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Recognition of specified errors of Individual Tree Detection methods based on Canopy Height Model

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ABSTRACT

In the last two decades, many individual tree detection (ITD) methods have been developed based on Airborne Laser Scanner (ALS) data, but their application still has some shortcomings. In complex and dense forest stands, the number of tree segments extracted from Canopy Height Model (CHM) are frequently over- and under-estimated, reducing the ability to predict stand structure. This study presents the possibility of distinguishing correct from erroneous segments resulting from the ITD methods based on CHM. For this purpose, three machine learning methods were tested: Random Forest (RF), Support Vector Machine and k-Nearest Neighbor among which the RF algorithm gave the best results. Groups of predictors based on segment geometry as well as structural and intensity metrics from the ALS point cloud were used. From the whole set of predictors, the ratio of segment perimeter to its area proved to be the most important. Using RF classifier, it was possible to identify under-segmentation and over-segmentation errors, as well as correct segments, with high accuracies for training (OA = 87.0% and $\kappa = 0.794$) and test data (OA = 85.3 and $\kappa = 0.641$). Recognition of specific segmentation errors is important in that it can be used to determine which conditions favour the occurrence of errors and which tree species are more likely to be incorrectly segmented. Therefore, the study verified the error susceptibility of individual tree species. This can help improve calibration and development of segmentation algorithms according to the tree species analysed.

1. Introduction

Remote sensing opens new possibilities for operational forest inventories, in particular Airborne Laser Scanning (ALS), which has been widely used in the last two decades and has contributed to increasing the productivity of local inventories (Næsset, 2007; Camarretta et al., 2019). With these data, it is possible to obtain information about an individual tree (Hyypä and Inkinen, 1999).

Individual tree detection (ITD) methods, using ALS data, can be mainly divided into point cloud-based, raster-based in the form of a Canopy Height Model (CHM) and methods that combine both datasets. There are also studies using hybrid techniques that combine different types of geospatial data with a variety of *a priori*, e.g. tree shape parameters (Lähivaara et al., 2014), or allometric information (Swetnam and Falk, 2014). By 2015, practically two third of all ITD methods using ALS data were based on a raster (Zhen et al., 2016). However, in recent years, research has focused more and more on using the distribution of the whole point cloud in segmentation process (Vega et al., 2014; Ayrey et al., 2017). Methods combining both raster and ALS point cloud spatial distribution are also being developed (Yang et al., 2020). There are also studies that have investigated full-waveform ALS systems for individual tree detection

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ARTICLE

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The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests

Heatwaves exert disproportionately strong and sometimes irreversible impacts on forest ecosystems. These impacts remain poorly understood at the tree and species level and across large spatial scales. Here, we investigate the effects of the record-breaking 2018 European heatwave on tree growth and tree water status using a collection of high-temporal resolution dendrometer data from 21 species across 53 sites. Relative to the two preceding years, annual stem growth was not consistently reduced by the 2018 heatwave but stems experienced twice the temporary shrinkage due to depletion of water reserves. Conifer species were less capable of rehydrating overnight than broadleaves across gradients of soil and atmospheric drought, suggesting less resilience toward transient stress. In particular, Norway spruce and Scots pine experienced extensive stem dehydration. Our high-resolution dendrometer network was suitable to disentangle the effects of a severe heatwave on tree growth and desiccation at large-spatial scales in situ, and provided insights on which species may be more vulnerable to climate extremes.

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The number of tree species on Earth

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One of the most fundamental questions in ecology is how many species inhabit the Earth. However, due to massive logistical and financial challenges and taxonomic difficulties connected to the species concept definition, the global numbers of species, including those of important and well-studied life forms such as trees, still remain largely unknown. Here, based on global ground-sourced data, we estimate the total tree species richness at global, continental, and biome levels. Our results indicate that there are ~73,000 tree species globally, among which ~9,000 tree species are yet to be discovered. Roughly 40% of undiscovered tree species are in South America. Moreover, almost one-third of all tree species to be discovered may be rare, with very low populations and limited spatial distribution (likely in remote tropical lowlands and mountains). These findings highlight the vulnerability of global forest biodiversity to anthropogenic changes in land use and climate, which disproportionately threaten rare species and thus, global tree richness.

biodiversity | forests | hyperdominance | rarity | richness

In 1994, Robert May (1) provided the optimistic observation that, by 2044, we would roughly know the current number of species on Earth. Half of that time period has already lapsed, and we are still far from that goal. Even for trees, which are among the largest and most widespread organisms on the planet (2–6), provide a wealth of ecosystem services for humans

(7–9), and support much of terrestrial biodiversity (10), we still lack a fundamental understanding of how many species exist on our planet (3, 4, 11–13).

A growing body of evidence highlights details and mechanisms regarding the biogeographic patterns in tree species diversity, such as the number of species increasing consistently toward equatorial regions (14–16). With a manageable number of taxa, tree species in the higher latitudes are relatively well characterized. However, if hyperdominance of a small fraction of species in the tropics (17) is a general phenomenon, it would mean that these regions generally harbor a very large number of rare species, many of which are endemic. The contribution of rare species to ecosystem services may be relevant and is a topic of active research (18, 19), but it is challenging as most remain poorly documented (20–26). Therefore, estimating the number of tree species is essential to inform, optimize, and prioritize forest conservation efforts across the globe. Knowing

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Article

Semantic Segmentation (U-Net) of Archaeological Features in Airborne Laser Scanning—Example of the Białowieża Forest

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Abstract: Airborne Laser Scanning (ALS) technology can be used to identify features of terrain relief in forested areas, possibly leading to the discovery of previously unknown archaeological monuments. Spatial interpretation of numerous objects with various shapes and sizes is a difficult challenge for archaeologists. Mapping structures with multiple elements whose area can exceed dozens of hectares, such as ancient agricultural field systems, is very time-consuming. These archaeological sites are composed of a large number of embanked fields, which together form a recognizable spatial pattern. Image classification and segmentation, as well as object recognition, are the most important tasks for deep learning neural networks (DLNN) and therefore they can be used for automatic recognition of archaeological monuments. In this study, a U-Net neural network was implemented to perform semantic segmentation of the ALS-derived data including (1) archaeological, (2) natural and (3) modern features in the Polish part of the Białowieża Forest. The performance of the U-Net segmentation model was evaluated by measuring the pixel-wise similarity between ground truth and predicted segmentation masks. After 83 epochs, the Dice-Sorensen coefficient (F1 score) and the Intersect Over Union (IoU) metrics were 0.58 and 0.5, respectively. The IoU metric reached a value of 0.41, 0.62 and 0.62 for the ancient field system banks, ancient field system plots and burial mounds, respectively. The results of the U-Net deep learning model proved very useful in semantic segmentation of images derived from ALS data.

Keywords: deep neural networks; convolutional neural network; U-Net; ancient field systems; Celtic fields; Polish part of the Białowieża Forest; UNESCO World Heritage Site; LiDAR; ALS; DTM



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1. Introduction

The archaeological heritage of forested areas representing traces of past human activities remains poorly researched and inventoried. Conducting an archaeological inventory is limited by available research methods. In recent years, Airborne Laser Scanning (ALS) technology has greatly increased the chance for discovering archaeological objects in these areas. In Poland, forests cover over 30% of the country's territory and the ALS data of the ISOK system (Informatyczny System Osłony Kraju) cover the entire national territory.

The most common method of detecting archaeological objects in forested areas is their visual recognition and identification based on ALS data processing. Techniques based on manual labelling and georeferencing of objects require a lot of desk work and are very time-consuming. Therefore, the process of ALS data analysis has been supported by human-supervised procedures for semi-automatic or automatic recognition of potential

Article

Correcting the Results of CHM-Based Individual Tree Detection Algorithms to Improve Their Accuracy and Reliability

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Abstract: Individual tree detection algorithms (ITD) are used to obtain accurate information about trees. Following the process of individual tree detection, it is possible to use additional processing tools to determine tree parameters such as tree height, crown base height, crown volume, or stem volume. However, many of the methods developed so far have focused on parameterising the algorithms based on the study area, height structure or tree species analysed. Applying the parameters of the method can be challenging in areas with dense and heterogeneous forests with a diverse stand structure. Therefore, this work aimed to develop a method to correct the results of ITD algorithms to identify individual trees more reliably, taking into account different ITD methods based on the Canopy Height Model. In the present study, we proposed a three-step approach to correct segmentation errors. In the first step, erroneous (under- and over-segmentation errors) and correct segments were classified. After classification, the second step was to refine the under-segmentation errors. The final step was to merge segments from the over-segmentation class with correct segments based on the specified conditions. The study was conducted in one of the most complex and diverse forest communities in Europe, making tree identification a major challenge. The accuracy of the segmentation improvements varied depending on the method applied and tree species group examined. Thus, based on the results, the paper advocates for the correction method due to its efficiency in mixed forest stands. Therefore, the present study offers a possible solution to reduce segmentation errors by considering different forest types and different CHM-based ITD methods for identifying individual trees.

