Subtropical forest biomass spatio-temporal change analysis: An application of multi-sensor SAR and optical imagery

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ABSTRACT

Forest biomass assessment is a critical element influencing the decisions of stakeholders involved in forest management. In tropical and subtropical biodiversity hotspots, accurate measurement of aboveground biomass (AGB) is crucial for ecosystem sustainability. However, estimating AGB in these forests is challenging due to complex vegetation, necessitating data integration from various sources. Methods for mapping AGB in forest ecosystems have progressed from a destructive sampling approach to non-destructive sampling techniques that utilize allometric models and remotely sensed vegetation variables (Muhe and Argaw, 2022). Remote sensing platforms, including active and optical sensors, have proven to be effective alternatives for assessing and monitoring AGB across different landscapes and scales (Su et al., 2016). Among the optical sensors, Sentinel-2 with its enhanced spectral band and improved spatial resolution of 10-20 meters, is considered to provide superior opportunities for estimating AGB in subtropical and tropical areas compared to other low-resolution satellite images (Pandit et al., 2018). However, optical sensors face challenges in providing structural information due to their inability to penetrate deeply into the upper canopy layers and their susceptibility to being obstructed by frequent cloud cover (Hyde et al., 2006).

Synthetic Aperture Radar (SAR) provides an innovative approach to minimize the challenges in optical remote sensing. The sensitivity of SAR sensors to forest biomass is dependent on its wavelength. Generally, longer wavelengths penetrate deeper into the forest and are better suited for AGB estimation as they can reach the canopy and interact directly with the trunk (Ouchi, 2013). However, using longer wavelength data can be challenging due to the limited number of operational satellites and the high costs associated with such data. While the Sentinel-1 mission from the European Space Agency (ESA) provides free high-resolution C-band SAR data globally, its limited penetration capability makes it insufficient for forest biomass estimation on its own (Ghosh and Behera, 2018). As a result, researchers commonly combine SAR with optical remote sensing data to achieve more accurate and comprehensive forest biomass measurements (Moghimi et al., 2023).

In this research, we investigated the feasibility of integrating ground-based measurements with multi-sensor SAR and optical remote sensing data to analyze the spatio-temporal changes in biomass within the subtropical forest of Hong Kong, and evaluated our AGB maps through uncertainty analysis, offering insights into the effectiveness of biomass estimation. Random forest (RF) machine learning model was utilized for the AGB mapping. Correlation analysis was conducted to examine the relationship between the measured AGB and radar backscatter polarimetric data, optical reflectance bands, and spectral indices. Recursive Feature Elimination with 5-fold cross-validation (RFECV) was employed to eliminate redundant information in satellite images. Additionally, the gray level co-occurrence matrix (GLCM) method of texture analysis, was employed to extract various texture variables to enhance the discrimination of spatial information regardless of tone whiles minimizing forest structural variations that are not related to biomass.

From the results, Random Forest (RF) model selected from other models demonstrated enhanced accuracy across all evaluated datasets. It achieved the highest performance for the 2023 dataset (R^2 = 0.907, RMSE = 20.479 tons/ha, RRMSE = 0.111 %, MAE = 14.027 tons/ha), followed by the 2022 dataset (R^2 = 0.899, RMSE = 21.319 tons/ha, RRMSE = 0.115 %, MAE = 16.384), and the 2024 dataset (R^2 = 0.860, RMSE = 25.054 tons/ha, RRMSE = 0.136 %, MAE = 18.216 tons/ha). Additionally, RF modeling approach demonstrated fewer deviations with the residuals exhibiting less variability in the AGB predictions. Further analysis identified specific vegetation indices and ALOS-2 PALSAR-2 backscatter combinations such as (HH+HV)_Cor, GNDVI, and NDI45, as influential predictors across all AGB ranges. In contrast, Sentinel-1 radar backscatter predictors demonstrated a weaker impact on biomass prediction. Finally, the regional distribution map of forest biomass generated via RF model revealed that district with significant biomass changes include Tai Po, Islands, Sai Kung, Sha Tin and Yuen Long. In these districts, significant spatial heterogeneity was observed. This research underscores the potential of machine learning approaches in conjunction with satellite remote sensing for mapping the spatio-temporal changes in biomass, offering valuable insights for forest management and conservation efforts nationwide. The findings contribute to the growing field of remote sensing applications in ecological studies and highlight the importance of selecting appropriate predictors for improving model accuracy.

