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Assessment of the Effectiveness of a Forest Biomass Estimation Approach Integrating Airborne LiDAR and Satellite Data

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Abstract: Accurate forest stem biomass is crucial for sustaining forest management. Recently launched Sentinel imagery offers a new opportunity for forest stem biomass mapping and monitoring. The purpose of this study was to assess the potential for estimating important parameters of forest stands with satellite and LiDAR (Light Detection and Ranging) data. We explored the relationship between forest stem biomass and LiDAR and satellite data using regression analysis. The stem biomass was indirectly estimated from tree height using allometric equations. Multispectral bands and vegetation indices of Sentinel-2, based on about 35 estimated forest stem biomass in the Izu Peninsula of Shizuoka Prefecture, were used to develop biomass prediction models through regression analysis. The results showed that the normalized difference vegetation index (NDVI) was a weak predictor for the forest stem biomass. This is likely attributable to 1) since the aerial laser survey was conducted in early March, it is the time when the deciduous trees are not foliage, Future work includes comparison with the Forestry Agency's Forest Group Map and the selection of data such as evergreen coniferous plantations, 2) the estimation formula is improved by using the trunk biomass as an input variable not only for the tree height but also for the canopy area, 3) the forest number will be increased across the eastern side of the Izu Peninsula and the southern foot of Mt. Fuji. The study was a proof-of-concept research effort and demonstrated encouraging results using freely accessible, high-resolution Sentinel imagery and LiDAR point clouds.

Key Words: Izu Peninsula, LiDAR, regression analysis, satellite, Sentinel-2

1. Introduction

In the forestry sector, concerns have been raised regarding the decline in the number of workers and the deterioration of the available labor force. Meanwhile, the supply of domestically produced timber has been increasing. In Shizuoka Prefecture, efforts are underway to sustainably expand timber production while maintaining a balanced relationship between supply and demand. However, forestry enterprises face difficulties in formulating species-specific production plans due to the absence of a fully developed, detailed forest database. Addressing this issue will directly contribute to one of Shizuoka Prefecture's key administrative priorities: developing the forestry industry as a growth sector through the cyclical use of forest resources [1].

In recent years, smart forestry has been actively promoted in Japan's forestry administration. There is a negative relationship between the efficiency and accuracy of measurement methods: higher efficiency is associated with lower accuracy, whereas higher accuracy is accompanied by lower efficiency. The levels of efficiency and accuracy required differ across spatial scales, making the selection of appropriate measurement techniques essential for meeting specific objectives. Accordingly, measurement methods are selected across three spatial scales by explicitly considering the required efficiency to achieve practical accuracy. The first scale involves analyzing point cloud data obtained from ground-based laser measurements at the stand scale (several hectares). The second involves analyzing imagery acquired by drones at the forest scale (tens of hectares). The third involves analyzing satellite imagery at the regional scale (several thousand hectares).

In the context of Airborn LiDAR, several approaches to forest measurement have been reported. At the stand-level scale (approximately one ha in extent), studies have estimated mean tree height [2]. For coniferous species with pointed apices, methods have been developed to identify the highest point of each tree crown and to evaluate

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individual tree heights [3]. In addition, techniques for quantifying crown extent, which represents the horizontal spread of individual trees, have been proposed [4].

Satellite imagery–based forest surveying encompasses several categories. These include free but low-resolution products such as Landsat (30 m per pixel) [5]; high-resolution but expensive products such as WorldView-2 and SPOT (0.5 m per pixel) [6][7]; and medium-resolution products that are available at no cost. For example, Sentinel-2 provides free medium-resolution imagery (10 m per pixel) [8]. The present study addresses the estimation of forest stem biomass at a regional scale (several thousand hectares) using satellite imagery. To this end, individual-tree heights were assessed by identifying the highest points of tree crowns, and medium-resolution (10 per /pixel) free Sentinel-2 imagery was employed.

Shizuoka Prefecture has been implementing airborn LiDAR surveys, beginning with the Izu Peninsula [9]. These data enable relatively accurate evaluations of tree height at the individual-tree level across extensive forested areas. However, the following survey schedule remains undecided due to high operational costs, making it impossible to monitor continuous tree growth. In this study, a quantitative relationship is established between forest stand biomass derived from airborn LiDAR and indices obtained from Satellite imagery. Once this relationship is established, continuous acquisition of Satellite imagery enables the estimation of forest stand biomass at regional scales (on the order of several thousand hectares), enabling consistent large-area monitoring.

