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Research Article

USING ARTIFICIAL INTELLIGENCE AND LIDAR DATA FOR HIGH-RESOLUTION FOREST INVENTORY AND ABOVE-GROUND BIOMASS ESTIMATION IN A SUMATRAN RAINFOREST

Nofirman Nofirman[1], Ahmed Shah[2], and Usman Tariq[3]
[1] Universitas Prof. Dr. Hazairin, SH., Bengkulu, Indonesia
[2] Aga Khan University, Pakistan
[3] COMSATS University Islamabad, Pakistan

Corresponding Author:
Nofirman Nofirman,
Department of Geography Education, Faculty of Teacher Training and Education (FKIP), Prof. Dr. Hazairin University, SH., Bengkulu.
Jalan Jenderal Ahmad Yani No 1, Kota Bengkulu, Prov. Bengkulu, Indonesia
Email: nofirman@unihaz.ac.id fir.rimbogiam@gmail.com

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Abstract
Accurate quantification of forest carbon stocks is critical for global climate change mitigation initiatives like REDD+. Traditional forest inventory methods are often labor-intensive, costly, and limited in scale, particularly in complex tropical ecosystems such as the Sumatran rainforest. The integration of advanced remote sensing technologies and artificial intelligence (AI) offers a transformative potential for overcoming these limitations. This study aimed to develop and validate a high-resolution model for individual tree detection and above-ground biomass (AGB) estimation in a Sumatran rainforest by synergizing airborne LiDAR data with machine learning algorithms. High-density LiDAR data was acquired over a 10,000-hectare study area. Concurrently, extensive field inventory data from 150 plots were collected to serve as ground truth. A deep learning model, specifically a Convolutional Neural Network (CNN), was trained to perform individual tree crown delineation (ITCD) from the LiDAR-derived canopy height model. Tree-level metrics were then used as predictors in a Random Forest algorithm to estimate AGB, which was calibrated against field-measured biomass. The CNN model successfully identified individual trees with an accuracy of 92.4%. The subsequent Random Forest model demonstrated high predictive power for AGB estimation, yielding a strong coefficient of determination (= 0.89) and a low Root Mean Square Error (RMSE) of 25.8 Mg/ha. The approach generated a high-resolution (1-meter) AGB map, revealing detailed spatial variations in carbon stock across the landscape. The fusion of AI and LiDAR data provides a highly efficient methodology for forest inventory and AGB mapping in dense tropical rainforests. This approach significantly enhances our capacity to monitor carbon dynamics, forest conservation and climate policy.

Keywords: Above-Ground Biomass, Artificial Intelligence, LiDAR, Forest Inventory, Sumatran Rainforest.

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INTRODUCTION

Tropical rainforests represent a critical component of the global climate system, functioning as the planet's largest terrestrial carbon sinks and hosting an unparalleled level of biodiversity (Kuang et al., 2024). The accurate quantification of their carbon stocks, particularly the above-ground biomass (AGB), is a fundamental prerequisite for the effective implementation of international climate change mitigation policies, including the Paris Agreement and the United Nations' Reducing Emissions from Deforestation and Forest Degradation (REDD+) framework (Müllerová et al., 2023). These initiatives depend on robust, transparent, and verifiable systems for monitoring, reporting, and verification (MRV) of forest carbon. Establishing a precise baseline of forest AGB and tracking its dynamics over time is therefore not merely an academic exercise but a global imperative for climate action and sustainable forest management.

The rainforests of Sumatra, Indonesia, are of particular global significance. They are among the most biodiverse and carbon-dense ecosystems on Earth, yet they are also facing one of the world's highest rates of deforestation due to the expansion of agriculture, illegal logging, and infrastructure development (J. Chen et al., 2024). The complex, multi-layered vertical structure and immense species diversity of these forests make them extraordinarily challenging environments for traditional forest inventory (Latue, Karuna, et al., 2024). The intricate canopy architecture, with overlapping crowns and dense undergrowth, poses significant obstacles to accurate measurement and monitoring, demanding a paradigm shift in the methodologies used for their assessment.

Traditional forest inventory methods, relying on the establishment of ground-based field plots, have long been the gold standard for AGB estimation (Ma et al., 2024). While providing high-accuracy data at the plot level, these methods are inherently limited by their cost, labor intensity, and small spatial footprint (Latue, Pakniany, et al., 2024). Extrapolating plot-level data across vast, heterogeneous landscapes introduces significant uncertainties. In response, the field of forestry has increasingly turned to remote sensing technologies, which offer the potential for large-scale, repeatable observations (Lin, 2024). While optical and radar sensors have contributed valuable insights, Light Detection and Ranging (LiDAR) has emerged as a transformative technology, capable of directly measuring the three-dimensional structure of forest canopies with unprecedented detail.

