remote sensing

Editorial

Advances in Vegetation Structure Modelling Using Remote Sensing to Support the Acquisition of Sustainable Development Goals through Forest Management

María Teresa Lamelas [1,2,*] and Darío Domingo [2,3]

[1] Centro Universitario de la Defensa Zaragoza, Academia General Militar, Ctra. de Huesca s/n, 50090 Zaragoza, Spain
[2] GEOFOREST-IUCA, Department of Geography, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain; dario.domingo@uva.es
[3] EiFAB-iuFOR, University of Valladolid, Campus Duques de Soria, 42004 Soria, Spain
* Correspondence: tlamelas@unizar.es; Tel.: +34-976-73-98-66

1. Introduction

Forest ecosystems cover 31% of the world [1], providing a wide range of essential ecosystem services in terms of climate and hydrological regulation, biodiversity protection, timber and food production, or recreation, as well as others. However, forests are subject to changes due to natural hazards and anthropogenic pressures, which are predicted to increase under current climate change and socio-economic demands. Sustainable forest management is paramount to reaching two sustainable development goals (SDGs) set out to be achieved in the 2030 Agenda: take actions for the environment by combatting climate change (Goal 13), and protect, restore, and promote the sustainable use of terrestrial ecosystems (Goal 15). Current and future forestry practices rely on quantitative and qualitative information traditionally collected using field-based surveys, and increasingly complemented or surrogated with remote sensing datasets.

The fast development of remote sensing techniques, which provides cost-effective and spatially explicit information [2], has broadened the applications in forest ecosystems. The characterization of forest structure, as an essential variable of ecosystem function and diversity [3], has improved due to the development of active sensors such as Light Detection and Ranging (LiDAR), the open availability of medium-resolution datasets from passive programs, and the recent advance of unmanned aerial vehicles. In addition, the technique developments have been linked to advances in computational power and empirical or physical modelling methods. As an example, the use of multi-sensor approaches improves the temporal resolution for near real-time monitoring, the high-resolution of laser scanners might even surpass field measurements, and the use of unmanned aerial vehicles enables forest change and biodiversity monitoring at ad hoc spatial and temporal scales. This Special Issue is aimed at presenting state-of-the art studies covering the application of advanced remote sensing techniques to vegetation structure modelling, with the aim of supporting sustainable forest management.

2. Overview of the Published Contributions in This Special Issue

This Special Issue, entitled "Advances in Vegetation Structure Modelling to Support the Sustainable Development Goals Acquisition through Forest Management", presents the results from eight peer-reviewed papers and one peer-reviewed technical note. The contributions combine data across sensors, techniques, and modelling approaches adopting several modern applications for forest ecosystems. The contributions enrich the geographical knowledge of different ecosystems around the globe, including Central Europe, the semi-arid forests of the Zagros Mountains, the tropical forests of Brazil, and the Mediterranean region.

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Contextually, contributions fall within three major topics related to the 2030 Agenda SDGs 13 and 15: (i) promote the sustainable use of forest ecosystems; (ii) ensure the conservation of forest biodiversity while reducing the impact of invasive alien species; (iii) strengthen the resilience of forest ecosystems to hazards.

Forest ecosystems provide a wide variety of services from timber to non-timber products that can be predicted with remote sensing tools to identify management options while promoting sustainable uses of forests. Tupinamba et al. [4] assessed the technical configuration parameters of the handheld laser scanner (scanning path and point cloud transformation modes including rigid and non-rigid) to demonstrate its efficiency for forest inventory purposes (tree detection, diameter, and height) in a Mediterranean mixed forest composed of *Pinus pinaster*, *Quercus pyrenaica*, and *Alnus glutinosa*. Martinez-Rodrigo et al. [5] proposed a multi-source approach based on climate data, Landsat images, field data, and a mobile terrestrial laser scanner to analyse the influence of climatic, primary productivity, and structural drivers (biomass, basal area, or stand density) on triggering mushroom fruiting in Mediterranean *Pinus pinaster*.

The loss of biodiversity is one of the major conservation challenges that we face under the impact of current climate change [6]. García-Galar et al. [7] assessed the performance of single-photon LiDAR and Sentinel-2 to evaluate the conservation statuses in *Quercus robur*, *Quercus pyrenaica*, and *Quercus faginea* habitats of Spain. The authors revealed the usefulness of single-photon LiDAR metrics, mainly structural diversity and cover, for conservation statuses and showed that Sentinel-2 spectral indices had a low contribution. Hoffrén et al. [6] addressed the importance of mountain habitats to provide climate microrefugia to organisms by combining airborne laser scanning and Landsat series-derived datasets. Topographic variables, mainly elevation, are consistent predictors in soil and air microclimatic models, and forest variables (canopy closure, coefficient of variation of heights, and normalized vegetation index) contribute more to model maximum temperatures. Forests narrow thermal ranges and offset extreme temperatures at a local scale. The transformation of habitats due to invasive alien plants, namely *Acacia dealbata* Link, was assessed by Domingo et al. [8] using Sentinel-2 data in northwest Spain. A methodological approach based on phenological spectral differences between blooming and pre- or post-flowering months was proposed to support an early detection of invasive species.