Keywords: individual tree detection (ITD); error correction; under-segmentation; over-segmentation; canopy height model (CHM); airborne laser scanning (ALS)



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1. Introduction

Over the past decade, the term “precision forestry” has become increasingly popular. It encompasses the use of information technology, analytical tools, and a broad dataset to support decision-making processes related to economic, ecological, and sustainable aspects of forest management [1–3].

Since the beginning of aerial photography use for forest inventories in the 1950s, remote sensing has supported forest surveying and management [4]. Techniques for the efficient acquisition of precision remote sensing data have developed rapidly over the last two decades. Nowadays, high-resolution geographic information and remote sensing data are believed to be directly related to the concept of precision forestry [5]. Currently, one technology with great potential for forest inventory is aircraft-mounted LiDAR (Light Detection and Ranging, Airborne Laser Scanner—ALS). The use of ALS data allows the measurement or modelling of a selected tree and stand characteristics such as tree height [6,7], tree density [8], crown base height [9], crown volume [10], stem volume [11,12], or aboveground biomass [13]. Presently, it can be noted that traditional forest inventories, although time-consuming and expensive, are essential for planning future forestry activities and documenting events [14].

ORIGINAL PAPER

Classification of 'potential' forests based on remote sensing data

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ABSTRACT

The aim of this study is to estimate the area with forest vegetation that does not yet meet the criteria formulated in the FAO/UN definition (minimum height 5 m, minimum canopy cover 10%, minimum area 0.5 ha), but will potentially meet them in the future (5 years or more, depending on the individual site conditions), which means that (according to the definition) they also represent forest areas. The study was conducted in the Białowieża Glade. Tree species were classified individually and then divided into two groups: those that will reach a height of 5 m in the future and those that will not (grey willow, hawthorn). Hyperspectral (reduced with MNF transformation) and ALS-based features were used for classification with the SVM algorithm. Classification accuracy based on ALS data was better than that of hyperspectral data for individual species but similar for the two species groups – 95.5% (Kappa 87.5%). Information about species and height was used to perform the classification of a fishnet layer into 'forests', 'potential forests' and 'non-forests', with an accuracy of 96% (Kappa 87.7%). A map of forests and potential forest vegetation was created in the form of a thematic map, taking into account height, canopy cover, area of the complex and land use. This study provides new solutions in the context of climate change, deforestation and the need for reporting the forest area by individual countries (including Poland) to the FAO/UN.

KEY WORDS

species, classification, hyperspectral data, ALS data, potential forest area, reporting, FAO/UN forest definition

Introduction

Globally, there are various forest definitions. Some of them are formulated in national laws, others are international. The differences in forest definitions result from the different characteristics of forest vegetation around the world and the different forms of land use and forest management (Putz and Redford, 2009). There are also economic and political reasons why different countries consider certain areas to be forests (Sasaki and Putz, 2009). Poland (like many other countries) is required to its report forest area to the Food and Agriculture Organization of the United Nations (FAO/UN). For details, see the forest definitions of the 1991 Forest Act and the FAO/UN (Forest Resources Assessment 2004, 2007, 2012; Table 1). Post-agricultural areas with forest succession, which have not been officially reclassified from agricultural to forest lands, are not

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ORIGINAL PAPER

Influence of the correction method of CHM-based Individual Tree Detection results on the estimation of forest stand characteristics

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ABSTRACT

Information on stand characteristics is of great importance for forest inventory, management and conservation. For more than two decades, Airborne Laser Scanning (ALS) data have enabled remotely sensed estimation of forest stand attributes. Two main approaches are used to estimate biometric forest attributes using Airborne Laser Scanning (ALS): the area-based approach (ABA) and individual tree detection (ITD). So far, the ABA method has been much more commonly used in forestry, as it requires only point cloud metrics. However, with the requirement for precise height information and the development of ITD methods, it is increasingly used to estimate tree biometric characteristics and stand attributes. With this in mind, this study assessed the impact of an ITD correction method based on the Canopy Height Model (CHM) on the estimation of forest characteristics such as tree density and average tree height. The three-step correction method first classifies erroneous segments from ITD methods, which are then refined. In this study, two ITD methods were tested and their results subsequently corrected on a diverse forest area within Białowieża Forest in Poland. In general, more accurate estimates of stand attributes were obtained using the Local ITD method developed in this study area, while correction procedure produced greater improvement using the basic ITD method, which is a marker-controlled watershed with a kernel size of five pixels (MCWS 5×5). Both ITD methods were reliable for estimating tree density for deciduous trees. The correction worked most reliably for estimating tree density with both methods for the area consisted of deciduous trees, while it was most reliable for estimating average tree height with the Local method for the deciduous trees and with the MCWS 5×5 for the conifers. The results indicate that correction improved ITD estimates of stand characteristics, but this varied with species groups, tree height and amount of height variation. Therefore, further development of ITD methods is advisable, as estimating stand attributes using ALS at the individual tree level offers possibilities for improved forest management.

KEY WORDS

Airborne Laser Scanning, average tree height, Individual Tree Detection, parameter estimation, tree density

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Past decade above-ground biomass change comparisons from four multi-temporal global maps

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Above-ground biomass
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Map assessment
Global carbon cycle
Earth observation

ABSTRACT

Above-ground biomass (AGB) is considered an essential climate variable that underpins our knowledge and information about the role of forests in mitigating climate change. The availability of satellite-based AGB and AGB change (Δ AGB) products has increased in recent years. Here we assessed the past decade net Δ AGB derived from four recent global multi-date AGB maps: ESA-CCI maps, WRI-Flux model, JPL time series, and SMOS-LVOD time series. Our assessments explore and use different reference data sources with biomass measurements within the past decade. The reference data comprise National Forest Inventory (NFI) plot data, local Δ AGB maps from airborne LiDAR, and selected Forest Resource Assessment country data from countries with well-developed monitoring capacities. Map to reference data comparisons were performed at levels ranging from 100 m to 25 km spatial scale. The comparisons revealed that LiDAR data compared most reasonably with the maps, while the comparisons using NFI only showed some agreements at aggregation levels <10 km. Regardless of the aggregation level, AGB losses and gains according to the map comparisons were consistently smaller than the reference data. Map-map comparisons at 25 km highlighted that the maps

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Analysis of the level of knowledge of the local community about Białowieża Forest

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Abstract: The research focused on ecological awareness and knowledge regarding the Białowieża Forest, conducting two survey studies in 2015 and 2022. The analysis covered ecological awareness, knowledge of forest stands, project awareness, and opinions on government decisions. The local community exhibited an average knowledge level, accompanied by a notable decline in ecological awareness. A surprising discovery was the increased knowledge among tourists, contrasting with ecologists who emerged as the most well-informed group. The study also assessed the impact of government decisions, drawing conclusions from data gathered across various respondent groups. The findings underscored the nuanced dynamics of ecological awareness within the community, highlighting the need for targeted educational initiatives and fostering environmental consciousness among the local population. Furthermore, the fluctuating awareness levels among different groups emphasized the importance of tailored strategies for effective communication and outreach. The research contributes valuable insights into the evolving landscape of ecological awareness and knowledge, shedding light on areas for improvement in environmental education and conservation efforts in the context of the Białowieża Forest.

