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Comparison of UAV and Satellite Remote Sensing in Forest Biomass Estimation

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Abstract. Accurate estimation of forest biomass is crucial to research on the global carbon cycle. This review systematically reviews the application progress of Unmanned Aerial Vehicles (UAVs) and satellite remote sensing in this field in the past 5-10 years, and compares and analyzes the technical characteristics of two types of data sources: UAV Red-Green-Blue (RGB), multispectral, LiDAR and satellite multispectral, Synthetic Aperture Radar (SAR), etc. in terms of spatial resolution, timeliness, cost, etc. At the same time, it focuses on summarizing biomass estimation methods based on feature extraction and machine learning, including the applicability and accuracy of advanced algorithms such as random forests, support vector machines, and deep learning on different platforms, covering the development process from empirical models to intelligent algorithms. Research points out that the current field faces core challenges such as insufficient multi-source data fusion, prominent scale conversion problems, and weak model generalization capabilities. In the future, it is necessary to further develop collaborative observation technology and intelligent algorithms, strengthen multi-source data fusion and cross-scale modeling, provide support for achieving accurate and cross-scale forest carbon monitoring, and also provide a theoretical basis and practical reference for precise monitoring and management of forest resources.

Keywords: UAV remote sensing, satellite remote sensing, forest biomass, data fusion, model generalization

1. Introduction

Forests are the core of terrestrial ecosystems, and accurate estimation of their biomass is crucial for assessing carbon stocks and combating climate change [1]. Although traditional ground measurement methods have high accuracy, they are time-consuming and labor-intensive and difficult to apply to large areas [2].

Remote sensing technology provides an effective solution for this. Among them, satellite remote sensing (such as Landsat, Sentinel series) has become the cornerstone of large-scale forest monitoring due to its wide-area coverage capabilities. The global forest change data set constructed by Potapov et al. using Landsat data is a reflection of its macro-monitoring capabilities [3]. However, satellite images have limited spatial resolution and are easily affected by weather, leaving obvious deficiencies in fine-scale estimation.

In recent years, Unmanned Aerial Vehicles (UAVs), a remote sensing technology, have brought new breakthroughs in forest parameter estimation with their extremely high spatial resolution and flexible collection capabilities. It can be equipped with a variety of sensors and efficiently obtain centimeter-level forest structure information.

For example, Lei et al. used the L-band dual-station radar interferometry data of the domestic Land-Exploration 1 satellite to successfully invert the three-dimensional vertical structure and tree height of the Hainan tropical rainforest. The height estimation accuracy is about 5 meters and the relative error is only 10%-15%, which provides a new paradigm for the application of satellite remote sensing in the extraction of fine forest parameters [4]. Furthermore, machine learning algorithms (such as random forests, support vector machines, etc.) are widely used to estimate biomass from remote sensing features. The Large Vision Foundation Model (LVFM)-based method proposed by Huang et al. generates a high-precision canopy height map (CHM) from sub-meter-level satellite images. The coefficient of determination (R^2) of pixel-level tree height estimation reaches 0.78, and the biomass estimation results based on this CHM are highly consistent with the lidar reference value, fully verifying the applicability of machine learning in complex scenarios [5].

Although UAVs and satellite remote sensing have complementary advantages, current research mostly separates the two. UAV data coverage is small and difficult to directly extend to areas, while satellite data lacks accuracy in complex terrain. Therefore, how to collaboratively utilize the two types of data to achieve complementary advantages has become the focus and difficulty of current research. White et al. pointed out that multi-platform data fusion is the key to improving forest inventory capabilities, but there is still a lack of a universal technical framework [6]. At the same time, how to effectively apply the fine model developed based on UAV data to the satellite scale, that is, the generalization problem of the model, also poses a major challenge.

Therefore, this review aims to systematically summarize the application of UAVs and satellite remote sensing in forest biomass estimation over the past 5-10 years. By comparing the technical characteristics and estimation methods of the two types of data sources, this review focuses on analyzing the research progress and core challenges in data fusion and model generalization, to provide a reference for the accurate monitoring of forest resources.

2. Comparison of the technical characteristics of UAVs and satellite remote sensing

UAV remote sensing uses UAV platforms equipped with sensors such as RGB, multispectral, and LiDAR to fly flexibly at low altitudes and collect forest surface data. Its core principle is to leverage the advantages of close-range observation to capture fine information at the centimeter to meter level, directly or indirectly retrieving forest structure parameters, making it suitable for precise small-scale detection.