Despite the advancements offered by LiDAR technology, a significant methodological bottleneck persists in its application within structurally complex tropical rainforests (Blanton et al., 2024). The primary challenge lies in translating the raw three-dimensional point cloud data into accurate, spatially explicit estimates of AGB. Conventional approaches often rely on an area-based approach (ABA), where statistical relationships are developed between LiDAR-derived metrics (e.g., mean canopy height) and plot-level AGB. While effective at a coarse resolution (e.g., one hectare), this method fails to capture the fine-scale heterogeneity of the forest and masks the crucial contribution of individual large trees to total biomass (Basset & Zaldo-Aubanell, 2025). This averaging effect constitutes a major limitation for applications requiring high-resolution carbon mapping and detailed monitoring of forest degradation.

The transition to a more accurate individual tree-based approach (ITA) is contingent upon overcoming the formidable challenge of individual tree crown delineation (ITCD). In the dense, multi-layered canopies of Sumatran rainforests, where tree crowns are highly irregular and frequently interlock, conventional ITCD algorithms (such as watershed segmentation) often perform poorly. These methods typically result in significant errors of omission (merging multiple crowns) or commission (splitting a single crown), which propagate and amplify errors in subsequent AGB estimations (Zhu et al., 2025). The lack of a robust and reliable method for accurate ITCD in such complex environments is a critical problem that hinders the full realization of LiDAR's potential.

This methodological gap creates a fundamental problem for effective forest management and carbon accounting (Rather et al., 2025). Without the ability to accurately inventory individual trees and their biomass at scale, monitoring efforts cannot reliably distinguish between different drivers of forest change, such as selective logging versus complete deforestation. Furthermore, the inability to produce high-resolution, verifiable carbon maps at the landscape scale undermines the transparency and credibility of MRV systems required for performance-based climate finance mechanisms like REDD+ (Latterini et al., 2025). The core problem is the absence of a workflow that is simultaneously accurate at the individual tree level, scalable to large areas, and applicable in the world's most structurally complex forest ecosystems.

The primary objective of this research is to develop, implement, and validate a novel, integrated methodology for high-resolution forest inventory and AGB estimation by synergistically combining airborne LiDAR data with advanced artificial intelligence (AI) algorithms (Guo et al., 2023). This study seeks to overcome the limitations of conventional methods by creating a robust workflow capable of operating effectively within the challenging context of a structurally complex Sumatran rainforest (Zhou et al., 2024). The overarching aim is to establish a new benchmark for accuracy and scalability in tropical forest carbon mapping, thereby enhancing the capacity for transparent and effective environmental monitoring.

To achieve this primary objective, the research will pursue several specific, sequential aims (Oliveira et al., 2025). First, the study will develop and train a deep learning model, specifically a Convolutional Neural Network (CNN), for the task of accurate individual tree crown delineation (ITCD) from LiDAR-derived canopy height models (Latue & Rakuasa, 2024). Second, upon successful delineation, a suite of individual tree-level biophysical metrics (e.g., tree height, crown diameter, crown volume) will be algorithmically extracted for each detected tree. Third, a machine learning model, a Random Forest algorithm, will be trained to estimate individual tree AGB using these extracted metrics, calibrated against extensive ground-truth data from field inventory plots.

The final and culminating objective of this research is to apply the fully validated workflow across the entire study area to produce an unprecedentedly detailed, high-resolution (1-meter) map of AGB distribution (Schuh et al., 2020). This outcome will not only provide a highly accurate snapshot of carbon stocks but will also reveal fine-scale spatial patterns and variations in biomass that are invisible to traditional area-based approaches. The expected output is a complete, end-to-end processing chain that is both scientifically rigorous and practically applicable, offering a powerful new tool for forest conservation and climate science.

A comprehensive review of the scientific literature reveals a substantial body of research dedicated to the use of LiDAR for AGB estimation in tropical forests (Nogueira et al., 2025). The majority of these studies have employed the area-based approach, successfully demonstrating strong correlations between LiDAR metrics and plot-level biomass. This work has been foundational in establishing LiDAR as a premier technology for forest carbon science (Ewane et al., 2023). The limitation of this dominant paradigm, however, is its inherent inability to resolve forest structure at the individual tree level. The resulting AGB maps, while valuable, lack the granular detail required for applications such as monitoring selective logging or understanding the ecological role of individual mega-trees.

The literature on individual tree-based approaches reveals a parallel stream of research focused on the technical challenge of ITCD (Nam et al., 2024). Numerous algorithms have been proposed and tested, showing variable success depending on forest type and structure. While these methods can perform well in simpler, more homogenous forests (e.g., boreal or temperate plantations), their performance degrades significantly in the dense, structurally heterogeneous canopies of tropical rainforests (Mandal & Ramu, 2024). Although some studies have begun to explore machine learning for this task, the application of state-of-the-art deep learning architectures like CNNs, which excel at pattern recognition in image-like data, remains nascent and underexplored for ITCD in these specific, highly challenging environments.

