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Review

Sustainable Estimation of Tree Biomass and Volume Using UAV Imagery: A Comprehensive Review

Dan Munteanu [1,*], Simona Moldovanu [2,3], Gabriel Murariu [4,5] and Lucian Dinca [6,*]

[1] Faculty of Automation, Computer Sciences, Electronics and Electrical Engineering, Dunarea de Jos University of Galati, Domneasca Street No. 111, 800201 Galati, Romania
[2] Department of Computer Science and Information Technology, Faculty of Automation, Computers, Electrical Engineering and Electronics, Dunarea de Jos University of Galati, 47 Domneasca Str., 800008 Galati, Romania
[3] The Modelling & Simulation Laboratory, Dunarea de Jos University of Galati, 47 Domneasca Str., 800008 Galati, Romania
[4] Department of Chemistry, Physics and Environment, Faculty of Sciences and Environmental, Dunarea de Jos University of Galati, Românească Street No. 47, 800008 Galati, Romania; gmurariu@ugal.ro
[5] Rexdan Research Infrastructure, Dunarea de Jos University of Galati, 800008 Galati, Romania
[6] National Institute for Research and Development in Forestry "Marin Dracea", Eroilor 128, 077190 Voluntari, Romania
* Correspondence: dan.munteanu@ugal.ro (D.M.); dinka.lucian@gmail.com (L.D.)

Abstract

Accurate estimation of tree biomass and volume is essential for sustainable forest management, climate change mitigation, and ecosystem service assessment. Recent advances in unmanned aerial vehicle (UAV) technology enable the acquisition of ultra-high-resolution optical and three-dimensional data, providing a resource-efficient alternative to traditional field-based inventories. This review synthesizes 181 peer-reviewed studies on UAV-based estimation of tree biomass and volume across forestry, agricultural, and urban ecosystems, integrating bibliometric analysis with qualitative literature review. The results reveal a clear methodological shift from early structure-from-motion photogrammetry toward integrated frameworks combining three-dimensional canopy metrics, multispectral or LiDAR data, and machine learning or deep learning models. Across applications, tree height, crown geometry, and canopy volume consistently emerge as the most robust predictors of biomass and volume, enabling accurate individual-tree and plot-level estimates while substantially reducing field effort and ecological disturbance. UAV-based approaches demonstrate particularly strong performance in orchards, plantation forests, and urban environments, and increasing applicability in complex systems such as mangroves and mixed forests. Despite significant progress, key challenges remain, including limited methodological standardization, insufficient uncertainty quantification, scaling constraints beyond local extents, and the underrepresentation of biodiversity-rich and structurally complex ecosystems. Addressing these gaps is critical for the operational integration of UAV-derived biomass and volume estimates into sustainable land management, carbon accounting, and climate-resilient monitoring frameworks.

Keywords: unmanned aerial vehicles; tree biomass estimation; tree volume estimation; sustainable forest management; remote sensing; carbon stock assessment; machine learning; ecosystem services

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1. Introduction

Technological advances in unmanned aerial vehicles have made it feasible to obtain high-resolution imagery and three-dimensional (3D) data for assessing tree attributes and forest monitoring. Methods of data acquisition with remotely sensed aerial or satellite data at high spatial resolution have partially replaced conventional methods of field measurement for forest inventory purposes [1–4]. Repeated observations from modern satellites, as well as improvements in UAV technology, have contributed significantly to our understanding of the dynamics of complex ecosystems, particularly forests. Accurate quantification of tree basic parameters, such as height, crown diameter, and diameter at breast height (DBH), is essential for decision-making and planning. Modern techniques of remote sensing can provide accurate estimations of tree height and crown area characteristics at the individual level using a series of algorithms [5,6]. The individual tree identification (IDS) algorithm allows for the estimation of crown diameter [7], and the smoothing of the canopy height model (CHM) using local maxima techniques [8] can provide estimates of individual tree heights.

Volume and aboveground biomass (AGB) of small spatial extent areas can be derived with the help of forest inventory data. However, field measurements are typically unbiased, time-consuming, and expensive. For spatially larger areas, modelling of volume and biomass requires the use of remote sensing information for practical purposes. Additionally, remote sensing techniques are able to improve the value of inventoried data with detailed coverage at affordable costs [9–11]. The strength of remote sensing approaches based on very high resolution (VHR) images using aerial imagery or downscaling methods (i.e., calibration of satellite images based on UAVs) is that they allow for the construction of high-quality 3D digital surface models (DSMs) that can be used to estimate several forest tree attributes, such as height, DBH, and crown diameter [12].

Accurate information about forest cover, land use and aboveground biomass are critical parameters for many environmental studies as well as for conservation initiatives concerning the mitigation of global warming, such as REDD+ (Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries) [13–16]. By means of such data and their temporal development, the most vulnerable regions can be determined, and areas which deserve protection can be identified. In particular, natural forest cover is of utmost concern because it stores and sequesters large amounts of atmospheric carbon nearly 30% of the cumulative anthropogenic emissions [17–19]. By enabling the acquisition, processing, and analysis of high-resolution spatial and temporal tree data at the field scale, UAVs support improved forest and water management, especially in the climate change context [20–24].

Traditional field forest inventories are used for multi-temporal analysis based on tree height and crown growth measurements at different times. However, tree height growth can be demanding to estimate from the ground, because of the difficulty in determining the top of the crown [25,26], especially in species that do not display strong apical dominance. Crown growth is also difficult to determine when crowns overlap, as the edges of the crowns are often hidden by the branches of other trees [27]. Crown area is also difficult to estimate from field data; two cross crown diameters are usually measured and crowns are assumed to be ellipses, to simplify the calculations. Although field-measured data are commonly assumed to be ground truth values for remote sensing data, the associated measurement errors tend to be large [28,29]. In addition, forest mensuration with traditional field techniques is expensive and time-consuming, and measurements may take several years.

The suitability of remote sensing-based technologies for forest mensuration is widely acknowledged [12]. Since the 1990s, digital aerial photography (DAP), airbone laser

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scanning (ALS) [30,31] or a combination of both [32,33] have been increasingly used to support forest inventories at different scales. Interest in using UAVs to acquire both ALS and DAP data has increased greatly in recent years [34–36]. Indeed, ALS and red, green, blue (RGB) sensors mounted on UAV platforms are becoming cost-effective tools for monitoring forest structure because the high spatial (achieved by the low flight height) and temporal resolution (allowed by the relatively low cost of the flight surveys) meet the requirements of forest managers [37]. Multi-temporal UAV-acquired data can be used to help assess tree growth quickly, accurately and economically, providing up-to-date information to support decision-making in forest management [38,39]. Due to the low cost and operational flexibility, light UAVs equipped with inexpensive consumer grade cameras have recently emerged as a feasible option for monitoring three-dimensional (3D) forest structures [Puliti]. In this case, an innovative computer vision technique—structure-from-motion (SfM)—enables extraction of 3D information from UAV flights, providing 3D photogrammetric point clouds based on feature matches within overlapping images [40,41].

Numerous review articles have been published on the use of UAV imagery [42–46], as well as on applications in forest ecosystems [47–50]. However, to date, we have not identified a review that specifically and comprehensively analyzes the scientific literature focused exclusively on tree biomass or volume estimation derived from UAV imagery.

The aim of this article is to provide a comprehensive and critical synthesis of current scientific research on tree biomass and volume estimation derived from unmanned aerial vehicle imagery, with a particular emphasis on its contribution to sustainable forest management, sustainable agriculture, and climate-resilient land-use planning. By systematically reviewing methodological advances, sensor technologies, modeling approaches, and application domains, this study seeks to evaluate how UAV-based remote sensing supports resource-efficient, cost-effective, and environmentally sustainable alternatives to traditional field inventories. Furthermore, the review aims to assess the role of UAV-derived biomass and volume estimates in improving carbon stock assessment, ecosystem monitoring, and evidence-based decision-making, thereby contributing to long-term ecological sustainability, climate change mitigation, and the sustainable management of forest, agricultural, and urban green infrastructures.

2. Materials and Methods

2.1. Study Design and Data Sources

This review was conducted following a systematic and reproducible methodology designed to synthesize scientific knowledge on tree biomass and volume estimation using unmanned aerial vehicle (UAV) imagery. The review process consisted of two complementary stages: (i) a bibliometric analysis to identify publication trends, research hotspots, and collaboration patterns, and (ii) a qualitative content analysis to examine methodological approaches and application domains.

Relevant literature was retrieved from two major international bibliographic databases: Scopus and the Science Citation Index Expanded (SCI-Expanded) within Web of Science. These databases were selected due to their comprehensive coverage of peer-reviewed publications in remote sensing, forestry, ecology, and geospatial sciences.

2.2. Search Strategy and Keyword Selection

A structured search strategy was developed to ensure broad thematic coverage while maintaining relevance to UAV-based tree biomass and volume estimation. The core search string consisted of the terms: “tree biomass estimation from UAV images” OR “tree volume estimation from UAV images”.

To capture methodological diversity and application contexts, the core terms were expanded using additional keywords related to UAV platforms, photogrammetry, canopy structure, forestry, agriculture, and urban vegetation. Boolean operators (AND/OR), quotation marks, and wildcards were applied to refine and combine terms, allowing for plural forms and morphological variations.

2.3. Database Queries and Reproducibility

To ensure transparency and reproducibility, all search strings were documented in detail. Searches were conducted using advanced field tags specific to each database:

Scopus (advanced search; fields: TITLE-ABS-KEY):

TITLE-ABS-KEY ("tree biomass estimation from UAV images" OR "tree volume estimation from UAV images" OR "tree high estimation from UAV images" OR "tree diameter estimation from UAV images")

Web of Science—SCI-Expanded (topic search; TS):

TS = ("tree biomass estimation from UAV images" AND "tree volume estimation from UAV images" OR "tree high estimation from UAV images" AND "tree diameter estimation from UAV images")

Minor syntax adjustments were applied to accommodate database-specific requirements while preserving the logical structure of the queries.

2.4. Screening Protocol

All retrieved records were screened and refined in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. This approach ensured methodological transparency, consistency, and reproducibility throughout the review process [51].

2.5. Search Parameters

The search period was unrestricted and included all publications indexed up to the date of retrieval. Eligible document types comprised peer-reviewed journal articles, conference proceedings, book chapters, and review papers. Editorials, correspondence items, patents, and academic theses were excluded during the screening process.

2.6. De-Duplication and Data Quality Assurance

Duplicate records were removed using a two-step procedure. First, automated filtering based on Digital Object Identifiers (DOIs) and exact title matches was performed using Microsoft Excel. Second, remaining records were manually reviewed by comparing titles, first authors, publication years, and journal names to resolve cases with missing or inconsistent DOI information.

Data quality control procedures included verification of bibliographic metadata (titles, abstracts, author names, and publication years), correction of optical character recognition (OCR) errors, and standardization of author and institutional affiliations. All modifications were documented in a dedicated data-audit log.

2.7. Inclusion and Exclusion Criteria

Study selection followed a two-stage screening process consisting of (i) title and abstract screening and (ii) full-text assessment.

Inclusion criteria were as follows: Peer-reviewed articles or reviews published in English; A primary focus on tree biomass or volume estimation using UAV-derived data; Availability of sufficient bibliographic and methodological information

Exclusion criteria included the following: Non-peer-reviewed material (editorials, correspondence, posters, theses, patents); Studies unrelated to UAV-based tree biomass

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or volume estimation; Marginal or peripheral mentions of UAV imagery; Inaccessible full texts or missing abstracts.

Full-text exclusions were categorized using standardized codes:

(A) out of scope; (B) non-peer-reviewed content; (C) absence of relevant UAV-based biomass or volume estimation data; (D) inaccessible full text; and (E) insufficient methodological detail.

