

PERSPECTIVE

The role of ground-based laser scanning in quantifying and crediting tropical forest restoration: An Australian case study

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Abstract

1. Tropical forest restoration is a critical component of efforts to meet the global challenges of climate change, biodiversity decline and land degradation. Financing the adoption of large-scale restoration efforts requires accurate and robust evaluation of their benefits.
2. Ground-based techniques such as terrestrial or mobile laser scanning (TLS or MLS) allow for accurate, repeatable and importantly traceable determination of forest biomass and structure. The use of these techniques in assessing forest restoration offers an opportunity to both improve ecosystem models that underpin current carbon markets and provide for the direct tracking of carbon sequestration into regenerating forests over time. Furthermore, the evaluation of ecosystem structural metrics (e.g. canopy closure and structural complexity) can help provide robust and transparent data to underpin nascent environmental and biodiversity markets to help support forest restoration.
3. Here, we consider the emerging role of ground-based laser scanning in supporting tropical forest restoration using experiences from the Wet Tropics of Australia as one of the most mature carbon markets on earth, and one in which co-benefits of tropical forest restoration are being incorporated into restoration finance models.
4. *Solution:* Integrating ground-based laser scanning into the evaluation of tropical forest restoration can provide stakeholders with direct evidence of restoration outcomes, thus increasing confidence in carbon and biodiversity credit valuation. By directly addressing known barriers to adoption, we believe the use of ground-based laser scanning, especially when coupled with other emerging technologies, will help support the financing of large-scale forest restoration efforts.

KEYWORDS

carbon credits, carbon markets, LiDAR, restoration, tropical forest

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1 | INTRODUCTION

The active restoration of terrestrial ecosystems is an integral component of efforts to meet the global challenges of climate change, biodiversity decline and land degradation (Girardin et al., 2021). Given the large amounts of above- and below-ground carbon stored in forest systems (Pan et al., 2011), especially in the humid tropics (Griscom et al., 2020), halting and reversing forest declines seen across the Anthropocene (Lewis & Maslin, 2015; Malhi et al., 2014) is an obvious strategy in combatting global climate change (Bastin et al., 2019). As noted in the most recent IPCC report (Riahi et al., 2022), encouraging carbon sequestration into terrestrial vegetation and soils is the only CO₂ removal method currently being employed globally at scale. There is active debate as to the potential for global forest restoration to combat anthropogenic carbon emissions (see Bastin et al. (2019) and Strassburg et al. (2020), as well as their responses e.g. (Doelman & Stehfest, 2022; Lewis, Mitchard, et al., 2019)). However, it is clear that restoration of natural forest systems, especially in the humid tropics (Lewis, Wheeler, et al., 2019), can provide real mitigation benefits through the sequestration of atmospheric carbon in tree biomass. Additionally, restoration can help remnant forests to adapt to climate change by enhancing landscape connectivity and reducing fragmentation (thus facilitating species migration under climate change), preserving ecosystem biodiversity, avoiding soil degradation and protecting other natural resources (e.g. water and non-timber forest products) (Mansourian et al., 2022).

At the 2021 UN Climate Change Conference (UNFCCC, COP 26), 145 countries signed up to the Glasgow Leaders' Declaration on Forests and Land Use. They pledged to conserve forests and accelerate their restoration, in part by increasing both public and private finance and investment opportunities for active Afforestation, Reforestation and Revegetation (ARR) as well as Human-Induced Regeneration (HIR, i.e. restoring of landscapes through the removal of anthropogenic pressure). It was a welcome commitment, which added impetus to other forest restoration efforts made during the current UN Decade on Ecosystem Restoration (<https://www.decadeforestoration.org/>). In parallel to these governmental pledges, there has also been a rise in corporate interest in forest restoration from companies seeking to meet their net-zero commitments, alongside increased private finance from philanthropic organisations and individuals (Löfqvist & Ghazoul, 2019). As a result, voluntary carbon markets (VCMs) have expanded based on carbon credits issued by organisations such as the Verified Carbon Standard (VCS) (www.verra.org), Gold Standard (www.goldstandard.org) and Plan Vivo (www.planvivo.org). In Australia, the Australian Carbon Credit Units (ACCU, <https://cer.gov.au/schemes/australian-carbon-credit-unit-scheme>) scheme operates primarily as a government-regulated compliance mechanism; however, ACCUs can also be purchased or traded within voluntary markets.