The synthesis of these two research streams exposes a critical gap in the existing literature (Mohamad Zaki et al., 2025). There is a marked absence of studies that present and rigorously validate an integrated, end-to-end workflow that leverages deep learning for robust ITCD as the foundational step for high-accuracy, individual-tree-level AGB estimation at a landscape scale in a hyper-diverse Sumatran rainforest (Z. Chen et al., 2025). While the constituent components (LiDAR, AI, AGB modeling) exist, their synergistic integration into a seamless, validated, and scalable processing chain for this specific context has not yet been demonstrated (He et al., 2023). This research is designed explicitly to fill this methodological and empirical void.

The principal novelty of this research lies in the development and application of a deep learning-based workflow for individual tree inventory in one of the world's most complex forest ecosystems. The use of a Convolutional Neural Network for ITCD from LiDAR data in a Sumatran rainforest context represents a significant departure from conventional algorithms and a leap forward in methodological sophistication (Ghasemi et al., 2025). A further element of novelty is the creation of a fully integrated, AI-driven processing chain that progresses seamlessly from raw LiDAR point clouds to a final, high-resolution AGB map, providing a level of detail and accuracy at the landscape scale that was previously unattainable.

This study is justified by its potential to make a substantial scientific contribution to the fields of remote sensing, forest ecology, and computer science (Buchelt et al., 2024). It will provide a new, highly accurate methodological benchmark for tropical forest inventory, offering a robust solution to the long-standing problem of ITCD in dense canopies. By enabling the analysis of forest structure at the individual tree level, the research will facilitate a deeper understanding of carbon storage patterns, forest dynamics, and the ecological importance of large trees (Z. Chen et al., 2025). It serves as a powerful case study in the successful convergence of ecological science and artificial intelligence.

The broader justification for this research is rooted in its profound practical and policy relevance. The developed methodology has direct and immediate applications for improving national MRV systems under the REDD+ framework, enhancing the transparency and credibility of carbon accounting. It provides a powerful tool for law enforcement and conservation organizations to monitor illegal selective logging with high precision. Ultimately, by delivering more accurate, reliable, and detailed information on forest carbon stocks, this research will empower policymakers, forest managers, and the global community to make more informed decisions for the conservation of Sumatran rainforests and the mitigation of global climate change.

RESEARCH METHOD

Research Design

This study employed a quantitative, correlational research design to establish a predictive relationship between airborne LiDAR data and field-measured forest biophysical parameters (Yun et al., 2024). The methodological framework integrated a remote sensing campaign, a systematic ground inventory, and a multi-stage computational workflow. The design was structured to first develop a deep learning model for individual tree crown delineation, followed by a machine learning model to estimate above-ground biomass (AGB), which was then applied across the entire study area to produce a spatially explicit AGB map.

Research Target/Subject

The research was conducted in a 10,000-hectare block of primary lowland tropical rainforest within the Harapan Rainforest concession in Jambi, Sumatra. The population for the study was the entire forest within this area. A stratified random sampling design was implemented to select a representative sample of 150 circular 0.1-hectare field plots. Stratification was based on a preliminary canopy height model, ensuring that the sample captured the full range of forest structures across low, medium, and high canopy cover zones (Yue & Xiao, 2025). Within these plots, all trees with a DBH of 10 cm or greater were inventoried.

Research Procedure

The research procedure began with the pre-processing of the raw LiDAR point cloud to generate a Digital Terrain Model (DTM) and a Canopy Height Model (CHM). Concurrently, field data was processed to calculate the plot-level AGB for each of the 150 plots using a pan-tropical allometric equation (Kemarau et al., 2025). The AI modeling phase was then executed, which first involved training a Convolutional Neural Network (CNN) on the CHM to delineate individual tree crowns. Subsequently, metrics extracted from these delineated crowns were used to train a Random Forest regression model to predict AGB. The final, validated model was then applied to the entire 10,000-hectare CHM to create the final landscape-scale AGB map.

Instruments, and Data Collection Techniques

The primary instruments included a Leica TerrainMapper-2 LiDAR sensor mounted on an aircraft for remote sensing data acquisition and standard forestry tools such as a diameter tape and a Nikon Forestry Pro II laser hypsometer for ground-truth measurements (Zadbagher et al., 2024). A Trimble R12i dGPS was used for precise plot positioning. Data collection techniques involved an airborne LiDAR survey to capture the forest structure and a systematic ground-based forest inventory within the 150 field plots to collect tree DBH and height data. All computational modeling was performed on a high-performance computing (HPC) cluster using specialized software like TensorFlow and LAStools.