2.8. Screening and Reviewer Agreement

Two independent reviewers conducted the screening process. Titles and abstracts were evaluated independently, and records identified as potentially relevant by either reviewer were advanced to full-text assessment. Full texts were subsequently reviewed independently. Any disagreements were resolved through discussion with a third senior reviewer, who served as an adjudicator.

2.9. Final Dataset and Bibliometric Analysis

Following the completion of screening and consensus resolution, a final dataset of 181 publications was retained for analysis (Figure 1). Bibliometric analysis was conducted across nine dimensions: publication type, research discipline, temporal trends, geographic distribution, authorship patterns, institutional affiliations, journals, publishers, and keyword usage.

Data processing and visualization were performed using Scopus [52], the Web of Science Core Collection (version 5.35, Clarivate, Philadelphia, PA, USA) [53], Microsoft Excel (version 2024) [54], and Geochart version 2512 [55]. Network analyses of co-authorship, co-citation, and keyword co-occurrence were carried out using VOSviewer (version 1.6.20) [56].

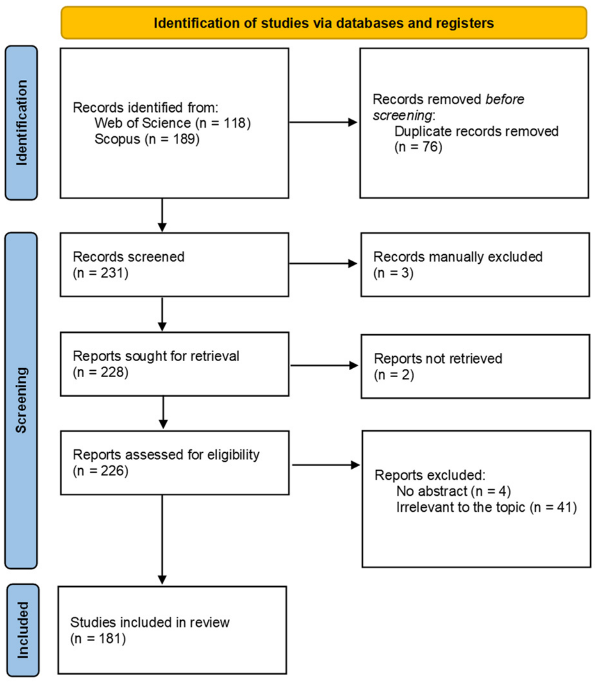

Figure 1. Selection process of the eligible reports based on the PRISMA 2020 flow diagram.

2.10. Qualitative Content Analysis

The second stage of the review involved an in-depth qualitative content analysis of the selected publications. This analysis enabled a detailed examination of methodological trends, data sources, modeling approaches, and application contexts.

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The reviewed literature was organized into five major thematic domains: (1) Methods and approaches for tree biomass and volume estimation using UAV imagery; (2) Tree species analyzed for biomass and volume estimation using UAV imagery; (3) UAV-based estimation of tree biomass and canopy volume in Agriculture; (4) UAV-based estimation of tree biomass and canopy volume in Forestry; (5) UAV-based approaches for urban tree biomass and green volume estimation.

The overall analytical workflow and thematic structure are summarized in Figure 2.

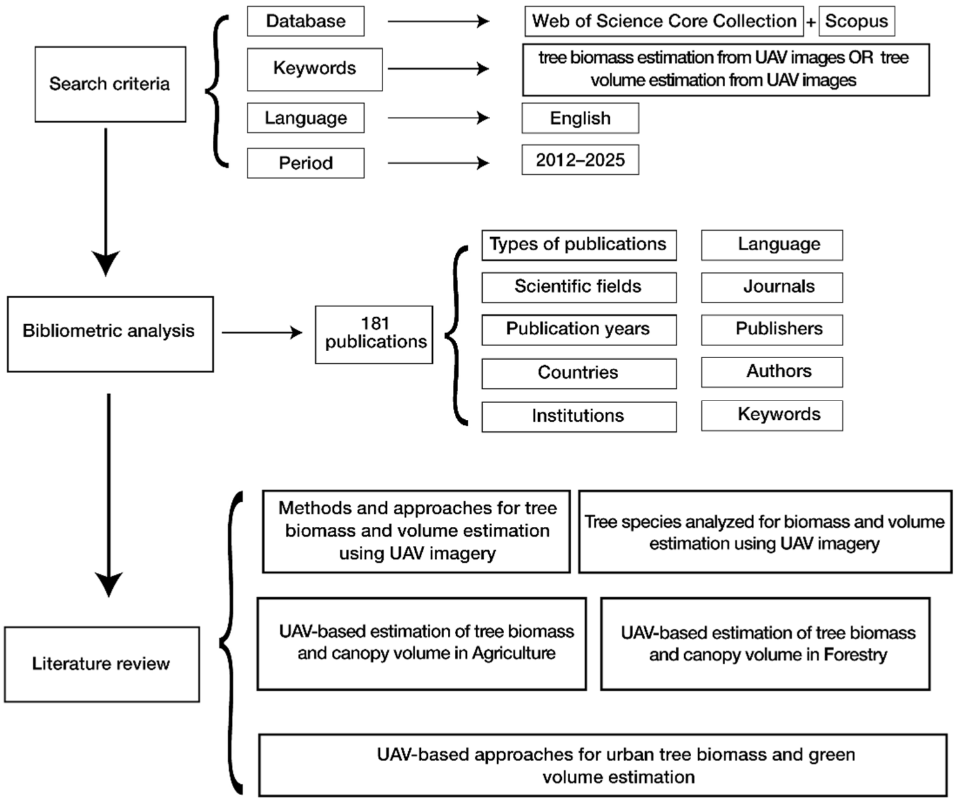

Figure 2. Schematic presentation of the workflow used in our research.

3. Results

3.1. A Bibliometric Review

The bibliometric analysis identified a total of 181 publications on this topic. The vast majority consisted of research articles (152 records, 84%), followed by 26 proceedings papers (14%), 2 review articles (1%), and 1 book chapters (1%) (Figure 3).

Although this research topic emerged relatively late in the scientific literature— with the first identified mention dating back to 2012—the number of published studies has increased steadily, particularly in recent years. The publication output has reached an average of approximately 25 articles per year, a number that is likely to be exceeded in the coming years (Figure 4).

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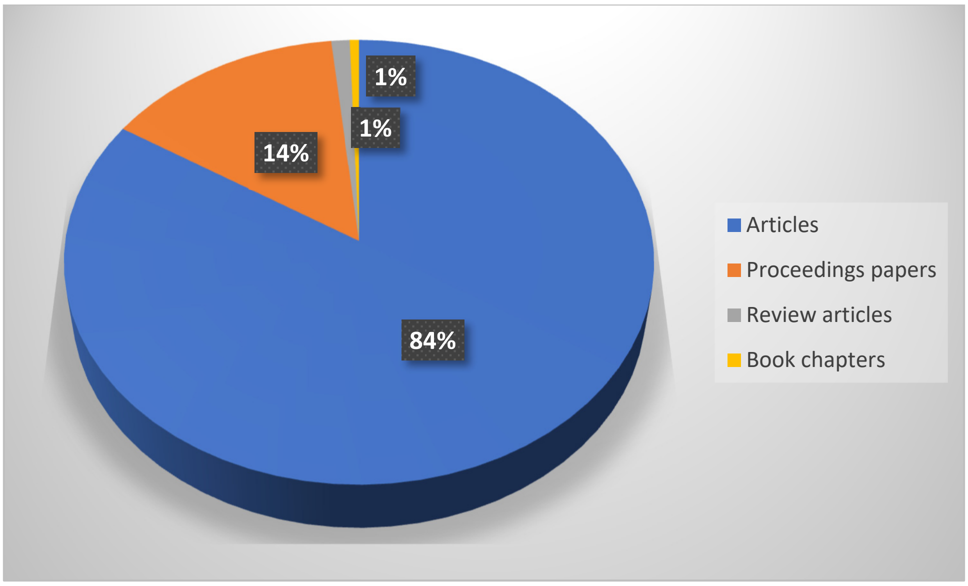

Figure 3. Overview of the principal publication types tree biomass and volume estimation from UAV images.

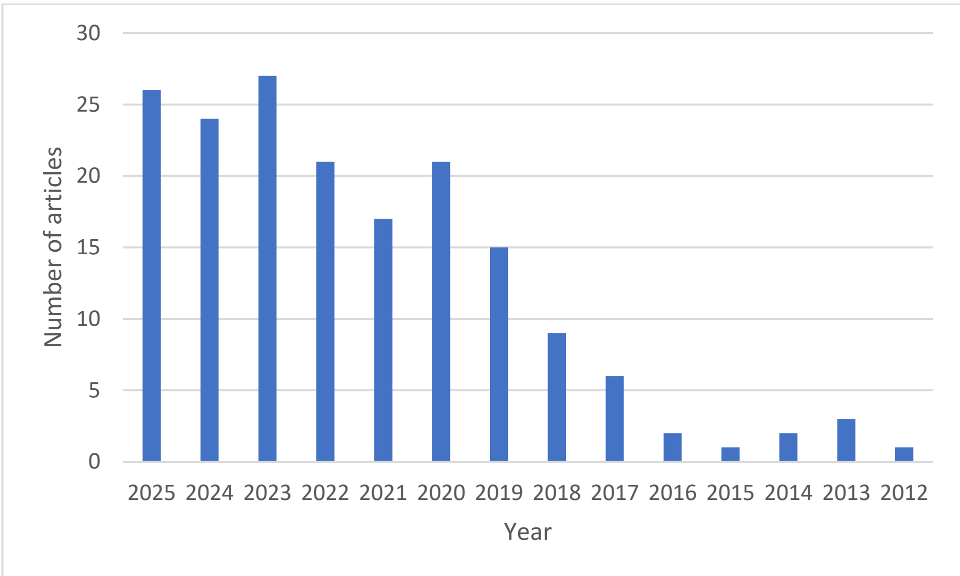

Figure 4. Distribution per year of articles concerning tree biomass and volume estimation from UAV images.

The distribution of publications across research areas reveals the dominance of three categories among the 22 identified: Remote Sensing (59 articles), Environmental Sciences/Ecology (49 articles), and Imaging Science and Photographic Technology (44 articles), respectively (Figure 5). These research areas differ notably in their primary objectives, modeling strategies, and technical challenges. Studies classified under Remote Sensing mainly focus on the development and evaluation of predictive models for tree biomass and volume estimation, often integrating UAV-derived spectral, structural, and textural features with machine learning or statistical regression approaches. In contrast, publications in Environmental Sciences and Ecology primarily emphasize forest resource assessment, carbon stock estimation, ecosystem monitoring, and sustainable forest management, where UAV-based biomass estimation serves as a critical input for ecological analysis and decision-making. Meanwhile, research categorized within Imaging Science and Photographic Technology is largely dedicated to advancing image acquisition, photogrammetric processing, point cloud generation, and 3D reconstruction techniques. These studies focus on improving data quality, automation, and algorithm robustness, which are essential for accurate tree parameter extraction. Together, these complementary research perspectives highlight the multidisciplinary nature of UAV-based tree biomass and volume estimation, demonstrating its broad relevance across technological development, ecological assessment, and operational forest monitoring.