Current VCM transaction volumes are dominated by credits issued for forestry and land use change (Forest Trends' Ecosystem Marketplace., 2025). However, concerns have been raised on the true carbon mitigation potential of projects certified under schemes such

as VCS (Guizar-Coutiño et al., 2022) and ACCU (Chubb et al., 2022; Macintosh, Butler, et al., 2024). These critiques have contributed to a loss of confidence in both voluntary and compliance carbon markets, reflected by substantial declines in the total volume of credits traded and their market price. Across the VCMs monitored by the Ecosystem Marketplace, an initiative of the non-profit organisation Forest Trends, the number of carbon credits issued for forestry and land use change has dropped from 113.0 MtCO₂e in 2022 to just 37 MtCO₂e in 2024 (Forest Trends' Ecosystem Marketplace., 2025). These declines pose particular challenges for those seeking to support tropical forest restoration through the issuing of carbon credits, given the potential complexity, and therefore expense, of establishing diverse tropical plantings (Tucker et al., 2023).

For carbon crediting to be credible and to genuinely support forest restoration, forest carbon monitoring and accounting methodologies must continue to evolve, delivering greater accuracy and a clearer understanding of project-level impacts. This requires robust approaches that establish appropriate baseline conditions, account for system leakage and demonstrate additionality (Macintosh, Evans, et al., 2024; Streck, 2021). For projects based on ARR and HIR, there is an additional need for repeatable and transparent techniques to accurately quantify carbon in vegetation, thereby providing the market with confidence in the integrity of resulting credits. Ground-based laser scanning is a transformative tool in this regard, providing precise, high-accuracy, three-dimensional measurements of forest structure that enable direct estimation of above-ground biomass (AGB) and thereby carbon sequestration.

In parallel, there is a growing recognition that the finance models that underpin ARR and HIR projects must also capture ecological and societal co-benefits beyond just carbon sequestration (Galatowitsch, 2009; Koh et al., 2021). However, delivering credible and scalable nature-based solutions requires strong, evidence-based frameworks to demonstrate benefits (Seddon et al., 2020). Globally, this shift is exemplified by the United Nations Environment Programme's Finance Initiative (UNEP FI; <https://www.unepfi.org>), which promotes sustainable finance practices across sectors. In Australia, similar principles have driven the establishment of both federal and state mechanisms including the Australia Commonwealth Nature Repair Act, 2023 and Queensland's Cassowary Credit Scheme (<https://www.cassowarycredits.com.au/>), funded through the Land Restoration Fund. These new schemes have sought to establish methodologies for measuring, reporting and verifying co-benefits arising from restoration projects (The Land Restoration Fund, 2023). However, all such programs face the challenge of accurately and cost-effectively assessing and documenting changes in biodiversity and ecosystem services resulting from effective forest restoration.

Recent advances in remote-sensing technologies have greatly improved the capacity to monitor forest restoration, with airborne and satellite-based platforms—such as LiDAR (light detection and ranging), synthetic-aperture radar (SAR) and multi- and hyperspectral sensors—providing unprecedented spatial coverage and temporal continuity (de Almeida et al., 2025). Nevertheless, these

approaches continue to face inherent constraints in resolving sub-canopy biomass and fine-scale forest structure, and their temporal resolution often limits the detection of rapid vegetation change and short-term structural dynamics within restoration sites (de Almeida et al., 2025). Ground-based laser scanning (Demol et al., 2022) in combination with airborne LiDAR scanning (Terry et al., 2022) and other remote sensing platforms (de Almeida et al., 2025) can address these limitations by providing direct, repeatable and verifiable measurements of three-dimensional forest structure. This can then be used as a direct assessment of changes in carbon sequestration and habitat complexity, or to help improve ecosystem modelling.

