

Application of Remote Sensing and Geographic Information Systems for Natural Resource Management of Forest Ecosystems

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1. Introduction

Forest ecosystems constitute one of the fundamental components of the terrestrial biosphere, as they perform essential functions in climate regulation, the carbon cycle, biodiversity conservation, hydrological regulation, soil protection, and the provision of ecosystem services. They also represent one of the main terrestrial carbon reservoirs and contribute to climate change mitigation through the capture and storage of CO₂ [1]. However, these ecosystems are exposed to multiple disturbances, including droughts, wildfires, pests, diseases, and land-use changes. The interaction and accumulation of these factors can alter the structure, composition, productivity, distribution, and resilience of forests ecosystems, generating complex responses across different spatial and temporal scales that are difficult to assess using conventional observation methods [2]. In this context, access to reliable spatial and temporal information has become essential for understanding the dynamics of forest ecosystems and strengthening decision-making aimed at their management and conservation. Traditionally, forest inventories have been one of the main sources of information for characterizing forest ecosystems, as they provide direct measurements of structural and ecological attributes. However, their application over large areas can require substantial human and financial resources.

In response to these limitations, advances in remote sensing technologies and Geographic Information Systems (GIS) have enabled their partial resolution through the integration of information acquired from remote sensors with field observations [3]. This integration facilitates the analysis of the distribution, structure, composition, and dynamics of forest ecosystems, as well as the monitoring of vegetation cover and condition across different spatial and temporal scales. Likewise, the development of sensors with higher spatial, spectral, and temporal resolution, together with advanced spatial processing and analytical techniques, has strengthened the capacity to generate timely and consistent information to support the assessment, monitoring, and sustainable management of forest ecosystems [4,5].

The need to integrate remote sensing with GIS for forest management and monitoring constituted the starting point for the Special Issue “Application of Remote Sensing and Geographic Information Systems to Natural Resource Management of Forest Ecosystems,” published in *Forests* within the Forest Inventory, Modeling and Remote Sensing section. The collection brought together nine research studies addressing different problems related to the inventory, monitoring, health, dynamics, vulnerability, and conservation of forest ecosystems through geospatial technologies [6–13]. The decision to bring these studies together responded to a specific scientific need. Contemporary forest research is moving



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from the isolated use of sensors and point-based measurements toward integrated systems for observation, analysis, and prediction. Although the nine articles address different problems and were conducted in diverse geographical contexts, they share a common scientific direction: transforming heterogeneous observations into spatially explicit information on the structure, condition, dynamics, and vulnerability of forest ecosystems.

From our perspective as Guest Editors, this convergence represents the main scientific contribution of the collection. The Special Issue is not simply a compilation of studies employing remote sensing and Geographic Information Systems (GIS); collectively, the contributions demonstrate a methodological transformation in forest science, characterized by a transition from point-based measurements toward multiscale, multitemporal, and multisensor observation approaches. This methodological evolution makes it possible not only to describe the structure and distribution of forest ecosystems, but also to understand their ecological processes and spatial dynamics, generating more robust information for assessment, conservation, and decision-making in forest management.

2. Overview of the Special Issue Articles

The nine articles comprising this collection present diverse applications of remote sensing, GIS, and advanced technologies for the observation and monitoring of forest ecosystems. Although each contribution addresses a particular problem and analytical scale, their collective consideration reveals a common scientific trend: the increasing adoption of multidisciplinary approaches that integrate diverse data sources, spatial and temporal scales, and analytical methods to provide a more comprehensive understanding of the dynamics, complexity, and functioning of forest ecosystems.

For example, Compeán-Aguirre et al. [6] evaluated five two-dimensional algorithms for estimating diameter at breast height (DBH) using terrestrial laser scanning (TLS) data. The study demonstrates the potential of three-dimensional point clouds to automate measurements traditionally conducted in the field. This contribution is important because DBH is one of the fundamental attributes of forest inventories and is used to estimate volume, biomass, and carbon. The use of TLS provides detailed information on tree structure and enable the exploration of automated procedures for extracting dendrometric variables. At the same time, the results show that algorithm accuracy depends on factors such as point-cloud density, occlusion, and forest structure. These considerations are consistent with previous research demonstrating the potential of terrestrial laser scanning for characterizing forest structure, while also highlighting challenges associated with crown complexity, occlusion, and the processing of large point clouds.