Forests are subject to changes caused by natural (e.g., droughts, heatwaves, insects, and wildfires) or anthropic (e.g., logging and deforestation) disturbances. Two articles proposed complementary approaches to monitoring forest changes as a consequence of recent repeated droughts (i.e., 2018) and heatwaves in Germany. Thonfeld et al. [9] revealed the usefulness of the spectral disturbance index (DI), derived from Sentinel-2 and Landsat 8 data, to map canopy cover loss at 10 m spatial and monthly temporal resolutions. Coniferous stands of central Germany were most heavily affected by forest loss due to natural disturbances and sanitation logging. Kacic et al. [10] proposed a multi-sensor approach combining the Global Ecosystem Dynamics Investigation (GEDI) mission as ground truth and Sentinel-1 and Sentinel-2 datasets to analyse changes in forest structure (cover, height, and biomass) between 2017 and 2022 at a national scale. The authors found a major decline in tree height, cover, and subsequent loss of aboveground biomass (AGB) in central and western Germany. Furthermore, Ghasemi et al. [11] evaluated the tree decline in a semi-arid oak forest in Zagros Mountain (Iran) using UAV imagery. The authors developed a new edge-detection method to delineate tree crowns, and subsequently, extract tree height and crown area. The computation of texture indices at crown level allows individual tree decline to be monitored. Entropy and dissimilarity texture indices, derived from the grey-level co-occurrence matrix (GLCM), show the highest correlations with the phenotypic decline index. The aforementioned three papers focus on forest losses after disturbances, while Stoddart et al. [12] analyse forest aboveground biomass change, in terms of losses and gains (i.e., regrowth) in the tropical forests of Brazil. The authors propose a conceptual model based on three ecosystem morphological traits (EMTs), namely height, cover, and complexity, to predict aboveground biomass change using multi-temporal

LiDAR data. The selection of EMT metrics with a biological link to forest ecosystems favour model standardization.

Technically, the contributions included in this Special Issue have used a variety of remote sensing passive (i.e., multispectral) and active (i.e., LiDAR and Synthetic Aperture Radar (SAR)) sensors mounted in terrestrial, unmanned aerial vehicles, airplanes, and satellite platforms to perform analyses at different spatial and temporal resolutions. Three contributions combined passive and active sensors for multipurpose applications serving not only to improve the accuracy of forest change [10], mushroom yield production [5], and microclimate [6] predictions, but also to provide a greater link to biological processes, including vegetation structure, or the possibility to increase temporal resolution in often cloudy environments. The remaining six contributions use only one remote sensing sensor. For example, the terrestrial handheld laser scanner constitutes a useful data source for individual tree detection (detection rates of 88 and 92%), tree diameter, and tree height (relative RMSE below 10%) [4], and similarly, the terrestrial laser scanner is a suitable choice for volume or canopy cover prediction [5]. Though the visualization geometry of terrestrial systems may slightly underestimate some metrics (i.e., height), it is more precise than field measurements in heterogeneous stands. Unmanned aerial vehicles, which can mount a variety of remote sensing sensors, provide both spectral and structural information (i.e., point clouds derived from Structure from Motion) and are also a suitable choice for predicting individual tree structural properties such as tree detection (F-score = 0.91), height, or crown area [11]. The applicability of airborne laser scanning, being one of the most widely used sensors for forest structure characterization, was reinforced by its capability to create standardizable models of AGB based on ecosystem morphological traits (EMTs) [12] and to predict conservation status [7]. Though active sensors provide a better fit for complex structural metrics (i.e., vertical structural complexity), the use of medium-resolution multispectral sensors is feasible for predicting canopy cover changes [9] and the presence of invasive alien species [8], nowadays constituting global open-source information for forest monitoring.

The technological developments took place not only in remote sensing platforms and sensors, but also in computational power and advances in modelling methods, with these ranging from empirical (parametric and non-parametric statistical approaches) to physical methods, such as Radiative Transfer Models (RTMs). Although RTMs provide broader universality and have been previously used for forest structure analysis [13,14], the contributions of this Special Issue focus on the use of empirical models. In particular, four contributions used machine learning algorithms, such as random forest [7,8,10], for classification and forest change analysis, and a support vector machine [11] for selecting edges in tree crown delineation. Furthermore, parametric models, such as linear regression, were used for forest inventory metric prediction [4,10], generalized linear models for microclimate prediction [6], and generalized additive mixed models, which combine the flexibility of generalized additive models while accounting for random effects (i.e., plot), were used for predicting yield mushrooms. The choice of different algorithms may be linked to dataset size, feasibility, or even the application, but should be parsimonious and pursue a biological meaning [12], so as to enhance sustainable forest management.

3. Conclusions

To summarize, the contributions of this Special Issue towards reaching forest-related sustainable development goals demonstrate the usefulness of remote sensing datasets. The analysis generated useful products for the community, enhancing model techniques, improving current methodologies, and broadening applications for forest ecosystems. The increasingly high density of 3D datasets and the open access to passive remote sensing information allows for new visions towards creating digital twins for the near real-time monitoring of forest ecosystems.

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