2 | ASSESSING CARBON SEQUESTRATION IN TROPICAL FOREST RESTORATION

In forest restoration, two principal approaches are commonly employed to estimate carbon sequestration for conversion into carbon credits: direct measurement of carbon pools, which can be extrapolated to the landscape scale using remote sensing tools, and model-based estimation of carbon sequestration using regional ecosystem models.

2.1 | Direct assessment of carbon sequestration

Direct assessment of carbon sequestration involves the determination of specific carbon pools in the landscape and, via repeated measurements over time, tracking how these change as a result of documented activities.

Such an approach forms the basis of VCS methodology VM0047: *Methodology for Afforestation, Reforestation and Revegetation Projects* (VERRA et al., 2025). Under this methodology, project proponents may choose between an area-based approach—combining remote sensing and monitoring plots—or a census-based approach where every planting unit (≤ 50 per ha) is individually enumerated and tracked over time. Under the area-based approach, monitoring plots are established to quantify significant carbon pools, such as AGB, with results extrapolated across the landscape via remote sensing proxies (e.g. canopy height or vegetation indices derived from satellites).

The direct measurement of AGB in individuals or across plots typically requires labour-intensive and time-consuming field surveys in which individual stems are labelled, taxonomically identified and measured for diameter at breast height (DBH) and (optionally) tree height. These measurements, often combined with wood-density estimates, are converted to per-tree biomass using allometric equations (Chave et al., 2014; Paul et al., 2016). However, such methods, especially in multi-species assemblages typical of tropical forests, are known to be inaccurate (Calders et al., 2020; Demol et al., 2022) while giving little information on tree architecture (Dorji et al., 2021) or habitat structural complexity. Within Australia, this form of direct measurement is now rarely used within the ACCU framework,

where all methods based on field-measured carbon stocks (e.g. *ERF Reforestation and Afforestation 2.0*) have been closed in favour of an ecosystem modelling approach. However, the application of ground-based laser scanning—to provide either direct measurement of structural metrics (see Section 3.2) or improved regionally-calibrated allometric models (see Section 3.3)—offers an improved capacity to directly measure carbon sequestration within monitored forest plots in a transparent and verifiable manner.

2.2 | Modelling carbon sequestration: Examples from Australia

Accurate, field-based measurement of carbon sequestration demands specialised expertise and ongoing monitoring, making it potentially costly and impractical at large scales. Consequently, ecosystem modelling has become a standard approach for estimating carbon uptake in HIR and ARR projects, offering a scalable and consistent means to assess likely carbon dynamics across the landscape. In Australia, the Full Carbon Accounting Model (FullCAM) (Brack & Richards, 2002) forms the core of the Australian Government's land-sector National Greenhouse Accounts, and underpins Australia's official reporting to the United Nations Framework Convention on Climate Change (DCCEE, 2025). FullCAM also underpins current ACCU methods employed by land-managers seeking vegetation-based carbon credits in Australia. In FullCAM, carbon sequestration into new vegetation is described by an empirical Tree Yield Formula (Data S1) applied at a specific location. The Tree Yield Formula predicts AGB growth, after which biomass allocation, litterfall, root slough, decomposition and carbon fractionation are applied to derive pool-specific carbon stocks (e.g. below-ground live biomass, standing dead and fallen coarse woody debris, soil) and associated fluxes from decomposition and soil carbon turnover (Forrester, England, Paul, Rosauer, & Roxburgh, 2024; Roxburgh & Paul, 2017).

FullCAM, like many ecosystem models, relies upon the following key assumptions: (i) the potential maximum AGB obtainable for a site varies spatially and reflects undisturbed remnant stands of woody vegetation in similar locations (Roxburgh et al., 2017; Roxburgh et al., 2019); (ii) growth increments of AGB vary in accordance with the spatio-temporal inputs of the dimensionless measure of Forest Productivity Index, derived from process-based forest growth modelling with inputs of soil fertility, sunlight, rainfall, vapour pressure deficit, temperature and frost (Kesteven et al., 2004); and (iii) empirically-derived parameters influencing the shape (G) and scaling (y) components of the TYF can be calibrated in such a way to fit observations of tree growth.