Key words: ecological awareness, Białowieża Forest, survey studies, environmental education

INTRODUCTION

The Białowieża Forest is a compact forest area located in two countries - Poland and Belarus. In total, it covers an area of 141,885 hectares. The Białowieża Forest, which has existed for at least 12,000 years, has been protected since at least the 14th century. Various forms of protection of the Białowieża Forest, applied for centuries, have made it possible to preserve the continuity of natural processes with little human influence on the forest. The area of the Białowieża Forest, included in the World Heritage List UNESCO, is considered the last forest with natural features in the lowland areas of Europe. (Niklasson et al 2010; Samojlik 2005). The possibility to study the natural environment of the Białowieża Forest, which is considered a reference point for other forest areas in Europe, is of great importance for science. The high importance of this area is evidenced by the very large number of scientific articles on the forests of the Białowieża Forest (Jaroszewicz et al 2019). The Białowieża Forest is a unique area for long-term biodiversity research. Many years of avifauna observations have been conducted (Tomiałojć and Wesółowski 2004; Wesółowski 2007), research on the ecology of mammals, including bison and wolves (Samojlik et al 2017; Smith et al 2022; Bramorska et al 2023), and sites of rare species have been discovered (Gawryś, Szulc, 2017; Ginszt et al 2022). Most importantly, the forests of the Białowieża Forest are of fundamental importance for the study of the natural environment of the forest (Jaroszewicz et al.2019). For almost 200 years, numerous scientific papers have been published on various aspects of forest management, in which scientists observe and describe the natural processes occurring in the Białowieża Forest, enabling their introduction in the context of forest management in the rest of the country



OPEN

An assessment of the habitat preferences of European bison with airborne laser scanning data in forest ecosystem

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Research on habitat preferences is an important part of contemporary ecology. For the European bison, the classic approach to distinguishing habitat features is still being followed, but the limitations of this approach cannot provide the standard features of optimal habitats for this species. The study consisted in comparing analyses of the habitat preferences of European bison that were based on either classic forest typology (habitat types) or airborne laser scanning data. The data for these analyses were collected from telemetry collars on European bison in Białowieża Forest. The model based on airborne laser scanning features presented better parameters (percent of correctly classified cases and ROC) than the model based on habitat types. The results show that it is possible to find universal indicators of European bison's preferences that are independent of local forest classification methodology. The indicators used suggest that European bison have a preference for forest habitats with low canopy cover and a small share of woody plants in the lower parts of the forest. Low canopy cover itself is not necessarily beneficial for European bison. Our study also indicates that airborne laser scanning is also useful in the assessment of habitat suitability for European bison in forest ecosystems.

Research on habitat preferences is an important part of contemporary ecology that arises from the need to understand the life demands of animals in a spatial context¹. This is of particular importance for species management and conservation (e.g.,^{2,3}) because proper recognition of optimal habitats helps in the effective conservation and reintroduction of a given species (e.g.,^{4,5}). In the case of protected species, habitat quality assessment is of particular importance when launching reintroduction programs, which incur significant costs and effort. One such species is the European bison (*Bison bonasus* L.), for which conservation activities have been carried out since the restoration of the wild population⁶.

Classic methods (similar to those used for other large mammals) of assessing the presence of animals (direct observations, tracks, feces) were the basis of the first assessments of European bison's habitat preferences. The habitat features that were chosen for analysis were mainly taken from forest maps, i.e., forest nomenclature was used. Borowski and Kossak⁷ found that about 75% of observations of European bison occurred in deciduous and mixed forests, but the study was performed without reference to available habitats. However, Krasieński⁸ indicated that European bison primarily preferred mixed forests, followed by deciduous forests, and then alder and coniferous forests. In subsequent studies, Krasieński et al.⁹ found that European bison visited deciduous forests (55%) more often than coniferous forests (42%) in the Polish part of Białowieża Forest; however, in the Belarusian part, 75% of observations occurred in coniferous forests. Daleszczyk et al.¹⁰ observed a change of habitat utilization by European bison over time: the use of coniferous forests decreased, while the use of deciduous forests and alderwoods increased. In mountains (Bieszczady), European bison preferred various habitat types, depending on the season. Wołoszyn-Gałęza et al.¹¹ found that, in winter periods, European bison preferred deciduous and mixed forest areas located at lower altitudes above sea level; however, in the growing season these animals were much more likely to stay in coniferous forest areas with a low canopy cover. Other studies have indicated that European bison have a preference for coniferous stands^{12,13}. Kuemmerle et al.¹⁴ showed that each European bison population's preferences for particular types of habitats differed significantly. These results suggest that the standard features of optimal habitats for the European bison are still unknown. Kerley et al.¹⁵ indicates open

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The global biogeography of tree leaf form and habit

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Understanding what controls global leaf type variation in trees is crucial for comprehending their role in terrestrial ecosystems, including carbon, water and nutrient dynamics. Yet our understanding of the factors influencing forest leaf types remains incomplete, leaving us uncertain about the global proportions of needle-leaved, broadleaved, evergreen and deciduous trees. To address these gaps, we conducted a global, ground-sourced assessment of forest leaf-type variation by integrating forest inventory data with comprehensive leaf form (broadleaf vs needle-leaf) and habit (evergreen vs deciduous) records. We found that global variation in leaf habit is primarily driven by isothermality and soil characteristics, while leaf form is predominantly driven by temperature. Given these relationships, we estimate that 38% of global tree individuals are needle-leaved evergreen, 29% are broadleaved evergreen, 27% are broadleaved deciduous and 5% are needle-leaved deciduous. The aboveground biomass distribution among these tree types is approximately 21% (126.4 Gt), 54% (335.7 Gt), 22% (136.2 Gt) and 3% (18.7 Gt), respectively. We further project that, depending on future emissions pathways, 17–34% of forested areas will experience climate conditions by the end of the century that currently support a different forest type, highlighting the intensification of climatic stress on existing forests. By quantifying the distribution of tree leaf types and their corresponding biomass, and identifying regions where climate change will exert greatest pressure on current leaf types, our results can help improve predictions of future terrestrial ecosystem functioning and carbon cycling.

Forest ecosystems, which contain 80–90% of global terrestrial plant biomass^{1,2} and a large proportion of terrestrial biodiversity³, regulate global biogeochemical cycles, and provide critical ecosystem services⁴. Leaves mediate forest energy and carbon inputs via photosynthesis, respiration, transpiration^{5,6} and litterfall^{7,8}, thereby regulating ecosystem structure and function, and water, nutrient and carbon cycles^{9–11}. Leaves of trees are highly diverse but can be broadly classified into four major types on the basis of leaf habit (evergreen vs deciduous) and form (broadleaved vs needle-leaved). These characteristics are linked to a vast array of functional traits associated with resource-use strategies and strongly depend on local growing conditions^{12–15}. Therefore, understanding variation in leaf types along

environmental gradients is critical to predicting global biogeochemical cycles and ecosystem functioning in a changing world. Yet, we still lack a global, quantitative understanding of forest leaf habit and form, informed by field-based observations.

Deciduous tree species evolved to tolerate seasonal climates and maximize the use of a short growing season^{16,17}. They usually have higher photosynthetic rates¹⁸ than evergreen species and reduce transpiratory water loss due to respiration by shedding their leaves during unfavourable seasons¹¹. Evergreen trees with longer leaf lifespans, by contrast, tend to have greater leaf construction costs¹⁹ and lower nutrient cycling rates²⁰. Growing season water-use strategy commonly differs between broadleaved and needle-leaved species²¹, with needle-leaved species

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Integrated global assessment of the natural forest carbon potential

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Forests are a substantial terrestrial carbon sink, but anthropogenic changes in land use and climate have considerably reduced the scale of this system¹. Remote-sensing estimates to quantify carbon losses from global forests^{2–5} are characterized by considerable uncertainty and we lack a comprehensive ground-sourced evaluation to benchmark these estimates. Here we combine several ground-sourced⁶ and satellite-derived approaches^{2,7,8} to evaluate the scale of the global forest carbon potential outside agricultural and urban lands. Despite regional variation, the predictions demonstrated remarkable consistency at a global scale, with only a 12% difference between the ground-sourced and satellite-derived estimates. At present, global forest carbon storage is markedly under the natural potential, with a total deficit of 226 Gt (model range = 151–363 Gt) in areas with low human footprint. Most (61%, 139 Gt C) of this potential is in areas with existing forests, in which ecosystem protection can allow forests to recover to maturity. The remaining 39% (87 Gt C) of potential lies in regions in which forests have been removed or fragmented. Although forests cannot be a substitute for emissions reductions, our results support the idea^{2,3,9} that the conservation, restoration and sustainable management of diverse forests offer valuable contributions to meeting global climate and biodiversity targets.

The continuing climate and biodiversity crises threaten ecosystems and human society^{10,11}. Representing 80–90% of the global plant biomass¹² and much of Earth's terrestrial biodiversity¹², forests play a key role in both climate-change mitigation and adaptation. So far, humans have removed almost half of Earth's natural forests^{13,14}, and we continue to lose a further 0.9–2.3 Gt C each year (about 15% of annual human carbon emissions) through deforestation¹⁵. In response to these pressing challenges, international environmental initiatives such as the UN Decade on Ecosystem Restoration¹⁶, the Kunming-Montreal Global Biodiversity Framework¹⁷ and the Glasgow Leaders' Declaration on Forests and Land Use¹⁸ have been established to reduce deforestation and revitalize ecosystems. A key step in guiding such environmental targets is gaining a comprehensive understanding of the global distribution of existing forest carbon stocks, as well as the potential for carbon recapture if healthy ecosystems are allowed to recover^{3,9}.

