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# Bibliometric Insights into Terrestrial Laser Scanning for Forest Biomass Estimation

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**Abstract:** Effective forest management and conservation are increasingly critical in addressing the challenges posed by climate change. Advances in remote sensing technologies, such as terrestrial laser scanning, offer promising tools for more accurate assessments in forestry research. This study explores the application of TLS in biomass estimation by conducting a bibliometric analysis of scientific articles indexed in Scopus and the Web of Science. By examining the literature from 2010 to 2024, the study identifies key trends, knowledge gaps, and emerging research opportunities, as well as practical applications in forest management and conservation. The analysis reveals a significant rise in scientific output on TLS, with an average annual growth rate of 8.16%. The most cited works address biomass estimation at the individual tree level using laser scanning data. China and the United States lead in the publication volume with 11 articles. The collaboration network highlights research disparities among regions such as Latin America. Overall, TLS has proven effective for the non-destructive measurement of forest variables and biomass.

**Keywords:** climate change; dendrometry; laser scanner; point cloud; three-dimensional; TLS

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## 1. Introduction

Forest sciences encompass a set of disciplines focused on the study and management of forest resources, with a particular emphasis on sustainability and ecosystem conservation. One of the primary challenges in this field is the accurate estimation of aboveground biomass (AGB). Biomass refers to the total mass of the living organisms in a specific area [1]. In forestry, AGB focuses on trees, including the stems, branches, and leaves. It is measured in terms of the mass per unit area, typically expressed in dry weight, which provides a more accurate measurement by excluding the water content [2]. This method is crucial for obtaining a clear assessment of the organic material present in a forest. Such a measurement is fundamental for evaluating forest productivity and the carbon storage capacity, providing essential information about the health and growth of forests, as well as their role in ecological cycles and the management of forest resources [3].

Traditionally, AGB estimation has been carried out using destructive methods, which involve the felling and weighing of trees. Although this approach provides direct measurements, it is impractical on a large scale due to its cost, environmental impact, and the effort required [4]. As an alternative, allometric equations have been developed, allowing for biomass to be inferred from more easily measurable parameters, such as the diameter at breast height (DBH) and tree height. However, it is important to note that these allometric equations rely on the existence of a weighed sample, which is obtained using destructive methods, to calibrate and validate the relationships between the measured parameters and biomass [5].

In recent years, the incorporation of remote sensing has revolutionized forest analysis, enabling detailed and non-destructive assessments of the forest [4]. Among these technologies, Light Detection and Ranging (LiDAR) has emerged as a key tool. LiDAR works by emitting laser pulses that, when reflected off objects, generate three-dimensional point clouds that accurately detail the forest structure [6].

The application of LiDAR in forest inventories has proven to be highly effective for obtaining precise measurements of key parameters such as the tree height, volume, and canopy structure, often surpassing the limitations of traditional measurement methods [7]. Notably, terrestrial laser scanning (TLS), a form of LiDAR, has become particularly valuable in forestry for its ability to accurately capture the three-dimensional structure of trees. This capability is crucial for generating robust biomass estimates that can be applied across various ecological conditions. By providing detailed data on the tree geometry and structure, TLS enhances the accuracy of biomass estimation, making it an indispensable tool in modern forest management and ecological research [8,9].

In this context, conducting a bibliometric study becomes essential to understanding the evolution and current state of research on the use of TLS for forest biomass estimation. A bibliometric analysis allows for the identification of key trends, influential authors, and areas of opportunity in the scientific literature, providing a detailed view of how this field has progressed and what challenges and advances have emerged over time. This type of analysis not only contextualizes technological and methodological developments but also offers a solid foundation to guide future research and policies in the field of forest sciences.

This study aimed to identify trends, challenges, and opportunities in the application of TLS for estimating biomass. The specific objectives were as follows: (1) to analyze scientific contributions on the subject; (2) to map scientific networks among authors and countries in this research field; and (3) to identify research trends involving TLS technology.

## 2. Materials and Methods

For our research, we utilized two key databases: Scopus and the Web of Science. These databases were chosen for their ability to provide reliable and comprehensive data. Both offer extensive coverage of the scientific literature and are noted for their rigorous content selection [10]. Their main advantage is that they contain indexed scientific information, which enables precise searches that are crucial for large-scale bibliometric analyses.

The systematic search was conducted using specific commands for each database. In Scopus, we used the command (TITLE (“terrestrial laser scanning” OR “tls” OR “terrestrial lidar”)) AND (TITLE (“biomass” OR “agb” OR “aboveground biomass”)). In Web of Science, the command was (TI = (“terrestrial laser scanning” OR “tls” OR “terrestrial lidar”)) AND (TI = (“biomass” OR “agb” OR “aboveground biomass”)). In both cases, the search focused exclusively on article titles, excluding abstracts and keywords. This approach was chosen to avoid scattered results and ensure that the studies were directly related to biomass calculation.

A total of 162 records were obtained from Scopus and the Web of Science. Duplicate records were then removed, because a journal can be indexed in both platforms. Next, publication types such as conference papers, errata, reviews, and proceeding papers were excluded, as they were not relevant to the analysis. This process resulted in 77 scientific articles for evaluation. The data curation process was conducted in RStudio [11]. Finally, 13 articles were discarded because they focused on grasslands, paddy fields, savannas, and other environments not directly related to forest ecosystems or trees. As a result, only 62 articles were retained for further analysis.

For our bibliometric analysis, we employed the Bibliometrix library within RStudio [11,12]. Bibliometrix provided advanced algorithms and statistical methods tailored for science mapping, including co-citation network generation, thematic analysis, and the calculation of bibliometric indicators such as citation counts, the h-index, and collaboration patterns. To facilitate interactive exploration and the visualization of our findings, we utilized Biblioshiny, a web-based interface built on top of Bibliometrix. Biblioshiny enabled dynamic visualizations and provided interactive dashboards and intuitive tools for exploring citation networks, co-authorship patterns, and thematic clusters.

We performed the following analyses to enrich our understanding of the research landscape:

- Temporal and citation analyses: We conducted a chronological analysis to visualize the evolution of scientific production over time, highlighting periods of significant increase in article publication. Annual citation averages were also assessed to understand the temporal impact of published articles.
- Identification of journals and authors: Key scientific journals and highly cited authors within the field were identified. This provided insights into primary sources and influential figures shaping the research in TLS applications for biomass estimation.
- Collaboration network analysis: An international collaboration network was constructed to visualize significant interactions among researchers and institutions globally. This analysis highlighted key research centers and international relationships contributing to advancements in TLS research.
- Conceptual structure analysis: Factorial analysis, thematic evolution analysis, and thematic mapping were employed to categorize and identify the main research themes. These analyses revealed evolving trends and emerging themes in the application of TLS for biomass estimation.

These methodological approaches collectively provided a comprehensive analysis of the scientific landscape surrounding TLS applications in biomass, capturing both quantitative growth and conceptual evolution over the study period.

## 3. Results

The articles in our analysis span from 2010 to 2024 and includes a total of 32 scientific journals indexed in Scopus and the WoS. A total of 62 documents were analyzed, with an average annual growth rate of 8.16% in research production. The average age of the documents is 5.31 years. Each document has an average of 39.15 citations, reflecting significant impact and sustained interest in the field.

In terms of content, 464 additional Keywords Plus and 183 Author's Keywords were identified, highlighting the thematic diversity and approaches within scientific studies using terrestrial laser scanning. A total of 284 authors contributed, with two documents authored by a single author. The average number of co-authors per document is 5.79, emphasizing the collaborative and multidisciplinary nature of the research. All information is concentered in Table 1.

**Table 1.** Summary of key data characteristics, authorship information, and TLS–biomass research metrics (2010–2024).

| **Main Information about Data** | |
|---|---|
| Timespan | 2010–2024 |
| Journals | 32 |
| Documents | 62 |
| Annual growth rate | 8.16% |
| Average document age | 5.31 years |
| Average citations per doc | 39.15 |
| **Document contents** | |
| Keywords Plus (ID) | 464 |
| Author's Keywords (DE) | 183 |
| **Authors** | |
| Authors | 284 |
| Single-authored docs | 2 |
| Co-authors per doc | 5.79 |

Figure 1 illustrates the annual evolution of scientific production in terms of published articles. A general increase in production is observed over time, although with fluctuations that result in declines during certain periods. Between 2011 and 2014, the number of articles rises significantly, reaching a peak in 2014, followed by a continuous decrease until 2017. From 2017 onward, there is a new increase in production, peaking at 10 articles in 2021, surpassing the previous high of 2014. However, in more recent years, production has declined again, reaching three articles.