2. Methods

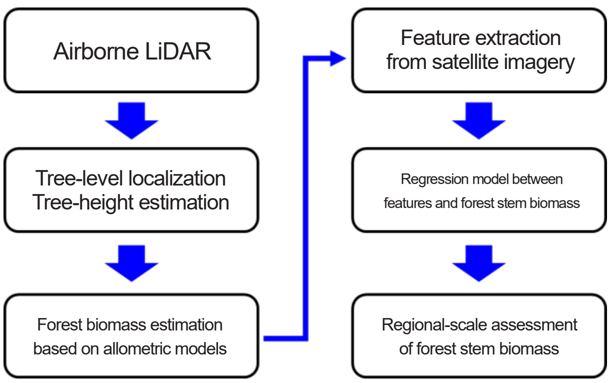

Fig. 1 Overview of the methodological workflow

2.1 Airborne LiDAR

Shizuoka Prefecture has publicly released its airborne LiDAR point cloud database and actively promotes its utilization. In particular, the southeastern area of Mt. Fuji and the eastern region of the Izu Peninsula have been prioritized in data acquisition and development [10]. In the present analysis, a total of 38 horizontally aligned mesh units forming a straight transect from Shuzenji in Izu City to the central district of Ito City were examined in their entirety. Each mesh unit is a 350-m square, corresponding to an area of 12.2 ha (Fig. 2). When the LiDAR point cloud data are processed using dedicated software (LiDAR 360), the output appears as shown in Fig. 3.

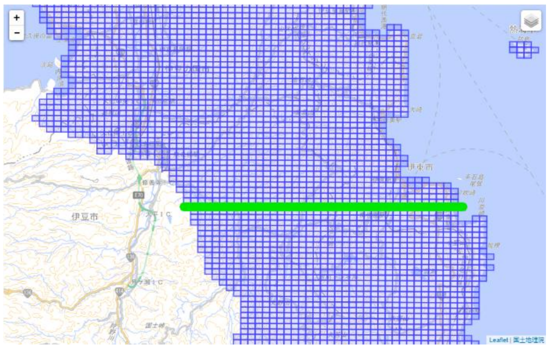

Fig. 2 The straight line connecting Shuzenji in Izu City and the central district of Ito City
A total of 38 horizontally arranged mesh units

Fig. 3 Point cloud data represented in LiDAR 360 software

Processing of the following LiDAR point cloud data was conducted using LiDAR360. The LAS files are designed to contain LiDAR point data records and generally integrate GPS, IMU, and laser pulse range measurements to generate X, Y, and Z point data.

Data preprocessing was conducted as follows. Point cloud data typically requires preprocessing before calculating forest metrics. The preprocessing procedures consisted of outlier removal, ground point classification, and data normalization. Normalization was applied to eliminate terrain's influence on point elevations, thereby providing a consistent basis for computing forest indices.

Outliers represent a common form of noise within airborne LiDAR datasets. High-level outliers typically arise from returns generated by high-altitude objects encountered during the data acquisition process (e.g., birds or aircraft). Low-level outliers correspond to returns produced at extremely low elevations due to multipath effects of laser pulses. These outliers were removed prior to subsequent analyses.

2.2 Individual tree positioning and tree height assessment

Estimation of forest stem biomass using airborne LiDAR was conducted as follows. Height points were extracted by computing the difference between the digital elevation model (DEM), derived from ground points, and the digital surface model (DSM), derived from laser returns from tree crowns. The maximum values at these height points were considered tree apices, enabling the identification of individual trees and the evaluation of tree height. To extract attributes of individual trees—such as spatial location, height, and canopy diameter—clusters of points representing trees in the point cloud data were segmented into individual tree units (Fig. 4). This regional segmentation process allowed separation of contacting objects, thereby facilitating the identification of each tree and the retrieval of its positional and height attributes.

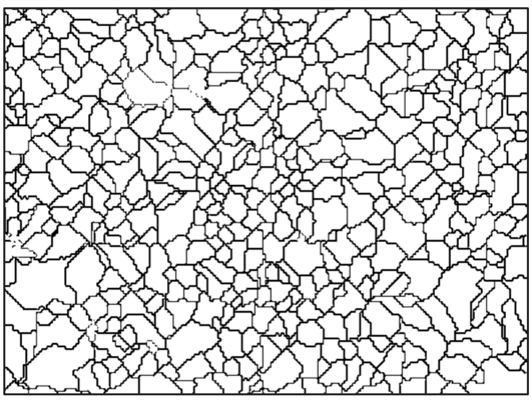

Fig. 4 Segmentation of individual trees

2.3 Assessment of forest stem biomass using an Allometric equation

An allometric equation for estimating individual stem biomass (M) from stem diameter and tree height has been reported [11], as follows:

$$M = \alpha \cdot (D^2 \cdot H)^{\beta}$$

where H denotes tree height, and D represents diameter at breast height (DBH). The symbols α and β denote model parameters. An allometric equation describing the relationship between stem diameter and tree height has been reported [12], as follows:

$$H = \gamma \cdot D^{\varepsilon}$$

where γ and ε are parameters. From these two equations, the following expression can be derived.

$$M = \alpha \cdot \left(\frac{H}{\gamma}\right)^{\frac{2\beta}{\varepsilon}} \cdot H^{\beta}$$

This procedure enables the estimation of stem biomass from tree height. Following the assessment of individual tree heights using airborne LiDAR, the estimated heights were substituted into the allometric equation for stem biomass, after which the stem biomass of each tree was aggregated and subsequently converted to a value per unit forest area.