Remote-sensing observations have been central to the development of spatially continuous models of global forest biomass^{2,7,8}. Building on these satellite-derived observations, a growing body of research has begun to use statistical extrapolations to estimate the potential extent of forest carbon stocks under natural conditions^{2–4}. In recent years, refs. 3,4 combined remote-sensing forest-area estimates with coarse (ecoregion-level or country-level) carbon-storage estimates to approximate the global carbon potential. More recently, Walker et al.² used satellite-derived biomass estimates from natural forested regions to statistically extrapolate potential forest biomass in the absence of human disturbance. Despite yielding carbon potential estimates ranging from 200 to 300 Gt C, inherent strengths and weaknesses of each approach have given rise to uncertainty across studies, with suggestions that these estimates may be up to 4–5 times too high^{19,20,21}. As a result, confidence in the carbon potential of forest ecosystems remains low. Without an independent, bottom-up assessment of global forest

carbon potential built directly from ground-sourced data, evaluating and benchmarking these satellite-derived trends remains challenging. Overcoming this controversy requires consideration of various independent approaches to identify the extent of confidence and uncertainty across different land uses around the world.

Another key challenge in the development of potential biomass estimates is how to approximate the 'natural' state of vegetation stocks. To do this, recent extrapolations of forest potential have been built from data collected in protected land³ or areas with minimal human disturbance². However, a limitation of such approaches is that the focus on undisturbed areas restricts data to a few regions, which can bias results towards environments systematically avoided by humans. Protected areas may, for example, often exist in regions of marginal agricultural value or that possess unique ecological features²². An alternative approach to avoid such biases is to use observations across the full gradient of human disturbance and then use statistical techniques to remove the human footprint²³. This method has proved successful in assessing the impact of historical human land use on soil carbon storage²³. By allowing the inclusion of larger datasets across a broader range of environmental conditions, this approach has the potential to improve the statistical strength of biomass potential estimates. Consideration of the results from these different modelling datasets and approaches will be necessary to develop a comprehensive understanding of the global forest carbon potential.

Here we used a combination of independent modelling approaches to generate spatially explicit estimates of potential forest biomass worldwide. The first set of analyses was based on 'bottom-up' models built directly from ground-sourced (denoted GS) aboveground live biomass estimates from forest inventory data of the Global Forest Biodiversity initiative (GFBI)⁶. This was contrasted with three 'top-down' models built from the latest satellite-derived (denoted SD),

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Corrections & amendments

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In the version of the article initially published, Stanislaw Miscicki's name incorrectly appeared as Miscicki Stanislaw. Additionally, the affiliation for Thomas T. Ibanez has been updated to "AMAP, University of Montpellier, CIRAD, CNRS, INRAE, IRD, Montpellier, France", and the second affiliation for Sharif A. Mukul has been updated to "Department of Environment and Development Studies, United International University, Dhaka, Bangladesh". The corrections have been made to the HTML and PDF versions of the article.

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Validating GEDI tree canopy cover product across forest types using co-registered aerial LiDAR data

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ABSTRACT

Reliable tree canopy cover (TCC) products are vital for national forest inventory, land process modeling and forest dynamic monitoring. The new generation of space-based laser altimeter, GEDI, offers a three-dimensional (3D) insight on the forest structure, shaping the paradigm of structural variable estimation. However, the generality of newly released GEDI level-2 TCC product version 2 was less investigated across various forest types. Additionally, satellite-derived product validation usually suffers from the geolocation mismatch between satellite and reference data. In this study, we comprehensively validated the GEDI TCC product across seven forest types using the reference TCC derived from several public and private aerial LiDAR datasets after geographical registration, and crossly compared with a commonly-used passive satellite product (i.e., GFOC TCC). As the reference aerial TCC maps were derived using various aerial LiDAR instruments, we investigated the consistency of TCC estimation among them using simulation datasets and found that the distributions of TCC relative bias (biasR, %) were almost identical and the differences of relative RMSE (rRMSE, %) was less than 0.2%. Through the registration process, we found that the geolocation offsets of GEDI footprints tended to be independent of azimuth directions and their average was about 10 m, verifying the necessity of registration during the validation process. Importantly, the post-registration validation of GEDI TCC showed an average RMSE of 0.10 and an average R^2 of 0.85 for all forest types, resulting in a decrease of RMSE of up to 0.15 and an increase of R^2 of up to 0.33 compared to the pre-registration validation. The inter-comparison also exhibited improved consistency between GEDI and GFOC TCC products after registration. Further, we found a non-negligible dependence of GEDI TCC on the slope factor but almost independence on forest type, encouraging the spread of GEDI TCC product.

1. Introduction

Satellite-derived products of tree canopy cover (TCC, also known as effective canopy cover) offered a wide and spatially-continuous insight into land surface dynamics, facilitating the agriculture, forest, and ecology applications at regional and global scales (Garrigues et al., 2009; Tang et al., 2019; Croft et al., 2020). Understanding the accuracy of TCC products in different forest types is particularly important for

effective use (Morissette et al., 2006; Fang et al., 2012; Guillevic et al., 2014). The advent of a new generation satellite laser altimeter, i.e., Global Ecosystem Dynamics Investigation (GEDI), providing a 3D insight into forest structure at a 25-m footprint level, facilitates explicitly tracing the spatiotemporal dynamics of global forest ecosystems (Dubayah et al., 2020). As a full-waveform light detection and ranging (LiDAR), GEDI has great potential for accurately retrieving forest canopy structural variables. The newly-released GEDI L2B product version 2

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High resolution remote sensing for biodiversity assessment and monitoring: A case study of dominant tree species in an old-growth forest

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ABSTRACT

Biodiversity assessment and monitoring in old-growth forests (OGFs) is crucial for their effective management and conservation amongst various natural and human-induced challenges. In the present study, the spatial and temporal species diversity were assessed in the mixed stands of Białowieża Forest (BF), a renowned UNESCO world heritage site recognized as an OGF. The BF has encountered challenges due to pest outbreaks peaking in 2016–2017 with adverse impacts on species composition. Utilizing airborne laser scanning (ALS) and color infrared (CIR) datasets from 2015 and 2019 (prior and following the peak, respectively), 30 variables were extracted and employed as input for the Random Forest algorithm to identify 14 species of broadleaved and coniferous individuals at plot levels (458 plots) within the BF. We calculated biodiversity indices (including α , β , and γ diversity), Importance Value Index (IVI), bivariate scale-dependent density of species, and temporal β diversity indices independently for data acquired from both field observation (FO) and species maps obtained through remote sensing analysis (RSA). The study found no significant differences in α diversity indices between the FO and RSA across the BF, however, notable discrepancies existed in species richness. Limited species detection was attributed to low species frequency and therefore, insufficient reference individuals. Average β and γ diversities from both datasets showed no significant differences. The RSA accurately identified top species and their changes in terms of IVI. Additionally, the RSA explored scale-dependent density changes of broadleaved individuals around conifers. Consistency was observed between FO and RSA in identifying dominance shifts from losses to gains within the BF communities. The comparison of diversity indices obtained from FO and RSA suggests that the RSA provided comparable results to FO in capturing the diversity of dominant tree species within the BF, providing a promising approach for advancing our understanding of forest biodiversity in OGFs.