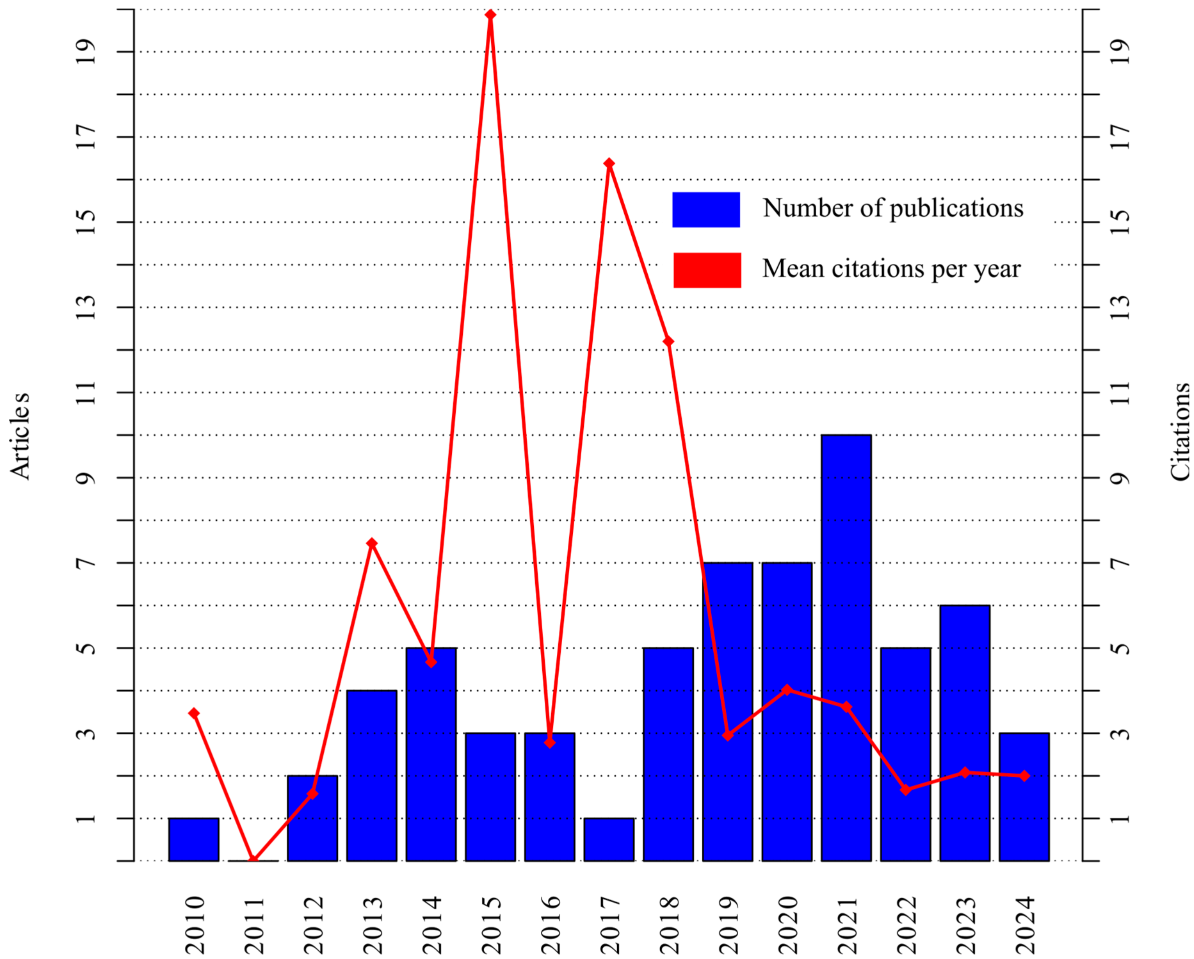


**Figure 1.** Number of publications and mean citations per year for scientific research on TLS and AGB (2010–2024).

The average citations per year represents the average number of citations that a set of publications receives annually. It is calculated by taking the total number of citations each publication has received, dividing that by the number of years since it was published, and then averaging these values across all the publications in the set.

In the analysis of annual citation averages (Figure 1), distinct patterns emerge over time. Overall, the data reveals generally low citation averages, indicating that most publications have not been heavily referenced. However, there are three significant peaks that have become key references in biomass estimation: in 2013 with a value of 7.46, in 2015 with a value of 19.87, and in 2017 with a value of 16.38. Notably, there is a marked minimum in 2016, reflecting a decline in the average citations during that period.

During 2015, only three publications were recorded in the field as generating the highest value for citations from the publication year, yet two of them stand out significantly. The first article, authored by Calders et al. [13], stands as the most cited work in this bibliometric analysis, with 471 citations according to database platforms and 611 citations reported by the British Ecological Society. This article has become a fundamental reference in biomass estimation. The methodology involves the collection of the tree height, DBH, and AGB data through traditional forest inventory methods, terrestrial laser scanning, and destructive sampling of 65 trees in a native Eucalypt Open Forest in Victoria, Australia. Individual trees were extracted from the point cloud, and quantitative structure models were applied to estimate the tree volume directly from the point cloud data. These volumes, combined with basic density information, were used to infer the AGB, which was then compared with estimates derived from allometric equations and destructive sampling. The error for AGB estimates using allometric equations increases exponentially with an increasing DBH, whereas the error for AGB estimates from TLS is not dependent on the DBH. The TLS method, which does not rely on indirect relationships with tree parameters or calibration data, shows better agreement with reference data compared to estimates from allometric equations. The second article, also published in 2015 by Hackenberg et al. [14], has accumulated 120 citations and ranks as the third most cited in our database. The methodology employed is similar to that of Calders et al. [13], utilizing terrestrial laser scanning data to predict the tree volume. By combining these volume estimates with density measurements, the study successfully predicts biomass.

Across 2017, only one article was published; however, it achieved a high citation count, with 132 citations according to the consulted databases. This work, conducted by Stovall et al. [15], presents an efficient and non-destructive method for estimating single-tree biomass using terrestrial LiDAR scan data, which was tested on 21 destructively sampled plots of *Pinus contorta*. The method estimates the branch and foliage volumes using voxelization and the trunk volume with a newly developed approach called the Outer Hull Model (OHM). The OHM iteratively fits convex hulls, accurately handling noisy scan data and conforming to the true shape of the trunk rather than forcing a cylindrical fit. The LiDAR-derived volume is then converted to biomass using density values from the literature and field sampling to assess the model's sensitivity to these values.

### *3.1. Journals, Journal Articles, and Authors*

The analysis of the sources of published articles in the field of study reveals a diverse distribution among various scientific journals. *Remote Sensing* leads with 10 articles, followed by *Forests* with 9 articles. Other notable sources include *Forest Ecology and Management* and *Methods in Ecology and Evolution*. The second most cited article in *Remote Sensing* is the work by Fan et al. [16]; this study introduces the AdQSM model for estimating the aboveground biomass of large tropical trees by reconstructing 3D models from point clouds obtained through terrestrial laser scanning. The results showed satisfactory coefficients of variation of the root mean square error and concordance correlation coefficients, indicating the effectiveness of AdQSM for precise AGB estimations and its potential for future applications in allometric equations. *Forests*, like *Remote Sensing*, are open access and peer-reviewed scientific journals published by MDPI. Additionally, the second article most cited in *Forests* was written by Lau et al. [17]. They developed allometric models to estimate the aboveground biomass of trees in Guyana using tree attributes (diameter, height, and crown diameter) obtained from terrestrial laser scanning of 72 tropical trees and wood density. The results provided more accurate AGB estimates than traditional pantropical models. Table 2 summarizes the key journals contributing to research in TLS applications for biomass estimation, including the year of the first TLS–biomass publication, the number of articles published, and the average number of articles per year from the first publication to the most recent.

Regarding the top ten most cited articles (Table 3), as mentioned, the work by Calders et al. [13] is currently the work with the highest number of citations. The second place is held by Kankare et al. [18] and focuses on estimating single-tree level aboveground biomass using models developed from terrestrial LiDAR data. The modeling dataset included 64 laboratory-measured trees. Models were developed for the total aboveground biomass, as well as for tree stem biomass, living branch biomass, and dead branch biomass. They recommend using geometric measurements of the stem curve and crown size obtained from point cloud data as the basis for allometric biomass models, rather than three-dimensional statistical metrics, because the latter depend on various scanning parameters and the characteristics of the tree's surroundings.