However, as highlighted in a recent sensitivity analysis, the carbon stocks estimated by FullCAM are highly dependent upon these assumptions, especially assumed mortality rates and the maximum potential AGB of a project site (Forrester, England, Paul, & Roxburgh, 2024). The potential maximum AGB represented by the M-data layer in FullCAM shows considerable variation across Australia, including within key bioregions such as the rainforests

of the Wet Tropics of Queensland (Figure S1). However, local-scale accuracy may be low. For example, when compared with AGB measurements from 20 long-term tropical forest inventory plots established and monitored by Australia's CSIRO (Commonwealth Scientific and Industrial Research Organisation) since the 1970s (Bradford et al., 2014), the M-data layer consistently underestimates potential maximum AGB for tropical forest sites, reporting values that are, on average, just 52% of that observed in the field using traditional allometric models (Figure 1).

This bias occurs due to the potential maximum AGB layer being based upon a parsimonious fit of climatic drivers of observed AGB at the continental scale (Joint Remote Sensing Research, 2021; Roxburgh et al., 2019). Although the underlying biomass inventory data for this (National Biomass Library, <https://field.jrsrp.com/>) contains records from over 11,180 sites, this represents just 16km², and only 5739 of these sites are considered undisturbed forest sites, with only one found within the tropical rainforests of north east Queensland (Roxburgh et al., 2019). Despite these shortcomings, FullCAM remains the primary methodology used in the determination of ACCU's from vegetation growth across tropical Australia (<https://cer.gov.au/markets/reports-and-data/accu-project-and-contract-register>).

Proponents of the ecosystem modelling approach might argue that, while these methods may lack precision at the project scale

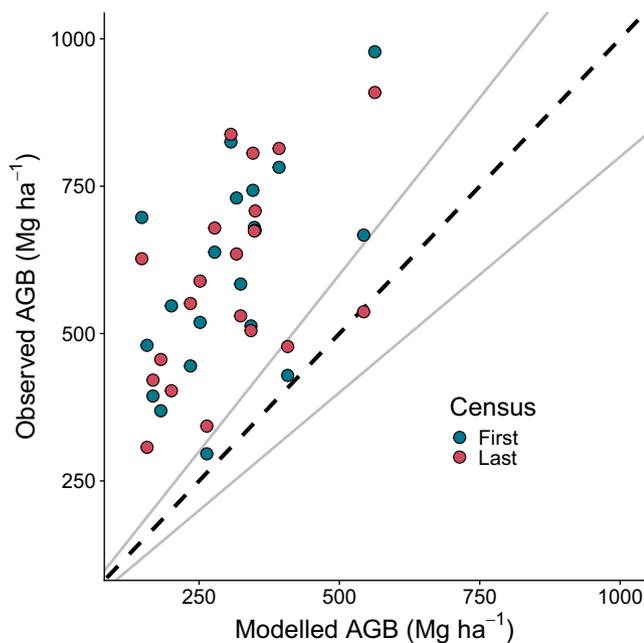


FIGURE 1 Comparison of modelled and observed Above-Ground Biomass (AGB) in 20 forested plots across intact rainforest of the Australian Wet Tropics Bioregion of northeast Queensland. Modelled potential maximum AGB (M-data layer) used in FullCAM was sourced from Department of Industry Science Energy and Resources (2020); see Roxburgh et al. (2019) for details, while observed AGB was sourced from 0.5 ha CSIRO long-term inventory plots established in the 1970s (Bradford et al., 2014). Given the impact of periodic cyclone activity in the area, we present AGB data from both first and last census available as per (Bradford & Murphy, 2019). Trend lines show 1:1 relationship $\pm 20\%$.

due to generalisation of parameters and their insensitivity to local conditions or species composition (Preece et al., 2017), they provide consistent and unbiased estimates suitable for continental-scale carbon inventories. However, these models are frequently being used at the project scale, and their reliability depends heavily on the quality of their calibration data and the extent to which they represent local vegetation structure and function (Yatsko et al., 2025). There is a clear need for approaches that can both improve ecosystem model accuracy and directly measure restoration outcomes.

