Reducing Tropical Forest Biomass Mapping Uncertainty
– Integrating Field plot data with 3D forest structure from LiDAR

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by

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Abstract

Tropical forests, with their high carbon storage and productivity, are vital to the Earth's carbon cycle. They act as both carbon sinks and sources, with nearly half their carbon stored in tree aboveground biomass (AGB). Therefore, accurate mapping and monitoring of forest AGB is crucial for designing effective carbon emission reduction strategies and gaining a deeper understanding of the dynamics of Earth's carbon cycle.

However, the large-scale AGB maps over Indian region from 1880 to 2021, generated through integration of Earth Observation (EO) and forest inventory plot data, reports markedly divergent AGB estimates despite accounting for reported uncertainties. These discrepancies stem from the inherent challenges involved in scaling up AGB measurements. While plot-level AGB values act as the primary basis for large-scale EO based AGB mapping, these values are estimated rather than directly measured. Consequently, plot-level AGB estimation introduces several uncertainties that cascade and magnify throughout the upscaling process when linked to EO data.

These uncertainties originate from several sources at both plot- and EO-level including (a) measurement errors inherent to field data collection at plot-level, (b) choice of allometric model to convert tree measurements to AGB, (c) plot size limitations and their representativeness across large area, (d) number of sample plots required for upscaling, (e) geolocation inaccuracies when linking field data to EO proxies, (f) saturation of EO signals with increasing biomass, potentially leading to underestimation. Finally, the generated AGB maps should incorporate uncertainty estimates through nested propagation of errors from various originating sources so as to not only develop defensible estimates at regional/national scales but also to enable robust biomass change detection to assess progress towards climate change goals.

This thesis attempts to address the challenges associated with estimating aboveground biomass (AGB) across large spatial scales in tropical Indian forests. It aims to establish a reference workflow or set of protocols to minimize uncertainties inherent in AGB estimations. Under this overarching aim, the objectives of this thesis are divided into four parts. First, the influence of plot size on the accuracy of plot-level AGB estimates was evaluated. Simulated forests plots were generated based on reference plot network (of 1-ha and 32-ha) across diverse Indian forest sites. The results show that relative error in plot-level AGB decreases with increasing plot size. While a 10x10 m plot yielded a 50% error, it significantly reduced to 5% at 70x70 m (0.49 ha) with a minimal reduction in

further increments to plot-size. Hence, 70x70 m was recommended the optimal plot size for reliable AGB estimation in Indian tropical forests.

Second, the most significant source of uncertainty in spatial AGB prediction – the choice of allometric model used to convert tree measurements to biomass is targeted. By using Terrestrial Laser Scanners (TLS), the study develops a method for non-destructively estimating tree volume using 3D point cloud data. Using the non-destructive tree volume from TLS allometric models were developed for central Indian tropical deciduous forests of India. TLS based models showed greater accuracy in estimating tree-level AGB when compared to the traditional allometric models. However at larger plot sizes (1 ha+) the errors have been minimal, highlighting the need for higher plot size in mitigating AGB uncertainty. However, comprehensive error metrics from the allometric model remain crucial for robust large-scale AGB estimation and uncertainty propagation.

Third, the established high-quality ground reference plots (1-ha each) were utilized to create reference AGB maps using Airborne LiDAR (Light Detection and Ranging) data. LiDAR offers 3D forest structure information and is found to directly link biomass estimated on ground to landscape level with high accuracy. For this, data from 13 sites across global tropics were collected and compiled (5 in Asia and 8 in Africa) and produced reference AGB maps by generating site-specific LiDAR-AGB models. Alongside, spatial uncertainty maps were also generated by propagating random errors from various potential sources through Monte Carlo method with 1000 iterations. This approach addresses the critical need for uncertainty propagation in the hierarchical chain of spatial AGB modeling, leading to robust and defensible regional estimates. The generated reference AGB maps were made available on open-access database and serve as valuable calibration and validation datasets for current and future EO missions (GEDI, BIOMASS, NISAR), ultimately enhancing the accuracy and reliability of large-scale AGB mapping initiatives. Finally, the practical application of these maps was demonstrated by using them to evaluate and refine the accuracy of the ongoing global AGB mapping mission using NASA's GEDI spaceborne LiDAR system, specifically over on Indian forests.

In essence, the current work examines the impact of several uncertainties from various ground and EO sources, highlighting the crucial role of high quality reference data at various stages in hierarchical modelling chain of spatial AGB estimation. The study advocates for adhering to best practices outlined by the Committee on Earth Observation Satellites (CEOS) to generate robust reference LiDAR aided reference AGB maps. This enables calibration of EO data and the creation of reliable and defensible regional and national AGB estimates, fulfilling the Intergovernmental Panel on Climate Change's (IPCC) needs for monitoring carbon stocks and fluxes.