**Table 2.** Overview of journal sources and publication metrics related to TLS and biomass research.

| Journal | Start of Publication | Articles | Articles per Year |
|---|---|---|---|
| *Remote Sensing* | 2010 | 10 | 0.71 |
| *Forests* | 2014 | 9 | 0.90 |
| *Forest Ecology and Management* | 2014 | 4 | 0.40 |
| *Methods In Ecology and Evolution* | 2015 | 4 | 0.44 |
| *Journal of the Indian Society of Remote Sensing* | 2019 | 3 | 0.60 |
| *Trees-Structure and Function* | 2016 | 3 | 0.37 |
| *Annals of Botany* | 2021 | 2 | 0.66 |
| *Canadian Journal of Remote Sensing* | 2018 | 2 | 0.33 |
| *International Journal of Geoinformatics* | 2020 | 2 | 0.50 |
| *Basrah Journal of Agricultural Sciences* | 2021 | 1 | 0.33 |

**Table 3.** Ten most cited publications on TLS for biomass estimation, including authors, journals, and citation metrics.

| Authors | Journal | Year | Citations | Citations per Year |
|---|---|---|---|---|
| Calders et al. [13] | *Methods in ecology and evolution* | 2015 | 471 | 52.33 |
| Kankare et al. [18] | *ISPRS Journal of photogrammetry and remote sensing* | 2013 | 220 | 20 |
| Gonzalez et al. [19] | *Methods in ecology and evolution* | 2018 | 176 | 25.14 |
| Stovall et al. [15] | *Remote sensing of environment* | 2017 | 131 | 21.83 |
| Hackenberg et al. [14] | *Forests* | 2015 | 121 | 24.20 |
| Momo et al. [20] | *Methods in ecology and evolution* | 2018 | 107 | 11.88 |
| Srinivasan et al. [21] | *Forest ecology and management* | 2014 | 80 | 11.42 |
| Kaasalainen et al. [22] | *Remote sensing* | 2014 | 75 | 10.71 |
| Yu et al. [23] | *Remote sensing letters* | 2013 | 72 | 7.20 |
| Stovall et al. [24] | *Forest ecology and management* | 2018 | 71 | 6.45 |

The third most cited work since its publication is the study by Gonzalez et al. [19], which presents a method to estimate the AGB of large tropical trees using three-dimensional modeling of TLS point clouds. In this study, 29 plots across Peru, Indonesia, and Guyana were scanned with terrestrial LiDAR, focusing on the largest tree per plot. The volume of these trees was calculated using quantitative structure models and converted to AGB with species-specific wood density. Aboveground biomass estimates were compared to those obtained from pantropical and local allometric models. This method proved to be particularly effective in reducing systematic biases commonly associated with allometric models, especially for large trees.

Table 4 provides a comprehensive summary of the methodologies, equipment, and software utilized in the top ten most cited articles that focused on estimating aboveground biomass using terrestrial laser scanning. These studies represent a diverse array of approaches, highlighting both the technological tools and methodological frameworks employed to achieve accurate and reliable biomass estimates in various forest environments. As can be observed, various techniques are employed in the reconstruction and analysis of three-dimensional structures, with methods such as QSM and the OHM standing out for their accuracy in volume estimation. QSM fits cylinders to different parts of the structure to calculate volume, while the OHM envelops the entire shape to obtain a global estimate, sometimes complemented by voxelization to capture the internal distribution of elements. Additionally, data registration methods are used to combine multiple scans and generate precise 3D models, which often require manual refinements in cases of complex geometries. These approaches, while effective, vary in their complexity and are selected based on the specific characteristics of the environment and the goals of the analysis.

**Table 4.** Summary of methodologies, equipment, and software used in 3D structure analysis and biomass estimation studies.

| Article | Methodology | Equipment Used | Software |
|---|---|---|---|
| Nondestructive estimates of above-ground biomass using terrestrial laser scanning [13] | AGB was inferred from tree volume estimates derived using QSM. | RIEGL VZ-400 (Riegl Laser Measurement Systems GmbH, Horn, Austria) | RiScan PRO, MATLAB, and Point Cloud Library (PCL) |
| Individual tree biomass estimation using terrestrial laser scanning [18] | A total of 83 TLS-based features were extracted from individual tree point clouds. | Leica HDS6100 TLS system (Leica Geosystems, Aarau, Switzerland) | Cyclone (Leica Geosystems), Terrascan (Terrasolid), and R |
| Estimation of above-ground biomass of large tropical trees with terrestrial LiDAR [19] | AGB was inferred from tree volume estimates derived using QSM. | RIEGL VZ-400 (Riegl Laser Measurement Systems GmbH, Horn, Austria) | RiScan PRO and Matlab (QSM) |
| Non-destructive aboveground biomass estimation of coniferous trees using terrestrial LiDAR [15] | Volume estimates derived from the OHM and voxelization methods were converted to biomass. | FARO Focus3D 120 (Faro Technologies, Lake Mary, Florida, United States) | Faro SCENE and CloudCompare |
| Non Destructive Method for Biomass Prediction Combining TLS Derived Tree Volume and Wood Density [14] | Biomass was predicted by multiplying the TLS-derived volume by species-specific wood density. | Z+F IMAGER 5010 (Zoller & Fröhlich GmbH, Wangen, Germany) | Z+F LaserControl and SimpleTree |
| Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: A comparison with traditional destructive approach [20] | The volume estimates derived from the QSMs were converted to AGB using species-specific wood density values. | Leica C10 ScanStation (Leica Geosystems, Aarau, Switzerland) | Leica Cyclone, simpletree, Geomagic Studio 12, and amapstudio-Scan |
| Multi-temporal terrestrial laser scanning for modeling tree biomass change [21] | Computed geometric and statistical parameters that were used for estimating AGB. | Leica ScanStation2 (Leica Geosystems, Aarau, Switzerland) | Quick Terrain Modeler (QTM) and CloudMetrics (FUSION/LDV) |
| Change Detection of Tree Biomass with Terrestrial Laser Scanning and Quantitative Structure Modelling [22] | QSM was used to detect changes in tree biomass over time. | Leica HDS6100 (Leica Geosystems, Aarau, Switzerland) | Z+F LaserControl, QSM, and TIN |
| Stem biomass estimation based on stem reconstruction from terrestrial laser scanning point clouds [23] | Trunk reconstruction using cylinder fitting; stem biomass estimation with regression based on TLS data. | Leica HDS6100 (Leica Geosystems, Aarau, Switzerland) | Custom tools for automatic modeling |
| Assessing terrestrial laser scanning for developing non-destructive biomass allometry [24] | Scanning of plots with TLS, 3D modeling of trees, and volume and biomass estimations using QSM. | Faro Focus 120 3D (Faro Technologies, Lake Mary, Florida, United States) | SCENE and CompuTree |

According to Lotka's Law, there is a distinctive distribution of the number of documents authored by individuals in a particular field of study. The findings indicate that the majority of authors have authored only one document, with 231 authors (81.3%) falling into this category, representing the highest proportion. Kim Calders has a scientific output of seven articles. He is the author of the most cited article, as previously mentioned, and a co-author in six other articles, with the work of Gonzalez et al. [19] being particularly noteworthy. Raumonen Pasi is a co-author of five articles, prominently featured in the works of Calders et al. [13] and Gonzalez et al. [19], which are among the most significant contributions in our bibliometric study. Juha Hyyppä is a co-author of four publications, with his participation in the work of Kankare et al. [18] being especially notable. The second most cited article involving Hyyppä is the one by Yu et al. [23], which explores the estimation of the stem biomass of individual trees using TLS. Destructive sampling was conducted to collect the biomass data, which were then used as a dependent variable in a regression analysis. The study investigated two biomass estimation models: one based on the diameter at breast height and another based on the sum of stem section volumes, both determined from the point cloud data. Finally, Atticus Stovall is the author of three articles, one of which has received a considerable number of citations, as discussed earlier. In another significant article by Stovall et al. [24], they virtually reconstructed 329 trees with diameters of up to 123 cm. These three-dimensional tree models formed the basis for 22 local allometric relationships, which were compared to the previous allometric equations. Overall, TLS allometry demonstrated a lower root mean square error and predicted higher tree-level biomass compared to the equivalent national equations. Figure 2 illustrates the top five authors with the most publications.

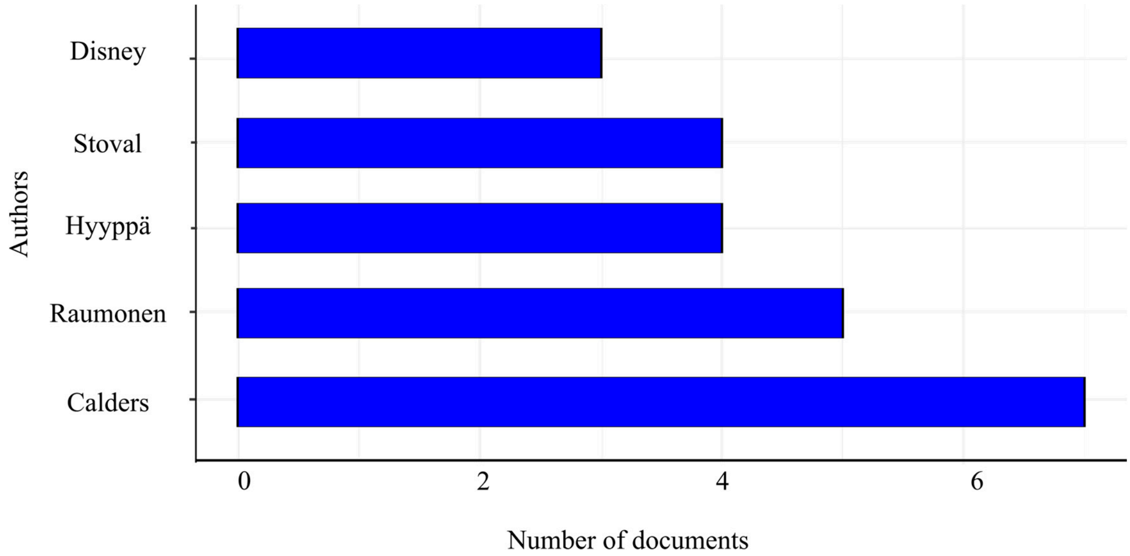


**Figure 2.** Scientific output of key authors in biomass estimation using TLS.

The analysis of scientific production shows that China and the United States lead in terms of publication frequency, with 11 publications each. The United States holds the top position, consistent with its extensive tradition in scientific research. China closely follows, reflecting its growing presence in the global scientific scenario.