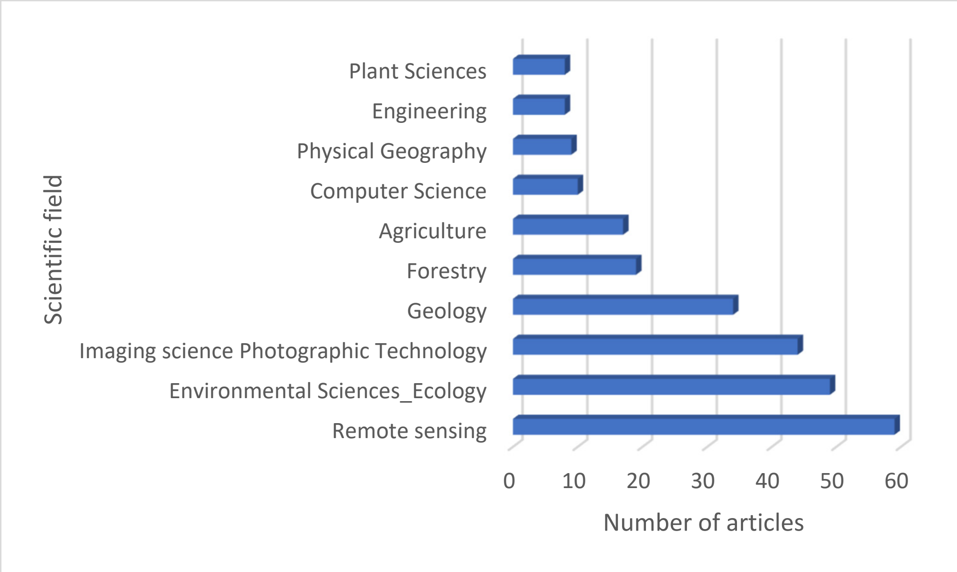

Figure 5. Distribution of the primary research areas in publications on tree biomass and volume estimation from UAV images.

Researchers from 42 countries across five continents contributed to publications on this topic (Figure 6). The most represented countries were China (49 articles), USA (15 articles), Spain (13 articles), and Portugal (7 articles), respectively.

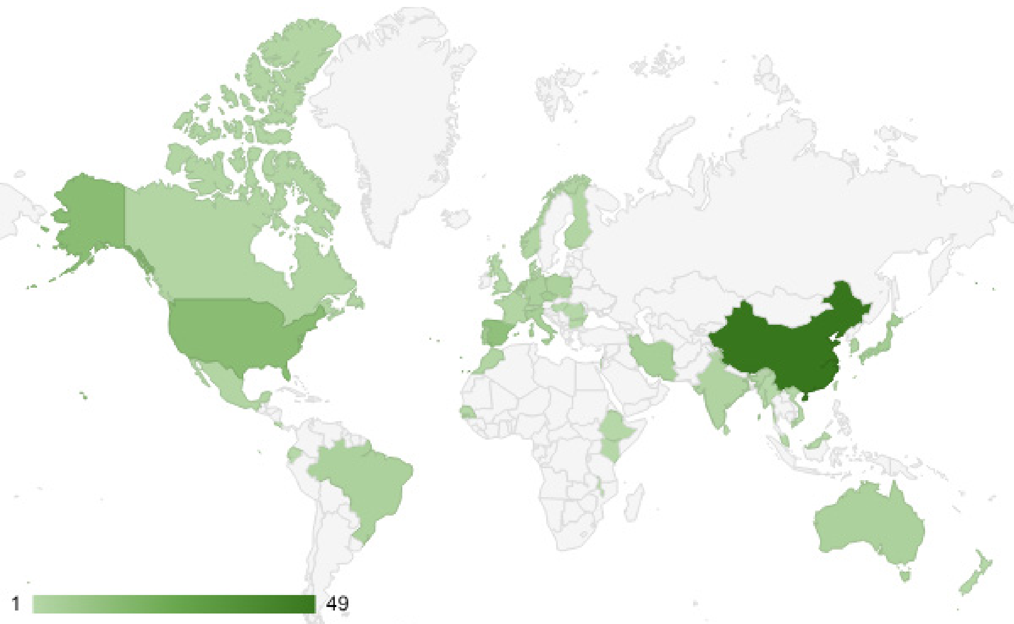

Figure 6. Geographic distribution of authors contributing to tree biomass and volume estimation from UAV images research.

The contributing countries were grouped into four clusters based on their co-occurrence in authorship networks, reflecting patterns of international research collaboration rather than geographical proximity. Cluster 1 includes Belgium, Bulgaria, the Czech Republic, China, Portugal, and the United States. Cluster 2 comprises Brazil, Malawi, the Netherlands, Norway, and Spain. Cluster 3 consists of Australia, Italy, South Korea, and Wales, while Cluster 4 includes Japan, Myanmar, Sri Lanka, and Taiwan. Although four clusters were identified by the clustering algorithm, their boundaries are not equally pronounced, and some countries exhibit weaker associations within their respective groups. With the exception of Cluster 4, which is composed exclusively of countries from East and Southeast Asia, no clear geographical or thematic pattern can be observed among the remaining clusters, as they include countries from different continents with no apparent direct connection. It should also be noted that, due to the need to reduce the scale of Figure 7 for readability, not all contributing countries and linkages are fully visible, which may limit the visual distinction among clusters.

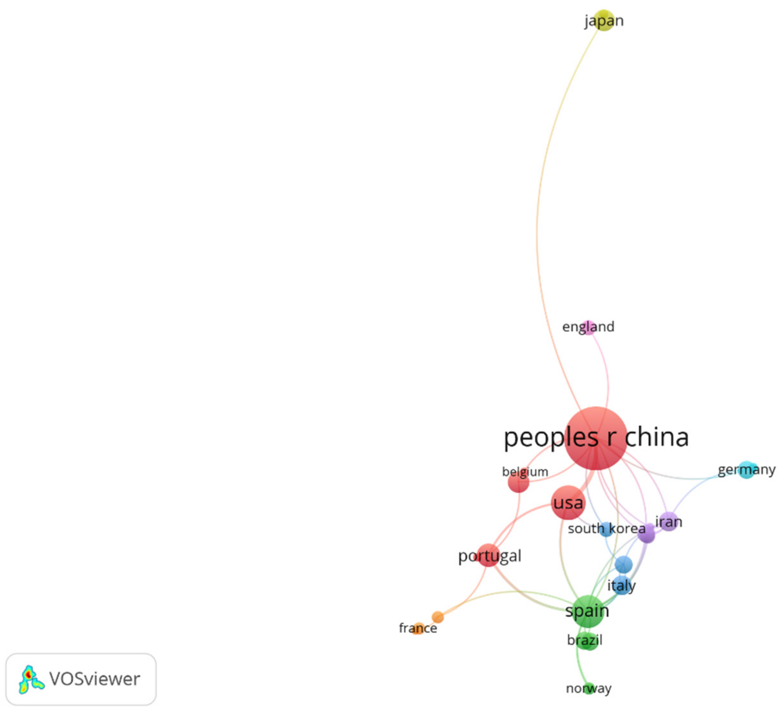

Figure 7. Country clusters of authors publishing on tree biomass and volume estimation from UAV images.

Papers on this topic were published in 59 journals. The most prominent journal was Remote sensing (with 29 articles), Forests (with 5 articles), International journal of remote sensing and International journal of applied earth observation and geoinformation (with 4 articles each) (Figure 8).

The most representative institutions for authors who have published on this topic were as follows: Chinese Academy of Sciences (with 12 articles), Czech University of Life Sciences Pague (with 5 articles), University of Chinese Academy of Sciences (with 5 articles), and Beijing Forestry University (with 4 articles). Among the publishers that have issued articles on this topic, the most prominent were as follows: MDPI (46 articles), Elsevier (28 articles), I.E.E.E. and Taylor & Francis (6 articles each).

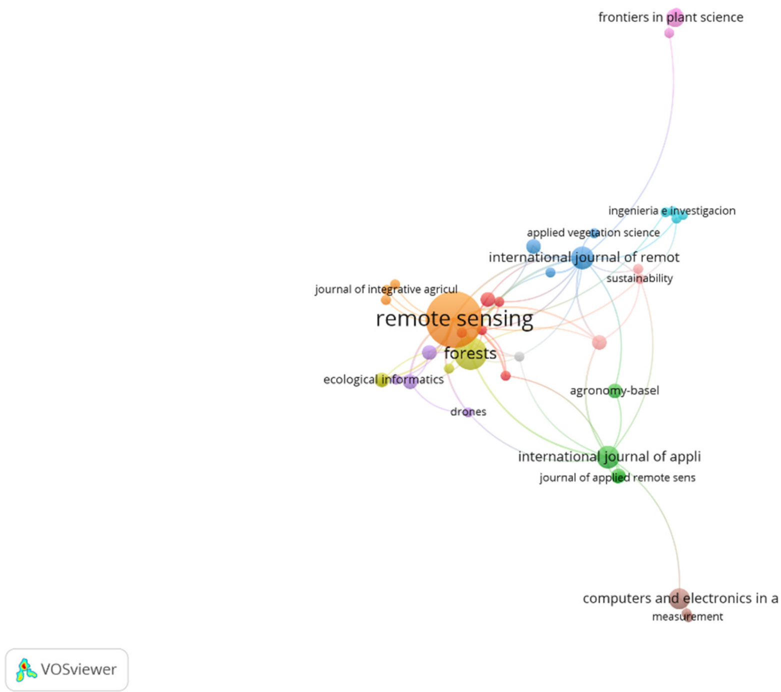

Figure 8. The main journals where articles on tree biomass and volume estimation from UAV images have been published.

The analysis of keywords used in the published articles, conducted using the VOSviewer software, reveals a predominant occurrence—alongside the search keywords employed in this study (biomass, UAV)—of the terms LiDAR, height, aboveground biomass, and forest (Table 1).

Table 1. The most frequently used keywords in articles on tree biomass and volume estimation from UAV images.

Cur. No.	Keyword	Occurrences	Total Link Strength
1	biomass	38	158
2	LIDAR	37	145
3	height	25	114
4	UAV	31	112
5	Unmanned Aerial Vehicle	22	81
6	forest	19	75
7	classification	16	71
8	aboveground biomass	21	66
9	photogrammetry	14	65
10	imagery	11	55
11	vegetation	11	55
12	point clouds	9	51
13	volume	13	45
14	forest inventory	9	44
15	remote sensing	10	43
16	tree height	11	43

The keywords can be grouped into three main clusters: the first included terms related to vegetation and forest: aboveground biomass, forest, hight, vegetation, vegetation indexes; the second included terms related to models and methods: airborn LIDAR, accuracy, biomass estimation, imagery, inventory, models, point clouds; the third included terms related to tree characteristics: biomass, density, stem volume (Figure 9).

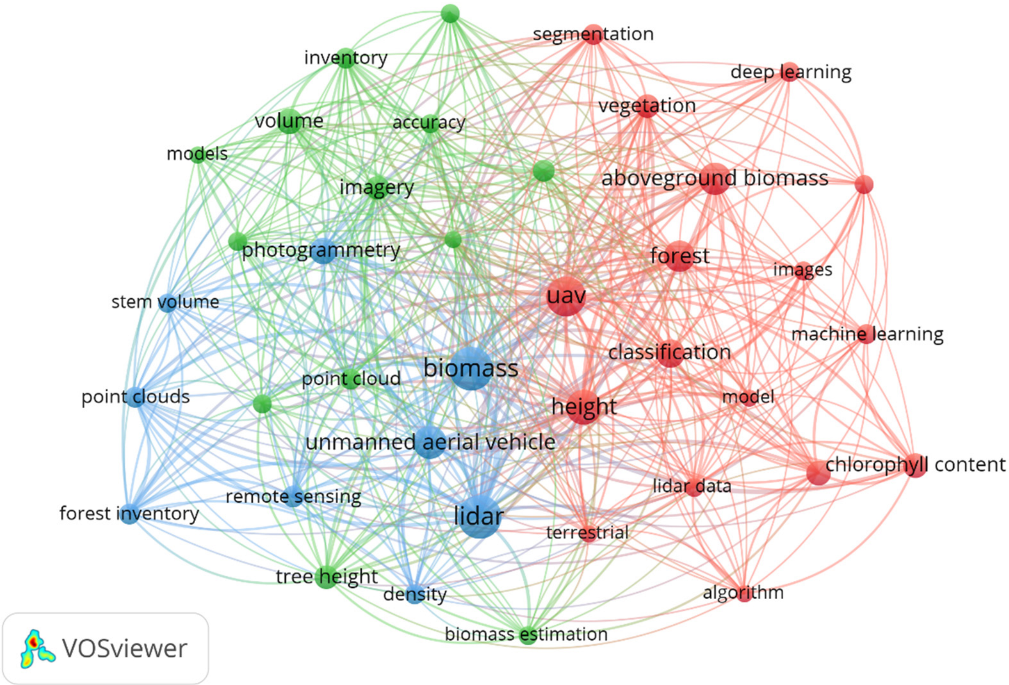

Figure 9. Commonly used keywords by authors in tree biomass and volume estimation from UAV images publications.