3 | THE ROLE OF GROUND-BASED LASER SCANNING

Ground-based laser scanning, also referred to as ground-based LiDAR, acquires XYZ coordinates of objects in the environment by emitting laser pulses towards surfaces and recording the time taken for each pulse to return to the sensor. Because the speed of light is known, this time-of-flight measurement is converted into a distance, enabling precise calculation of the position of the reflecting surface relative to the scanner. This broad suite of technologies can include the use of stationary systems deployed at fixed positions across a site—terrestrial laser scanning (TLS)—as well as mobile platforms that capture data while in motion—mobile laser scanning (MLS) (Bauwens et al., 2016). In either case, the resulting geo-located point cloud can subsequently be processed to extract information on the presence and dimensions of tree stems and canopy structure (Murtiyoso et al., 2024). TLS has already proven to be an accurate method for quantifying stem volume and habitat complexity in mature tropical forests (Calders et al., 2020; Calvert et al., 2024; de Gonzalez Tanago et al., 2018; Demol et al., 2022; Malhi et al., 2018). While MLS currently delivers lower precision, recent advances in positional accuracy (Liu et al., 2025) are closing this gap. Moreover, the ability of MLS to efficiently capture basic stem form and spatial arrangements (Tatsumi et al., 2023), and the ability to use this information alongside TLS-derived allometric models (Holvoet et al., 2025), positions MLS as a powerful, complementary tool for future large-scale forest monitoring and restoration assessment.

By directly quantifying tree volume, canopy structure and spatial distributions of biomass, laser scanning provides robust empirical data for validating and refining ecosystem models across tropical landscapes, bolstering confidence in predicted ecosystem value. Repeated laser scanning surveys further enable non-destructive tracking of forest recovery through time, offering precise estimates of biomass accumulation and structural change. In the following sections, we explore the role of ground-based laser scanning in assessing ARR and HIR projects, highlighting how it can strengthen model calibration, directly quantify stem volume and thereby carbon sequestration in restoration plantings, and capture additional indicators of ecosystem complexity relevant for restoration crediting.

3.1 | The role of laser scanning in improving ecosystem models

If ecosystem models such as FullCAM are to be relied upon to quantify carbon sequestration in ARR and HIR projects, there is a clear need to refine underlying model assumptions and minimise biome-specific biases. Ground-based laser scanning provides a pathway to address model uncertainties by delivering ecosystem-specific estimates of AGB in reference forests (Demol et al., 2022; Terryn et al., 2024). At the same time, it can deliver detailed structural information that allows the disaggregation of total biomass into stem, branch and canopy components (Terryn et al., 2022), thereby improving estimates of biomass allocation ratios and turnover rates (Forrester, England, Paul, Rosauer, & Roxburgh, 2024). Repeated scanning further provides the temporal data required to derive biome-specific tree-growth parameters that govern how forest biomass is modelled to approach its maximum potential over time. Stand-level estimates of observed AGB, its allocation and temporal changes—particularly when integrated with remote-sensing products derived from airborne (Terryn et al., 2022) and spaceborne (Dubayah et al., 2020) laser scanning—will provide the spatial coverage and level of mechanistic detail largely absent from traditional inventory data, both of which are needed to reduce structural uncertainty and provide a transparent empirical basis for model validation.

3.2 | The role of repeated laser scanning in monitoring forest restoration

The monitoring of forest restoration at a project scale has typically required the establishment of permanent, delineated survey plots representative of the project area with individual trees tagged, measured and monitored over time. However, in dense, rapidly establishing tropical forests, both stem mortality and natural recruitment make this a non-trivial process, especially at a spatial scale required to account for landscape heterogeneity. Furthermore, for there to be confidence in this direct measurement of carbon sequestration, there need to be careful protocols in place to ensure data quality and accuracy.

