Assessing Biomass Dynamics Using Multi-Year Airborne Laser Scanning and Forest Inventory Data

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Accurate and spatially consistent estimation of aboveground biomass (AGB) is a fundamental requirement for forest monitoring, as AGB is a key indicator of forest structure, productivity, carbon storage, and ecosystem functioning. Reliable biomass information underpins a wide range of applications, including the assessment of forest health, the evaluation of management and conservation strategies, and the quantification of carbon stocks and fluxes relevant to climate mitigation and reporting obligations. Despite its importance, consistent AGB estimation remains a major challenge, particularly in regions with heterogeneous forest structure, varying management regimes, and limited ground reference data. These limitations affect key stakeholders, including national park administrations, forest managers, conservation authorities, and institutions involved in carbon accounting and climate policy.

This study presents a scalable and operational workflow that integrates field inventory data and airborne laser scanning (ALS) to generate harmonized AGB maps for the transboundary Bohemian Forest Ecosystem, encompassing the Bavarian Forest National Park (Germany) and Šumava National Park (Czech Republic). The approach directly responds to practical needs for reliable, cross-border biomass monitoring in both protected and managed forests.

A central contribution of the work is the use of an extensive and temporally consistent reference dataset comprising 1,054 forest inventory plots collected in 2024, complemented by additional validation data from both countries. This comprehensive reference base enables robust model calibration and significantly improves the reliability of biomass estimates, addressing a recurring bottleneck in previous remote sensing studies.

Methodologically, field-based AGB estimates from forest inventory plots are upscaled using a suite of ALS-derived structural metrics capturing vertical and horizontal forest structure. These metrics are linked to plot-level biomass observations using convolutional neural networks, enabling robust, non-linear modeling of complex relationships between forest structure and AGB. Model training and validation are based on the extensive and harmonized reference dataset, ensuring spatial consistency across national borders. The trained models are subsequently applied to wall-to-wall ALS data to generate spatially continuous biomass maps. The availability of ALS data from three different acquisition years further enables the quantification of short- to medium-term biomass changes and supports the analysis of structural dynamics and disturbance-driven biomass development across the study area.

Based on the proposed workflow, three spatially consistent AGB maps were generated for the years 2012, 2017, and 2023. These maps allow for a direct comparison of biomass patterns and changes over time and provide clear evidence of spatially differentiated biomass dynamics within the study area. In particular, pronounced biomass losses are visible in the northern part of the Bavarian Forest National Park, reflecting the impact of large-scale bark beetle outbreaks. In contrast, other areas show stable or increasing biomass levels, highlighting differences in disturbance history and management strategies. Figure 1 illustrates the spatial distribution of AGB for the three reference years.

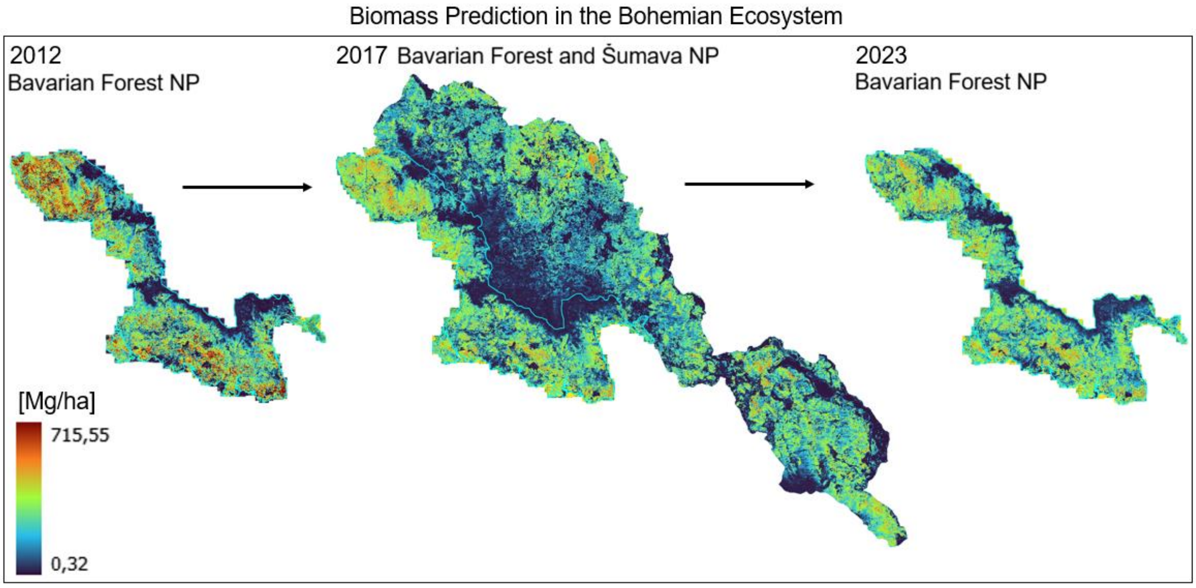

Figure 1: Spatial distribution of aboveground biomass (AGB) in the Bohemian Forest Ecosystem for the years 2012, 2017, and 2023 derived from forest inventory data and airborne laser scanning (ALS). The maps reveal substantial biomass losses in the northern part of the Bavarian Forest National Park, primarily caused by bark beetle disturbances.

The resulting biomass maps provide actionable information for forest management, conservation planning, and the assessment of disturbance impacts and management strategies in intervention and non-intervention areas. Moreover, the ALS-based biomass predictions form a robust reference for the planned transfer to satellite time series data. In this step, temporally consistent satellite observations will be linked to the ALS-derived biomass estimates to train models that enable spatially and temporally continuous AGB mapping beyond the ALS acquisition years. This integration will allow the reconstruction of harmonized, multi-decadal AGB dynamics, including retrospective analyses into the past, thereby supporting the identification of long-term trends in biomass development and disturbance-driven change.

Overall, the proposed strategy demonstrates high practical applicability: it is transferable, scalable across national borders, and directly supports evidence-based decision-making for forest conservation and climate-mitigation planning.