Canada and Finland share the third position, each with six publications. These countries exhibit notable scientific production, albeit on a smaller scale compared to the United States and China. Ethiopia, with five publications, completes the group of the five countries with the highest production frequency. Its inclusion highlights the presence of relevant scientific production across various regions of the world.

These data indicate the distribution of research activities among countries with different economic and scientific contexts, highlighting variations in the global capacity for scientific production, as shown Figure 3.

The citation analysis (Table 5) reveals a distinct pattern compared to scientific production. The Netherlands leads in the total citations, with 696 and an impressive average of 232 citations per article. Despite not being among the top five in publication frequency, the Netherlands demonstrates significant scientific impact. Finland ranks second, with 454 total citations and an average of 75.7 citations per article. This consistency in both the publication frequency and citation impact highlights Finland's influence in key research areas. The United States, which leads in the publication frequency, is third in total citations, with 435 and an average of 39.5 citations per article. This indicates high output but a more moderate citation impact per publication compared to countries like the Netherlands. China, despite being the second highest in publication frequency, has 174 total citations and an average of 15.8 citations per article, showing a lower citation impact relative to its extensive research output.

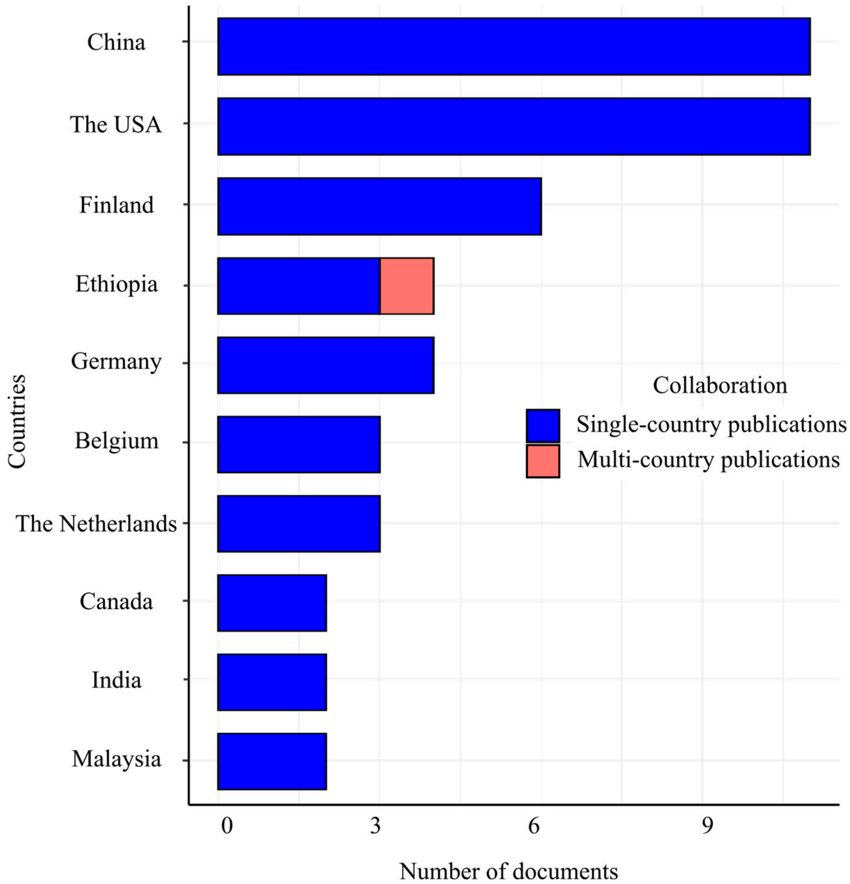


**Figure 3.** Top ten countries by number of publications in forest biomass assessment with terrestrial laser scanning.

**Table 5.** Most cited countries in forest biomass assessment research using terrestrial laser scanning.

| Country | Total Citations | Average Article Citations |
|---|---|---|
| The Netherlands | 696 | 232.00 |
| Finland | 454 | 75.67 |
| The USA | 435 | 39.55 |
| China | 174 | 15.82 |
| Cameroon | 107 | 107.00 |

Finally, an examination of term frequency within the relevant literature elucidates focal points within the field (see Figure 4). "Biomass" is the most prevalent term, appearing 68 times, indicating a strong focus on biomass studies. "Forestry", with 49 occurrences, underscores the importance of forest management and science within the analyzed works. The term "surveying instruments", cited 31 times, highlights a significant emphasis on the use of topographic and geodetic measurement tools, which are essential for accurate field data collection. "Terrestrial laser scanning", mentioned 27 times, reflects the widespread adoption of this technology for detailed surface mapping, particularly in forestry applications.

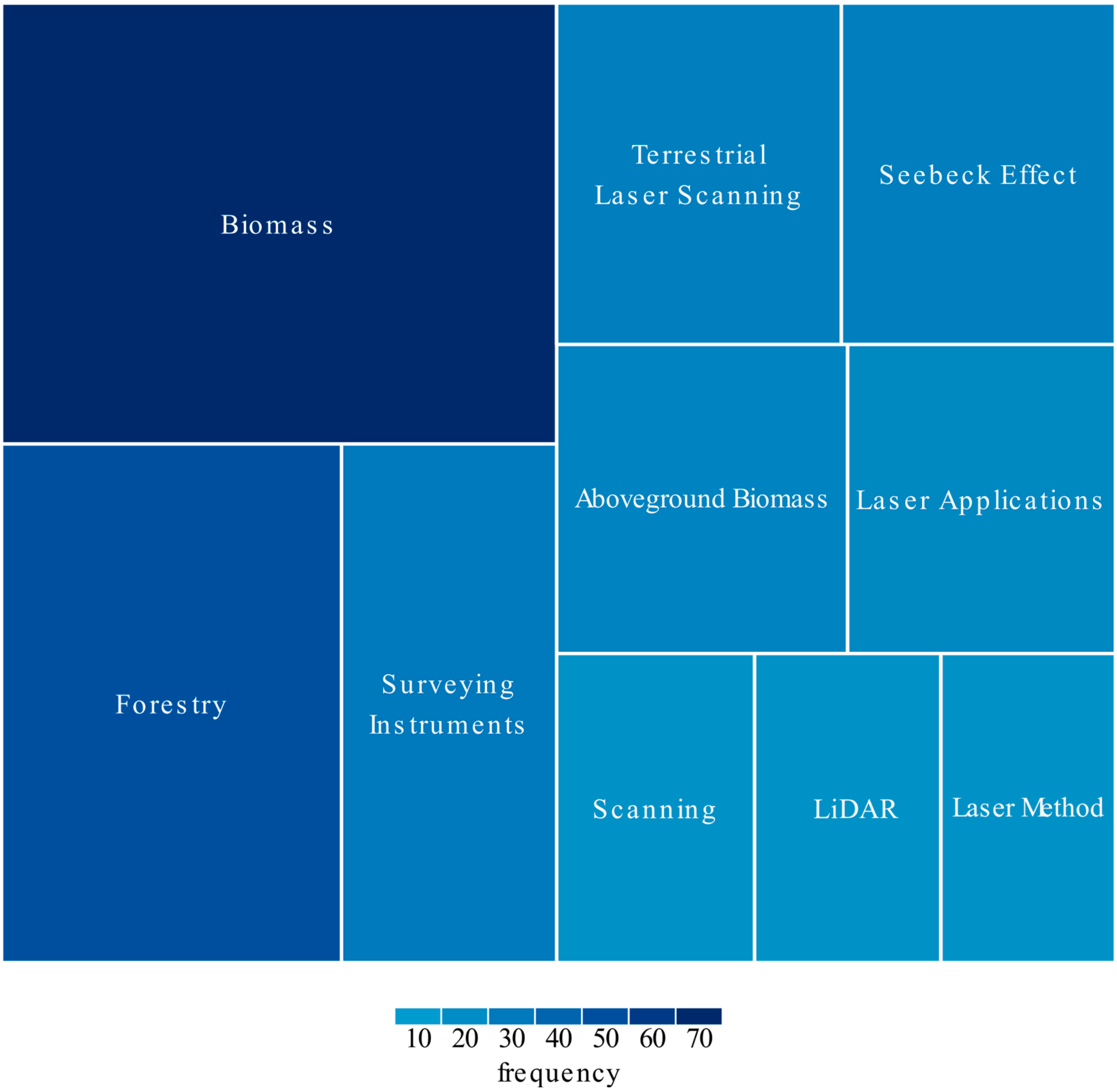


**Figure 4.** Word tree map in the field of TLS and biomass.

Other notable terms include "Seebeck effect" (26 occurrences) and "aboveground biomass" (25 occurrences), which reinforce the focus on thermoelectric phenomena and the quantification of aerial biomass in the analyzed studies. The presence of terms such as "laser applications" (23 occurrences), "scanning" (17 occurrences), "LiDAR" (16 occurrences), and "laser method" (15 occurrences) indicates a strong inclination towards laser technology and its application across various research domains. Collectively, these terms represent the key thematic areas in the reviewed articles, with a particular emphasis on biomass, forestry science, and the use of advanced technologies like terrestrial laser scanning and related methods.