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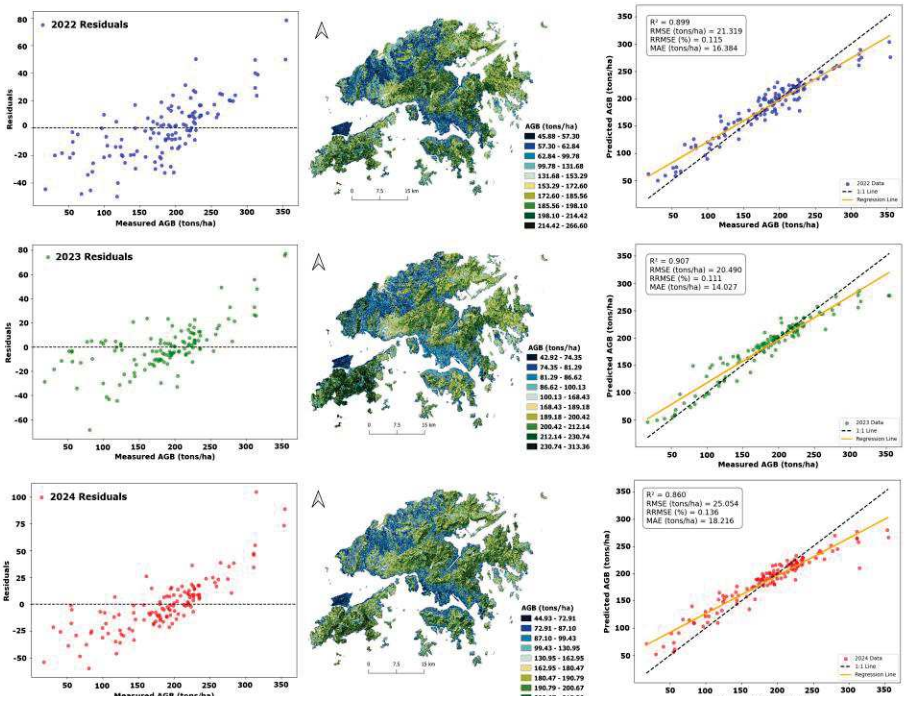

Figure 1. Scatter plot of predicted biomass from 2022, 2023 and 2024 imagery dataset

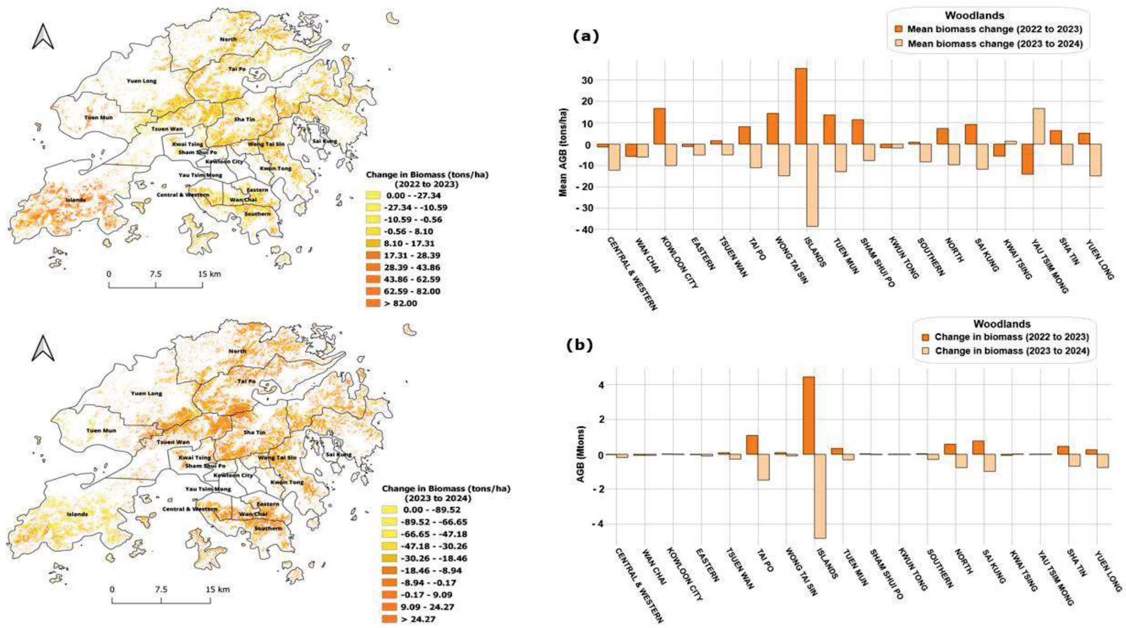

Figure 2. Forest biomass changes from 2022 to 2024

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