Satellite remote sensing uses satellites (such as the Landsat and Sentinel series) operating in Earth orbit, carrying multispectral and SAR sensors, to receive electromagnetic wave signals reflected or scattered by ground objects. Its principle is to leverage the global coverage and fixed orbital operation of satellites to achieve large-scale, periodic forest monitoring, providing data support for biomass assessments at regional to global scales.

Due to their different design intentions, operating modes, and cost structures, UAVs and satellite remote sensing platforms exhibit distinct technical characteristics in forest biomass estimation applications, forming a complementary relationship [6]. Their core differences are summarized in Table 1.

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Table 1. Comparison of technical characteristics of UAVs and satellite remote sensing in forest biomass estimation

Feature Dimension	UAV remote sensing	Satellite remote sensing
Spatial resolution	Extremely high resolution (centimeter-meter level) for detailed depiction of single-wood structures	Low-resolution (10 meters-kilometers), suitable for community or landscape scales
Coverage area	Limited application, suitable for small areas and specific sample plots	Wide-range, enabling seamless monitoring from regional to global scales
Revisit cycle	Flexible on demand, not limited by tracks	Fixed-range (several days to tens of days), beneficial for time-series analysis
Data cost	Low initial equipment investment, but high manpower cost per flight	Data acquisition is free or low-cost (e.g., Sentinel, Landsat)
Weather dependence	Can fly below clouds, highly resistant to weather interference	Severely affected by weather conditions such as clouds, rain, and snow
Main data source	RGB imagery, multispectral, hyperspectral, LiDAR point clouds	Multispectral imagery (e.g., Sentinel-2, Landsat 8/9), SAR

In summary, UAV platforms have an absolute advantage in terms of spatial resolution, data flexibility, and cloud-based operation capabilities, making them very suitable for accurate biomass estimation at the plot scale, algorithm model development, and providing ground validation for satellite remote sensing products. The core advantage of satellite platforms lies in their macroscopic coverage and fixed revisit cycle, making them an irreplaceable tool for dynamic monitoring and assessment of large-scale forest carbon storage [3]. The choice of platform depends on the specific research scale, accuracy requirements, and budget constraints.

3. Major remote sensing data sources and their information dimensions in biomass estimation

Different sensor data provide different dimensions of information reflecting forest structure and physiological state, which are the basis for driving biomass estimation models.

3.1. Optical image data

Optical images (including RGB, multispectral, and hyperspectral) primarily use vegetation indices (such as Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), etc.) to infer the canopy chemical and physiological properties of forests, such as leaf area index and chlorophyll content, and thus indirectly estimate biomass.

The UAV platform can acquire ultra-high resolution images with centimeter-level resolution (such as 7.6 cm ground sampling distance), which is sufficient to distinguish the crown width of a single tree or even large branches, providing the possibility for single tree segmentation and crown width extraction [7]. The photogrammetric canopy height model (photo-CHM) generated based on the image can estimate the height of a single tree with a root mean square error (RMSE) as low as 1.04 m (relative error 4.7%), a stand dominance overestimation RMSE of 1.65 m (relative error 8.4%), and a correlation coefficient with the lidar canopy height model (LiDAR-CHM) as high as 0.96 [7]. Its multispectral data can more accurately calculate vegetation indices and reduce the impact of mixed pixels. In contrast, satellite platforms such as Sentinel-2 provide multispectral data

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with a resolution of 10 meters, enabling continuous monitoring of forest health over a wider area with higher spatial resolution, but their estimation accuracy tends to saturate in dense forests.

3.2. Active remote sensing data

Active remote sensing technologies, especially lidar and synthetic aperture radar, can directly perceive the three-dimensional vertical structure information of forests and have a stronger correlation with biophysical quantities, thus becoming the mainstream data source for biomass estimation.

Among them, lidar includes drone LiDAR and satellite LiDAR. LiDAR drones, by emitting high-density laser pulses, can penetrate the canopy and directly and accurately measure structural parameters such as tree height, canopy volume, and canopy density. These parameters, along with empirical or theoretical models established for biomass, have high accuracy and are widely considered the "gold standard" for estimating aboveground biomass. However, the LiDAR drone is limited by its endurance (the flight time is usually around 40 minutes), and the effective detection range of a single flight is usually only a few square kilometers (for example, some models can cover about 200 hectares in a single flight), making it difficult to quickly cover a large area [7]. Moreover, the high-density laser pulse data is extremely large, and the subsequent data processing procedures, such as point cloud denoising, filtering, and single tree segmentation, are complex, requiring professional software and technical personnel to operate, which is time-consuming and requires high computing power. At the same time, in dense primeval forests, laser pulses are easily completely blocked by the upper canopy, making it difficult to penetrate to the understory to obtain topographic and understory vegetation data, which may lead to errors in the estimation of understory biomass.