1. Introduction

Old-growth forests (OGFs), characterized by their structurally diverse vegetation and acknowledged as a vital developmental phase within forest ecosystems, play a crucial role in maintaining not only regional but also global biodiversity and ecological balance (Lindemayer and Bowd, 2022; Martin and Valeria, 2022; Borghi et al., 2024). They provide a diverse range of habitats, including decaying wood, tree canopies, and understory vegetation cover that support a wide variety of plant and animal species. The structural diversity within these ecosystems offers unique environments for numerous species, contributing to higher overall biodiversity levels. Additionally, they act as reservoirs of genetic diversity, and their almost intact nature helps maintain

ecological balance, supporting the interconnected web of life. The complex web of life within these forests creates a rich diversity of species, encompassing species that may be rare or even unique to these habitats (Mosseler et al., 2003; Spies, 2004; Vaglio Laurin et al., 2020; Gilhen-Baker et al., 2022). Conservation and restoring OGFs is therefore essential for safeguarding biodiversity and ensuring the long-term health of forest ecosystems. Furthermore, monitoring biodiversity in OGFs and understanding the dynamics of their ecosystems is fundamental for their effective conservation (Borghi et al., 2024; Watson et al., 2018). Biodiversity assessment and monitoring in these ecosystems goes beyond the mere enumeration of species; it sheds light on the role of each species in maintaining ecological balance, explores the interconnected relationships between organisms, and identifies

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Towards global spaceborne lidar biomass: Developing and applying boreal forest biomass models for ICESat-2 laser altimetry data

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ABSTRACT

Space-based laser altimetry has revolutionized our capacity to characterize terrestrial ecosystems through the direct observation of vegetation structure and the terrain beneath it. Data from NASA's ICESat-2 mission provide the first comprehensive look at canopy structure for boreal forests from space-based lidar. The objective of this research was to create ICESat-2 aboveground biomass density (AGBD) models for the global entirety of boreal forests at a 30 m spatial resolution and apply those models to ICESat-2 data from the 2019–2021 period. Although limited in dense canopy, ICESat-2 is the only space-based laser altimeter capable of mapping vegetation in northern latitudes. Along each ICESat-2 orbit track, ground and vegetation height is captured with additional modeling required to characterize biomass. By implementing a similar methodology of estimating AGBD as GEDI, ICESat-2 AGBD estimates can complement GEDI's estimates for a full global accounting of aboveground carbon. Using a suite of field measurements with contemporaneous airborne lidar data over boreal forests, ICESat-2 photons were simulated over many field sites and the impact of two methods of computing relative height (RH) metrics on AGBD at a 30 m along-track spatial resolution were tested; with and without ground photons. AGBD models were developed specifically for ICESat-2 segments having land cover as either Evergreen Needleleaf or Deciduous Broadleaf Trees, whereas a generalized boreal-wide AGBD model was developed for ICESat-2 segments whose land cover was neither. Applying our AGBD models to a set of over 19 million ICESat-2 observations yielded a 30 m along-track AGBD product for the pan-boreal. The ability demonstrated herein to calculate ICESat-2 biomass estimates at a 30 m spatial resolution provides the scientific underpinning for a full, spatially explicit, global accounting of aboveground biomass.

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The global distribution and drivers of wood density and their impact on forest carbon stocks

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The density of wood is a key indicator of the carbon investment strategies of trees, impacting productivity and carbon storage. Despite its importance, the global variation in wood density and its environmental controls remain poorly understood, preventing accurate predictions of global forest carbon stocks. Here we analyse information from 1.1 million forest inventory plots alongside wood density data from 10,703 tree species to create a spatially explicit understanding of the global wood density distribution and its drivers. Our findings reveal a pronounced latitudinal gradient, with wood in tropical forests being up to 30% denser than that in boreal forests. In both angiosperms and gymnosperms, hydrothermal conditions represented by annual mean temperature and soil moisture emerged as the primary factors influencing the variation in wood density globally. This indicates similar environmental filters and evolutionary adaptations among distinct plant groups, underscoring the essential role of abiotic factors in determining wood density in forest ecosystems. Additionally, our study highlights the prominent role of disturbance, such as human modification and fire risk, in influencing wood density at more local scales. Factoring in the spatial variation of wood density notably changes the estimates of forest carbon stocks, leading to differences of up to 21% within biomes. Therefore, our research contributes to a deeper understanding of terrestrial biomass distribution and how environmental changes and disturbances impact forest ecosystems.

Wood density, defined as the dry mass per fresh volume of wood, is a fundamental functional trait which reflects the carbon investment of trees. It is closely linked to the life history and functional attributes of trees, including mechanical and physiological properties^{1–3}. Wood density plays a crucial role in determining the competitive ability of tree species and shapes the composition, structure and function of forest ecosystems^{4–7}. These dynamics affect the rate of tree mortality⁸ and wood decomposition⁹, which are central to how ecosystems respond to environmental changes. Furthermore, the strong link between wood density and biomass production¹⁰ makes it a vital factor in quantifying

terrestrial carbon uptake and storage^{10–23}. Over one-third of the total variation in aboveground biomass in tropical forests can be explained by spatial differences in wood density¹⁴. Yet, until now, we lack a spatially continuous understanding of the variation in wood density in angiosperms and gymnosperms that would be necessary for representing this information in global forest carbon storage estimates.

In recent decades, empirical and theoretical studies have identified a wide range of factors that shape global variation in tree wood densities, including abiotic variation, biotic conditions, successional stages and human disturbances^{19,20,25–28}. The evolution of wood density

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Determination of forest canopy cover of different sized stands with diverse structure using ALS data: case study of the Białowieża Forest (Poland)

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ABSTRACT

The need for objective methods to determine tree canopy cover (CC) across large numbers of stands has led to the development of techniques that utilise airborne laser scanning (ALS) data, which provides a reproducible and detailed representation of canopy geometry. We developed a method for determining CC area and evaluated the estimation accuracy for stands of different sizes, structure and composition. This method is based on tree crown geometries obtained from ALS data, and verified with field measurements using data for 3245 stands of the Białowieża Forest District in Poland. In relatively large stands (3–5 ha), the theoretical error of prediction decreased from 0.13 to 0.10 with increasing stand area. In stands larger than 10 ha, however, the error in estimating CC was less than ± 0.10 . Although every estimation method comes with its own assumptions and errors, the presented method eliminates the subjectivity in observer bias prevalent in traditional field-based ocular assessments and provides a more transparent and methodologically uniform approach for estimating CC in forests.

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Canopy; canopy height model; segmentation; individual tree detection; area-based approach; forest features

Introduction

The efforts to lower operational costs and improve measurement accuracy in forest inventories often drive the search for new methods to observe tree metrics used in forest stand descriptions. Information on these metrics is used in the planning of silvicultural treatments, the inventory of growing stock volume or, more generally, in the study and modelling of forest growth and yield. The spatial distribution of trees and the geometry of their crowns influence the amount, as well as the spatial and temporal patterns, of light reaching various layers of the forest stand (Cannell and Grace 1993; Angelini et al. 2015). This variation in light availability, in turn, affects key environmental factors such as humidity, temperature, and soil moisture – effectively creating microclimatic differences within the stand (Mitscherlich 1981; Geiger et al. 2009; von Arx et al. 2012). Furthermore, these changes in light and microclimate not only shape the internal forest environment; they also affect the distribution and behaviour of wildlife communities in and around forests (Hunter 1990).

One of the most important characteristics for describing forest stands is the degree of coverage by tree crowns – the canopy cover (or crown cover). Canopy cover (CC) refers to the proportion of the forest covered by the vertical projection of the tree crowns (Jennings et al. 1999). Nowadays in Poland, canopy cover is used as an auxiliary feature in determining harvesting intensity prior to felling, in conjunction with the “Tables of intermediate felling efficiency” (IBL 1974). It is also used to formulate economic guidelines for

specific stands, e.g. to determine the urgency of clearing or thinning, to assess the possibility of initiating regeneration, to assess the growing conditions of younger tree regeneration layers, and to assess the need to increase the growing stock volume. Forest science professionals use CC to visually estimate stocking (the ratio between the actual stand and the optimal stand) and tree density, which supports model predictions of stand and forest growth (Bruchwald et al. 1996). Additionally, CC, described numerically, is utilised in remote sensing methods to determine growing stock volume (Loetsch and Haller 1964).

Forest canopy cover can be determined in two ways. First, the degree of cover is given based on the form of horizontal contact of tree crowns and the estimate of how many new crowns would fit into the open spaces. CC determined in this way is qualitative in nature. Such a method is used in forest management in Poland, but it has also been used to describe sample plots in large-scale inventory scenarios, e.g. in Switzerland (Zingg 1988). The second is to determine the part of the forest stand area covered by the vertical projections of the tree crowns (Avery and Burkart 1994).

Among the most popular field-based methods for obtaining information on crown geometry include visual assessments using a canopy scope (Brown et al. 2000; Chmura et al. 2016) and using hemispherical images (Valverde and Silvertown 1997; Strzeński 2006). In forest inventories, a surveyor most often determines CC in the field by ocular estimation of the portion of the sky hemisphere that is occupied by tree crowns (Pawłowski 1977). The surveyor generally

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Global patterns and environmental drivers of forest functional composition

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Positive feedbacks and alternative stable states in forest leaf types

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The emergence of alternative stable states in forest systems has significant implications for the functioning and structure of the terrestrial biosphere, yet empirical evidence remains scarce. Here, we combine global forest biodiversity observations and simulations to test for alternative stable states in the presence of evergreen and deciduous forest types. We reveal a bimodal distribution of forest leaf types across temperate regions of the Northern Hemisphere that cannot be explained by the environment alone, suggesting signatures of alternative forest states. Moreover, we empirically demonstrate the existence of positive feedbacks in tree growth, recruitment and mortality, with trees having 4–43% higher growth rates, 14–17% higher survival rates and 4–7 times higher recruitment rates when they are surrounded by trees of their own leaf type. Simulations show that the observed positive feedbacks are necessary and sufficient to generate alternative forest states, which also lead to dependency on history (hysteresis) during ecosystem transition from evergreen to deciduous forests and vice versa. We identify hotspots of bistable forest types in evergreen-deciduous ecotones, which are likely driven by soil-related positive feedbacks. These findings are integral to predicting the distribution of forest biomes, and aid to our understanding of biodiversity, carbon turnover, and terrestrial climate feedbacks.