### *3.2. Social Structure*

Figure 5 displays the scientific collaboration between countries, where the size of each node represents the number of articles published by that country. The lines represent the collaboration between countries, and the thickness of the lines also depends on the number of collaborations. Despite high scientific output, countries like China and the United States show virtually no collaboration with each other. Overall, the figure reveals a stark lack of meaningful collaboration between most countries, with very few significant connections observed, such as the one between Ethiopia, Malaysia, and The Netherlands.

This highlights a concerning trend where, despite substantial research output, global scientific collaboration remains fragmented and limited.

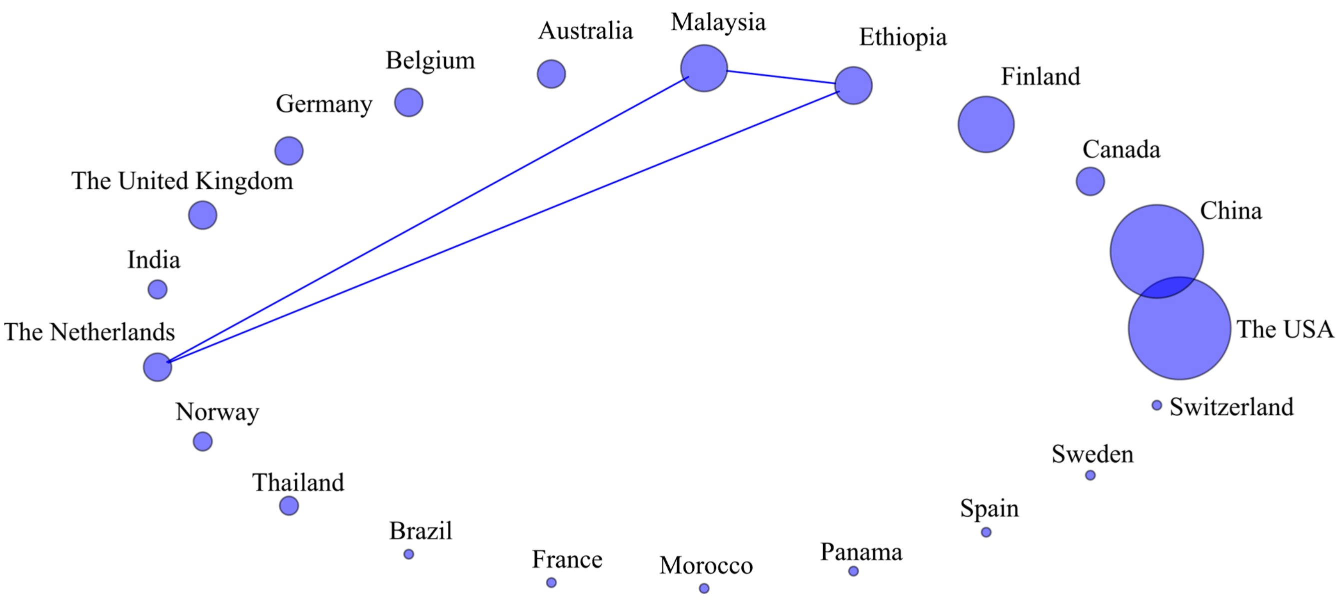


**Figure 5.** Collaboration network between countries.

### *3.3. Conceptual Structure*

The factorial analysis generated using multiple correspondence analysis provides a visual representation of the relationships among key terms in the analyzed literature. This type of analysis allows for the identification of clusters of terms that share conceptual similarities, offering insights into the thematic structure of the research field. In this case, three clusters were identified based on the Keywords Plus (Figure 6).

The first cluster, located in the upper-left quadrant, is centered around terms such as "biomass", "estimation", "regression analysis", and "forest biomass". This grouping indicates a focus on the estimation and modeling of biomass within forest ecosystems, emphasizing statistical methods and models for biomass quantification. The terms in this cluster suggest an interest in the methodological aspects of biomass estimation, particularly in the context of forestry research.

The second cluster, situated in the upper-right quadrant, is associated with terms like "terrestrial environment", "volume", "height", and "terrestrial LiDAR". This cluster reflects a focus on terrestrial environments and the volumetric estimation of forest structures, primarily through the application of LiDAR technology. The inclusion of terms such as "models" and "laser" highlights the use of advanced remote sensing techniques to measure and model forest attributes, particularly tree height and volume.

The third cluster, located in the lower section of the map, encompasses a broader range of terms related to laser scanning technology and its applications in environmental monitoring. Key terms in this cluster include "terrestrial laser scanning", "climate change", "remote sensing", and "biomass." This grouping suggests a strong focus on the application of terrestrial laser scanning in environmental studies, particularly for assessing the impact of climate change on forest ecosystems and quantifying biomass at various scales. The presence of terms like "surface analysis" and "sampling" indicates the practical aspects of data collection and analysis in this research domain.

The spatial arrangement of the clusters along the two main dimensions of the map suggests distinct conceptual orientations within the research field. The first dimension appears to separate research focused on advanced measurement technologies, such as LiDAR, for forest structure analysis from those that emphasize broader methodological approaches to biomass estimation. The second dimension may differentiate between methodological concerns related to measurement and estimation and the specific applications of scanning technologies and remote sensing in environmental research. Overall, the map provides a comprehensive overview of the thematic structure of the research field, highlighting key areas of focus and the interconnectedness of different research themes in biomass analysis and terrestrial laser scanning technology.

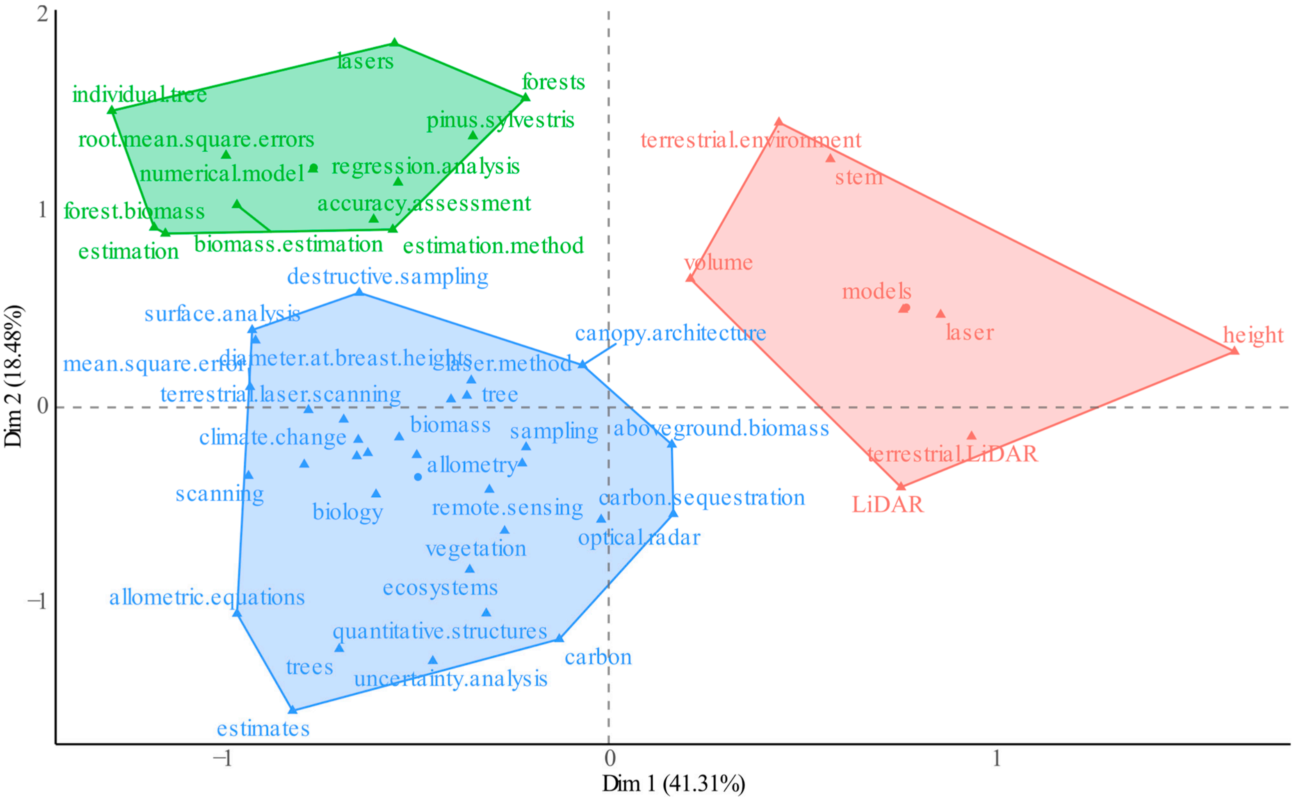


**Figure 6.** Multidimensional scaling analysis of high-frequency keywords in articles using TLS in biomass research (the colors are only used to distinguish the clusters).