The bibliometric results provide a quantitative overview of the rapid growth, geographic distribution, and thematic focus of UAV-based biomass and volume estimation research. To complement this macroscopic perspective, the following literature review examines how these publication trends translate into concrete methodological choices, species-specific applications, and ecosystem-level outcomes. The qualitative synthesis is therefore structured to link methodological developments with their practical implementation across tree species and application domains, including forestry, agriculture, and urban environments.

3.2. Literature Review

3.2.1. Methods and Approaches for Tree Biomass and Volume Estimation Using UAV Imagery

Across the reviewed studies, the commonly cited advantages of UAV platforms—high spatial resolution, operational flexibility, and cost efficiency—should be understood as enabling conditions rather than distinguishing findings; methodological performance is instead primarily driven by sensor configuration, three-dimensional data quality, and modeling strategy.

Recent advances in unmanned aerial vehicle technology have substantially expanded the range of methods available for estimating tree structural parameters, biomass, and volume. The reviewed literature demonstrates a clear evolution from classical photogrammetric approaches toward multi-sensor data fusion and advanced machine learning techniques.

Early studies primarily focused on UAV-based photogrammetry using structure-from-motion (SfM) algorithms to derive individual tree attributes. Abdollahnejad et al. [57] demonstrated that UAV-derived point clouds can reliably estimate tree height, crown diameter, diameter at breast height (DBH), and stem volume at the individual-tree level. By correlating UAV data with high-resolution satellite imagery, the authors further showed that UAV measurements can be extrapolated to larger spatial extents, achieving coefficients of determination of 0.71 for stem volume and 0.87 for tree height. These results highlighted the feasibility of combining UAV and satellite data as a cost-effective alternative to exclusive reliance on very high-resolution satellite imagery.

Building upon this concept, Effiom et al. [58] investigated the integration of UAV RGB imagery with multispectral satellite data for carbon estimation. Their object-based image analysis framework significantly improved tree crown projection area segmentation and species classification accuracy when UAV images were combined with multispectral satellite bands. The improved segmentation and classification accuracies indicated strong potential for enhancing aboveground biomass and carbon modeling through UAV–satellite data fusion.

Beyond spectral integration, several studies have emphasized the role of three-dimensional structural information. Ni et al. [59] analyzed how UAV stereo-image acquisition parameters affect the reconstruction of forest vertical structure, using airborne LiDAR as a reference. Their results demonstrated that appropriate combinations of image resolution and forward overlap are critical for maintaining canopy height estimation accuracy while reducing computational costs. This work underscored the importance of optimized flight and imaging configurations for reliable biomass-related metrics.

LiDAR-equipped UAV platforms have further improved biomass and carbon estimation accuracy. Chumbimune-Vivanco et al. [60] applied UAV-based multispectral and LiDAR data to estimate aboveground forest biomass and carbon stocks in Prosopis plantations. Models incorporating LiDAR-derived height and crown area, combined with vegetation indices, achieved strong predictive performance (R^2 = 0.77), confirming the advantages of integrating structural and spectral information. Similarly, Gonzalez et al. [61] compared RGB-based SfM and multispectral vegetation index approaches for aboveground biomass estimation and validated them against LiDAR-derived estimates. Their findings showed that photogrammetric RGB methods can approach LiDAR-level accuracy (R^2 = 0.85), provided that high-quality terrain models are available, while NDVI-based approaches were limited by saturation effects in dense forests.

More recent studies reflect a growing shift toward machine learning and deep learning techniques. Afsar et al. [62] demonstrated that deep learning-based object detection and segmentation significantly improve individual tree crown delineation from UAV imagery, achieving a high correlation with manually digitized reference data (R^2 = 0.97). Accurate canopy segmentation is a critical prerequisite for reliable canopy volume, biomass, and yield estimation. Dorbu [63] further highlighted the role of deep learning in agricultural contexts, showing that UAV imagery combined with convolutional neural networks can effectively identify individual crop conditions relevant to biomass assessment.

Tree-level modeling approaches have also gained prominence in carbon estimation studies. Duan et al. [64] developed an ensemble regression model to estimate aboveground carbon at the individual-tree level in mangrove ecosystems, using UAV-derived point clouds. Their comparison between LiDAR and photogrammetric point clouds revealed that both data sources can produce accurate biomass estimates, although LiDAR provided superior performance due to additional intensity metrics.

Finally, advances in data fusion and allometric modeling have improved the estimation of specific tree parameters such as DBH and forest health indicators. Erfanifard et al. [65] showed that combining vertical and oblique UAV imagery substantially enhances DBH estimation accuracy, with multi-angle point clouds outperforming simpler regression-based approaches. In parallel, Ghasemi et al. [66] demonstrated that fusing UAV RGB imagery with multispectral satellite data improves the monitoring of tree decline severity, offering a cost-effective solution for forest health assessment in semi-arid ecosystems.

Overall, the reviewed studies indicate that UAV-based biomass and volume estimation has evolved from single-sensor photogrammetric approaches toward integrated frameworks that combine 3D structural data, multispectral information, and machine learning. These advances have significantly improved estimation accuracy while maintaining operational flexibility and cost efficiency, particularly for individual-tree-level assessments.

Accurate characterization of canopy geometry and tree structural parameters is a fundamental prerequisite for biomass and volume estimation, particularly in orchards and heterogeneous forest stands where canopy distribution is spatially nonuniform. Recent studies increasingly leverage UAV-based photogrammetry combined with advanced segmentation and learning algorithms to balance accuracy, efficiency, and cost.

Several works have focused on canopy volume estimation using UAV-derived RGB imagery and digital surface models (DSMs). Han et al. [67] developed a comprehensive pipeline integrating SfM-derived RGB and DSM orthophotos with multiple canopy segmentation techniques, including U-Net, OTSU, and RANSAC. Their results demonstrated that deep learning-based segmentation achieved the highest accuracy, with the U-Net model trained on RGB and DSM inputs yielding superior segmentation performance (MIoU = 84.75%, MPA = 92.58%). For canopy volume estimation, the DSM-only U-Net configuration achieved the lowest error (RMSE = 0.410 m^3), outperforming traditional thresholding approaches. Nonetheless, in scenarios where manual labeling is impractical, partitioned OTSU provided a viable alternative with acceptable accuracy for smaller canopy volumes.

Tree height estimation remains a core variable in forest inventories and plantation monitoring. He et al. [68] evaluated UAV-based structure-from-motion (SfM) and Semi-Global Matching (SGM) photogrammetry combined with Radial Basis Function (RBF) neural networks to generate high-resolution canopy height models (CHMs) in mountainous terrain. By improving Digital Terrain Model (DTM) interpolation using spectral indices and neural networks, the authors achieved centimeter-level DSM accuracy and demonstrated strong agreement between estimated and measured tree heights. Their results confirmed the suitability of low-cost UAV photogrammetry for height estimation in complex topography.

Beyond height, detailed crown geometry and biovolume estimation has gained attention as a proxy for biomass and productivity. Hnida et al. [69] proposed a multi-view UAV imaging framework integrating fine-tuned deep learning segmentation with geometric modeling to estimate crown volume and predict yield. Using top- and side-view imagery, advanced segmentation models, and geometric reconstruction, their approach achieved canopy volume estimation accuracies exceeding 95% and strong correlations between predicted and observed productivity (R^2 up to 0.98), highlighting the value of multi-view UAV data for precision agriculture and tree-level biomass estimation.

At broader spatial and temporal scales, digital aerial photogrammetry (DAP) has emerged as a cost-effective alternative to airborne laser scanning (ALS). Janiec et al. [70] demonstrated that bi-temporal DAP-derived top height estimates can support forest growth and site index modeling when corrected using a limited set of reference measurements. Their bias-correction framework reduced systematic errors and confirmed that DAP can substitute traditional field-based measurements in forest inventories and growth assessments.

The extraction of individual tree information is further enhanced by deep learning-based Individual Tree Detection (ITD), particularly when using UAV LiDAR data. Jarahizadeh et al. [71] introduced Tree-Net, a one-stage deep learning detector designed to exploit multi-band rasterized LiDAR features such as canopy height and vertical structure. Their method significantly outperformed existing YOLO-based architectures in detection accuracy and computational efficiency, demonstrating strong potential for tree-level inventory and biomass estimation applications.

At the plot and stand levels, biomass estimation accuracy is strongly influenced by data representation, seasonality, and modeling approach. Jayathunga et al. [72] evaluated the performance of DAP-derived point cloud and CHM metrics for estimating dominant height and biomass in uneven-aged forests. Their results showed that point cloud-derived metrics and random forest models consistently outperformed linear approaches, particularly under leaf-on conditions, while leaf-off imagery improved conifer biomass estimation. These findings highlight the importance of tailoring data sources and modeling strategies to forest structure and composition.

Methodological choices in SfM processing also significantly affect derived tree metrics. Kameyama et al. [73] systematically compared multiple SfM software version 2.3 packages under varying flight conditions and found statistically significant differences in estimated tree height and crown area. Although overall accuracy remained limited, Pix4Dmapper consistently produced lower RMSE values, underscoring the influence of processing workflows on biomass-related parameter estimation.

At the individual-tree scale, UAV oblique photogrammetry has been shown to be particularly effective for aboveground biomass estimation. Lei et al. [74] demonstrated that incorporating RGB color space intensity features into regression models substantially improved individual tree aboveground biomass estimation for Chinese fir plantations ($R^2 = 0.79$). Their analysis also revealed sensitivity to spatial resolution and viewing direction, emphasizing the importance of image configuration in IT-AGB modeling.

Scaling individual-tree estimates to larger spatial extents introduces additional uncertainties. Ma et al. [75] proposed a multiscale framework combining UAV hyperspectral imagery and multi-platform laser scanning to upscale aboveground biomass estimates from tree to landscape levels while explicitly quantifying uncertainties. Their results showed that tree species classification contributed the largest share of uncertainty, reinforcing the importance of accurate ITD and species mapping in large-scale biomass assessments.

Recent studies have also explored alternative pathways for estimating key structural parameters such as DBH. Mao et al. [76] demonstrated that two-dimensional image-based textural metrics extracted from UAV RGB imagery exhibit strong correlations with DBH, outperforming traditional combinations of spectral and structural features in some cases. Their findings suggest that carefully selected 2D features can provide efficient and accurate DBH estimation without reliance on complex 3D metrics.

Finally, Moreira et al. [77] provided a comprehensive evaluation of survey design and processing choices for UAV-based DBH estimation using SfM point clouds. By optimizing flight parameters and processing settings, they achieved RMSEs below 5% in agricultural settings and below 12.5% in forested environments, representing some of the most accurate UAV-based DBH estimates reported to date.

Collectively, the reviewed studies demonstrate a clear trend toward tree-level, geometry-aware, and learning-based UAV methodologies for biomass and volume estimation. While photogrammetric approaches alone can provide reliable estimates under optimized conditions, the integration of deep learning, multi-view geometry, LiDAR, and uncertainty-aware modeling frameworks substantially enhances robustness and scalability. These developments position UAV remote sensing as a central tool for next-generation forest inventory, carbon accounting, and precision forestry.

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3.2.2. Tree Species Analyzed for Biomass and Volume Estimation Using UAV Imagery

The analysis of tree species investigated in UAV-based biomass and volume estimation studies provides an essential link between methodological developments and real-world application scenarios. Species selection directly influences canopy structure complexity, segmentation performance, and model transferability, and therefore determines how UAV-based approaches perform across forestry, agricultural, and urban contexts. Rather than representing an isolated thematic category, the reviewed species reflect the practical ecosystems in which UAV methods are applied, including managed plantations, orchards, natural forests, mangroves, and urban green spaces.