By creating geolocated point clouds of all objects within the project area, ground-based laser scanning has the capacity to rapidly capture the structure of forests, which can be used to estimate AGB and carbon sequestration using either species-specific or stand-level estimates of wood density and carbon content. This can be achieved without the need for permanent tagging and marking of individual trees, while allowing for accurate determination of stem volumes in irregular tree forms (i.e. multi-stem and buttressing) often seen in tropical trees (Disney et al., 2018; Nölke et al., 2015). Although techniques such as TLS have been employed in mature forests of the Australian Wet Tropics (Brede et al., 2022; Terryn et al., 2022), their use within ARR and HIR projects remains limited. Several open-source workflows are now available to model tree volumes and estimate carbon storage or structural attributes

from LiDAR data, including TLS2trees (Wilkes et al., 2023), ITSM (Terryn et al., 2023), and canopy-complexity metrics (Yopez-Rincon et al., 2021). However, in regenerating forests where trees are small, these approaches face challenges as most LiDAR processing pipelines were developed for determining biomass of mature forest stands (Yang et al., 2025). Current-generation quantitative structure models (QSMs), based on TLS data collected under ideal conditions, can typically resolve stems and branches down to around 3 cm in diameter (Morhart et al., 2024). Yet, recent advances in QSM processing—particularly the introduction of Real Twig correction methods (Morales & MacFarlane, 2025a, 2025b)—are extending this capability to finer structural elements. In parallel, new leaf-wood separation algorithms (Chen et al., 2025) are improving the discrimination between photosynthetic and non-photosynthetic tissues within dense point clouds, further enhancing model accuracy. Together, these developments enable more accurate prediction of twig- and branch-scale biomass, which is critical in young, regenerating forests where fine structures contribute disproportionately to above-ground biomass and canopy-structure metrics (Yang et al., 2025).

As ground-based laser platforms become cheaper and their analysis workflows standardised for tropical ARR/HRR activities, it will be possible to track not only changes in individual stems over time (Figure 2), but to rapidly record and assess plot-level measurement of AGB during forest restoration. This will give landowners the capacity to visualise and then account for site level differences in planting methodology, fertility and growth success that cannot otherwise be accounted for in ecosystem models (Figure 3, Table 1). In doing so, these emerging techniques have the potential to provide market confidence in true project valuation, and encourage restoration best-practice to enhance gains that would not otherwise be valued.

3.3 | Using laser scanning to improve allometric models

Allometric models underpin most estimates of AGB and therefore the assessment of carbon stocks in forests. However, traditional allometries derived from limited destructive sampling often fail to capture the structural and taxonomic diversity of tropical forests, particularly among large trees that store the majority of total AGB (Bradford & Murphy, 2019). Recent advances in TLS have transformed our ability to quantify three-dimensional tree structure and develop new, non-destructive allometric relationships that can be applied at scale. These can include both species-specific models (Stovall et al., 2023; Terryn et al., 2025) and those calibrated to diverse multi-species assemblages. For example, Muledi et al. (2025) used TLS-derived QSMs to construct a local allometric equation for the structurally complex wet Miombo forests of the Democratic Republic of the Congo. This locally calibrated model substantially reduced the systematic underestimation of observed stem volumes when compared with widely used pan-tropical allometric equations.

Importantly, these refined allometric relationships can now be applied at scale through their integration with other laser scanning

technologies. MLS offers the capacity to rapidly capture key stem characteristics such as diameter, form and stem density across plot areas (Holvoet et al., 2025; Mak et al., 2025), while airborne laser scanning (ALS) can rapidly cover the landscape to provide complementary information on canopy height and structure (Terry

et al., 2022). When integrated with local TLS-calibrated allometric models, these data streams will enable scalable, non-destructive estimation of stem volumes and associated carbon stocks in monitored restoration plots.