Satellite LiDAR, such as ICESat-2/ATLAS, has a footprint of 12 m, a point spacing of 0.7 m along the orbit, a beam spacing of 90 m between the inner beams and 3.3 km between the outer beams across the orbit, and provides forest height products from global sampling. However, its footprint is discrete, and its coverage is discontinuous. It is usually not used as a direct data source, but rather for building regional models or validating other satellite products [4]. Satellite SAR, a type of synthetic aperture radar, is a crucial data source unique to satellite platforms. Its long-wave signals (such as the L-band) have strong penetrating power, and their backscattering intensity is positively correlated with forest biomass before reaching saturation, making it crucial for large-scale forest biomass mapping in cloudy and rainy regions. However, the signal is susceptible to topography and humidity, and exhibits a significant saturation phenomenon.

It is worth noting that Lei et al. innovatively used spaceborne L-band dual-station single-polarization, single-baseline radar interferometry technology to break through the traditional SAR's dependence on multi-polarization and multi-baseline, and realized the synchronous inversion of forest vertical profile, understory topography, and tree height [4]. The tree height retrieved by this technology is about 5 m in tropical forests with a height of up to 45 m (relative error of 10% - 15%). The deviation between the retrieved digital terrain model (DTM) and the airborne lidar DTM is negligible. The uncertainty varies with the terrain slope: 3 m when the slope is <2°, 4 m when the slope is 2° - 6°, 7 m when the slope is 6° - 25°, and 9 m when the slope is >25°. Finally, a parameter distribution map of the Hainan tropical rainforest covering 27,400 square kilometers was generated, providing a new low-cost and high-precision solution for large-scale active remote sensing monitoring [4].

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4. Main methods for forest biomass estimation

From remote sensing data to biomass estimation, the development has mainly progressed from empirical statistical models to modern machine learning models.

4.1. Parametric regression and empirical models

Early studies relied primarily on parametric regression models, which establish linear or nonlinear mathematical relationships between remote sensing observations and field-measured biomass.

First, vegetation index models establish a regression relationship between optical vegetation indices such as NDVI and biomass. While simple, these models are prone to saturation and exhibit significant underestimation in forests with high biomass. Second, linear and power-law models are primarily applied to active remote sensing data. For example, power-law regression models are established using canopy height indicators (such as height quantiles) extracted from LiDAR and biomass. These models are robust within the data range but have limited generalization ability.

In recent years, the combination of traditional empirical models and multi-source data fusion has become a new trend. For example, Su Di et al. constructed a forest stock estimation model based on UAV aerial survey point cloud data and integrated eight feature factors, such as the number of tree crowns, average tree height, and slope aspect, through partial least squares regression. This model effectively solved the problem of multicollinearity of independent variables and provided a practical reference for improving the accuracy of empirical models [8].

4.2. Machine learning and deep learning models

With the diversification of data sources and the improvement of computing power, machine learning and deep learning models have become the mainstream methods for forest biomass estimation due to their powerful nonlinear fitting and high-dimensional feature processing capabilities.

First, traditional machine learning algorithms, such as random forests and support vector machines, excel at integrating multi-source features (e.g., combining optical vegetation indexes with LiDAR height metrics). They can automatically assess feature importance and are somewhat resistant to overfitting. These methods reduce reliance on prior physical models, but their performance still largely depends on the quality of manual feature engineering.

Secondly, deep learning models, such as convolutional neural networks (CNNs), can automatically extract deep and abstract features directly from raw remote sensing images (such as orthophotos), achieving end-to-end biomass estimation and reducing information loss. Especially when processing high-resolution drone imagery, CNNs can simultaneously identify the location, crown shape, and texture information of trees, thereby building more accurate estimation models. However, deep learning models typically require a large amount of sample data, and their application and model generalization ability face severe challenges in areas with limited field survey samples in forests.

The CHM generation method based on a pre-trained large visual model (DINOv2) proposed by Huang et al. effectively solves the shortcomings of traditional CNN and Transformer in capturing fine-grained features [5]. The model repairs spatial details through a self-supervised feature enhancement module and combines a lightweight tree height mapping module to achieve high accuracy in artificial forest canopy height estimation with an average absolute error of 0.09 meters and a root mean square error of 0.24 meters. Furthermore, the single tree detection accuracy based

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on this CHM exceeds 90%, providing a new path for the engineering application of deep learning in forest biomass estimation [5].