From our bibliographic survey, we identified several species or species groups that have been the subject of studies on tree biomass and volume estimation using UAV imagery (Table 2).

Table 2. The tree species, countries, and references of UAV-based biomass and volume estimation studies.

Cur. No.	Tree Species	Country	Citing Article
1	*Abies faxoniana* Franch.	China	You-yun et al., 2016 [78]
2	Apple orchard	Spain	Apolo-Apolo et al., 2020a [79]
3	Carob trees (*Prosopis* sp.)	Peru	Chumbimune-Vivanco et al., 2025 [60]
4	Chesnuts orchard	Italy	Di Gennaro et al., 2020 [80]
5	Chinese fir forest (*Cunninghamia lanceolata* (Lamb.) Hook.)	China	Chen et al., 2024 [81]
6	*Cinnamomum camphora* (L.) J. Presl.	China	Wang et al., 2023 [82]
7	Citrus trees	Spain	Apolo-Apolo et al., 2020b [83]
8	*Eucalyptus* sp.	Portugal	Guerra-Hernandez et al., 2017 [84]
9	*Ginkgo* sp.	China	Qiu et al., 2024 [85]
10	Laricio-Pine forest	Italy	De Luca et al., 2023 [86]
11	*Larix kaempferi* (Lamb.) Carrière	Japan	Karthigesu et al., 2023 [87]
12	Litchi (*Litchi chinensis* Sonn.)	China	Bai et al., 2023 [88]
13	*Liriodendron sino-americanum* forests	China	Shi et al., 2025 [89]
14	*Malania oleifera* Chun et S. K. Lee	China	Gong et al., 2023 [90]
15	Mango orchard	Pakistan	Afsar et al., 2024 [62]
16	Mangrove forest	China, Kenya, Vietnam	Chen et al., 2023 [91]; Fu et al., 2025 [92]; Duan et al., 2025 [64]; Ngo et al., 2023 [93]
17	Mediterranean riparian forest	Portugal	Fernandes et al., 2020 [94]
18	Norway spruce (*Picea abies* L. Karst.) and beech (*Fagus sylvatica* L.) forest	Romania	Apostol et al., 2020 [95]; Tudoran et al., 2021 [96]
19	Oil palm (*Elaeis guineensis*)	Malaysia	Fawcett et al., 2019 [97]
20	Olive trees	Italy	Caruso et al., 2019 [98]

21	Orange trees	Spain	Estornell et al., 2024 [99]
22	Peach tree	China	Hu et al., 2022 [100]
23	*Picea abies* L.	Czech Republic	Panagiotidis et al., 2017 [29]
24	Pine forest	Greece	Barmpoutis et al., 2020 [101]
25	*Pinus eldarica* ten.	Iran	Hosingholizade et al., 2023 [102]
26	*Pinus halepensis* Mill.	Spain	Nemmaoui et al., 2024 [103]
27	*Pinus massoniana* Lamb.	China	Liao et al., 2022 [104]
28	*Pinus pinea* L.	Portugal	Guerra-Hernandez et al., 2017 [84]
29	*Pinus sylvestris* L.	Poland	Janiec et al., 2024 [70]
30	*Quercus ilex* L.	Portugal	Juan-Ovejero et al., 2023 [105]
31	*Sonneratia apetala* Blanco	China	Yu et al., 2023 [106]
32	*Tectona grandis* L.	Costa Rica	Porras-Granados et al., 2022 [107]
33	Tropical woodland	Malawi	Domingo et al., 2019 [108]

The reviewed studies demonstrate a broad diversity of tree species and forest types used for estimating tree biomass and volume from UAV imagery (Table 2). Overall, 33 case studies were identified, spanning natural forests, plantations, agroforestry systems, and orchards, and covering a wide geographical range across Europe, Asia, Africa, and the Americas.

The majority of the analyzed species belong to temperate and subtropical forest ecosystems, with a strong emphasis on coniferous species. Several studies focused on *Pinus* species, including *Pinus pinea* (Portugal), *Pinus sylvestris* (Poland), *Pinus halepensis* (Spain), *Pinus massoniana* (China), and *Pinus eldarica* (Iran), reflecting the ecological and economic importance of pine forests in biomass estimation research [70,84,102–104]. Other coniferous forests included *Picea abies* in Central and Eastern Europe [29,95], *Larix kaempferi* in Japan [87], *Abies faxoniana* in China [78], and *Cunninghamia lanceolata* forests in China [81].

Broadleaf forests and mixed stands were also well represented. These included *Quercus ilex* in Portugal [105], *Fagus sylvatica* mixed with Norway spruce in Romania [95], *Cinnamomum camphora* in China [82], and *Liriodendron sino-americanum* forests [89]. Mediterranean and riparian forest ecosystems were addressed in Portugal [94], highlighting the applicability of UAV-based approaches in structurally complex environments.

A significant portion of the reviewed studies focused on orchards and plantation crops, particularly in agricultural landscapes. These included apple orchards [79], citrus and orange trees [83,99], olive groves [98], mango orchards [62], peach trees [100], litchi plantations [88], oil palm plantations [97], and carob trees (*Prosopis* sp.) in Peru [61]. These studies generally targeted individual-tree biomass and volume estimation, benefiting from the regular spacing and simplified canopy structures typical of managed orchards.

Mangrove ecosystems were investigated across multiple countries, including China, Kenya, and Vietnam [64,91–93], with a particular focus on *Sonneratia apetala* [106]. These studies underline the growing interest in UAV-based biomass estimation for coastal and wetland forests, which are often difficult to access using traditional field methods.

Finally, tropical forest environments were represented by studies in Costa Rica (*Tectona grandis* plantations; [107] and Malawi (tropical woodland; [108], illustrating the expanding application of UAV imagery in high-biomass and structurally complex tropical systems.

3.2.3. UAV-Based Estimation of Tree Biomass and Canopy Volume in Agriculture

Recent studies demonstrate that UAV-based remote sensing is a robust tool for estimating tree geometric parameters, biomass proxies, and growth dynamics in agricultural systems. Across diverse perennial crops—including olive, citrus, chestnut, peach, oil palm, apple, and litchi—UAV imagery combined with photogrammetric and machine learning techniques has shown strong performance in capturing canopy structure, volume, and biomass-related indicators.

Early work using RGB and multispectral UAV imagery established strong relationships between canopy geometry derived from structure-from-motion (SfM) and field-measured parameters. In olive, vineyard, and citrus orchards, canopy height and volume extracted from digital surface models (DSM) showed high agreement with ground measurements (R^2 = 0.79–0.90; RMSE = 0.08–0.22 m), while vegetation indices such as NDVI were consistently correlated with leaf area index (LAI) (R^2 = 0.63–0.88), confirming the suitability of UAV platforms for rapid canopy characterization [98].

Subsequent experiments in fully productive olive orchards further refined these findings by linking UAV-derived canopy volume dynamics with irrigation regimes and plant water status. Canopy volume estimated from UAV RGB imagery correlated well with field-measured canopy volume (R^2 = 0.71–0.86), and temporal changes in canopy volume were strongly associated with cumulative water stress in rainfed trees (R^2 = 0.99). The highest accuracy in canopy height estimation was achieved at lower flight altitudes (50 m AGL), yielding RMSE values as low as 0.16 m [109]. Complementary work demonstrated that UAV RGB and thermal imagery could simultaneously capture canopy growth and water stress, with canopy volume strongly related to LAI (R^2 = 0.84–0.88) and thermal-based crop water stress indices correlating with stem water potential (R^2 = 0.83) [110].

Beyond canopy volume estimation, UAV-SfM-derived 3D point clouds have been successfully applied to above-ground biomass estimation in fruit trees. In abandoned orange orchards, crown metrics extracted from UAV point clouds—particularly crown area—produced accurate biomass estimation models (R^2 = 0.85; RMSE = 10.17 kg), highlighting the potential of UAV data for carbon stock assessment and bioenergy planning in neglected agricultural landscapes [99]. Similar outcomes were reported for oil palm plantations, where UAV-SfM point clouds enabled the extraction of individual palm height and stem metrics, achieving RMSE values of 0.27–0.45 m and supporting per-palm above-ground biomass estimation across plantation ages [97].

UAV-based canopy volume differences have also been used to quantify management-induced biomass changes. In chestnut orchards, both supervised and unsupervised crown segmentation approaches yielded strong correlations between UAV-derived crown volume reduction and measured pruning biomass (R^2 = 0.53–0.83). The unsupervised approach showed particularly high operational potential, detecting trees with only 1.7% omission error and demonstrating robustness for large-area monitoring [80].

More recent studies increasingly rely on deep learning to improve canopy delineation and phenological monitoring. In peach orchards, a conditional generative adversarial network (cGAN) significantly outperformed traditional segmentation methods for crown extraction, achieving F-measure values of 0.846 and enabling crown volume estimation with a relative RMSE of 14.93% compared to LiDAR reference data [100]. In litchi orchards, a modified U-Net architecture incorporating MobileNetV3 and attention mechanisms successfully detected and tracked winter flushes, improving mean pixel accuracy to 93.4% and enabling quantitative analysis of flush growth processes under varying temperature conditions [88].

Finally, UAV imagery combined with object detection and time-series learning has proven effective for yield-related applications closely linked to biomass and canopy development. In citrus and apple orchards, deep learning models such as Faster R-CNN and region-based CNNs achieved high fruit detection accuracy (R^2 up to 0.86), while LSTM-based models enabled per-tree and total yield estimation with errors below those of expert visual assessments [79].

3.2.4. UAV-Based Estimation of Tree Biomass and Canopy Volume in Forestry

Pine Forests

Across pine-dominated forest systems, UAV-based photogrammetry and LiDAR have consistently demonstrated strong capability for estimating individual-tree structural attributes and aboveground biomass. Early work using low-cost UAV platforms over *Pinus pinea* plantations showed that structure-from-motion (SfM)-derived canopy height models (CHMs), combined with object-based image analysis (OBIA), enabled accurate delineation of individual tree crowns and estimation of tree height and biomass. In this context, UAV-derived tree height closely matched field measurements ($R^2 = 0.96$), while SfM-derived predictors explained up to 86–87% of the variability in biomass, allowing detection of significant spatio-temporal growth differences over a two-year period [84].

Subsequent studies refined tree height estimation approaches in pine plantations. In *Pinus eldarica* stands, height estimation based on UAV-derived shadow length—after correcting for terrain slope—produced unbiased results relative to field data, although CHM-based methods achieved higher precision [102]. These findings highlight the importance of topographic correction and confirm the superior robustness of CHM-based height retrieval.

For sparsely planted *Pinus sylvestris* forests in semi-arid regions, UAV-derived crown diameter (CD) and height extracted from CHMs closely matched in situ measurements and supported the development of reliable aboveground biomass allometric equations ($R^2 = 0.731$) [111]. Similarly, comparative analyses of raster-based and point cloud-based segmentation algorithms demonstrated that UAV photogrammetric point clouds outperform low-density airborne laser scanning (ALS) for individual tree detection and height estimation in Aleppo pine stands, though crown diameter estimation remained challenging [104].

Beyond photogrammetry, UAV-mounted LiDAR systems proved effective in pine forests when integrated with hypsometric dendrometry. In Calabrian laricio pine stands, LiDAR-derived height information enabled indirect yet reliable estimation of tree diameters and stand-level volume, confirming the operational applicability of UAV-LiDAR for professional forestry [86].

Other Resinous Species Forests

In non-pine coniferous systems, UAV data have been successfully integrated with machine learning and multisource remote sensing. In Chinese fir plantations (*Cunninghamia lanceolata*), UAV-derived spectral vegetation indices combined with random forest regression accurately predicted individual-tree aboveground biomass, with NDVI and OSAVI emerging as dominant predictors [81]. Topographic variables further influenced spatial biomass distribution, underscoring the need to integrate terrain information.