In turn, Tran et al. [7] broadened this perspective by comparing different Light Detection and Ranging (LiDAR) data acquisition methods for pine forest inventories in Korea. The comparison between airborne LiDAR (ALS) and terrestrial mobile laser scanning (HMLS) systems demonstrates the potential for combining platforms with different observation scales and perspectives. While airborne LiDAR enable the coverage of extensive areas, terrestrial systems provide detailed information on the structure of individual trees. This complementarity is particularly important for advancing toward three-dimensional and automated forest inventories. More broadly, the integration of LiDAR data with field information has proven to be an effective strategy for estimating forest attributes and variables related to volume and biomass.

These two studies illustrate a transition toward three-dimensional, automated, and potentially multiscale forest inventories. Forest inventory is progressively moving away from exclusive reliance on manual measurements conducted on individual trees or plots and is beginning to incorporate digital representations of the complete forest structure [5]. This trans-

formation may have important implications for biomass and carbon monitoring, particularly when LiDAR data are integrated with satellite information and field measurements.

Insects, pathogens, droughts, and other stressors can produce spatial and temporal changes that are not always readily detectable through conventional observations. Accordingly, another important aspect of the Special Issue was the monitoring of forest disturbances and health. In the study conducted by Dumarevskaya and Parent [8], forest mortality associated with a spongy moth outbreak in temperate forests of Rhode Island was modeled using Landsat-derived defoliation information and environmental variables. The integration of spectral information with variables related to soil, drought, and forest characteristics demonstrates the importance of considering ecological context in disturbance models. This approach is consistent with the evolution of forest monitoring systems based on Landsat time series, which enable the detection of disturbances and recovery processes across broad spatial and temporal scales.

Complementarily, Šmits et al. [9] analyzed the relationship between stand properties and the accuracy of damage detection caused by *Ips typographus*. Their study raises a fundamental question: the accuracy of remote detection depends not only on the sensor or algorithm, but also on stand characteristics and spatial context. This observation is particularly important in heterogeneous forest landscapes, where stand structure, composition, and density can affect the signal recorded by sensors and, consequently, the ability to detect disturbances. This conclusion has important implications for the development of operational forest surveillance systems. Satellites provide extensive spatial coverage and temporal continuity, whereas unmanned aerial vehicles (UAVs) can provide higher-resolution information for verifying potentially affected areas.

The contribution by Arcidiaco et al. [10] provided another example of integration by combining information acquired using UAVs with climatological and meteorological data and phytosanitary assessments to monitor the health of *Abies nebrodensis*. The research demonstrates that spectral information gains greater value when interpreted jointly with environmental variables and direct observations of tree condition. This approach is particularly relevant for threatened species or small populations, where the ability to conduct high-resolution observations using UAVs can provide an important advantage. UAVs have experienced considerable expansion in forestry applications because of their ability to acquire high-resolution imagery, conduct repeated flights, and focus on specific areas. Their use has demonstrated potential for inventory, structural characterization, health monitoring, damage assessment, regeneration, and phenological change detection. However, their greatest potential does not necessarily lie in replacing satellites, but rather in complementing satellite observations within multiscale systems.

Among the studies addressing forest vulnerability and adaptation to climate change, Özel et al. [11] analyzed the vulnerability and adaptation of the coastal forests of İğneada Longos, Türkiye, using historical land-cover and land-use information and future climate change scenarios. The study represents an important transition from describing the current state of an ecosystem toward assessing potential future scenarios. This predictive capacity is one of the main opportunities offered by geospatial information applied to forest management. Landsat time series constitute an exceptional source for this type of analysis because of their continuity of observations over several decades. The incorporation of Sentinel-2 complements these capabilities through higher spatial and spectral resolution and an acquisition frequency suitable for vegetation monitoring.

The work by Tejjido-Murias et al. [12] addressed a fundamental aspect of this new generation of analyses: the quality and consistency of image processing. The authors evaluated different atmospheric, topographic, and bidirectional reflectance correction procedures for Sentinel-2 imagery implemented in Google Earth Engine. Their results show that processing

decisions can significantly influence land-cover classification, particularly in regions with complex topography. This contribution is especially relevant given the growing availability of satellite imagery and cloud-computing platforms. Google Earth Engine, for example, provides access to and enable the processing of large volumes of geospatial information and facilitates the development of multitemporal analyses at regional and global scales.