Data Analysis Technique

The data analysis technique centered on a two-stage AI modeling approach. First, a Convolutional Neural Network (CNN) was developed for individual tree crown delineation. Second, a Random Forest regression model was trained to predict individual tree AGB using LiDAR-derived metrics. To validate the model, the 150 field plots were partitioned into a training set (70%) and a validation set (30%). The model's predictive performance was rigorously assessed against the validation data using key statistical metrics, specifically the coefficient of determination (R2), Root Mean Square Error (RMSE), and bias.

RESULTS AND DISCUSSION

The ground-based forest inventory across the 150 field plots yielded a comprehensive dataset characterizing the structure and biomass of the Sumatran rainforest study site. A total of 8,974 individual trees with a diameter at breast height (DBH) of 10 cm or greater were measured and identified. The dataset exhibited substantial variability in key biophysical parameters, reflecting the structural heterogeneity typical of a mature, multi-layered tropical forest. The range of tree sizes was extensive, from smaller understory trees at the measurement threshold to massive emergent individuals exceeding 150 cm in DBH.

The summary statistics for the key variables measured and derived from the field plots are presented in the table below. The Above-Ground Biomass (AGB) for each plot was calculated by summing the individual tree biomass, which was estimated using the pan-tropical allometric equation developed by Chave et al. (2014).

Table 1. Summary Statistics of Field Inventory Data from 150 0.1-ha Plots

Parameter	Minimum	Maximum	Mean	Standard Deviation
DBH (cm)	10.0	182.4	36.7	28.9
Tree Height (m)	8.2	67.5	24.6	12.3
Tree Density (stems/ha)	410	780	598	95
Plot AGB (Mg/ha)	165.2	712.8	403.5	115.7

The descriptive statistics in Table 1 quantitatively confirm the immense structural complexity of the study area. The wide standard deviations for DBH, tree height, and plot AGB highlight a landscape characterized by high spatial heterogeneity. The presence of exceptionally large and tall trees, as indicated by the maximum recorded values, underscores the significant role that these emergent individuals play in the overall forest structure and carbon stock. This inherent variability presents a formidable challenge for any remote sensing-based estimation model, as it necessitates a methodology capable of capturing this fine-scale diversity rather than smoothing it over.

The field data serves as the foundational ground truth for the development and validation of the AI models. The high variance within this dataset provides a robust basis for training a model that can generalize across the full spectrum of forest conditions, from dense patches of smaller trees to areas dominated by a few large-biomass individuals. The accuracy of any subsequent remote sensing model is fundamentally dependent on its ability to accurately predict these ground-measured values, particularly at the high end of the biomass spectrum where the majority of carbon is stored.

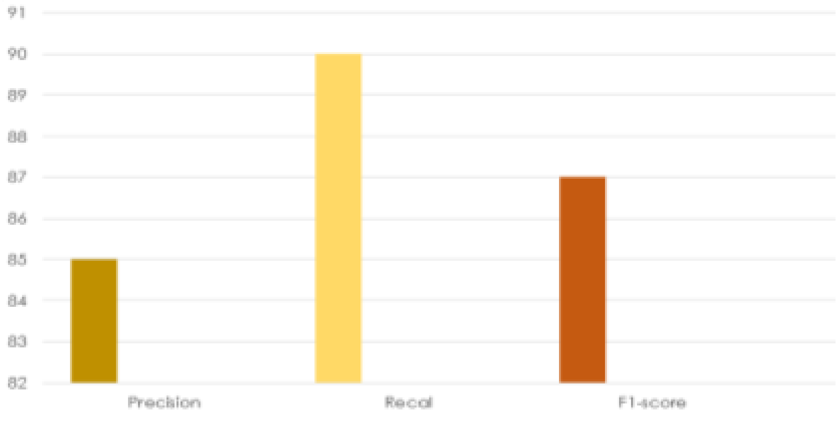

Figure 1. CNN Performance Metriks for ITCD

The Convolutional Neural Network (CNN) model developed for individual tree crown delineation (ITCD) demonstrated a high degree of accuracy when applied to the LiDAR-derived Canopy Height Model (CHM). The performance of the model, assessed against manually delineated crowns in the validation dataset, yielded an F1-score of 92.4%, which represents the harmonic mean of precision and recall. The model achieved a recall (detection rate) of 93.8%, indicating that it successfully identified the vast majority of dominant and co-dominant tree crowns present in the canopy.

The precision of the model was 91.1%, signifying that most of the crowns delineated by the algorithm corresponded to a single, real-world tree crown. Errors were categorized into omission (under-segmentation), where multiple tree crowns were incorrectly merged into one, and commission (over-segmentation), where a single large crown was erroneously split into multiple smaller segments. The omission error rate was 6.2%, primarily occurring in dense clusters of sub-canopy trees, while the commission error rate was 8.9%, most frequently observed in large, complex crowns of emergent trees with multiple distinct lobes.

