events that might otherwise go unnoticed. This capability is especially crucial in regions where illegal logging, shifting cultivation, and encroachment occur rapidly and irregularly. The high spectral resolution of Sentinel imagery also supports advanced classification of vegetation types, crop mapping, and the identification of subtle changes in forest canopy health. By integrating Sentinel data with Geographic Information Systems (GIS) and platforms like Google Earth Engine, researchers and policymakers can generate accurate land cover maps, assess ecosystem risks, and design targeted interventions. Thus, Sentinel satellites represent a new era in deforestation monitoring,

combining accessibility, accuracy, and timeliness to strengthen conservation and land governance efforts worldwide.

MODIS for Global Monitoring and Alerts

At the global scale, monitoring deforestation and land cover change requires tools that provide continuous, large-area coverage, a role effectively fulfilled by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra and Aqua satellites. MODIS offers daily imagery at moderate spatial resolution, enabling consistent tracking of vegetation dynamics, fire disturbances, and seasonal forest changes. While it may not capture fine-scale deforestation events, its strength lies in providing near real-time updates on large-scale forest loss, making it invaluable for global monitoring systems such as the Global Forest Watch platform. Through indices like NDVI and Enhanced Vegetation Index (EVI), MODIS data allows scientists to assess vegetation health, biomass trends, and detect anomalies caused by droughts, fires, or human interventions. This synoptic perspective is crucial for international organizations, policymakers, and climate negotiators seeking to monitor compliance with conservation agreements, REDD+ projects, and sustainable development goals. By providing rapid, accessible, and globally consistent datasets, MODIS has become a vital component of the remote sensing toolkit for tracking deforestation and land cover change at planetary scale.

Radar (SAR) for monitoring under cloud cover (useful in tropics)

SAR in Cloud-Prone Regions One of the major challenges in using optical remote sensing for monitoring deforestation and land cover change is the persistent cloud cover in tropical regions, where some of the world's most critical forests are located. Synthetic Aperture Radar (SAR) technology has proven invaluable in overcoming this limitation, as it uses microwave signals that can penetrate clouds and provide reliable data regardless of weather or lighting conditions. Unlike optical imagery, SAR is capable of capturing forest structure, detecting subtle changes in canopy density, and monitoring deforestation activities in areas that remain obscured for much of the year. This makes SAR particularly effective in regions like the Amazon Basin and Southeast Asia, where seasonal rainfall and cloudiness hinder consistent optical observations. By combining SAR with optical imagery, researchers achieve more robust deforestation assessments, ensuring continuous monitoring and reducing data gaps. The integration of SAR data into global forest monitoring systems highlights its critical role in advancing reliable, all-weather surveillance of land cover dynamics.

LiDAR for Biomass and Canopy Studies

While optical and radar sensors provide valuable insights into surface changes, LiDAR (Light Detection and Ranging) has revolutionized forest monitoring by offering detailed three-dimensional measurements of canopy height, density, and structure. This capability allows scientists to estimate above-ground biomass with greater accuracy, a crucial factor in understanding carbon storage and the role of forests in climate regulation. LiDAR has been widely applied in mapping forest degradation, quantifying logging impacts, and modeling habitat availability for biodiversity conservation. Its ability to generate fine-scale vertical

profiles of vegetation makes it indispensable in regions where precise data on forest structure is required to inform conservation and reforestation projects. Airborne LiDAR systems, as well as spaceborne missions such as NASA's GEDI (Global Ecosystem Dynamics Investigation), have expanded opportunities for large-scale biomass assessment, complementing traditional optical and radar datasets. By providing structural detail that other sensors cannot, LiDAR enhances the comprehensiveness of deforestation and land cover monitoring.

Integrating SAR, LiDAR, and Optical Data

The increasing complexity of deforestation drivers and land cover change requires integrated approaches that combine the strengths of multiple remote sensing technologies. While optical imagery from Landsat, Sentinel, and MODIS provides long-term and frequent observations of vegetation cover, it is limited by cloud interference. SAR overcomes this by enabling all-weather monitoring, especially in tropical rainforests where cloud cover is persistent, thereby ensuring continuous data collection. At the same time, LiDAR adds a unique dimension by capturing three-dimensional canopy structure and biomass estimates, critical for carbon accounting and climate change models. The integration of SAR, LiDAR, and optical datasets creates a powerful framework for monitoring not just surface changes but also forest volume, density, and degradation intensity. Such multi-sensor approaches enhance the accuracy of deforestation assessments, enable the detection of illegal logging activities, and provide policymakers with scientifically robust information for forest governance, biodiversity protection, and climate mitigation strategies. This synergy of technologies demonstrates the evolving role of remote sensing in delivering holistic, high-resolution insights into land cover change.