2.4 Feature extraction from satellite imagery

The acquisition and processing of satellite imagery were conducted using Tellus, a cloud-based platform that enables the integration and analysis of satellite and ground-based datasets [13]. Tellus is a Japan-originated satellite data platform that is both open and free, and it aggregates data from around the world, including information obtained from satellites. The platform is also being advanced as part of national initiatives to promote the utilization of governmental satellite data.

Satellite imagery with a 10 m spatial resolution acquired from Sentinel-2 [14] was used. Sentinel-2 is one of the satellites launched by the European Space Agency, and its observational data are publicly available at no cost. First, the imagery corresponding to the area of interest was obtained. In a Jupyter Notebook environment, Python was used to access the Sentinel-2 dataset via its API. The analysis incorporated folium for geospatial visualization, geopandas—an extension of pandas suitable for handling satellite imagery—and rasterio, which is effective for applying mask operations and other raster-based processing. Airborne laser scanning was conducted in March 2020. Because this period corresponds to the season when deciduous broad-leaved trees shed their foliage, satellite imagery was also retrieved for the winter period between 1 January and 31 March 2020. Among the available scenes, the images with the lowest cloud-cover percentage during this period were used for analysis. The study area comprised 38 mesh units, identical to those used in the airborne laser-scanning survey.

Satellite imagery is not immediately available for analysis upon acquisition by artificial satellites; instead, multiple preprocessing procedures are implemented. One such procedure is the conversion to surface reflectance. Because top-of-atmosphere radiance varies depending on differences in solar irradiance and illumination geometry, surface reflectance—defined as the ratio of satellite-observed radiance to solar irradiance—is incorporated to minimize these effects. Among the spectral bands, surface reflectance data for the visible red, green, and blue bands, each with a 10 m/pixel spatial resolution, were used to generate an RGB composite image. In addition, surface reflectance data for the visible red and near-infrared bands were used to calculate the normalized difference vegetation index (NDVI).

$$\mathrm{NDVI} = \frac{NIR - R}{NIR + R}$$

where *NIR* and *R* denote the surface reflectance data of near-infrared (Band 8) and visible red (Band 4), respectively, the NDVI, which is widely employed in the field of remote sensing, is an indicator based on the characteristic spectral response whereby areas with greater vegetation abundance exhibit higher near-infrared reflectance and lower visible-red reflectance. Consequently, NDVI values are higher in vegetation-rich areas.

2.5 Construction of a regression equation between features and forest stem biomass

Nonlinear simple regression analysis was conducted using NDVI derived from satellite imagery as the independent variable, and stem biomass per unit area estimated from airborne LiDAR and an allometric equation as the dependent variable.

3. Results and Discussion

As a result of the nonlinear regression, the coefficient of determination (R^2) was 0.32, indicating a weak functional relationship. This outcome suggests that stem biomass increases exponentially as NDVI rises. However, the presence of errors implies that additional analysis is required in future investigations.

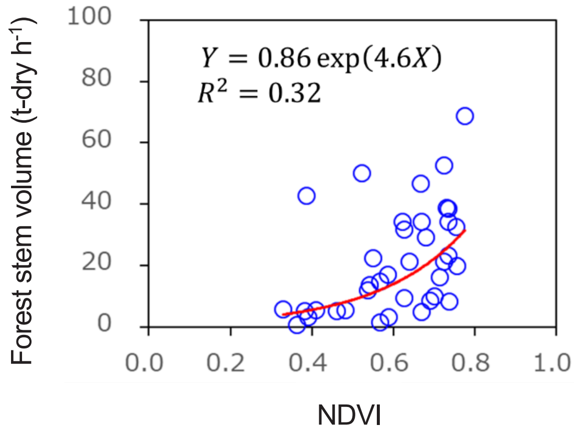

Fig. 5 Relationship between forest stem biomass and the normalized difference vegetation index (NDVI)

The inclusion of errors can be attributed to several factors. Because the airborne LiDAR data were acquired in early March, deciduous broadleaf trees were leafless. In the present analysis, stands containing deciduous species were not distinguished from coniferous plantations, which is considered a significant source of error in the evaluation of tree height. Future work should incorporate stand-type information, for example, by referencing the Forest Management Compartment Maps, to restrict the analysis to Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*) plantations. A second source of error likely arises from the allometric equation used to estimate stem biomass. Refinement of the estimation model is recommended, such as incorporating not only tree height but also crown area as explanatory variables. Finally, expanding the survey meshes to include additional areas on the eastern Izu Peninsula and the southern foothills of

Mt. Fuji will be necessary to increase the number of surveyed coniferous forest stands.

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