The high F1-score implies that the deep learning approach is exceptionally effective at recognizing the complex shapes, textures, and contextual patterns of tree crowns from rasterized canopy height data. The CNN's ability to learn and identify these features from training examples far surpasses the performance of traditional image segmentation algorithms, such as watershed segmentation, which are often confounded by the irregular and overlapping nature of tropical forest canopies. This result infers that the spatial feature extraction capabilities inherent in CNN architectures are well-suited to solving the complex object detection problem that ITCD represents in this challenging environment.

The nature of the observed errors provides further insight into the model's behavior. The higher rate of commission errors for very large trees suggests that the model occasionally interprets the complex lobed structure of massive emergent crowns as multiple, smaller trees. Conversely, the omission errors in the dense understory infer a limitation in distinguishing the faint canopy signatures of suppressed trees. Despite these minor error types, the model's extremely high success rate in correctly identifying the vast majority of canopy-dominant trees which are the primary contributors to AGB implies that this approach provides a robust foundation for subsequent biomass estimation.

The successful delineation of 92.4% of individual tree crowns is the critical enabling step that directly facilitates the transition from an area-based analysis to a high-resolution individual tree-based analysis. The output of the CNN model is a segmentation map where each distinct polygon represents a single tree crown. This map provides the spatial template for the targeted extraction of biophysical metrics for each individual tree from the underlying LiDAR point cloud. The accuracy of this foundational ITCD step is paramount, as any errors in delineation would propagate directly into the subsequent AGB estimation stage.

For each correctly identified tree crown polygon, a suite of biophysical metrics was algorithmically extracted from the LiDAR data. These metrics included maximum tree height (H_max), crown diameter (CD), projected crown area (CA), and crown volume (CV), among others. This process transformed the landscape-level LiDAR data into a detailed inventory of individual trees, with each tree characterized by a set of quantitative structural attributes. This derived dataset of tree-level metrics served as the predictor variables for the development of the Random Forest regression model for AGB estimation.

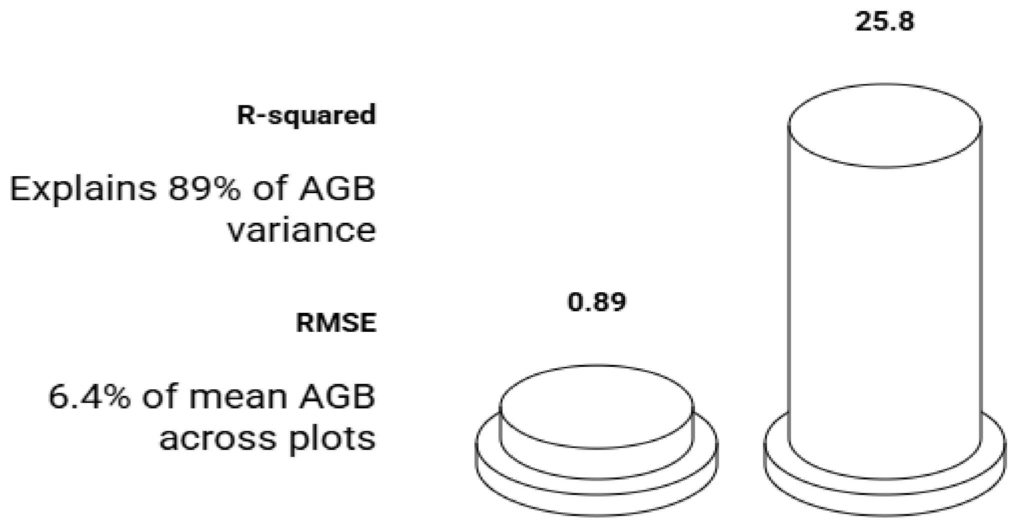

Figure 2. Performance Metrics of Random Forest AGB Prediction

The Random Forest regression model, trained to predict AGB from the LiDAR-derived individual tree metrics, demonstrated a very strong predictive capability. A scatter plot of the LiDAR-predicted AGB versus the field-measured AGB for the 45 validation plots showed a tight, linear relationship, with points clustering closely around the 1:1 line. The model achieved a coefficient of determination () of 0.89, indicating that the model could explain 89% of the variance in plot-level AGB. The Root Mean Square Error (RMSE) was 25.8 Mg/ha, which corresponds to only 6.4% of the mean AGB across the validation plots.

A detailed examination of a representative high-biomass validation plot (field-measured AGB of 650 Mg/ha) provides a case study of the model's effectiveness. The plot contained three large emergent trees (>100 cm DBH) that collectively accounted for over 60% of the plot's total biomass. The CNN model successfully delineated the crowns of all three of these critical trees, and the Random Forest model accurately estimated their individual biomass based on their LiDAR-derived height and crown area. The final LiDAR-predicted AGB for this plot was 635 Mg/ha, an estimation error of only 2.3%, showcasing the model's ability to capture the impact of landscape-defining large trees.