Multi-platform approaches combining UAV, terrestrial laser scanning (TLS), and satellite SAR data also improved forest volume estimation in Japanese cypress forests. Random forest regression outperformed support vector regression, particularly when high-resolution UAV canopy metrics were included, demonstrating the added value of fine-scale UAV data for plot-level volume estimation [112].

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Oak Forests

In broadleaved Mediterranean systems, UAV-derived RGB imagery proved highly effective for estimating biomass and carbon stocks of young oak plantations. In 5-year-old holm oak (*Quercus ilex*) stands, UAV-extracted crown area, height, and biovolume explained up to 89% of the variability in aboveground biomass and carbon stocks. UAV-based models performed comparably to traditional allometric equations while offering substantial gains in efficiency and scalability for early-stage plantation monitoring [105].

Other Broadleaved Tree Species

In heterogeneous and tropical systems, UAV photogrammetry supported biomass estimation under varying environmental and methodological conditions. In miombo woodlands, biomass prediction accuracy increased with finer image resolution and RGB sensors, while reductions in side overlap offered opportunities to reduce flight costs with minimal accuracy loss [108]. Terrain slope influenced prediction errors, though its effect remained moderate.

Advanced image analysis and deep learning further expanded UAV applicability. In mixed forests containing the protected species *Malania oleifera*, high-resolution UAV-RGB imagery combined with Mask R-CNN achieved high canopy segmentation accuracy (90%) and enabled the first individual-tree aboveground biomass estimation for this species [90].

UAV photogrammetry and LiDAR were also shown to deliver individual-tree volume estimates in *Eucalyptus* spp. plantations, with comparable performance to ALS data and no significant bias relative to field measurements [84].

Mixed Forests

In even-aged mixed stands, UAV data integrated with ALS supported accurate extraction of species-specific dendrometric parameters. In spruce–beech forests, ALS-derived height and crown metrics enabled reliable DBH prediction, though detection accuracy varied between species, with conifers outperforming broadleaves [95,96].

Mangrove Forests

Mangrove ecosystems, characterized by structural complexity and difficult field access, benefited substantially from UAV-LiDAR and multi-sensor integration. UAV-LiDAR-derived CHMs served as reliable reference data for mangrove height estimation when combined with optical and SAR imagery, yielding R^2 values up to 0.71 [91]. Advanced machine learning approaches further improved height inversion accuracy across dominant mangrove species, with random forest and mixture density networks achieving R^2 values up to 0.875 [92].

UAV multispectral imagery also enabled effective biomass mapping in mangrove forests, with log–log regression models providing the highest accuracy and facilitating spatially explicit biomass assessment for carbon service applications [93].

Riparian and Afromontane Forests

In Mediterranean riparian forests, UAV multispectral imagery combined with OBIA enabled species-level biomass and carbon stock estimation, revealing strong interspecific differences driven by stand structure and successional stage [94]. Multispectral imagery were used to measure tree canopy and stand structure in hybrid poplar plantations, using models based on image texture/dissimilarity [113]. In dry Afromontane forests, photogrammetric UAV imagery explained 89% of field-measured tree height variability, and uncertainties in height estimation had negligible influence on aboveground biomass calculations, supporting UAV-based approaches for biomass estimation in data-scarce dryland regions [114].

3.2.5. UAV-Based Approaches for Urban Tree Biomass and Green Volume Estimation

Recent studies demonstrate the strong potential of UAV-based remote sensing for estimating tree biomass, canopy structure, and green volume in urban and sub-urban environments, where vegetation is often fragmented and heterogeneous.

Comparative analyses between UAV-derived photogrammetric and LiDAR point clouds show that both techniques can generate highly accurate three-dimensional representations of urban tree canopies. In an urban park setting, point clouds derived from UAV photogrammetry and UAV-LiDAR exhibited extremely high correlations, with coefficients of determination exceeding 99% for point cloud consistency and over 95% for estimated canopy parameters, confirming the suitability of both approaches for detailed urban forest structure assessment [115].

Several studies focused on aboveground biomass estimation at the individual-tree and plot scales. Using integrated UAV hyperspectral and LiDAR data in tropical urban forests, Ferreira et al. [116] evaluated both area-based and individual tree crown (ITC)-based strategies. Area-based approaches benefited from increasing grid sizes, with the coefficient of determination improving from 0.24 to 0.61 when grid resolution increased from 10 m to 50 m, primarily due to reduced border effects. The integration of canopy height models and hyperspectral data further improved aboveground biomass estimation accuracy (R^2 up to 0.70), with green peak and red-edge wavelengths identified as key spectral regions. In contrast, ITC-based aboveground biomass estimates showed limited improvement from data fusion, as biomass was strongly driven by tree height and crown area alone.

High-accuracy aboveground biomass estimation was also achieved using dual-source UAV point clouds derived from photogrammetry and LiDAR. Lin et al. [117] combined these data sources to extract tree height and canopy radius for individual dawn redwood trees in an artificial urban forest. The derived structural parameters showed strong agreement with field measurements ($R^2 > 0.90$), and the newly developed allometric model yielded highly accurate aboveground biomass estimates ($R^2 = 0.95$, RMSE = 17.59 kg).

UAV-based three-dimensional reconstruction techniques further demonstrated their effectiveness in single-tree biomass estimation. Zhao et al. [118] employed multi-angle UAV imagery and multiple-view stereo (MVS) algorithms to generate realistic 3D tree models for urban street trees. Structural parameters extracted from these models, including tree height, crown diameter, and crown volume, were strongly correlated with field measurements (R^2 ranging from 0.87 to 0.90). Biomass models based on crown volume and tree height achieved the highest accuracy, with validation R^2 values reaching 0.96 for ginkgo and 0.92 for camphor trees, comparable to LiDAR-based estimates.

Beyond biomass, UAV imagery has been widely used to quantify urban green volume metrics. Hong et al. [119] introduced a Mean of Neighboring Pixels (MNP) algorithm using UAV RGB imagery to estimate three-dimensional green volume (3DGV) in urban green spaces. Compared with convex hull- and voxel-based approaches, the MNP algorithm consistently produced lower relative bias and RMSE at both plot and individual tree scales, demonstrating superior performance without explicit tree detection.

Similarly, Li et al. [120] proposed a multi-source data fusion framework for estimating three-dimensional green quantity (3DGQ) by integrating UAV-derived structural parameters with Sentinel-2 vegetation indices. UAV imagery enabled accurate extraction of tree height and crown dimensions ($R^2 \geq 0.84$), while machine learning models achieved robust predictive performance (R^2 ranging from 0.67 to 0.85). The Random Forest model outperformed other approaches, maintaining high accuracy even after feature simplification and enabling large-scale 3DGQ mapping across urban built-up areas.

At a broader methodological level, Guascal et al. [121] compared UAV-based biomass estimation with radar remote sensing in an urban park environment. While radar-based models achieved higher overall correlation with field biomass (R^2 = 0.74), UAV-derived models captured abrupt changes in tree height more effectively, highlighting the sensitivity of UAV data to fine-scale structural variability in urban forests.

Finally, UAV RGB imagery has also been applied beyond biomass estimation to forest health monitoring in sub-urban environments. Barmpoutis et al. [101] demonstrated that high-resolution UAV imagery combined with deep learning architectures (Faster R-CNN and Mask R-CNN) could accurately detect insect-infested trees in a suburban pine forest, supporting timely ecosystem monitoring and management.

4. Discussion

4.1. Bibliometric Review

Similar to other published studies [122–125], articles represent the dominant proportion of the analyzed publications. However, unlike other cases—where the share of conference proceedings typically ranges between 5–7% [126–129]—their proportion in this field is approximately double. This can be explained by the large number of symposia dedicated to inventories and measurements conducted using UAVs. Furthermore, the number of review articles and book chapters is negligible compared with other bibliometric studies [130–132], indicating that recent research in this area has not yet been sufficiently consolidated and critically synthesized at a comprehensive level.

Although these studies appeared relatively late (the earliest work identified in our analysis dates back to 2012), publications addressing this topic have increased markedly in terms of quantity, the diversity of scientific fields involved, and the number of contributing authors. With respect to the countries of affiliation of these authors, the top two—China and the United States—are consistently reported in many other studies [133–135], either in the same or reversed order. Notably, the prominent presence of Iberian countries (Spain and Portugal) among the leading contributors is of particular interest, as UAVs are extensively used in these countries for biometric analyses of trees in agricultural and agroforestry systems.

Given the relatively recent emergence of this research topic, MDPI—a comparatively new publisher—dominates among journal editors, in contrast to more established publishers such as Elsevier or Springer Nature, which lead in many other research areas. Finally, the keywords used in the published articles largely reflect the core disciplinary domains relevant to the studied topic.

4.2. Methodological Progress and Emerging Paradigms in UAV-Based Tree Biomass and Volume Estimation

The reviewed results collectively demonstrate a rapid methodological evolution in UAV-based estimation of tree biomass and volume, characterized by increasing integration of three-dimensional structural data, multi-sensor fusion, and advanced learning-based models. This Discussion synthesizes the reported findings by critically analyzing methodological trends, strengths, and remaining limitations, focusing exclusively on the evidence presented in Section 3.

A consistent outcome across studies is the proven capability of UAV-based photogrammetry to derive reliable tree structural parameters at the individual-tree level. Early structure-from-motion (SfM) approaches successfully estimated tree height, crown dimensions, DBH, and stem volume when high-quality point clouds and terrain models were available [57,61]. These studies confirmed that photogrammetric UAV data can approach LiDAR-level accuracy under optimized conditions, reinforcing UAV photogrammetry as a cost-effective alternative for localized inventories. However, the results also indicate that photogrammetric accuracy is highly sensitive to flight configuration, image overlap, spatial resolution, and SfM processing workflows, as demonstrated by Ni et al. [59] and Kameyama et al. [73]. This sensitivity highlights a fundamental limitation of single-sensor approaches: methodological choices can propagate substantial uncertainty into biomass and volume estimates.

The integration of UAV imagery with complementary data sources emerges as a key strategy to overcome these limitations. Multiple studies showed that fusing UAV RGB imagery with multispectral satellite data significantly improves crown delineation, species classification, and carbon estimation [58,66]. Similarly, LiDAR-equipped UAV platforms consistently outperformed photogrammetry-only approaches in biomass and carbon modeling due to their ability to capture vertical canopy structure and intensity-based metrics [61,64]. These findings collectively suggest that structural–spectral complementarity is central to improving robustness, particularly in dense or heterogeneous forest conditions where optical saturation and occlusion remain challenging.

Another prominent trend is the increasing reliance on machine learning and deep learning methods to extract biologically meaningful features from UAV data. Deep learning-based canopy segmentation and individual tree detection achieved substantially higher accuracies than traditional thresholding or rule-based methods [62,67,71]. High segmentation accuracy directly translated into improved canopy volume, biomass, and productivity estimates, underscoring segmentation as a critical bottleneck in UAV-based modeling pipelines. The superior performance of convolutional neural networks, including U-Net–based architectures and one-stage detection frameworks, indicates that learning-based models are increasingly necessary to fully exploit the spatial and geometric richness of UAV data.

The reviewed studies also reveal a clear shift toward tree-level, geometry-aware modeling. Individual-tree approaches using point clouds, multi-view imagery, and ensemble regression frameworks consistently outperformed plot-level linear models, particularly in structurally complex or uneven-aged stands [69,72,74]. This shift reflects a broader recognition that biomass and volume are emergent properties of tree geometry, not merely spectral response. Crown volume, canopy shape, and fine-scale vertical structure were repeatedly shown to be strong proxies for biomass and productivity, especially when derived from multi-angle UAV imagery and three-dimensional reconstructions.

