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RESEARCH ARTICLE

Integrating terrestrial and canopy laser scanning for comprehensive analysis of large old trees: Implications for single tree and biodiversity research

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Keywords
biodiversity, canopy laser scanning, LiDAR, occlusion, terrestrial laser scanning, tree crowns

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Funding information
BD was supported by FWO (PhD fellowship Strategic Basic Research) (grant number 1S26724N). AA was supported by the Swedish Research Council (grant number 2019-05191), the Swedish Foundation for Strategic Environmental Research MISTRA (Project BioPath), AG Stiftelse and the Kew Foundation. KC and WC were supported by the European Union (ERC-2021-STG Grant agreement No. 101039795). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. The 'Life on Trees' (LOT) Program was supported by the Fonds de Dotation Biotope pour la Nature. The Tasmanian campaign was supported by the Australian

Abstract

Large old trees provide multiple ecosystem services and contribute disproportionately to forest biomass and biodiversity. Yet their canopies remain among the least-explored terrestrial habitats, despite their structural influence on key ecological processes such as light interception, moisture regulation, carbon storage and habitat formation. While terrestrial laser scanning (TLS) captures tree structure primarily from the ground, it struggles with occlusion and reduced precision in dense upper canopies, limiting information on fine-scale branches and canopy vegetation. To address this, we introduce canopy laser scanning (CLS). We lifted a high-end laser scanner into the canopy of six large, old trees by using scaffolding or climbers. Four trees are in diverse tropical rainforests in Colombia, Brazil and Peru and have large complex crowns with dense foliage. Two 'giant' trees stand out in Tasmania's wet, temperate eucalypt forests. Combining canopy and terrestrial scans resulted in a consistent high point cloud quality. The combined point clouds exhibited uniform point densities throughout the entire tree (downsampled to 1 cm), enabling a thorough examination of both the tree structure and its associated vegetation. Quantitative Structure Models (QSMs) showed, on average, a 20% increase (compared to TLS) in estimated branch volume and length, particularly concentrated in the upper crown region. We identified key epiphytic groups for a 5 × 5 × 5 m^3 subset of a tree. Our results show that CLS improves point cloud precision and reduces occlusion, enabling more accurate assessments of tree architecture and canopy biodiversity. Where feasible, this advancement creates new opportunities for 3D modelling of microhabitats, estimating aboveground carbon stocks, monitoring species and studying ecological dynamics.

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Research Council (ARC) (grant numbers DP180103460, LP170101090).

Editor: Nathalie Pettorelli
Associate Editor: Javier Lopatin

Received: 7 March 2025; Revised: 6 June 2025; Accepted: 4 July 2025

doi: 10.1002/rse2.70021

Introduction

Large old trees, characterized by their exceptional age, height and girth, feature extensive buttressing, cavities, complex crowns and prominent branches (Lindenmayer & Laurance, 2017). The structural complexity of their crowns creates diverse microhabitats, influencing the distribution of epiphytes and other organisms (Woods et al., 2015). Studies, such as de Souza Amorim et al. (2022), show significant differences in species richness and abundance between the canopy and the ground.

Large trees also shape forest structure, affecting basal area distribution, vertical complexity and biomass storage. Trees with a DBH over 60 cm comprise 41% of aboveground biomass (AGB; Lutz et al., 2018) and account for 70% of variation in pan-tropical AGB (Slik et al., 2013). Despite their importance, assessments of large old trees are limited. In particular, more research is needed on the biodiversity they support—including the wide range of organisms that live in, on and around them—and how these organisms interact with the tree and with each other (Leponce et al., 2024).

Highly detailed 3D information on the tree structure is necessary to accurately understand the impact of large old trees in forest ecosystems and better understand interactions and organism distributions inside the canopy (Bader et al., 2000). The most commonly used method to map organisms is to use the zonation system of Johansson (1974), in which the tree is divided into different zones (stem-base, stem, inner crown, middle crown, outer crown). This method, however, addresses the heterogeneity of tree crowns only partially. Modern LiDAR technologies offer new possibilities for understanding the spatial organization of tree crowns (Calders et al., 2020; Roşca et al., 2018).