Another prominent application of these technologies was the analysis of temporal ecosystem dynamics, particularly phenology, as a sensitive indicator of vegetation responses to environmental conditions and changes associated with climate change in forest ecosystems. Park et al. [13] evaluated the feasibility of detecting phenological events using UAV orthomosaic time series and color-based indices. The study demonstrates that these platforms can provide information at the tree or crown scale, with a level of spatial resolution that is difficult to achieve using conventional satellite sensors. The importance of this contribution lies in the use of UAVs to observe individual trees and plots at very high spatial resolution, while satellites enable the analysis of patterns at stand and landscape scales. Integrating both perspectives could improve our understanding of how individual tree responses are expressed as regional phenological patterns.

The study by Wang et al. [14] focused on the use of GIS for conservation, connectivity, and spatial planning. Wang et al. [14] developed a forest ecological security pattern for the source region of the Huai River–Dabie Mountains by integrating ecosystem services, spatial analysis, landscape connectivity, and circuit theory. The study demonstrates how GIS can evolve from tools primarily intended for map production into analytical systems capable of identifying priority areas for conservation, restoration, and connectivity.

As Guest Editors, we consider that the nine articles included in this Special Issue reflect a significant transformation in forest ecosystem research and management: the transition from approaches based on individual observations and sensors toward integrated strategies that combine different information sources, spatial and temporal scales, and analytical methods. The complementarity among TLS and LiDAR, UAVs, satellite sensors such as Landsat and Sentinel, climatic and meteorological data, field observations, machine learning, and GIS enable a more comprehensive understanding of forest ecosystem structure, dynamics, condition, and vulnerability.

This integration is particularly relevant because of the complexity, heterogeneity, and dynamics of forests, whose characterization can hardly be addressed using a single information source. While optical sensors enable the analysis of vegetation spectral properties, LiDAR provides detailed information on three-dimensional structure, UAVs enable high-resolution observations at the local scale, and satellite sensors allow these observations to be extended across broader regional and temporal scales. In this context, machine learning represents an increasingly important tool for classification, prediction, and change and disturbance detection; however, its application should be accompanied by rigorous validation, uncertainty assessment, interpretability, and model transferability across different environmental conditions.

A key contribution of this collection is to demonstrate that the full potential of geospatial technologies extends beyond the generation of cartographic products, encompassing their capacity to integrate diverse sources of information and transform them into actionable knowledge to support informed decision-making. GIS plays an articulating role in this process by enabling the integration of spatial, temporal, environmental, and socioecological information within a common analytical framework. In this way, maps cease to be merely final products and instead become components of monitoring, modeling, and management-support systems.

The studies included also demonstrate that the future of forest monitoring will increasingly depend on multisensor and interdisciplinary systems capable of connecting different

observation scales: from individual trees to landscapes, and from field measurements to satellite observations. This perspective is particularly relevant in the face of climate change, the increasing frequency of disturbances, and the need to develop more adaptive and evidence-based management strategies. Collectively, the nine articles represent different expressions of this scientific transformation, addressing aspects related to the three-dimensional structure of forests, forest health and mortality, UAV-based monitoring, climate vulnerability, satellite time series, phenology, and conservation [11–14]. Although each contribution addresses specific research questions, they share a fundamental premise: the integration of spatial and temporal information is an essential tool for understanding complex forest ecosystems and supporting more efficient management decisions.

As Guest Editors, we consider that this Special Issue contributes to consolidating a vision in which remote sensing, GIS, LiDAR, UAVs, satellite sensors, field data, and machine learning should not be understood as isolated technologies, but rather as components of an information ecosystem aimed at observing, understanding, predicting, and managing forest resources. The next challenge will be to advance toward more interoperable, reproducible, and operational systems while strengthening independent validation, uncertainty assessment, and model transferability across regions and environmental conditions.

3. Conclusions

The studies presented in this Special Issue demonstrate the growing importance of integrating remote sensing, GIS, forest science, ecology, and data science to address the complexity of contemporary forest management. Ultimately, advancing forest management will depend on integrating geospatial technologies with interdisciplinary knowledge to transform increasingly complex environmental observations into actionable, evidence-based decisions. This integration requires not only continued technological development but also stronger collaboration among specialists and the effective integration of diverse sources of knowledge. Collectively, the contributions of this Special Issue highlight the potential of innovative geospatial approaches to support more precise, adaptive, sustainable, and evidence-based forest management and to address the environmental challenges increasingly affecting forest ecosystems.

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