Alternative stable states exist in ecological, climatic, and social systems^{1–3}. In such systems, feedbacks maintain the state of the system unless gradual forcing or perturbations become too large and cause abrupt, critical transitions between stable states². An important example of alternative biome states is the forest *versus* savanna distinction, whereby fire feedbacks play a key role in maintaining one or the other state^{4,5}. Yet, it remains unclear whether different tree functional groups form alternative stable states within forest systems, and

what feedbacks might drive them, limiting our capacity to predict state changes that affect terrestrial carbon turnover, water dynamics and nutrient cycling⁶.

Forests are either deciduous or evergreen or a mix of the two⁷, and the distribution of these forest leaf types underlies dynamic global vegetation models^{8–9}. Deciduous trees that shed all leaves during unfavorable periods differ from evergreen trees in a variety of ecologically- and climate-relevant leaf traits, such as life span, nutrient

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Article

Assessing Ash (*Fraxinus excelsior* L.) Dieback Dynamics in the Białowieża Forest, Poland, Using Bi-Temporal High-Resolution Remote Sensing Data

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Abstract The ash dieback epidemic, caused by the fungus *Hymenoscyphus fraxineus*, has been a significant issue in Europe for over 20 years, severely affecting ash tree populations (*Fraxinus excelsior* L.). In the Białowieża Forest, ash trees now represent less than 1% of the species composition, with a sharp decline observed over the past several decades. This study aims to map the dynamics of ash mortality in the Białowieża Forest and assess the influence of habitat and stand factors on the severity of mortality. We utilized bi-temporal high-resolution remote sensing data from 2015 to 2019 to track the decline of ash trees and to identify factors affecting mortality. The analysis employed a combination of Boosted Regression Trees (BRTs) and hotspot analyses. Our results show that between 2015 and 2019, 29% of the living ash trees in the canopy layer of the forest died. The findings indicate that ash mortality was most pronounced in stands with a high proportion of ash trees, particularly where dead deciduous trees were already present. Intensive dieback of other deciduous trees was also noted in these stands. This study provides valuable insights into the factors influencing ash mortality dynamics and demonstrates the potential of remote sensing for large-scale monitoring of tree health. The results have important implications for forest management and conservation, offering baseline data that can inform strategies to manage ash dieback and guide targeted interventions in affected forest areas.

Keywords: ash; Boosted Regression Trees; tree mortality; disturbance; spatial autocorrelation; Białowieża Forest; mortality determinants



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1. Introduction

Tree dieback has become a critical environmental challenge, potentially leading to the mortality of individual trees or entire forest ecosystems [1]. Several factors contribute to tree dieback, including pests, diseases, climate change, pollution, and deforestation [2]. These factors can weaken trees, making them more susceptible to further damage and ultimately causing their demise. Tree dieback has severe ecological consequences, as it affects biodiversity, disrupts ecosystems, and reduces the availability of essential resources such as oxygen and habitats for wildlife [3].

The emergence of ash dieback is seen as a global challenge since many countries and regions are facing diseases affecting their native tree species due to changing climate. The

Article

Remote Sensing of Forest Gap Dynamics in the Białowieża Forest: Comparison of Multitemporal Airborne Laser Scanning and High-Resolution Aerial Imagery Point Clouds

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Abstract: Remote sensing technologies like airborne laser scanning (ALS) and digital aerial photogrammetry (DAP) have emerged as efficient tools for detecting and analysing canopy gaps (CGs). Comparing these technologies is essential to determine their functionality and applicability in various environments. Thus, this study aimed to assess CG dynamics in the temperate European Białowieża Forest between 2015 and 2022 by comparing ALS data and image-derived point clouds (IPC) from DAP, to evaluate their respective capabilities in describing and analysing forest CG dynamics. Our results demonstrated that ALS-based point clouds provided more detailed and precise spatial information about both the vertical and horizontal structure of forest CGs compared to IPC. ALS detected 27,754 (54%) new CGs between 2015 and 2022, while IPC identified 23,502 (75%) new CGs. Both the average gap area and the total gap area significantly increased over time in both methods. ALS data not only identified a greater number of CGs, particularly smaller ones (below 500 m²), but also produced a more precise representation of CG shape and structure. In conclusion, precise, multi-temporal remote sensing data on the distribution and size of canopy gaps enable effective monitoring of structural changes and disturbances in forest stands, which in turn supports more efficient forest management, e.g., planning of forest regeneration.

Keywords: canopy gaps; forest dynamics; ALS; DAP; IPC



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1. Introduction

Openings in the forest canopy, called canopy gaps (CGs), have a major impact on ecosystem processes and vegetation changes [1–5]. Generally, a canopy gap is an opening in a forest stand with vegetation height up to two metres above the ground level [6]. CGs exert a pivotal influence on ecological processes within forest ecosystems, significantly shaping forest structure, particularly in mature and old-growth forests [7,8]. CGs can emerge through different mechanisms, either naturally (e.g., windfalls, fires, insect outbreaks) or due to human activities (e.g., timber harvesting, silvicultural treatments) [9,10]. The formation of a CG significantly alters local habitat conditions, affecting factors such as light and nutrient availability, humidity, temperature, wind strength, duration of snow

Effect of climate on traits of dominant and rare tree species in the world's forests

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Species' traits and environmental conditions determine the abundance of tree species across the globe. The extent to which traits of dominant and rare tree species differ remains untested across a broad environmental range, limiting our understanding of how species traits and the environment shape forest functional composition. We use a global dataset of tree composition of >22,000 forest plots and 11 traits of 1663 tree species to ask how locally dominant and rare species differ in their trait values, and how these differences are driven by climatic gradients in temperature and water availability in forest biomes across the globe. We find three consistent trait differences between locally dominant and rare species across all biomes; dominant species are taller, have softer wood and higher loading on the multivariate stem strategy axis (related to narrow tracheids and thick bark). The difference between traits of dominant and rare species is more strongly driven by temperature compared to water availability, as temperature might affect a larger number of traits. Therefore, climate change driven global temperature rise may have a strong effect on trait differences between dominant and rare tree species and may lead to changes in species abundances and therefore strong community reassembly.

Plant communities typically consist of a relatively few dominant and many rare species (MacArthur, 1957; Preston, 1948). Dominant and rare species both contribute to ecosystem function: dominant species provide the majority of ecosystem services, and rare species can increase ecosystem multifunctionality by expanding trait diversity^{1–4}. Species traits in combination with abiotic and biotic environmental conditions therefore drive the relative abundance of species in local communities⁵. Macroclimate is an important abiotic trait filter that determines the global distribution of forest biomes^{6,7} and tree species^{8,9}. Climate change will therefore have a strong effect on the occurrence and distribution of forest biomes, traits, and consequently, forest ecosystem functioning^{10–12}. However, the extent to which individual traits of locally dominant and rare tree species differ, and how these differences are affected by climate, remains largely unexplored at a global scale. This lack of knowledge limits our understanding on the processes determining species abundances, functional significance of dominant and rare tree species across the globe and how this is affected by climate¹³.

Community assembly is the process by which species are filtered out from the regional species pool into the local community based on their functional traits, ecological niches or stochastic processes. In this process, climatic factors such as temperature and precipitation, as well as biotic factors such as facilitation, competition, herbivory and pathogens act as filters on species membership in particular assemblages^{14,15}. It is suggested that the strength of different filters depend on the environment, with stronger abiotic filtering at higher latitudes because of harsh environmental conditions and stronger biotic filtering at lower latitudes, because of intense competition under productive conditions¹⁶.