An examination of thematic evolution reveals a nuanced progression in the topics explored within the articles analyzed using the TLS system (Figure 7). Between 2010 and 2016, key terms include "biomass", "aboveground biomass", "destructive sampling", and "regression analysis". During this period, the research primarily focused on the quantification and estimation of biomass, utilizing destructive sampling methods and regression analysis to model and predict biomass in forest areas.

In the period from 2017 to 2020, the focus on "biomass" continues, but new terms like "diameter at breast height" and "diameter estimation" emerge. This suggests a transition towards more specific measurement and estimation methods, particularly concerning the diameter at breast height, a critical metric in forestry studies for estimating biomass and other forest attributes.

During 2021, the interest in "biomass" persists, but new terms like "optical radar" and "carbon" are introduced. This evolution indicates a shift towards the integration of optical and radar technologies in biomass measurement and a growing interest in the role of carbon in environmental studies, reflecting the importance of carbon sequestration in the context of climate change.

Finally, in the period from 2022 to 2024, "biomass" remains prominent, but "scanning" and "neural networks" also stand out. This suggests a trend towards the use of advanced technologies such as laser scanning and machine learning (neural networks) to improve the accuracy and efficiency of biomass estimation and other forestry studies.

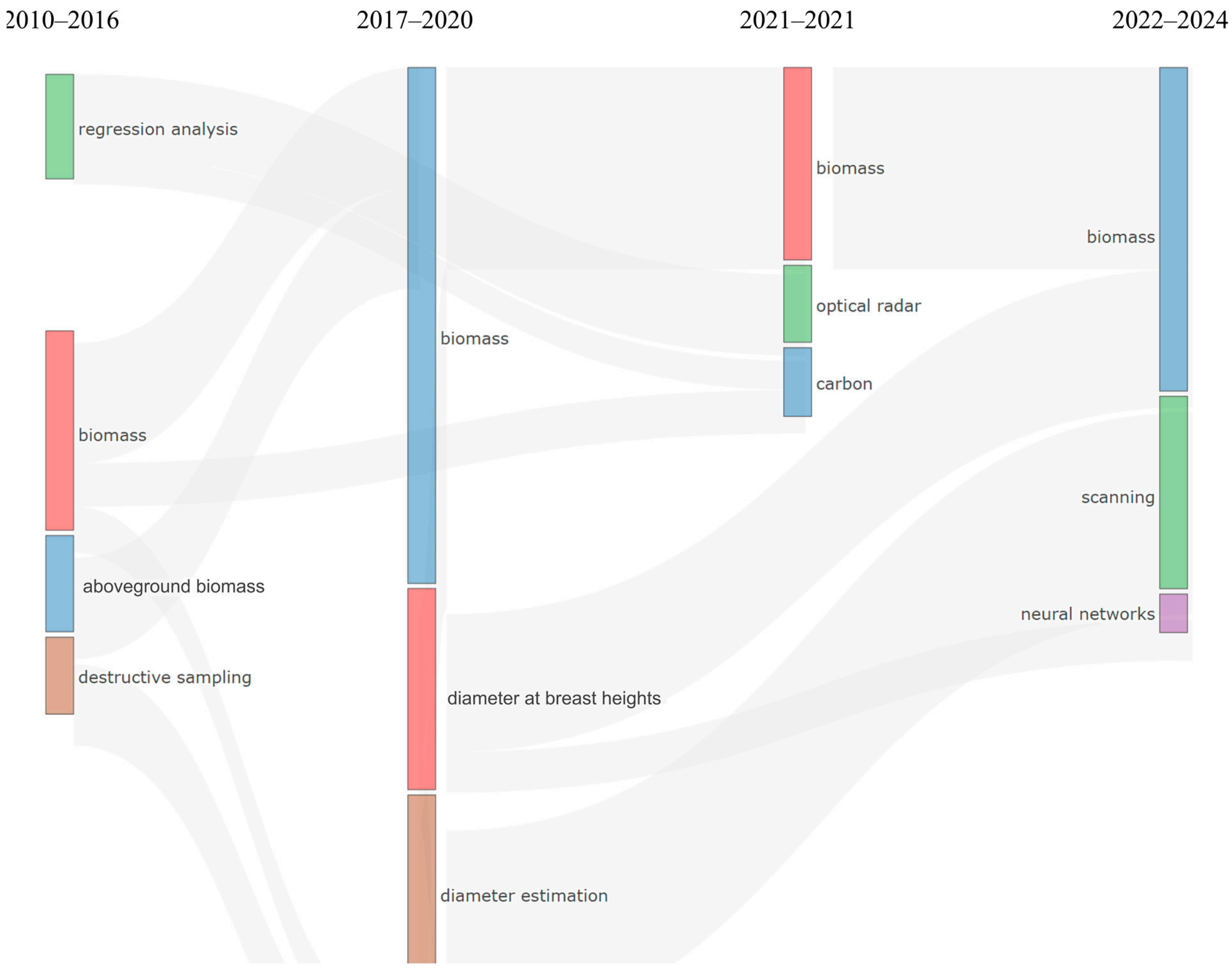


**Figure 7.** Thematic evolution of the field of TLS and biomass.

The thematic map presented (Figure 8) has been generated to identify and categorize research themes in regard to the use of TLS in biomass estimation. The themes are distributed on a Cartesian plane defined by two axes: the degree of development (density) on the vertical axis and the degree of relevance (centrality) on the horizontal axis. The presence of strong motor themes like "biomass estimation", "regression analysis", and "estimation method" highlights well-established areas that are critical to the field's advancement. These themes drive the core research efforts, focusing on essential methodologies and techniques that underpin much of the current scientific inquiry. Niche themes, such as "terrestrial environment", "terrestrial LiDAR", and "bioenergy", while specialized, offer depth in specific research contexts, contributing to the diversity of knowledge within the field. These themes play a crucial role in pushing the boundaries of understanding in specialized areas, providing the field with innovative approaches and solutions.

The emerging or declining themes, including "diameter estimation", "non-destructive examination", and "tree detection", point to areas that could either gain momentum or fade over time, requiring further observation. These themes represent potential areas of growth, where new methodologies or technologies could transform them into central areas of research, or alternatively, they might decline if not adequately developed. Finally, the basic themes, such as "carbon sequestration", "carbon stocks", "volume", and "height", underscore the need for continued foundational research to support the more advanced and specialized topics. These themes are essential, as they form the bedrock of the field, ensuring that the necessary groundwork is laid for more complex and innovative research endeavors in the future.

