Estimation of Forest Stereoscopic Above-ground Biomass Based on Airborne LiDAR in Daxing'anling, China

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1.Introduction

Optical remote sensing has been extensively utilized in estimating Above-Ground Biomass (AGB) across large regional scales and over extended time series due to its extensive coverage and multi-temporal consistency. The fundamental approach involves deriving pertinent forest characteristic indices from spectral information, texture information, and vegetation indices, and subsequently establishing either linear or nonlinear correlations with measured biomass data (Dube et al., 2015; Ou et al., 2019). This methodology facilitates dynamic monitoring of forest resources at varying scales. However, it is susceptible to external environmental factors and encounters saturation issues in complex vegetation cover, leading to inaccuracies in estimation (Lu et al., 2016).

Utilizing medium-resolution multi-spectral Landsat 8 Operational Land Imager (OLI) imagery, Dube et al. (2015) applied machine learning algorithms to estimate AGB for plantation forests based on spectral bands, spectral vegetation indices, and combinations of these feature variables. Notably, the model incorporating both spectral bands and vegetation indices demonstrated the highest estimation accuracy. When compared with Landsat 7 data, Landsat 8 exhibited superior estimation accuracy in the South African basin, with an R^2 value of 0.42. Nevertheless, in densely vegetated areas, as AGB and vegetation coverage increase, the sensitivity and accuracy of optical sensors diminish significantly, a phenomenon known as saturation, which results in a decline in the precision of AGB estimation using optical remote sensing data (Houghton et al., 2009).

By actively emitting laser pulses and receiving echo signals, Light Detection and Ranging (LiDAR) technology can obtain high-precision distance information for the target and operates continuously throughout the day. Owing to its penetration capabilities, LiDAR holds significant advantages in acquiring high-precision vertical structural information on forest height and vegetation (Ni et al., 2014; Jiang et al., 2020; Lian et al., 2021; Brede et al., 2022). It is one of the most frequently employed methods for accurately estimating above-ground biomass (Beland et al., 2019). To investigate the impact of stratified and non-stratified forest types and stand structures on AGB estimation, Jiang et al. (2020) developed stratified and non-stratified AGB estimation models based on subtropical forest LiDAR and field survey data using linear regression and random forest methodologies. The findings indicate that appropriate stratification can enhance the accuracy of AGB estimation, albeit necessitating a larger volume of sample site data. The optimal stratification method employed in the study achieved an R^2 value of 0.8. Furthermore, the integration of LiDAR data with multispectral data can further improve the accuracy of AGB estimation.

Currently, the estimation of AGB utilizing optical remote sensing data or LiDAR data primarily relies on the AGB plane density associated with individual pixels, expressed in units such as "ton/hectare (t/ha)" or "gram/square meter (g/m^2)", which is subsequently multiplied by the pixel area to derive the pixel-level AGB. This approach incorporates ground sample observations and pixel-by-pixel regional monitoring. However, this planar density metric solely captures variations in AGB distribution across a two-dimensional plane, failing to account for differences in vertical structure, thereby limiting further enhancements in the accuracy of forest AGB estimation.

Addressing these limitations, this research introduces a novel forest AGB estimation methodology, termed "stereoscopic density × volume," which incorporates measurable canopy height information, encompassing arithmetic mean height, weighted average height at breast height, and weighted average canopy height (Huang et al., 2022). Specifically, the traditional AGB plane density unit (t/ha) is transformed into a stereoscopic density unit (t/ha/m), thereby supplementing vertical AGB information. This transformation aims to mitigate the underestimation of AGB due to height discrepancies in optical remote sensing data, ultimately striving to enhance the precision of forest AGB estimation.

2.Methodology

In accordance with our previously established conventional methodology (Fu et al., 2017), we initially employed the allometric growth equation to derive the AGB of the sampled plots, utilizing tree species, diameter at breast height (DBH), and tree height data collected from ground surveys. This AGB value was then divided by the product of the plot dimensions to ascertain the AGB plane density (t/ha). Additionally, LiDAR point cloud data from these plots was leveraged to extract forest feature parameters at the stand level. A stepwise linear regression analysis was conducted, leading to the development of a plot-scale forest AGB plane regression model. This regression model, in conjunction with airborne LiDAR data, was utilized to extract forest characteristic parameters on a grid basis, enabling the calculation of AGB across the flight area and the subsequent generation of an AGB plane density distribution map.