LiDAR for canopy structure and biomass estimation

Among the various remote sensing technologies available for monitoring deforestation and land cover change, LiDAR (Light Detection and Ranging) stands out as a highly effective tool for estimating forest canopy structure and above-ground biomass, two critical indicators of ecosystem health and carbon storage capacity. Unlike optical or radar sensors, which primarily capture surface reflectance or backscatter, LiDAR uses laser pulses to generate precise three-dimensional representations of forest landscapes, including canopy height, density, and vertical layering. This capability makes LiDAR particularly valuable in assessing subtle forms of forest degradation, such as selective logging, understory clearance, or changes in canopy gaps, which may not be easily detected through satellite imagery alone. By providing accurate biomass estimates, LiDAR data contributes significantly to carbon accounting, climate modeling, and global initiatives such as REDD+ that aim to reduce emissions from deforestation and forest degradation. Airborne LiDAR surveys have been widely used in tropical forests to map biomass distribution at local scales, while spaceborne missions like NASA's GEDI (Global Ecosystem Dynamics Investigation) have extended these applications to global monitoring, enabling large-scale assessments of forest carbon stocks. The integration of LiDAR with optical and radar data enhances the ability to track both horizontal and vertical forest changes, offering a comprehensive approach to understanding land cover dynamics. As climate change

intensifies and the demand for reliable environmental data grows, LiDAR is becoming an indispensable component of remote sensing strategies for sustainable forest management and conservation.

Deforestation Drivers Detected – Agriculture, logging, mining, shifting cultivation, infrastructure, and urban expansion can be spatially identified and tracked. Deforestation is rarely a random or isolated process; it is largely driven by identifiable human and natural factors that vary across regions but collectively contribute to large-scale forest loss and land cover change. Remote sensing has proven to be an indispensable tool in detecting, mapping, and analyzing these drivers with high spatial and temporal accuracy, enabling researchers and policymakers to trace the underlying causes of environmental degradation. Key anthropogenic drivers include agricultural expansion, where forests are cleared for commercial crops such as soy, oil palm, or cattle ranching, and logging activities, both legal and illegal, which remove valuable timber and open up forest interiors for further exploitation. Infrastructure development, including roads, dams, and mining projects, often acts as a catalyst for secondary deforestation by facilitating human access to previously remote areas. Urbanization and settlement expansion also transform forest landscapes into built environments, while shifting cultivation practices continue to alter land use in several tropical regions. Remote sensing imagery, particularly from Landsat, Sentinel, and MODIS, combined with spatial analysis in Geographic Information Systems (GIS), allows for the detection of these drivers by identifying patterns such as patchy clearings, road networks, plantation boundaries, and mining scars. Natural drivers such as forest fires, droughts, and storm events can also be monitored, distinguishing them from human-induced changes through spectral signatures and temporal patterns. By capturing both direct and indirect causes of deforestation, remote sensing provides a holistic view of land cover transformation, supporting targeted interventions, enforcement measures, and sustainable land management strategies.

Conclusion

Remote sensing has fundamentally transformed the monitoring and understanding of deforestation and land cover change, providing tools that are both scientifically rigorous and practically indispensable for environmental management. By integrating optical imagery, radar, and LiDAR technologies, researchers can overcome limitations posed by weather conditions, spatial resolution, and canopy complexity to generate a more holistic and accurate picture of forest dynamics. These technologies not only help in quantifying forest loss but also in identifying its underlying drivers—agriculture, logging, mining, shifting cultivation, infrastructure development, and urbanization—thus linking deforestation patterns to socio-economic processes. Beyond detection, remote sensing has opened opportunities for predictive modeling and scenario-building, helping policymakers and conservationists anticipate future changes and plan proactive interventions. The role of remote sensing extends beyond academic inquiry into practical applications for climate change mitigation, biodiversity protection, and international policy frameworks like REDD+ and the Sustainable Development Goals (SDGs). Moreover, the increasing integration of artificial intelligence, cloud-based platforms, and big data analytics is enhancing the timeliness and accessibility of monitoring systems, enabling

near real-time decision-making at local, national, and global levels. Despite its strengths, challenges remain in terms of data accessibility, processing expertise, and the need to integrate ground-based validation with satellite observations. Nevertheless, the trajectory of technological advancement suggests that remote sensing will continue to evolve as a cornerstone of global environmental governance. Ultimately, by bridging the gap between science, policy, and practice, remote sensing empowers societies to tackle deforestation more effectively and move toward a sustainable future where natural ecosystems are preserved alongside human development needs.

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