Terrestrial laser scanning (TLS), also called terrestrial LiDAR, enables the creation of highly detailed 3D point clouds of the environment, which can be used to investigate the spatial arrangements of forest elements, quantify tree biomass and simulate the light environment (Calders et al., 2020). The quality of the acquired point cloud highly depends on the complexity of the site, the distance to the object of interest, the weather at the time of observation and the scanner quality (Terryn et al., 2021).

In practice, TLS data are generally collected from a stationary tripod at multiple ground locations, after which all scans are combined into a single point cloud. Scanning from the ground results in occlusion of the upper canopy due to plant material blocking the direct view between the instrument and the top of the canopy (Abegg et al., 2017; Schneider et al., 2019). Additionally, the top of the point cloud exhibits a lower precision as the laser's beam divergence results in a larger laser footprint due to the increased distance between the instrument and the top of the canopy. Large old trees are particularly affected by these limitations. While the dimensions of the crown and major branches can be approximated, detailed information on smaller branches and the vegetation living on them is virtually unattainable.

Studies have been able to limit occlusion in the canopy by combining TLS measurements with unmanned aerial vehicle laser scanning (UAV-LS) above the canopy (Schneider et al., 2019; Terryn et al., 2022). It was shown that point clouds derived from TLS underestimate the plant area density in the upper canopy compared to combined TLS and UAV-LS point clouds (Schneider et al., 2019). However, due to the large distance between the UAV scanner and the area of interest, the platform's instability, and a more complex point registration, the canopy is still captured with relatively low precision and a lower spatial accuracy compared to TLS (Brede et al., 2019).

To address the two key limitations—occlusion and precision—we introduce a new concept called canopy laser scanning (CLS). This method enables detailed observation of the 3D structure of the crown of large old trees at a similar level of detail as TLS currently offers for small trees. The method involves operating a laser scanner from fixed points at several locations within the tree canopy, reducing occlusion and the distance between the area of interest and the instrument. The laser instrument can be attached to large branches by climbers or to a scaffold

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installed in the canopy. The aim of this study is to develop, test and evaluate CLS and its applicability to ecological research.

Materials and Methods

Study Sites

We collected TLS and CLS data for six large old trees across diverse forest types (Table 1). Three trees (PER1, PER2, COL; aka LOT01, 2, 3) are part of the Life On Trees core program (www.lifeontrees.org), which surveys all eukaryotic organisms on individual trees (Leponce et al., 2024). They span an altitudinal gradient from the Andes to the Amazon (Fig. A.1 in Appendix S1), from tropical rainforest (PER1) to cloud forests (PER2, COL). One tree (BRA) is in Brazil's Atlantic Forest, part of the Atlantic Forest Research and Conservation Alliance hosted by the Hidden Universe: Biodiversity initiative (www.hu-b.org). Trees were selected based on forest type and accessibility (max. 1-h hike or boat ride from lodging). Two trees (AUS1, AUS2) are famous giants located in the Huon (AUS2) and Styx Valley (AUS1) in Tasmania (Southern Australia). The Tree Projects define Tasmanian giants as trees over 75 m high, with a volume of 200 m^3 or a DBH of 2.5 m or greater (The Tree Projects, n.d.).