Subsequently, by dividing the aforementioned AGB plane density by various canopy height data, we obtained AGB three-dimensional density values stratified by height. A stepwise linear regression analysis was performed with plot-based forest characteristic parameters to assess their relationship with this stratified AGB density. Concurrently, canopy height data and plot-based forest characteristic parameters were also analyzed through stepwise linear regression. Airborne LiDAR data was once again used to extract grid-based forest feature parameters, and an AGB stereodensity regression model was applied to compute the AGB stereodensity (t/ha/m) within the flight area. This stereodensity value was multiplied by height information (m) derived from the canopy height regression model, yielding a distribution map of forest AGB stereoscopic monitoring results stratified by different mean heights (t/ha). The applicability of the AGB plane monitoring method, the stereo monitoring method, and canopy height data was compared using R^2 and RMSE indices.

Utilizing the ChinaCover2015 dataset, a forest area mask was created for the Greater Khingan Mountains research area. Based on high-precision AGB stereodensity data derived from airborne laser radar flight areas and incorporating canopy height information, we integrated terrain factor bands, vegetation indices, and Landsat 8 multispectral data. Linear regression analysis was conducted, resulting in the construction of multiple mean height AGB stereodensity estimation models at the regional scale. Optimal mean height and its corresponding stereodensity estimation model were selected based on R^2, RMSE, rRMSE, NRMSE, and other metrics. The AGB stereodensity was calculated and multiplied by the canopy height dataset to ascertain optimal canopy height information, ultimately yielding a regional-scale AGB density map for the Greater Khingan Mountains. This map was independently evaluated and verified against AGB plane estimation results, allowing for an assessment of the accuracy and effectiveness of the three-dimensional methodology.

3.Result

The primary findings and conclusions of this study are delineated as follows:

(1) The monitoring outcomes of the AGB model on a quadrilateral scale indicate that the precision of the AGB stereo monitoring technique, which relies on the arithmetic mean height (R^2=0.835), slightly surpasses that of the planar monitoring approach (R^2=0.832). Within the context of the quadrilateral scale, the stereo method does not appreciably enhance monitoring accuracy, as the forest parameters derived from airborne Lidar point cloud data exhibit a strong correlation with AGB. Both methodologies are efficacious in monitoring AGB.

(2) Utilizing the monitoring results obtained on the flight area scale, in conjunction with terrain factors, spectral bands, and vegetation indices, estimation models for both methods were formulated. The results reveal that the accuracy of the AGB stereo estimation based on the arithmetic mean height (R^2=0.549) is notably superior to that of the planar estimation (R^2=0.475). An independent accuracy verification, employing 98 ground survey data points from Daxing'anling research area, demonstrates that the validation accuracy of the stereo AGB estimation based on the arithmetic mean height (R^2=0.4595) is significantly better than that of the traditional planar AGB estimation (R^2=0.3619).

(3) An analysis of the disparities between the stereo and planar AGB estimation results, alongside an examination of the gradient, forest height gradient, and forest type, reveals that as forest height increases, AGB also augments. The planar estimation results are markedly lower than those of the stereo estimation, yet no discernible correlation with forest type is observed. The stereo estimation method transforms planar density into stereo density, building upon the planar estimation method, thereby enriching the information pertaining to the vertical structure of the forest. Consequently, it can substantially mitigate the underestimation of AGB due to variations in forest height in traditional planar estimation methods, thereby effectively enhancing estimation accuracy.

4. Discussion

This study introduces an innovative stereo forest AGB estimation model, which exhibits superior applicability in Daxing'anling compared to the conventional planar estimation model. In the research process, the arithmetic mean height was selected as the optimal mean height, balancing estimation accuracy and data accessibility. Future research should consider alternative, more effective methods for acquiring height information data to further refine accuracy. Given the relatively simple vegetation in Daxing'anling, the applicability and portability of this method in other regions, such as subtropical areas, merit further investigation. Additionally, the integration of multi-temporal and multi-spectral remote sensing data into the stereo estimation model can facilitate the acquisition of high-precision, long-term forest AGB dynamic mapping, offering a novel methodology and perspective for monitoring forest dynamics and assessing forest carbon sequestration capacity.

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