Despite these advances, scaling remains a persistent challenge. While individual-tree estimates showed high accuracy, uncertainty increased when upscaling to plot, stand, or landscape levels (Ma et al., 2025 [75]). Species misclassification and individual tree detection errors were identified as dominant sources of uncertainty, emphasizing the need for robust ITD and species mapping before large-scale biomass extrapolation. Bias correction and hybrid frameworks, such as those applied to digital aerial photogrammetry for forest growth modeling [69], demonstrate promising pathways for mitigating systematic errors but require careful calibration and reference data.

An important methodological insight from the reviewed literature is that increasing model complexity does not universally guarantee improved performance. In several cases, carefully optimized photogrammetric workflows, simple regression models, or two-dimensional textural features yielded competitive results for parameters such as DBH and tree height [76,77]. These findings suggest that method selection should be guided by application scale, forest structure, and operational constraints rather than by technological sophistication alone.

In summary, the reviewed results indicate that UAV-based biomass and volume estimation has transitioned from experimental photogrammetric applications to mature, integrated frameworks capable of supporting forest inventory, carbon accounting, and precision forestry. The strongest performance is consistently achieved when three-dimensional structural data, multispectral information, and machine learning models are combined in geometry-aware, tree-level approaches. Nevertheless, sensitivity to survey design, processing workflows, and scaling uncertainties remains a critical consideration. Addressing these challenges through standardized methodologies, uncertainty-aware modeling, and multi-sensor integration will be essential for the operational adoption of UAV-based biomass and volume estimation at broader spatial scales.

Another prominent trend is the increasing reliance on machine learning and deep learning methods to extract biologically meaningful features from UAV data. Across the reviewed literature, approximately two-thirds of the studies published after 2020 employed machine learning-based regression or classification models, and nearly one-third explicitly adopted deep learning architectures for canopy segmentation or individual tree detection. In contrast, studies published prior to 2018 relied predominantly on linear or allometric regression frameworks. Deep learning-based canopy segmentation and individual tree detection achieved substantially higher accuracies than traditional thresholding or rule-based methods [62,67,71]. High segmentation accuracy directly translated into improved canopy volume, biomass, and productivity estimates, underscoring segmentation as a critical bottleneck in UAV-based modeling pipelines. The superior performance of convolutional neural networks, including U-Net–based architectures and one-stage detection frameworks, indicates that learning-based models are increasingly necessary to fully exploit the spatial and geometric richness of UAV data.

The reviewed studies also reveal a clear shift toward tree-level, geometry-aware modeling. More than 70% of studies published in the last five years adopted individual-tree-level modeling strategies, compared with fewer than half of the earlier studies that primarily relied on plot-level averages. Individual-tree approaches using point clouds, multi-view imagery, and ensemble regression frameworks consistently outperformed plot-level linear models, particularly in structurally complex or uneven-aged stands [69,72,74]. This shift reflects a broader recognition that biomass and volume are emergent properties of tree geometry, not merely spectral response. Crown volume, canopy shape, and fine-scale vertical structure were repeatedly shown to be strong proxies for biomass and productivity, especially when derived from multi-angle UAV imagery and three-dimensional reconstructions.

4.2.1. Horizontal Methodological Comparison and Operational Implications

To address the need for cross-method comparability, the reviewed studies were synthesized through a horizontal comparison of the most widely adopted UAV-based technologies and modeling strategies, focusing on accuracy, operational cost, scalability, and applicability across ecosystem types.

SfM photogrammetry versus UAV-LiDAR

Structure-from-motion (SfM) photogrammetry based on RGB imagery remains the most commonly applied approach due to its low sensor cost, high spatial resolution, and operational simplicity [57,59,61,73]. When high image overlap, appropriate flight altitude, and accurate digital terrain models are available, SfM-derived canopy height and crown metrics can achieve accuracy comparable to UAV-LiDAR for individual-tree height, crown area, and biomass estimation, particularly in open canopies, plantations, and orchards [61,74,84]. However, multiple studies consistently show that SfM performance degrades in dense, multilayered, or shadowed canopies due to occlusion and limited penetration to lower canopy layers [59,91].

In contrast, UAV-LiDAR provides superior representation of vertical forest structure and is less sensitive to illumination conditions, terrain complexity, and canopy closure [64,86,91]. LiDAR-based metrics consistently improved biomass and carbon estimation accuracy in mature forests, mangroves, and structurally complex ecosystems, although at higher acquisition and processing costs. Consequently, SfM photogrammetry is best suited for cost-efficient, high-frequency monitoring at local scales, whereas UAV-LiDAR is more appropriate for structurally complex forests and applications requiring higher robustness and vertical accuracy.

Traditional regression versus machine learning approaches

Classical allometric and linear regression models remain effective when based on well-defined geometric predictors such as tree height, crown diameter, and canopy volume [57,76,77]. These models offer transparency, interpretability, and low computational demand, making them suitable for operational forestry and agricultural applications with limited data availability.

Machine learning methods—particularly random forest, ensemble regression, and deep learning architectures—consistently outperform traditional models when input feature spaces are high-dimensional or non-linear, such as when combining structural, spectral, and textural variables [62,64,72,81]. Deep learning-based segmentation and individual tree detection significantly reduce errors in crown delineation, which directly propagates into improved biomass and volume estimation [67,71]. However, these approaches require larger training datasets, careful model tuning, and greater computational resources, which may limit their immediate operational deployment in data-scarce regions.

Applicability across spatial scales

At the individual-tree scale, geometry-aware and learning-based approaches consistently provide the highest accuracy across agricultural, forest, and urban contexts [69,74,118]. At plot and stand levels, area-based models benefit from spectral–structural integration and reduced edge effects but are more sensitive to species composition and scaling uncertainty [72,116]. Landscape-scale applications require multi-platform integration and bias correction, as demonstrated in multi-scale UAV–satellite frameworks [58,75].

Overall, no single methodology is universally optimal. Instead, method selection should be guided by forest structure, spatial scale, budget constraints, and required accuracy, rather than by sensor sophistication alone.

4.2.2. Practical Operational Guidance and Implementation Templates

Based on the reviewed evidence, several recurring operational patterns emerge that can guide practical implementation of UAV-based biomass and volume estimation.

Template 1: Orchard and plantation systems (precision agriculture).

For regularly spaced trees with limited canopy overlap, low-cost UAV platforms equipped with RGB sensors and SfM photogrammetry are sufficient for reliable estimation of canopy volume and biomass proxies [79,80,97,99]. Recommended workflows include high forward and side overlap (>80%), low flight altitude (≤60 m AGL), and tree-level modeling using canopy volume or crown area as primary predictors. Deep learning-based crown segmentation improves robustness where crown shapes are irregular or pruning effects must be quantified [80,100].

Template 2: Managed and plantation forests.

In even-aged coniferous plantations, UAV-SfM-derived CHMs combined with object-based crown delineation and regression or random forest modeling provide accurate estimates of tree height, DBH, and biomass at low operational cost [29,84,104]. Periodic UAV surveys enable effective growth monitoring and detection of spatial variability in biomass accumulation [70].

Template 3: Structurally complex or inaccessible forests.

In dense, multi-layered forests, mangroves, or steep terrain, UAV-LiDAR or multi-sensor integration is recommended to ensure reliable vertical structure reconstruction [64,91,92]. Biomass estimation accuracy in these systems benefits from machine learning models that incorporate LiDAR height metrics and spectral variables, while uncertainty should be explicitly quantified when upscaling [75].

Template 4: Urban and peri-urban environments.

For fragmented urban forests, individual-tree approaches using UAV photogrammetry or LiDAR are highly effective due to clear crown separation [117,118]. Where tree delineation is difficult, pixel-based green volume methods provide scalable alternatives without explicit tree detection [119]. Integration with satellite data enables city-scale mapping of urban biomass and green volume [120].

By linking methodological choices to concrete application scenarios, these templates illustrate how UAV-based biomass and volume estimation can be operationalized to support sustainable land management, carbon accounting, and decision-making.

4.3. Tree Species Representation in UAV-Based Biomass and Volume Studies

The reviewed literature reveals that UAV-based biomass and volume estimation has been applied across a wide spectrum of tree species and ecosystem types, with a notable concentration on coniferous forests, orchard systems, and intensively managed plantations. This distribution reflects both methodological suitability and practical research priorities.

Coniferous forests dominate the dataset, particularly *Pinus*, *Picea*, *Abies*, and *Larix* species. These forests typically exhibit relatively simple vertical structures and conical crown shapes, which are well suited to canopy height model (CHM) extraction from UAV-derived point clouds. The repeated investigation of pine forests across different countries suggests a strong consensus on their suitability as benchmark systems for UAV-based biomass modeling [29,70,84,101].

In contrast, broadleaf and mixed forests were less frequently studied, despite their ecological significance. The presence of complex crown architectures, overlapping canopies, and heterogeneous stand compositions likely increases segmentation and modeling uncertainty, which may explain their lower representation. Nevertheless, recent studies on *Quercus ilex*, *Fagus sylvatica*, and riparian forests demonstrate growing confidence in UAV methods for structurally diverse stands [94,95,105].

Orchards and plantation crops constitute another major category in the reviewed literature. The regular planting patterns and isolated crowns characteristic of orchard systems facilitate individual-tree detection and crown delineation, leading to high model accuracy and repeatability. This explains the increasing use of UAV imagery in precision agriculture contexts, including fruit trees and oil palm plantations [62,79,97,98]. These systems serve as important testbeds for refining UAV-based biomass estimation techniques at the tree level.

Mangrove and tropical forest studies remain comparatively limited but are of high relevance. Mangroves, in particular, benefit from UAV approaches due to their inaccessibility and sensitivity to disturbance, while tropical woodlands and teak plantations represent challenging environments with high biomass variability [91,106,108]. The growing number of studies in these ecosystems indicates a gradual expansion of UAV applications beyond temperate regions.

Overall, the reviewed data suggest that current UAV-based biomass and volume estimation research is biased toward structurally simpler and economically important forest types, while complex natural forests remain underrepresented. Future research should aim to balance this distribution by increasing studies in mixed-species, uneven-aged, and tropical forests, thereby improving the generalizability of UAV-based biomass estimation methods across global forest ecosystems.

4.4. UAV-Based Estimation of Tree Biomass and Canopy Volume in Agricultural Systems

The reviewed studies collectively confirm that UAV-based remote sensing provides accurate, flexible, and scalable solutions for estimating tree canopy volume and biomass-related parameters in agricultural systems. Across species and management contexts, canopy volume derived from UAV imagery emerges as a central structural variable, strongly linked to LAI, biomass, water status, and yield components.

A consistent finding is the robustness of SfM-derived 3D products for capturing tree geometry. Canopy height and volume estimates derived from UAV point clouds show strong agreement with field measurements, particularly when flight parameters such as altitude and image overlap are optimized [97,98]. These geometric parameters serve as effective proxies for biomass, especially when direct destructive sampling is impractical, as demonstrated in orange, chestnut, and oil palm systems [80,97,99].

The integration of spectral information further enhances biomass-related assessments. Vegetation indices, especially NDVI, consistently correlate with LAI and canopy vigor, supporting combined structural–spectral approaches for improved biomass estimation [98,110]. Moreover, the ability to link canopy volume dynamics to water stress highlights UAV data as a valuable tool for interpreting biomass responses to environmental and management drivers.

Deep learning techniques represent a major advancement in this field. Semantic segmentation and object detection models substantially improve crown delineation, phenological monitoring, and fruit detection compared to traditional threshold-based or manual approaches [79,88,100]. These methods are particularly relevant for complex canopies, irregular crown shapes, and small-scale orchards, where conventional geometric assumptions may fail. However, their reliance on labeled datasets and computational resources remains a practical limitation for widespread adoption.