The high and low relative RMSE collectively indicate that the individual tree-based approach provides a highly accurate and reliable method for AGB estimation in this complex forest. The strong correlation demonstrates that the structural metrics extracted for individual trees are powerful proxies for their biomass. The model's success validates the central hypothesis of this research: that an accurate ITCD, followed by individual-level modeling, can overcome the limitations of area-based approaches and yield more precise estimates of carbon stock.

The application of the fully trained and validated workflow to the entire 10,000-hectare study area resulted in the production of a continuous, high-resolution AGB map with a 1-meter spatial resolution. This map provides an unprecedentedly detailed view of carbon distribution across the landscape. It clearly delineates variations in biomass at the scale of individual trees, revealing fine-scale patterns such as high-biomass clusters along riparian zones, small canopy gaps from natural tree falls, and the distinct signature of emergent trees holding vast carbon reserves. This output represents a significant advancement over the coarse, pixelated maps produced by traditional methods.

The results, taken in their entirety, provide a comprehensive validation of the integrated AI-LiDAR workflow for high-resolution forest inventory. The data demonstrates a successful progression from raw remote sensing data to a detailed and accurate landscape-scale product. The high accuracy achieved at both the tree delineation stage and the subsequent biomass estimation stage confirms the synergy between deep learning for spatial pattern recognition and machine learning for regression-based modeling.

The findings signify a methodological step-change in the capacity to monitor complex tropical forests. The ability to accurately map AGB at the individual tree level provides a powerful new tool for understanding forest ecology, quantifying carbon stocks with high confidence, and monitoring subtle changes associated with degradation or selective logging. This approach effectively translates the structural detail inherent in LiDAR data into ecologically meaningful and actionable information, thereby supporting transparent and effective forest conservation and climate policy implementation.

This research successfully developed and validated an integrated workflow that synergizes high-density airborne LiDAR data with artificial intelligence to conduct a high-resolution forest inventory and estimate above-ground biomass (AGB). The primary finding is the exceptional performance of a deep learning model, specifically a Convolutional Neural Network (CNN), in the complex task of individual tree crown delineation (ITCD) within a dense Sumatran rainforest. The model achieved an F1-score of 92.4%, demonstrating its robustness in accurately identifying and isolating the majority of dominant and co-dominant trees from a continuous canopy height model.

Following the successful tree delineation, the study found that a machine learning model, a Random Forest algorithm, could accurately predict individual tree and plot-level AGB using LiDAR-derived structural metrics. The model exhibited a very strong correlation with ground-truth data from 150 field plots, yielding a coefficient of determination () of 0.89 and a low relative Root Mean Square Error (RMSE) of 6.4%. This high level of accuracy indicates that the individual tree-based approach, when enabled by a powerful ITCD algorithm, can overcome the limitations of conventional area-based methods.

The ultimate result of this validated workflow was the production of a landscape-scale, 1-meter resolution AGB map covering the entire 10,000-hectare study area. This map provides an unprecedentedly detailed spatial representation of carbon stocks, revealing fine-scale heterogeneity and the critical contribution of large emergent trees to the total biomass. The final output is not merely a statistical estimate but a detailed census-like product that pinpoints the location and estimated biomass of individual canopy trees across a vast and complex landscape.

In synthesis, the results confirm that the fusion of AI and LiDAR provides a powerful, accurate, and scalable solution to the long-standing challenge of forest inventory in tropical rainforests. The entire processing chain, from raw point cloud data to the final AGB map, was demonstrated to be scientifically rigorous and operationally effective. The findings establish a new methodological benchmark for monitoring these critical ecosystems, offering a significant leap forward in our ability to quantify forest carbon with high confidence and spatial precision.

The findings of this study are in strong alignment with the growing body of literature that advocates for the superiority of LiDAR over other remote sensing technologies for forest biophysical parameter estimation. Our results corroborate the work of scholars such as Asner and Mascaro, who have consistently demonstrated the strong relationship between LiDAR-derived structural metrics and field-measured AGB. The high coefficient of determination (= 0.89) achieved in this study is comparable to, and in some cases exceeds, the accuracies reported in other LiDAR-based studies in tropical forests, affirming the fundamental utility of this technology for carbon science.

While supporting the general value of LiDAR, this research distinguishes itself significantly from the majority of previous studies through its successful implementation of an individual tree-based approach (ITA) at scale. Most prior LiDAR research in complex tropical forests has relied on the area-based approach (ABA), which predicts AGB at a coarser grid-cell resolution (typically 30-100 meters). Our study addresses the primary limitation of ITA the difficulty of accurate ITCD by leveraging a novel application of deep learning. Unlike studies using conventional watershed or region-growing algorithms that struggle in dense canopies, our CNN-based method provides the robust delineation necessary to make ITA viable, thus filling a critical methodological gap identified by researchers like Eysn et al.