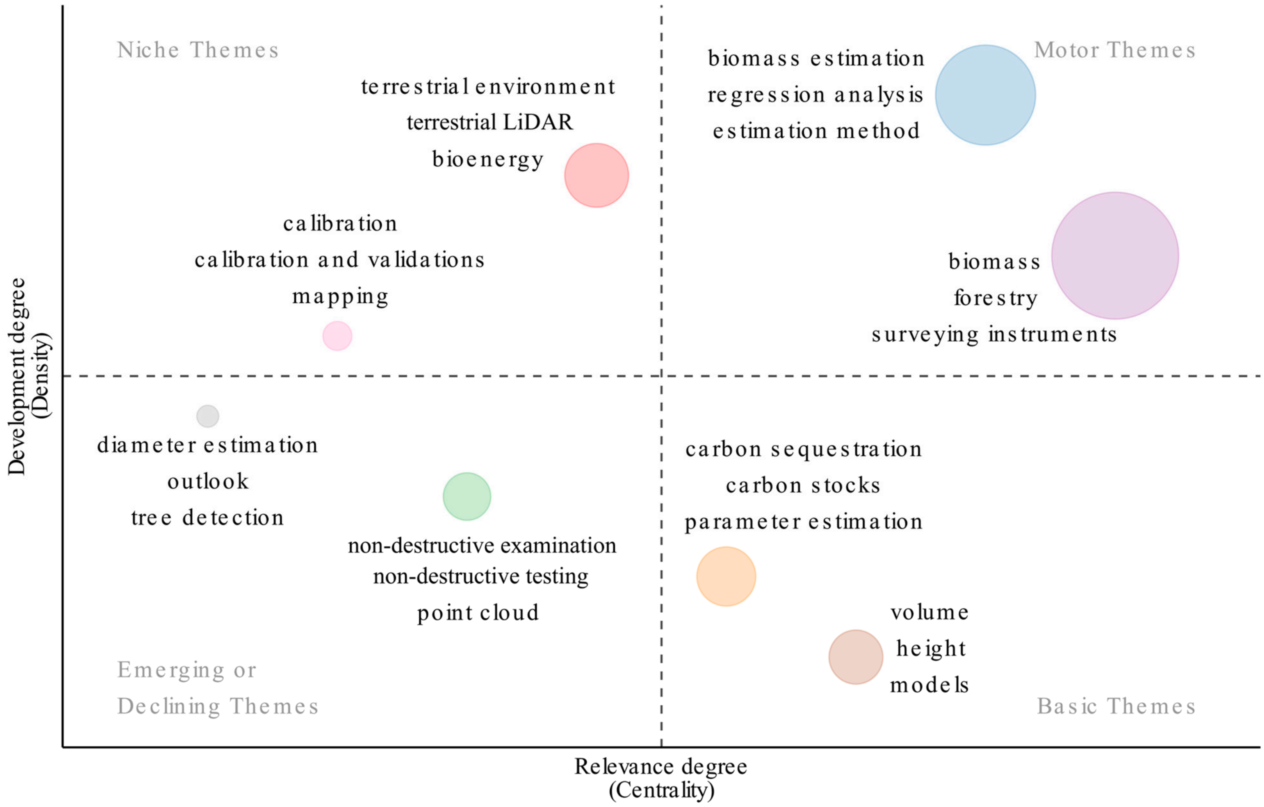


**Figure 8.** Thematic map of the field of TLS and biomass.

## 4. Discussion

This research provides a detailed analysis of the evolution and current status of terrestrial laser scanning in estimating forest biomass. The scientific production patterns revealed in the results likely correlate with technological development. During the initial period (2010–2013), the limited number of publications can be attributed to the recent adoption of terrestrial LiDAR and the ongoing adaptation of technology for point cloud processing. Biomass estimation during this phase primarily relied on in situ measurements [25].

The substantial increase in publications observed from 2013 onwards can be linked to the widespread adoption of advanced remote sensing technologies, particularly TLS. This period coincides with a growing interest in and funding for biomass research, reflected in the rising curve of scientific output [26]. For instance, in 2014, five papers were published, with the study by Srinivasan et al. [21] receiving the highest number of citations that year. This study utilized multi-temporal terrestrial laser scanning datasets to estimate changes in the aboveground biomass at the tree level in east Texas. Researchers enhanced traditional models (mainly based on the diameter at breast height) by developing models using parameters derived from TLS. By extracting various geometric and statistical parameters, they created both general and localized models for loblolly pines.

However, fluctuations observed between 2015 and 2017 may indicate a period marked by the validation of new methodologies. The need to integrate data from different sources and resolve uncertainties associated with terrestrial LiDAR may have led to a temporary moderation in scientific output. For instance, the work "Examination of Uncertainty in Per Unit Area Estimates of Aboveground Biomass Using Terrestrial LiDAR and Ground Data" [27] examines three sources of error in aerial biomass estimation: measurement error, model error, and sampling error. Monte Carlo simulations were used to analyze these errors and compare the total uncertainty between TLS and traditional forest inventory instruments. The results suggest that TLS can significantly reduce measurement errors in estimating aerial biomass compared to traditional methods.

The notable peak in scientific production during the 2018–2021 period is likely related to two key factors. First, recent technological advances have improved the precision and accessibility of laser scanners, particularly TLS, broadening their applications in detailed natural resource measurement. These advances have facilitated research that was previously impossible, driving interest and expansion in the field. Second, the increase in TLS-related scientific production may be due to the growing global need for sustainable natural resource management.

The observed decline in production after 2021 might be a result of the field's maturation and the consolidation of existing methodologies. Additionally, the COVID-19 pandemic significantly impacted field research and collaborations, which could have contributed to the decrease in publications. However, the rate of scientific output has slowed considerably.

It is evident that the years with the highest number of publications (2021 with 10 articles and 2020 with 7 articles) do not necessarily correspond to those with the greatest impact in terms of citations. For example, although more articles were published in 2021, the total number of citations is relatively low (145) compared to 2015, where only 3 articles were published, but 596 citations were accumulated. This reflects the dynamics discussed by Zhang et al. [28], where the visibility and impact of interdisciplinary research (such as the analyzed articles that combine forestry sciences, remote sensing, and data modeling for biomass estimation) can be subject to delayed recognition or fluctuations that do not always correlate with the volume of publications. This finding suggests that traditional impact metrics, such as citation counts in the early years of publication, may be insufficient or even inappropriate for capturing the value of interdisciplinary research. However, D'Este and Robinson-García [29] emphasize that interdisciplinarity, particularly when it extends to multiple and distant scientific fields, increases the social visibility of science, yet the phenomenon of "delayed impact" remains present and may even counteract social reach.

In this context, the work "Prominent but Less Productive: The Impact of Interdisciplinarity on Scientists' Research" [30] provides a critical additional dimension by revealing that despite the promises of innovation and visibility, interdisciplinarity may lead to lower productivity. This phenomenon may be attributed to the cognitive and operational challenges that arise when combining multiple disciplines, which could dilute the focus and increase the difficulties of effective collaboration. This finding complements the observations of Laursen and colleagues, who note that current evaluations of interdisciplinarity are inadequate for capturing the complexity of the phenomenon.

Regarding financial support, the article "How Does National Scientific Funding Support Emerging Interdisciplinary Research: A Comparison Study of Big Data Research in the US and China" [31] compares how the United States and China fund Big Data research, revealing divergent approaches to interdisciplinarity. While the USA approach prioritizes interdisciplinarity, China focuses more on specific disciplines. This contrast in funding policies underscores the need for more refined evaluation frameworks, such as those proposed by Laursen et al., to adequately assess the impacts of different funding strategies on interdisciplinary scientific production.

Although the use of TLS in biomass estimation represents a promising interdisciplinary approach, it faces similar obstacles to those identified in the literature, such as delayed recognition, impact fluctuations, and challenges in integrating knowledge and methods from different disciplines.

The studies converge on the use of TLS as a non-destructive tool for AGB estimation; however, the diversity in technologies employed, processing approaches, and results obtained reveal both the potential and inherent limitations of this technique.

In terms of technology, the most cited studies use various TLS scanner models and processing software, resulting in significant variations in the data quality and accuracy. For example, the Leica C10 ScanStation used in the article "Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: A comparison with traditional destructive approach" [20] offers a detailed capture capability with a resolution that allows for 0.05 m separations between points at a distance of 100 m, which is crucial for accurately reconstructing large tropical trees. This contrasts with the use of the FARO Focus3D 120 in "Non-destructive Aboveground Biomass Estimation of Coniferous Trees Using Terrestrial LiDAR" [15], a phase-based scanner with a high point-capture rate, which, although effective for large, clear trunks, may present limitations in dense canopy penetration due to its greater susceptibility to occlusion. This variability in equipment highlights the importance of selecting the appropriate scanner based on the forest structure and the specific objectives of each study.

The software used for processing TLS data also plays a crucial role in the accuracy of AGB estimates. Simpletree, widely used for generating QSM, provides a robust foundation for automatic tree segmentation and modeling, but it shows significant limitations when faced with complex structures and occlusions, especially in dense canopies and buttressed trunks. This is evident in studies like "Non Destructive Method for Biomass Prediction Combining TLS Derived Tree Volume and Wood Density" [14] where the Simpletree model consistently underestimates the volume of thinner branches. To mitigate these limitations, other studies have complemented Simpletree with advanced software such as Geomagic Studio 12 and AmapStudio-Scan. These programs allow for more precise modeling through manual improvements in trunk and branch geometries and topologies, particularly in correcting errors in critical areas like the base of the trunk and the tree canopy. This contrast between automated processing and the need for manual intervention highlights the current insufficiency of automated tools to effectively handle the structural complexity of trees in natural environments.

The accuracy of AGB estimates obtained through TLS compared to traditional destructive methods also shows significant variations. In "Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: A comparison with traditional destructive approach" [20], a coefficient of determination of 0.98 is reported, indicating high agreement with destructive measurements. However, studies such as "Non Destructive Method for Biomass Prediction Combining TLS Derived Tree Volume and Wood Density" [14] and "Non-destructive Aboveground Biomass Estimation of Coniferous Trees Using Terrestrial LiDAR" [15] reveal that while TLS can provide accurate trunk volume estimates, it faces considerable challenges in estimating the biomass for branches and canopies. These studies report overestimations in thinner branches and underestimations in dense canopies due to occlusion and internal laser beam dispersion, which reduces the reliability of estimates when automatic models are applied without manual adjustments.

A critical observation in several studies is the limitation of TLS to accurately capture smaller branches and canopy structures in dense forest environments. This is particularly evident in tropical forests, where complex canopies and trunk buttresses present unique challenges. In "Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: A comparison with traditional destructive approach" [20], scanner saturation points are identified in branches with diameters smaller than 5 cm, resulting in the underestimation of up to 4.7% of total biomass, a critical aspect when considering accuracy in large-scale estimates. This finding contrasts with studies in coniferous forests, such as "Non-destructive Aboveground Biomass Estimation of Coniferous Trees Using Terrestrial LiDAR" [15], where the simpler structures of canopies and trunks allow for greater accuracy in volume capture, though challenges remain in capturing the foliage density.