From a biomass estimation perspective, most studies rely on indirect relationships between UAV-derived canopy metrics and field-measured biomass or yield. While these relationships are generally strong, their transferability across species, training systems, and phenological stages is still uncertain. This is evident in the variability of R^2 values reported for pruning biomass and fruit yield estimation [79,80]. Consequently, site- and species-specific calibration remains necessary.

Overall, the reviewed literature demonstrates that UAV imagery—particularly when combining 3D structural reconstruction with advanced machine learning—offers a reliable and cost-effective approach for tree biomass and volume estimation in agricultural systems. Future research should focus on improving model generalization, integrating multi-temporal datasets, and linking UAV-derived metrics more directly to physiological biomass components to strengthen their applicability in precision agriculture and carbon accounting frameworks.

4.5. Advances and Challenges in UAV-Based Estimation of Forest Biomass and Structure

The reviewed studies collectively demonstrate that UAV-based remote sensing has matured into a reliable and versatile tool for estimating tree height, crown dimensions,

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biomass, and volume across a wide range of forest types and ecological conditions. Across coniferous, broadleaved, mixed, and mangrove forests, UAV-derived structural metrics consistently showed strong agreement with field measurements, particularly when CHMs or LiDAR point clouds were used as primary inputs.

A central pattern emerging from these results is the dominance of tree height and crown-related variables as predictors of biomass and volume. CHM-based height estimation repeatedly outperformed alternative methods such as shadow-length approaches, especially in complex terrain, although slope-corrected shadow methods can provide acceptable accuracy in simpler plantation settings [84,102]. This reinforces the importance of three-dimensional canopy reconstruction for robust biomass modeling.

Methodological comparisons further indicate that sensor choice and data density strongly influence accuracy. UAV photogrammetry frequently outperformed low-density ALS for individual tree detection in open or semi-open canopies, whereas UAV-LiDAR provided superior vertical structure representation in dense or structurally complex forests, such as mangroves and mature conifer stands [91]. The integration of UAV data with TLS and satellite SAR consistently improved model performance, emphasizing the complementary nature of multi-source remote sensing [111].

Forest type emerged as a key determinant of UAV performance. Plantation forests, particularly young and sparsely planted stands, exhibited higher segmentation and biomass estimation accuracy than structurally heterogeneous mixed or broadleaved forests. Species-specific crown architecture influenced detection rates and model precision, with conifers generally yielding more reliable results than broadleaved species in mixed stands [95]. Conversely, UAV-based RGB imagery proved especially effective for young broadleaved plantations, where traditional allometric models are scarce or poorly parameterized [105].

In challenging environments such as mangroves and dry Afromontane forests, UAV-based approaches offered substantial advantages over conventional field methods by reducing logistical constraints while maintaining acceptable accuracy. Notably, uncertainties in UAV-derived height had limited impact on biomass estimates in dry forests, suggesting a degree of robustness in aboveground biomass modeling [114].

Overall, the reviewed evidence supports UAV remote sensing as a cost-effective, scalable, and accurate solution for individual-tree and plot-level biomass and volume estimation. Remaining limitations include crown diameter estimation in dense canopies, species-specific segmentation in mixed forests, and sensitivity to terrain effects. Addressing these challenges through improved algorithms, sensor fusion, and standardized workflows will be critical for advancing UAV-based forest inventory and carbon accounting applications.

4.6. Opportunities and Challenges of UAV-Based Biomass and Volume Estimation in Urban and Sub-Urban Forests

The reviewed studies collectively demonstrate that UAV-based remote sensing is a robust and versatile tool for estimating tree biomass, canopy structure, and green volume in urban and sub-urban environments. Across diverse ecological and urban contexts, UAV data consistently enabled high-accuracy extraction of key structural parameters, which form the foundation of reliable biomass and volume estimation.

One recurring finding is the strong dependence of aboveground biomass estimation accuracy on tree structural attributes such as height, crown area, crown volume, and canopy radius. Studies employing individual-tree approaches consistently reported high coefficients of determination when these parameters were accurately derived from UAV point clouds or 3D models [117,118]. This highlights the suitability of UAV platforms for

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individual-tree analyses in fragmented urban forests, where traditional plot-based field measurements are often impractical.

The integration of multiple UAV sensors produced mixed outcomes depending on the estimation scale. While data fusion of hyperspectral and LiDAR imagery significantly improved area-based aboveground biomass estimates by reducing border effects and enhancing spectral–structural relationships [116], similar benefits were not consistently observed for individual-tree models. This suggests that, at the tree level, geometric structure may dominate biomass estimation, whereas spectral information becomes more valuable when aggregating biomass across spatial units.

Comparative analyses between photogrammetry and LiDAR indicate that both technologies can deliver highly accurate canopy representations in urban settings [113]. The choice between them may therefore depend more on operational constraints, such as cost, sensor availability, and required point cloud completeness, rather than on fundamental differences in estimation accuracy.

Beyond biomass, the estimation of three-dimensional green volume and quantity introduces an important complementary perspective on urban vegetation structure. Pixel-based methods such as the MNP algorithm [119] demonstrated that reliable green volume estimates can be achieved without explicit tree segmentation, which is particularly advantageous in complex urban landscapes. Meanwhile, machine learning frameworks integrating UAV and satellite data [120] showed strong scalability, enabling city-wide assessments of urban green infrastructure.

The comparison between UAV and radar-based biomass estimation [121] further underscores the strength of UAV data in capturing fine-scale structural changes, which are common in urban and peri-urban forests due to anthropogenic disturbance. This sensitivity also supports broader ecosystem monitoring applications, such as pest and disease detection, as demonstrated by UAV-based deep learning approaches for identifying infected trees [101]. Also, the UAV is used in forest genetics research to analyze the field tests locations, regarding provenances distribution within trials blocks, the microenvironmental effects on the phenotypic results (e.g., slope position, edge effects, sun exposure), and the NDVI of different provenances in different environments [136–141].

Overall, the reviewed results indicate that UAV imagery provides a high-resolution, flexible, and cost-effective solution for urban tree biomass and volume estimation. While challenges remain in standardizing methodologies and optimizing data fusion strategies, UAV-based approaches clearly enhance the capacity to monitor urban forest structure, carbon storage, and ecosystem health at multiple spatial scales.

4.7. Research Gaps and Future Directions

Despite the rapid methodological progress in UAV-based estimation of tree biomass and volume, several important research gaps remain that must be addressed to fully realize the potential of these technologies in support of sustainable forest management, sustainable agriculture, and long-term ecosystem resilience.

First, there is a clear need for greater methodological standardization. Current studies employ highly heterogeneous UAV platforms, sensor configurations, flight parameters, data processing workflows, and modeling strategies. This lack of harmonization limits the comparability and transferability of results across regions and forest types, reducing their usefulness for sustainable monitoring frameworks, national forest inventories, and international climate reporting. Future research should focus on developing standardized, open, and reproducible protocols for UAV data acquisition and biomass estimation that can support consistent and scalable sustainability assessments.

Second, uncertainty quantification and error propagation remain insufficiently addressed. While many studies report high accuracy metrics, few explicitly evaluate how uncertainties arising from individual tree detection, crown delineation, species classification, and scaling propagate into biomass and carbon stock estimates. Robust uncertainty-aware modeling is essential for credible carbon accounting, REDD+ reporting, and science-based sustainability policies. Future work should therefore integrate uncertainty analysis, sensitivity testing, and confidence intervals as standard components of UAV-based biomass estimation workflows.

Third, scaling individual-tree estimates to landscape, regional, and national levels remains a major challenge. Although UAVs provide highly detailed local information, their limited spatial coverage constrains their direct use for large-area monitoring. Future research should prioritize multi-scale and multi-platform integration, combining UAV data with satellite imagery, airborne LiDAR, and national inventory data to support sustainable, cost-efficient upscaling strategies while minimizing uncertainty and redundancy.

Fourth, the long-term sustainability of UAV-based monitoring itself requires further consideration. Relatively few studies exploit the full potential of multi-temporal UAV datasets to assess biomass dynamics, forest degradation, restoration success, or adaptive management outcomes over time. Future research should emphasize longitudinal monitoring approaches that link UAV-derived biomass and volume changes to ecosystem services, disturbance regimes, and climate adaptation strategies.

Fifth, while machine learning and deep learning techniques have significantly improved canopy segmentation and biomass modeling, their dependence on large, labeled training datasets raises concerns regarding reproducibility, transparency, and transferability. Future directions should include the development of data-efficient, interpretable, and transferable models that can operate across regions and species, thereby enhancing their contribution to sustainable decision-making and reducing the environmental and computational footprint of model training.

Finally, the integration of UAV-based biomass and volume estimation into operational management and policy frameworks remains limited. Bridging the gap between research and practice will require closer collaboration among scientists, forest managers, policymakers, and local stakeholders. Future studies should explicitly link UAV-derived indicators to sustainability metrics, ecosystem service valuation, and policy-relevant reporting frameworks, ensuring that technological advances translate into tangible benefits for sustainable land management, climate mitigation, and societal well-being.

Addressing these gaps will be critical for advancing UAV-based biomass and volume estimation from a predominantly research-oriented tool to a robust, operational component of sustainable environmental monitoring systems worldwide.

5. Conclusions

This review demonstrates that UAV-based remote sensing has evolved from experimental photogrammetric applications into a mature and versatile framework for estimating tree biomass and volume across forest, agricultural, and urban ecosystems. Beyond merely replicating traditional field-based measurements, UAV methodologies increasingly provide new structural insights at the individual-tree level, enabling more efficient, spatially explicit, and environmentally sustainable monitoring strategies.

A key synthesis emerging from the reviewed literature is that tree height, crown geometry, and three-dimensional canopy volume consistently represent the most robust predictors of biomass and volume, regardless of ecosystem type. Approaches that explicitly exploit three-dimensional structure—through canopy height models, point clouds, or multi-view reconstruction—outperform methods relying solely on spectral information. While UAV-based photogrammetry can achieve accuracies comparable to LiDAR under optimized conditions, the highest and most stable performance is obtained through multi-sensor frameworks that combine structural and spectral information, particularly in dense, heterogeneous, or high-biomass environments.

The review also highlights a clear methodological transition toward learning-based and geometry-aware models. Machine learning and deep learning approaches substantially improve crown delineation, individual tree detection, and biomass estimation, especially when canopy overlap or irregular crown shapes limit rule-based methods. However, increased model complexity does not universally translate into better performance. Several studies demonstrate that carefully optimized photogrammetric workflows and parsimonious models can achieve competitive accuracy, underscoring the importance of aligning methodological choices with application scale, forest structure, and operational constraints.

From a sustainability perspective, UAV-based biomass and volume estimation offers significant advantages by reducing field effort, minimizing ecological disturbance, and enabling frequent, repeatable measurements. These capabilities are particularly valuable for monitoring biomass dynamics, assessing carbon stocks, and supporting climate mitigation initiatives such as REDD+ and urban green infrastructure planning. Nevertheless, the review reveals persistent challenges that limit large-scale operational adoption.

Four priority research directions emerge from the synthesized evidence:

1. Methodological standardization: There is a critical need for harmonized protocols covering UAV data acquisition, processing, and modeling to improve reproducibility and comparability across studies and regions.
2. Uncertainty-aware modeling: Future studies should systematically quantify uncertainty and error propagation from individual-tree detection through biomass estimation, particularly for applications in carbon accounting and policy reporting.
3. Scalability and integration: Bridging the gap between local UAV surveys and regional or national biomass assessments requires tighter integration with satellite imagery, airborne LiDAR, and forest inventory data.
4. Ecosystem representativeness: Complex, biodiversity-rich forests—such as mixed broadleaved and tropical systems—remain underrepresented and should become a focal point of future UAV-based biomass research.

In conclusion, UAV remote sensing has become a key enabling technology for sustainable biomass and volume estimation. Its greatest potential lies not in replacing existing methods, but in complementing and enhancing multi-scale monitoring frameworks, thereby supporting evidence-based forest management, sustainable agriculture, and long-term ecosystem stewardship.

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