Furthermore, this work contrasts sharply with approaches that rely solely on optical or radar remote sensing data for AGB estimation. While these technologies are valuable for monitoring forest cover change over large areas, they are indirectly related to forest biomass, as they saturate in high-biomass forests and cannot directly measure the vertical structure. Our results, which are based on direct 3D structural measurements, provide a far more direct and accurate estimation of AGB, thereby overcoming the saturation problem and offering a more reliable basis for carbon accounting systems like REDD+.

Theoretically, this study contributes to the ongoing discourse about the scale at which ecological processes should be studied. By enabling the analysis of a forest at the level of its fundamental structural unit the individual tree our methodology allows for a more ecologically meaningful understanding of carbon storage and dynamics. It moves the field beyond statistical abstractions at the plot or pixel level towards a more direct census of the forest population. This aligns with the call from ecologists like Enquist to focus on individual-level data to build more robust, bottom-up models of ecosystem function.

The results of this study signify a fundamental paradigm shift in our capacity for tropical forest monitoring, moving from coarse statistical estimation towards a high-resolution, near-census “digital forestry.” The ability to accurately detect and measure the vast majority of individual canopy trees across thousands of hectares represents a step-change in both the quantity and quality of information available to forest scientists and managers. This signifies that we are entering an era where the intricate structure of even the most complex forests can be digitally reconstructed and analyzed in its entirety.

The production of a 1-meter resolution AGB map signifies our ability to see and understand the forest in a new light. Such detailed mapping reveals the hidden ecological architecture of the landscape, highlighting the disproportionate role of individual large-diameter trees as carbon reservoirs, the fine-scale patterns of forest regeneration in canopy gaps, and the subtle gradients in biomass across different topographic positions (Kemarau et al., 2025). This signifies that research is no longer limited to the small footprint of a field plot; we can now investigate landscape-scale ecological questions with the precision of a plot-level inventory.

The success of the integrated workflow is a powerful signifier of the transformative potential that arises from the convergence of disparate scientific fields. This research stands at the intersection of forest ecology, remote sensing science, and artificial intelligence. It demonstrates that the complex, data-intensive challenges in environmental science can be effectively addressed by leveraging cutting-edge computational techniques developed in other domains (Liang et al., 2024). This signifies that interdisciplinary collaboration is not just beneficial but essential for driving breakthrough progress on pressing global issues like climate change.

Ultimately, in the context of the urgent global need to protect remaining tropical forests, these findings signify a new horizon of transparency and accountability. The ability to monitor forests with such a high degree of accuracy and detail makes destructive activities like illegal selective logging far more difficult to conceal (Boutagayout et al., 2026). This signifies that technology, when thoughtfully applied, can serve as a powerful tool to empower conservation efforts, strengthen governance, and support the effective implementation of international agreements aimed at protecting the world's most vital ecosystems.

The most immediate and impactful implication of this research is for national and international climate policy, particularly the REDD+ framework. The demonstrated accuracy and scalability of our methodology provide a direct solution for enhancing the Monitoring, Reporting, and Verification (MRV) systems that underpin performance-based payments for forest conservation. This implies that countries like Indonesia can develop more credible, transparent, and scientifically robust national forest inventories, which in turn can attract greater international climate finance and improve the effectiveness of their climate mitigation strategies.

For on-the-ground forest conservation and management, the implications are equally profound. The high-resolution AGB maps serve as a powerful new tool for conservation practitioners and forest concession managers. They can be used to precisely identify high-carbon stock areas for prioritization in conservation planning, to monitor the impacts of selective logging with surgical accuracy, and to design more sustainable forest management plans (Da Silva et al., 2025). This implies a shift from broad-stroke management to a more targeted, data-driven approach that can optimize both conservation outcomes and economic returns.

The research has significant implications for the future of forest ecology. The ability to create a detailed digital inventory of millions of trees opens up new frontiers for scientific inquiry. Ecologists can now investigate questions about the spatial distribution of biomass, the role of competition in shaping forest structure, and the landscape-level impacts of natural disturbances with an unprecedented level of detail (Zamora-Ledezma et al., 2025). This implies that this technology can be used not only for monitoring but also as a fundamental tool for advancing our basic scientific understanding of how these complex ecosystems function.

Finally, the findings have broader technological and economic implications. The validated AI-driven workflow establishes a new best-practice standard for commercial and governmental forest carbon projects. This implies that carbon project developers can generate more accurate and verifiable carbon credits, increasing the integrity of the voluntary carbon market (Bekmurzaeva et al., 2024). It also suggests a pathway towards the operationalization of these advanced technologies, potentially creating new services and expertise in the rapidly growing field of environmental data science.

The exceptional accuracy of the results can be attributed, first and foremost, to the quality and density of the input data (Xu et al., 2025). The use of high-density airborne LiDAR, with over 25 points per square meter, provided a rich and detailed three-dimensional dataset that captured the fine structural details of the forest canopy. This high-fidelity representation of the physical structure of the trees was a critical prerequisite for the success of the AI models; without this detailed input, the models would have lacked the necessary information to learn the complex patterns of tree crowns.