After a species' establishment, its abundance is defined besides habitat suitability by competitive ability related to species' traits¹⁷. A trait is defined as any morphological, physiological or phenological feature measurable at the individual plant level that affects plant performance¹⁸. In forests across the globe, high wood density and low specific leaf area (SLA) are associated with a stronger competitive ability¹⁹. Higher wood density generally increases tissue longevity and

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ECOLOGY

Mycorrhizal symbioses and tree diversity in global forest communities

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Unravelling the mechanisms underlying the maintenance of species diversity is a central pursuit in ecology. It has been hypothesized that ectomycorrhizal (EcM) in contrast to arbuscular mycorrhizal fungi can reduce tree species diversity in local communities, which remains to be tested at the global scale. To address this gap, we analyzed global forest inventory data and revealed that the relationship between tree species richness and EcM tree proportion varied along environmental gradients. Specifically, the relationship is more negative at low latitudes and in moist conditions but is unimodal at high latitudes and in arid conditions. The negative association of EcM tree proportion on species diversity at low latitudes and in humid conditions is likely due to more negative plant-soil microbial interactions in these regions. These findings extend our knowledge on the mechanisms shaping global patterns in plant species diversity from a belowground view.

Comprehensive mapping of individual living and dead tree species using leaf-on and leaf-off ALS and CIR data in a complex temperate forest

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Abstract

Tree species information is crucial both for understanding forest composition and supporting sustainable forest management, but also for monitoring biodiversity and assessing ecosystem services. Remote sensing data has been widely used to map the spatial distribution of tree species across large areas. However, there is currently a lack of studies demonstrating the potential of airborne laser scanning data collected during different seasons to identify multiple individual tree species/genera, including dead individuals. The main objective of this study was to map the ecologically valuable forest area constituting the Polish part of the Białowieża Forest using leaf-on and leaf-off airborne laser scanning (ALS) data and color-infrared imagery. Eleven living species/genera (alder, ash, aspen, birch, hornbeam, lime, maple, oak, pine, spruce and other deciduous) and four dead classes (dead deciduous, dead pine, dead spruce and snag) were classified at the individual tree level. Applying the Random Forests algorithm and a set of 30 predictor variables, 15 classes were classified with an overall accuracy of 82 per cent. The mapping of nearly 20 million individual trees revealed that in 2015, the most common tree species in the upper part of the Białowieża Forest stands was spruce (20.1 per cent), followed by alder (19.0 per cent) and pine (18.1 per cent). Among dead trees, dead deciduous trees (2.2 per cent) and dead spruce (1.7 per cent) were the most common. Our results can serve as a first cornerstone for carrying out further in-depth analyses of forest biodiversity using remote sensing data in this exceptional forest area.

Keywords: tree species; mapping; airborne laser scanning (ALS); leaf-on and leaf-off data; Białowieża Forest; dead tree detection; Random Forests

Introduction

Knowledge of tree species is an essential component of forest inventories (Gillis et al., 2005), offering valuable insights into the structure, composition, and dynamics of forests. For effective natural resource management and conservation, accurate information about tree species' location and distribution are needed to monitor biodiversity, assess ecosystem services and manage forests sustainably (Chiarucci and Piovesan, 2020). Furthermore, information on tree species distribution proves invaluable for assessing forests' vulnerability to insect infestations (Kärvelo et al., 2014), evaluating wildfire risks (Bernier et al., 2016) and carbon modeling (Goetz et al., 2009; Chen et al., 2018). Forest inventories, which rely on the analysis of aerial imagery alongside field measurements, are recognized as a reliable data source in many countries and regions (Shifley et al., 2017). However, obtaining tree species information via traditional image interpretation approaches is often prohibitively costly and time-consuming. As a result, there is a growing demand for automated remote sensing approaches to enhance the efficiency of species inventories.

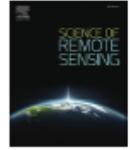
Over the past two decades, the use of optical remote sensing, encompassing both airborne and spaceborne multispectral and

hyperspectral imagery, has significantly advanced in the classification and mapping of tree species (Leckie et al., 2003; Boschetti et al., 2007; Grabska-Szwagrzak et al., 2019, 2024; Axelsson et al., 2021; Jia and Pang, 2023). This technology facilitates large-scale, efficient, and accurate mapping of tree species distribution, which is critical for effective forest management and conservation. Despite advancements in optical remote sensing solutions, it has become evident that using this data for species classification purposes has some limitations. One of the limitations is that the spectral reflectance of the same tree species can vary across different parts of the forest due to the position of the sun. Moreover, in mixed stands, where mixed pixels (containing spectral information from different tree species or both trees and other vegetation) are more common, the influence of adjacent trees can cause significant spectral overlap. This is particularly problematic in the near-infrared band, making it difficult to distinguish between species (Korpela et al., 2011). A promising solution to address these limitations is the integration of object-based image analysis (OBIA) methods. OBIA segments images into objects (e.g. individual tree crowns) rather than individual pixels, thereby reducing the effects of mixed pixels and enhancing the use of both spectral and structural information (Blaschke, 2010; Immitzer et al., 2012).

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Sub-hectare resolution forest biomass mapping from Copernicus DEM with low-dimensional models

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ABSTRACT

Accurate, sub-hectare resolution mapping of above-ground biomass density (AGBD) of the global forests is needed for many applications, including carbon accounting, forest resource management, and biodiversity research. Surveys based on airborne lidar and *in situ* data fulfill the accuracy requirements but lack global applicability, while the globally available optical, lidar, and radar backscatter data suffer from poor sensitivity to AGBD and/or spatial resolution. We here assess the global applicability of an alternative approach that exploits the publicly available, interferometric radar-based Copernicus digital elevation model (DEM) paired with a coarse-resolution digital terrain model (DTM). For eleven boreal, temperate and tropical test sites on four continents, we show that the DEM-DTM difference represents the average canopy elevation above ground and is well-correlated with AGBD maps derived from airborne lidar and *in situ* data. Within each climate zone, the estimated power law model parameters varied moderately and indicated an almost linear relationship between AGBD and the DEM-DTM difference. Using site-specific power law models resulted in an ensemble root-mean-square difference (RMSD) at 50 m resolution of 43.7 t/ha (18 % of the average AGBD of 246 t/ha) and a coefficient of determination (R^2) of 0.90. Climate zone-specific and a single, global scaling model performed almost equally well, with an overall RMSD of 20–21 % and an R^2 value of 0.87. The global scaling model performed substantially better than the ESA Climate Change Initiative Biomass dataset on AGBD and indicated high potential for global application with the upcoming near-global DTM from ESA's BIOMASS mission (launched on 29 April 2025).

1. Introduction

Earth's forests play a key role in climate change mitigation and adaptation, and are a valuable economic and societal resource that needs to be monitored and protected. Of particular interest is the monitoring of above-ground biomass density (AGBD), which is the total dry mass per unit area of above-ground, live and dry organic matter stored in vegetation. As a proxy for carbon density, AGBD is one of the Essential Climate Variables defined by the Global Carbon Observing

System (Bojinski et al., 2014) and a key variable in carbon accounting (Watson, 2009). AGBD is highly correlated with growing stock volume, a quantity commonly used by national forest inventories and forestry companies to assess forest resources (Santoro et al., 2015). Moreover, knowledge of AGBD can provide valuable information on biodiversity (Potter and Woodall, 2014) and fuel load (Vega et al., 2022).

Mapping of AGBD is challenging because a mass cannot be measured remotely, but rather has to be estimated from other measurements and field data (Chave et al., 2019; Woodhouse et al., 2012). One of the

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A new lens on biodiversity assessment: The reliability of high-resolution remote sensing in investigating tree species diversity in old-growth forests

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ABSTRACT

Describing and monitoring biodiversity in complex ecosystems is crucial for conservation and sustainable forest management. This study investigates the effectiveness of high-resolution remote sensing (RS) in assessing tree species diversity within the Białowieża Forest, one of the most natural lowland forests in Europe and a UNESCO World Heritage Site. The research aimed to evaluate two hypotheses: (H1) that RS can reliably assess canopy tree species diversity across different spatial contexts, and (H2) that there is a strong correlation between RS-derived biodiversity estimates and field measurements, with the correlation varying based on forest management and species composition. The study employed active (Airborne Laser Scanning - ALS) and passive (Color Infrared - CIR) RS data, along with XGBoost, to create species maps, which were compared with field measurements collected across three species compositions and three management categories. Findings suggest that RS is particularly reliable in stable environments with homogeneous species distributions, such as in mixed stands and managed forests, where RS closely aligned with field measurements. However, challenges emerged in capturing rare species and accurately estimating species densities in stands with complex vertical stratification, such as broadleaved stands and strict reserves. These limitations were identified as a critical determinant of the success of RS in biodiversity monitoring, whereas weaker correlations between canopy and understory diversity had a comparatively lesser impact. Overall, this study underscores the potential of RS in assessing tree species diversity, including both canopy and understory, and emphasizes its significance in supporting biodiversity monitoring and conservation.