3.4 | Quantify additional ecosystem metrics

Recognition of the need to value co-benefits from carbon sequestration projects has led to the emergence of 'biodiversity credits': schemes that incentivise investment in broader ecological gains which extend beyond carbon storage. Within these biodiversity markets, there is growing recognition that restoration success should be evaluated using attributes of ecosystem structure and function (Edens et al., 2022; Perring et al., 2015) as they are closely interdependent with compositional characteristics of ecosystems (McElhinny et al., 2005). For example, under the federally

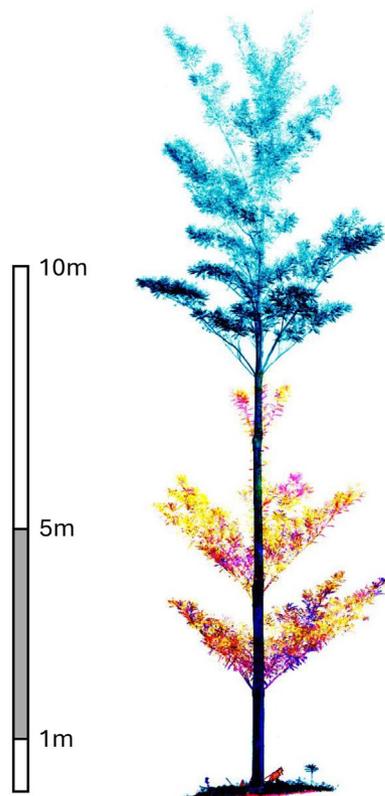


FIGURE 2 Terrestrial laser scanning over multiple years allows for the accurate determination of tree-level changes in biomass and structure. Data shown here represents coaligned point-clouds of an *Elaeocarpus grandis* tree scanned in September 2021 (red shades) and 2024 (blue shades). Data collected using a Riegl VZ-400i Laser Scanner (RIEGL Laser Measurement Systems, Horn, Austria) on the panoramic setting at 40 millidegrees and 1200kHz/s—with image processing using RiSCAN PRO 2.19.



FIGURE 3 Ground-based laser scanning (specifically TLS) was used to record the structure of three restored lowland tropical rainforest plots in the Wet Tropics of Australia. Plots were established in March and November 1993 and March 1995 under different management strategies and planting regimes. Scans were captured over 2 days (16 and 17th of October 2021). Image presented here is a cross section of one plot planted in Nov. 1993 and now dominated by *Nauclea orientalis*, with the image showing a transverse (10m wide) section in a NS orientation.

TABLE 1 Above-Ground Biomass (AGB) of three restored lowland tropical rainforest plots in the Wet Tropics of Australia as determined by terrestrial laser scanning and as estimated by regional ecosystem model FullCAM.

	AGB (Mg·Cha ⁻¹)	
	TLS	FullCAM
Site 1—March 1993	86.8	65.9
Site 2—Nov 1993	63.0	66.4
Site 3—March 1995	58.0	60.9

Note: AGB for each plot was taken from cylinder fitting of TLS data (see Calvert et al. (2024) and Yatsko et al. (2025) for details) and compared with no-leaves output of FullCAM ecosystem modelling for the sites given a known planting date. In converting cylinder volumes to an estimate of AGB we used standard carbon density employed as part of FullCAM (i.e. not accounting for species identity). The model performed reasonably well at predicting AGB after 28 years of growth in these plots with FullCAM underestimating observed AGB by just 8% on average, but with a RMSE of 12.4 Mg·Cha⁻¹, 20% of predicted AGB across three diverse plots employing differences in planting methodology.

regulated method for native forest and woodland restoration under the Australian Nature Repair Act 2023, proponents must quantify ecosystem 'condition' before and after restoration, with measures of vegetation structure serving as a core indicator of condition relative to an ecosystem's reference state (Australian Federal Government, 2025).

Ground-based laser scanning thus provides a direct, quantitative means to capture the three-dimensional structure of vegetation, enabling detailed assessment of habitat potential (Holland et al., 2024). A suite of ecologically relevant structural metrics can be derived, including canopy height distribution, foliage density profiles, stem density and size distributions, gap fraction, understorey complexity and coarse woody debris volume, all structural features known to influence species richness and community composition. For instance, greater vertical heterogeneity and canopy layering are associated with increased microhabitat diversity and resource partitioning among birds, bats, and invertebrates (Perles-Garcia et al., 2021). Likewise, measures of structural connectivity and surface roughness derived from TLS point clouds correlate strongly with faunal habitat suitability and are increasingly being explored as quantitative proxies for 'habitat complexity indices' within emerging biodiversity credit frameworks (Atkins et al., 2023).