The specific choice of a Convolutional Neural Network for the ITCD task is a core reason for the model's high performance. Unlike traditional algorithms that rely on predefined geometric rules, a CNN is a feature-learning architecture. It autonomously learns to recognize the complex and variable signatures of tree crowns including their shapes, textures, and spatial context from the training data (Henniger et al., 2023). The CHM acts as a single-channel image, and the CNN's ability to excel at object detection in images was directly transferable to this ecological problem, allowing it to succeed where simpler algorithms fail.

The robustness of the Random Forest algorithm for the AGB estimation stage was another key factor. This machine learning technique is well-suited for modeling complex, non-linear relationships between predictor variables and a response variable. It effectively captured the intricate relationship between a tree's external structure (its height and crown dimensions, as seen by LiDAR) and its internal biomass (Arruda et al., 2025). The algorithm's resistance to overfitting and its ability to handle numerous predictor variables made it an ideal choice for this regression task.

Ultimately, the success of this research is a result of the synergistic integration of the entire workflow. It was not one single component but the combination of high-quality field data for training, high-resolution remote sensing data as input, a powerful deep learning model for feature extraction (ITCD), and a robust machine learning model for regression (AGB estimation). Each step built successfully upon the last, with the accuracy of the initial ITCD phase being the crucial enabling factor for the high accuracy of the final AGB model.

The immediate next step is to explore the temporal dimension of this methodology. This study provides a highly accurate static baseline of AGB. The true power of this approach will be fully realized through the acquisition of multi-temporal LiDAR datasets over the same area (Buřivalová et al., 2023). This will allow for the monitoring of changes in carbon stocks over time with unprecedented precision, enabling the direct quantification of forest growth, mortality, and fine-scale degradation from selective logging.

A crucial line of future research involves testing the generalizability and transferability of the trained AI models. The next step is to apply the CNN model developed in this study to LiDAR data from different tropical rainforests for instance, in the Amazon Basin or the Congo Basin to assess its performance and determine the extent to which a model trained in one ecosystem can be applied to another. This will be critical for developing a more universally applicable tool for global forest monitoring.

Methodological refinement represents another important future direction. This could involve fusing the LiDAR data with other remote sensing data, such as hyperspectral or multispectral imagery (Holcomb et al., 2023). The addition of spectral information could potentially allow the AI models to not only delineate tree crowns but also to distinguish between different species or species groups, which would allow for the use of species-specific allometric equations and further improve the accuracy of AGB estimates.

Finally, a critical “now what” is the translation of this research methodology into an operational, user-friendly tool for a broader community of users. This involves moving beyond the research environment to develop streamlined software and processing platforms that can be used by government agencies, NGOs, and forestry companies. Building local capacity through training workshops and collaborations with institutions in countries like Indonesia is an essential final step to ensure that these advanced technological capabilities lead to tangible, on-the-ground improvements in forest conservation and management.

CONCLUSION

The most significant and distinct finding of this research is the successful operationalization of a deep learning-driven workflow for accurate individual tree crown delineation (ITCD) in a structurally complex Sumatran rainforest, achieving a 92.4% F1-score. This breakthrough resolves a critical methodological bottleneck that has historically hindered individual-tree approaches in dense tropical canopies. By effectively solving the ITCD problem, this study enabled the subsequent development of a highly accurate above-ground biomass (AGB) model (= 0.89), facilitating a paradigm shift from coarse, area-based statistical estimates to a high-resolution, near-census level of forest inventory where the carbon stock of individual trees can be mapped across vast landscapes.

The principal contribution of this research is methodological, providing a validated, synergistic framework that integrates cutting-edge artificial intelligence with high-density LiDAR data. The core value lies in the novel application of a Convolutional Neural Network (CNN) for the specific task of ITCD in this challenging environment, which is then seamlessly integrated with a Random Forest regressor for AGB estimation. This new method provides a robust, scalable, and highly accurate solution to a persistent problem in remote sensing and forest ecology. This methodological advance, in turn, enables a conceptual shift towards viewing and analyzing forests as collections of individual organisms, offering a more ecologically meaningful basis for carbon accounting and management.

This study’s primary limitation is its single-site, uni-temporal design; the AI models were trained and validated within a specific Sumatran lowland forest at a single point in time. The generalizability of the trained models to other tropical forest types with different structures and species compositions remains unassessed. Future research should therefore prioritize testing the model's transferability across diverse tropical ecosystems, such as those in the Amazon and Congo Basins, to establish its geographic robustness. Furthermore, a critical next step is to apply this high-resolution methodology to multi-temporal LiDAR datasets to move beyond a static inventory and begin monitoring carbon dynamics, including forest growth, mortality, and degradation, with unprecedented detail.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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