A key aspect that emerges from this review is the focus on volumetric calculation as a basis for biomass estimation in several of these studies. The use of TLS to calculate the wood volume and then convert it into biomass presents clear advantages, such as accuracy in capturing the tree's three-dimensional structure and independence from traditional allometric equations, which can be limited and not always applicable in different ecological contexts. This methodology is particularly effective in large trees with complex structures, as observed in studies like "Estimation of Aboveground Biomass of Large Tropical Trees with Terrestrial LiDAR" [19].

However, volumetric calculation also has notable disadvantages. Although it provides detailed estimates, the process is complex and computationally intensive, which may limit its applicability in large-scale studies. Moreover, while volumetric models are accurate for trunks and main branches, they tend to underestimate or fail to adequately capture smaller branches and foliage, which can lead to significant errors in the total tree biomass estimation, as mentioned in "Non-destructive Aboveground Biomass Estimation of Coniferous Trees Using Terrestrial LiDAR" [15]. This limitation is critical in species with dense canopies and complex branching structures.

Additionally, the conversion of volume to biomass critically depends on wood density values, which can vary considerably between species and within the same species, introducing another source of uncertainty. The variability in wood density, coupled with the technical challenges of volumetric calculation, underscores the need for a more integrated and flexible approach that combines the automatic capabilities of TLS with manual intervention when necessary.

Despite the highlighted limitations, studies agree on the potential of TLS in forest biomass estimation, especially in conservation contexts and carbon monitoring. However, this optimism must be balanced with a critical evaluation of persistent technical challenges. Data processing automation is a key area for improvement, as the continued reliance on manual intervention reduces the efficiency and increases the cost and time required for large-scale analysis. Although some studies suggest that improvements in the automatic segmentation of leaves and wood could expand the use of TLS, the reality is that until significant advances are made in automation and the accuracy of automatic models, TLS technology will remain limited in its widespread application in complex forest environments.

In summary, while terrestrial LiDAR represents a significant advancement in non-destructive biomass estimation, current technical deficiencies (particularly in automation and the ability to capture complex structures accurately) limit its effectiveness and applicability in large-scale studies. A more integrated approach is needed, combining terrestrial laser scanning automatic capabilities with the flexibility of manual corrections to maximize the accuracy and efficiency of AGB estimates in a variety of forest environments. Only through such technological and methodological improvements will TLS reach its full potential as an essential tool in forest science and global conservation.

In 2023, two articles were published that incorporate artificial intelligence (AI) into forest biomass estimation, demonstrating a significant advance in analyzing complex data and improving predictions from point clouds.

In the first article [32], the combination of machine learning with radar and laser scanning data resolved the saturation problem in dense forest areas. The use of models such as Random Forest (RF) and Artificial Neural Networks (ANNs) facilitated the integration of different data sources, demonstrating the robustness of these algorithms in contexts of high variability. RF, in particular, showed superior capability in handling complex data and providing more accurate estimates, highlighting the potential of AI to improve precision in forestry applications.

The second article [33] explores modeling the biomass of individual trees using parameters derived from laser scanning. Here, AI applied through non-parametric models such as RF and ANNs significantly outperformed traditional methods, better capturing individual tree variability. This approach enabled more accurate estimations by integrating data on canopy structure and tree height, highlighting the versatility of artificial intelligence in forest data analysis.

However, despite these advances, it is important to recognize that the integration of artificial intelligence in this field has not yet reached its full potential. Although AI is a trending topic in many sectors, its adoption in three-dimensional data remains limited and in the early stages. Most studies have used AI primarily to replace traditional biomass estimation models but have not explored its direct application to processing and analyzing point clouds derived from laser scanning.

In terms of scientific production related to the use of terrestrial laser scanning for biomass estimation, the United States and China lead, with 11 published articles each. This dominance reflects a significant concentration of resources in these countries, perpetuating a scientific gap that marginalizes developing nations. While this concentration of resources may seem efficient from an economic standpoint, it also raises concerns about equity and diversity of approaches in global science, as noted by Petersen [34]. The preeminence of the United States and China in the number of publications does not necessarily translate into the highest scientific impact, as countries like the Netherlands and Finland, with more modest production, lead in citations. This suggests that these countries may be applying more advanced and effective forest management, highlighting the importance of not only increasing scientific output but also focusing on the quality and relevance of research.

Despite having vast forested regions that could benefit from the use of TLS, Latin America stands out for its lack of scientific production in this field. This lack of contribution underscores the structural inequalities in research funding in the region, as discussed in "Concentration or dispersal of research funding?" [35], which emphasize the need for a more equitable distribution of research resources to avoid concentrating them in a few nations. Additionally, this situation reflects a disconnect between local needs and the scientific capacity to address them, which aligns with the observations of Nguyen and Choung [36] on the importance of diversifying research policies to better adapt to specific national contexts.

To close this gap and promote more balanced scientific development, it is essential to foster greater international cooperation that strengthens endogenous capacities [37]. These authors stress the importance of adapting science, technology, and innovation (STI) policies to local realities, avoiding dependence on imported models that may not be applicable in the Latin American context. In this sense, international cooperation should be seen not only as a means to transfer knowledge but also as a tool to promote scientific and technological autonomy in regions like Latin America, enabling these nations to contribute significantly to the advancement of global knowledge.

The thematic map suggests that topics such as "biomass estimation", "terrestrial LiDAR", and "carbon sequestration" are drivers within the field. These topics are not only central but also well developed, indicating significant consolidation in the use of TLS for biomass estimation. This reflects a growing recognition of the importance of terrestrial LiDAR as a fundamental tool for precise and non-destructive measurements in forest and carbon studies. The position of these topics in the driver quadrant suggests that terrestrial laser scanner is becoming a standard technology in biomass research, driven by its ability to provide detailed and accurate data that are essential for modeling and validating forest biomass and carbon sequestration.

However, the analysis also reveals some obstacles and less developed areas. Topics such as "non-destructive testing" and "point cloud", which appear in the niche topics quadrant, highlight the need to advance the integration and application of specific TLS data analysis methods. Although these topics are specialized and have significant potential, their lower centrality and density indicate that they have not yet reached sufficient development to widely influence the field. This could be related to the technical complexity of point cloud processing and the lack of standardized tools that allow for their broader and more efficient use. Overcoming these obstacles will require a more concerted focus on developing specialized software and creating more accessible methodologies for researchers.

The MCA provides more context on the relationships between key concepts in biomass estimation with TLS. The proximity of terms such as "biomass estimation", "terrestrial laser scanning" and "allometry" highlights interdependence in studies that combine the use of TLS with traditional allometric methods. However, the dispersion of terms like "climate change" and "canopy architecture" suggests that although important, these aspects are not yet fully integrated into the main body of TLS and biomass research. This may indicate a challenge in applying terrestrial LiDAR to multidimensional studies that address not only biomass but also other ecological and environmental factors such as climate change and canopy architecture, which require more integrated and sophisticated approaches.

In summary, the use of TLS for forest biomass estimation has made progress, being driven by technological advancements. However, despite improvements in its accuracy and accessibility, significant challenges remain, particularly in the automation of data processing and the precise capture of complex structures. In some cases, TLS alone is insufficient in providing complete and accurate estimates; its effectiveness can be significantly enhanced by integrating data from other sensors or field measurements, including AI-based methodologies. Despite its potential, the large-scale application of terrestrial laser scanner remains limited. Additionally, the uneven adoption of this technology, as evidenced by the concentration of resources and publications in certain countries, underscores the urgent need for more equitable international cooperation to close the scientific gap and enable all regions to contribute to global knowledge advancement in this field.

## 5. Conclusions

This scientific article provides a comprehensive assessment of the use of terrestrial laser scanning in estimating aboveground biomass, emphasizing its relevance and applicability in forest sciences. The bibliometric analysis conducted has identified key research trends, influential authors, and areas of opportunity, laying a solid foundation for future studies. The findings confirm that TLS is a powerful and precise tool for measuring the three-dimensional structure of forests, presenting itself as an effective alternative to traditional destructive methods.

However, the development and application of TLS are not without challenges. Technical limitations, such as the difficulty in capturing details in dense vegetation and the variability in precision due to the diversity of equipment and software, highlight the need for the continued improvement of this technology. To fully realize the potential of TLS, it is essential to overcome these barriers through the standardization of methodologies and the development of technological advancements that enable more accurate and reliable analysis across a wide range of forest conditions.

Additionally, the article highlights a significant disparity in scientific production between countries, reflecting differences in their access to resources and research capabilities. This inequality presents a challenge to the global adoption of TLS, as it limits the dissemination and application of this technology in less developed regions. Addressing this challenge requires fostering greater international cooperation and strengthening local capacities, which will allow for the advancements in TLS to be more equitably distributed and benefit a broader range of forest ecosystems.

A promising avenue for future research that could address some of these limitations is the integration of artificial intelligence (AI) into TLS data analysis. AI has the potential to significantly improve tasks such as segmentation and the classification of elements within point clouds, thereby increasing the accuracy and efficiency of biomass estimation. The incorporation of these advanced technologies would not only optimize the use of TLS but also expand its applications to more varied and complex ecological contexts.

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