An additional advantage of TLS is the ability to revisit and audit conclusions drawn from the data. Archived point clouds can be re-analysed as new biodiversity or habitat-complexity metrics are developed, allowing for temporal changes in ecosystem structure (and associated ecosystem values) to be transparently demonstrated to stakeholders. Quantifiable, structure-based indicators provide an essential bridge between carbon accounting and biodiversity assessment, ensuring that restoration projects can be quantitatively evaluated in terms of ecosystem recovery.

4 | THE FUTURE OF GROUND-BASED LASER SCANNING IN TROPICAL FOREST RESTORATION

The capacity of ground-based laser scanning to provide rapid, repeatable and highly accurate data on tropical forest structure represents a new standard in forest measurement and modelling (Åkerblom & Kaitaniemi, 2021). By delivering precise and scalable estimates of stem volume, structural complexity and ecosystem attributes, ground-based laser scanning directly addresses key challenges in restoration assessment and carbon market valuation. It can not only improve assumptions underpinning ecosystem models but also enable accurate, plot-level tracking of changes in biomass and habitat complexity over time, information that can be visualised and communicated to landholders and project financiers.

Future advances are likely to come from integrating ground-based scanning with airborne laser scanning (ALS) and other remote-sensing platforms, creating multi-scale datasets that bridge

ground-level accuracy with landscape-level coverage (de Almeida et al., 2025). Such integration will enable calibration and validation of ALS-derived biomass and canopy metrics, refine model upscaling from plots to regions, and enhance confidence in estimates of carbon stocks and biodiversity recovery at a landscape scale (Yatsko et al., 2025). Combining these technologies within national accounting frameworks (e.g. FullCAM) would improve both the precision and transparency of forest carbon monitoring.

At the same time, emerging work such as the For-Species20K initiative (Puliti et al., 2025)—although focussed primarily on European taxa—demonstrates how advances in integrated datasets and artificial intelligence are rapidly improving automated species classification. Similar approaches are now being extended to complex tropical systems, where high-resolution UAV-borne LiDAR and multispectral imaging are enabling the identification of individual tree species and functional groups at landscape scales (Pereira Martins-Neto et al., 2023). When combined with structural metrics derived from TLS or MLS, these capabilities open the door to species-specific allometric modelling, allowing stem-volume estimates to be more accurately translated into above-ground biomass.

Moreover, because digital LiDAR point clouds and raw project files can be cryptographically verified using hash functions, they offer an auditable data trail linking on-ground observation to carbon and habitat valuation. This capacity to generate verifiable, open and traceable measurements is essential for maintaining confidence in nature-based climate solutions and ensuring that restoration investments deliver genuine benefits for both carbon and biodiversity.

Yet despite the enormous promise of these technologies, similar barriers to adoption exist as those seen in other sectors of commercial forestry (Fassnacht et al., 2024). Overcoming them will require clear demonstration of value to end-users, improved knowledge transfer between researchers, service providers and land managers, and open data frameworks that ensure long-term accessibility and comparability of measurements. Building local capacity in data processing and integration will be essential if ground-based laser scanning is to move from research to routine application in tropical forest restoration.

AUTHOR CONTRIBUTIONS

Alexander W. Cheesman led the writing of the manuscript, with data and imagery from Keith Cook, Jed Calvert, and Abbey R. Yatsko. All authors contributed to the content and editing of the manuscript and approved the final version.

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CONFLICT OF INTEREST STATEMENT

Abbey R. Yatsko is an employee of ArborMeta.

PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70213>.

DATA AVAILABILITY STATEMENT

The data used for this research is found within the article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. The Tree Yield Formula (Equation 1) used in ecosystem models like FullCAM to predict the annual change in Above Ground Biomass (AGB) of trees growing in restoration planting.

Figure S1. Variation in modelled maximum potential Above Ground Biomass (AGB, Mg ha⁻¹) across the landscape.

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