5. Current challenges and future directions

Despite significant progress made by UAV and satellite remote sensing in forest biomass estimation, a number of key challenges remain in moving towards an operational and precise monitoring system.

5.1. Insufficient depth of multi-source data fusion

Current research mostly focuses on the application or simple comparison of data from a single platform, and an organic fusion system has not yet been formed between UAV and satellite data [6]. Future research should focus on developing more advanced fusion algorithms. For example, high-precision three-dimensional structural information acquired by UAV LiDAR can be used as prior knowledge to correct and optimize inversion models based on satellite data (such as SAR or multispectral data), thereby achieving multi-scale, integrated biomass monitoring that combines "point and surface" data.

The multi-scale biomass measurement framework proposed by Hu et al. provides an important reference for data fusion. This framework integrates multi-source information such as spaceborne lidar, optical imagery (MOD13Q1 EVI), climate data and topographic data, and uses the random forest algorithm to achieve high-precision estimation of global mangrove aboveground biomass (AGB) in 2004 [9]. The 250-meter resolution global mangrove AGB map generated by it shows that the global average AGB density of mangroves is 115.23 Mg/ha (standard deviation 48.89 Mg/ha), and the total reserves are 1.52 Pg. After verification by 342 ground sampling points, the adjusted coefficient of determination R^2 is 0.48 and the root mean square error RMSE is 75.85 Mg/ha [9]. The framework effectively solves the problem of complementarity in spatial coverage and accuracy of different data sources, and in particular overcomes the defects of the discrete footprint of single star-borne lidar and easy saturation of optical images. However, its fusion effect in complex ecosystems such as temperate and cold forests still needs further verification [9].

5.2. Weak model generalization and transfer capabilities

Biomass estimation models developed based on specific regions or forest stand types often show a significant decline in performance when applied to new geographical regions or different forest types [10]. This is mainly due to the differences in the forest structure-spectral relationship under different environments. Future research directions include adapting existing models using transfer learning techniques; building a larger standard sample library covering more forest types; and developing semi-mechanistic models that embed physical mechanisms to enhance their universality.

5.3. Integrated application of new technologies and platforms

Future technological advancements will offer possibilities for further overcoming these challenges. Next-generation lidar sensors (such as single-photon lidar) and higher-resolution synthetic aperture radar missions promise to acquire more detailed global forest structure data from space. Simultaneously, cloud computing platforms have significantly enhanced the ability to process massive amounts of satellite data, providing the computational foundation for validating and running complex biomass estimation models on a macroscopic scale. Integrating UAVs, manned aircraft, and

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different types of satellites (optical, SAR, LiDAR) into a collaborative observation network represents the ultimate vision for achieving high spatiotemporal resolution global forest carbon monitoring.

6. Conclusions

This review systematically summarizes and compares the technological applications, data characteristics, and methodological evolution of UAVs and satellite remote sensing in forest biomass estimation over the past 5-10 years. From a technical perspective, drones, with their ultra-high spatial resolution of centimeters to meters, on-demand revisit capabilities, and cloud-based operation capabilities, have become the core tool for fine-grained observation at the plot scale, model development, and satellite product verification. Satellite remote sensing, with its advantages of coverage of 10 meters to kilometers, fixed-time observation, and low cost, supports dynamic monitoring of carbon storage at regional to global scales. The two complement each other rather than replace each other in key characteristics. In terms of data application, RGB, multispectral, and LiDAR data from UAVs and multispectral and SAR data from satellites provide key information from fine structure and macro pattern, respectively. Among them, active remote sensing data such as LiDAR and spaceborne L-band SAR have become core data sources for improving estimation accuracy because they can capture the three-dimensional structure of forests. The estimation methods have gradually evolved from early linear and power-law empirical models to traditional machine learning algorithms such as random forests, and then to deep learning methods based on CNN and large visual models. By optimizing the feature extraction method, the accuracy and efficiency of biomass inversion have been significantly improved.

However, development in this field remains limited by the depth of multi-source data fusion and the generalization ability of estimation models. Future research should focus on establishing data links between drones and satellites, developing robust estimation models across regions and forest types, and actively embracing emerging remote sensing technologies and computing platforms. Through a multi-platform collaborative approach, remote sensing technology is expected to provide stronger and more reliable technical support for the dynamic monitoring and assessment of global forest carbon sinks.

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