1. Introduction

Biodiversity, especially tree species diversity, is a basis of forest ecosystem health, resilience, and sustainability (Brockerhoff et al., 2017; Bai et al., 2024). In old-growth forests (OGF), which represent one of the most complex and undisturbed ecosystems on Earth, biodiversity plays an even more critical role. These forests are characterized by their rich species composition, structural complexity, and long ecological background, making them vital reservoirs of genetic, species, and functional diversity (Mosser et al., 2003; Spies, 2004). Tree species diversity in OGFs contributes to the overall resilience of these ecosystems, helping them withstand and recover from environmental stressors,

such as climate change, pest outbreaks, and natural disturbances such as fire or storm (Price et al., 2020; Czerepko et al., 2021). The presence of diverse tree species supports a range of ecological processes essential for forest function. For example, species diversity promotes nutrient cycling, enhances soil fertility, and regulates water balance, all of which are crucial for sustaining forest health. Moreover, a variety of tree species provides habitats for other organisms, supporting a rich web of life that includes plants, animals, fungi, and microorganisms (Gilhen-Baker et al., 2022; Chen et al., 2023). In the era of global environmental change, OGFs with high species diversity are more capable to adapt to shifting conditions, as the presence of multiple species increases the likelihood that some species will be well-suited to the new

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Detekcja pojedynczych martwych świerków w Puszczy Białowiejskiej na podstawie integracji danych satelitarnych z danymi lotniczego skanowania laserowego

Detection of dead Norway spruce individuals in the Białowieża Forest based on the integration of satellite imagery with airborne laser scanning data

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Abstract. The Białowieża Forest, a unique lowland forest complex in Central Europe, has undergone significant ecological changes in recent years, primarily due to a massive outbreak of the spruce bark beetle (*Ips typographus* L.). This outbreak, which peaked in 2016, caused extensive Norway spruce (*Picea abies* (L.) H. Karst) mortality, leading to major changes in forest structure and functioning. Ground-based forest inventory methods remain a fundamental and accurate source of ecological information. However, they are time-consuming and relatively expensive, particularly when applied across large or inaccessible areas such as protected areas or wetlands. For this reason, alternative approaches are increasingly being explored – especially those leveraging remote sensing techniques, which allow for faster, spatially consistent and repeatable forest condition assessments. Satellite imagery and airborne laser scanning (ALS) data have proven to be powerful tools for monitoring forest condition at different spatial scales.

This study investigates the feasibility of integrating high-resolution multispectral satellite imagery (Pléiades, 2 m spatial resolution) with ALS data (11 points/m²) to detect and map individual dead spruce trees in the Polish part of the Białowieża Forest. The methodological framework (Fig. 2) included pre-processing steps such as cloud masking, shadow elimination, canopy gap removal and segmentation of individual tree crowns from ALS data. These procedures aimed to enhance the classification accuracy and spatial alignment of the datasets. A supervised maximum likelihood classification was applied to the satellite imagery, distinguishing three vegetation classes: dead trees, conifers and broadleaves. The classification resulted in a high accuracy for dead trees (producer's accuracy: 96.8%, user's accuracy: 94.6%; Tab. 4, Fig. 3).

A multistep integration method was used to detect individual dead trees by correlating spectrally classified pixels with tree crown segments derived from ALS data. Each crown was assessed for spatial proximity and spectral coverage of the classified dead pixels. By applying optimized thresholds for proximity and coverage, the algorithm identified individual dead spruce trees with a detection accuracy of 71.1% – true positives and a false positive rate of 22.0% (Tab. 9), validated against manually interpreted reference data. The final detection map indicated over 381,000 individual dead spruce trees in the forest area (Tab. 8, Fig. 5).

The integration of ALS and satellite data proved to be effective, especially in forest compartments with lower structural and species complexity. However, limitations were observed in areas such as the Białowieża National Park, where diverse canopy structures, species heterogeneity and occlusion effects significantly reduced detection rates. In such areas, the satellite pixels often represent mixed spectral signals, which reduces the reliability of the classification for individual tree identification.

The study emphasizes the utility of combining complementary remote sensing datasets to enable cost-effective, large-scale monitoring of forest health. It also highlights the temporal constraints of integrating data collected in different years, as forest conditions may change due to logging or vegetation regrowth. Although data mismatches can lead to errors, these can be mitigated by excluding known logged areas.

This research contributes to the development of practical approaches for operational forest monitoring and supports sustainable forest management under increasing ecological pressures. The proposed method, when adapted to specific forest conditions, can improve forest inventory systems. Future work should explore improvements in tree crown segmentation, the use of multi-temporal satellite data and the integration of additional spectral indices or Deep Learning-based classification algorithms.

Słowa kluczowe: detekcja pojedynczych drzew, integracja danych, klasyfikacja największego prawdopodobieństwa, lotnicze skanowanie laserowe (ALS), monitoring stanu zdrowotnego lasu, Pléiades, Puszcza Białowiejska, zamieranie drzew
Keywords: individual tree detection, data integration, maximum likelihood classification, airborne laser scanning (ALS), forest health monitoring, Pléiades, the Białowieża Forest, tree mortality

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RESEARCH ARTICLE OPEN ACCESS

Spatiotemporal Variability of Dendroecological Indicators in Pedunculate Oak (*Quercus robur* L.) Tree-Rings Across Europe in Relation to Species Distribution Models

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Keywords: climate change scenarios | climate-growth relationships | climatic water balance | growth synchrony | range contraction | vapor pressure deficit

ABSTRACT

Climate is a primary, but non-stationary, driver of tree growth. Climate change is altering the sensitivity of forest growth to water availability and temperature over time. It is considered that pedunculate oak (*Quercus robur* L.) will cope with the changing climatic conditions in Europe in the near future. However, while species distribution models project expansion zones, they also

For affiliations refer to page 13.

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Bridging spatio-temporal gaps in ALS data using Landsat time series and forest disturbance-recovery metrics via multi-task neural networks

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ABSTRACT

European forests contribute to climate change mitigation by sequestering carbon, conserving biodiversity, and enhancing water retention. However, climate-induced disturbances such as fires, windthrows, droughts, and pest outbreaks underscore the need for stronger forest monitoring systems. National Forest Inventories (NFIs) serve as the primary source of forest data and information in Europe. Yet, inconsistencies in timing, coverage, methodologies, and data quality highlight the need for a more harmonized and spatially detailed approach. Critically, predicting forest variables directly from satellite data remains challenging, mainly due to the difficulties in aligning remote sensing with ground data. Meanwhile, the operational use of airborne laser scanning (ALS) data is limited by high costs, infrequent updates, and inconsistent coverage from different sensors and flight conditions. This study presents a novel approach relying on fully connected neural networks to integrate Landsat satellite time series and forest disturbance and recovery metrics with ALS data to predict forest height metrics, which can then be used to accurately predict critical forest variables, such as growing stock volume (GSV) and stand basal area (BA). The method was tested across five ecologically and geographically diverse European forest regions: Tuscany (Italy), the Netherlands, the Canton of Grisons (Switzerland), Białowieża Forest (Poland), and the Vindöfjärden-Juhtatähkka Biosphere Reserve (Sweden). ALS forest height metrics were predicted with R^2 values ranging from 0.47 to 0.68. Then, based on field data, forest height metrics were used to predict GSV ($R^2 = 0.78$) and BA ($R^2 = 0.69$). Our method addresses the issue of limited spatial and temporal availability of ALS data by predicting ALS-derived height metrics using Landsat time series. This study examines the challenges of combining satellite and NFI data, building on the premise that satellite data can be effectively used to predict forest height metrics derived from ALS, which in turn can be used to accurately quantify several forest variables. The methods presented here support scalable and cost-effective forest monitoring by providing the spatially and temporally detailed information needed to implement climate-smart forestry.

1. Introduction

Forests cover more than one-third of the European land area (FISE, 2021) and provide a wide range of beneficial effects to the environment and citizens (Orsi et al., 2020), such as climate change mitigation (Peterson et al., 2022), carbon storage (Fahey et al., 2010), biodiversity conservation (Burrascano et al., 2023), and water retention (Ellison et al., 2017). Nevertheless, in the past decades, European forests experienced an increase in natural disturbances, possibly related to global

warming (Palahí et al., 2021) and future scenarios forecast a serious increase in windthrow, fires, and insect attacks (Forzieri et al., 2021). Applying international policies to monitor, manage, and protect European forests against climate change and related threats is more pivotal than ever.

In this context, harmonized forest information is needed for international conventions involving forests, such as the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity at the pan-European level. A large part of the

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