Data Collection

Summary

Laser scanning data were collected with the RIEGL VZ-400 (PER1) and RIEGL VZ-400i (PER2, COL, BRA, TAS1, TAS2), depending on availability. The scanners are time-of-flight (TOF) TLS systems, which currently offer the highest spatial detail available for capturing tree architecture (Calders et al., 2020; Newnham et al., 2015). Both instruments operate at a wavelength of 1550 nm with a beam divergence of 0.35 mrad and can detect multiple laser returns. The exit beam diameters are 7 mm (RIEGL VZ-400) and 6.5 mm (RIEGL VZ-400i), resulting in a beam diameter of ~10.5 mm at 10 m and ~42 mm at 100 m. The instruments cover a 30–130° zenith angle range in the upright position. An additional scan at a 90° tilt from the horizontal was performed to cover the entire

Table 1. Information on the trees, their location, forest type and scan information.

Tree species	ID	Location	Forest type	Altitude (m)	Collection date	# Canopy scans	# Ground scans	Pulse repetition rate (kHz)	Scan resolution (°mrad)
Dussia tessmannii	PER1	Rio Abiseo National Park, Peru	Lower Andean Amazon foothills	394	Apr 2022	4 (2 at 2 locations)	35	300	0.04
Ficus americana subsp. *andicola*[a]	PER2	Yanachaga –Chemillén National Park, Peru	Andean mountain forest	2240	Apr 2023	12 (2 at 6 locations)	63	600	0.04
Ficus cestrifolia[b]	BRA	RPPN Alto da Figueira, Brazil	Atlantic rainforest	1370	Oct 2023	12 (2 at 6 locations)	53	1200	0.04
Brosimum cf. *utile*	COL	Forest near Orito, Colombia	Upper Andean Amazon foothills	860	Feb 2024	12 (2 at 6 locations)	29	1200	0.04
Eucalyptus globulus (Lathamus Keep)	AUS2	Huon Valley Tasmania, Australia	Wet temperate forest	303	Dec 2023	12 (2 at 6 locations)	62	1200	0.04, 0.02[c]
Eucalyptus regnans (Gandalf's staff)	AUS1	Styx Valley Tasmania, Australia	Wet temperate foresst	455	Dec 2023	10 (2 at 5 locations)	106	1200	0.04, 0.02[c]

Note: *Ficus* trees and their host are considered here as a single 'tree'.
[a]Surrounding its host: a *Beilschmiedia latifolia*.
[b]Surrounding its host: *Sloanea garckeana*.
[c]High-resolution tilted scans were collected (ground) only when the wind was absent.

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hemisphere (Fig. B1 in Appendix S2). The instruments weigh around 10–12 kg.

We collected ground and canopy scans of all trees (Table 1, Fig. 1). Ground scans were processed first. Canopy scan locations were selected based on the TLS point cloud and climber experience. We selected climber-accessible locations that offered alternative viewpoints, prioritizing certain positions to maximize the additional information gained from each extra scan location. We used different pulse repetition rates (PRR) and scan resolutions for different trees based on prior knowledge, gained expertise and practical constraints (Table 1). We scanned in windless to light wind conditions (<5 m/s, avoiding wind gusts).

Ground Scans

Ground scans were collected in a circular pattern around the tree where possible, at 1–2 m, 5–10 m, and up to 30 m from the trunk because scans further away can still considerably add information about the tree crown (Wilkes et al., 2017). Exact scan locations were picked opportunistically based on ease of access and to minimize occlusion (Fig. 1). We acquired more scans than necessary and discarded excessive scans that did not contribute to the point cloud or added more noise.

Canopy Scans

One or two climbers and a team leader conducted the canopy scans at multiple locations that were vertically and horizontally distributed in the tree, under the supervision of a laser scanning scientist. The tilt mount (Fig. 2A), which allows the VZ-400i scanner to be inclined for comprehensive data capture, was first installed on the tree using drills and ropes. The scanner was then lifted in the tree and attached to the tilt mount, and scans were carried out at multiple angles. The scanner was manoeuvred in and out of the tree crown between scans (Fig. 2). We used two tilt mounts (PER2, COL) to speed up the process. In the BRA tree, a scaffold was built around the tree, consisting of three towers. Scans were taken on the different platforms of the scaffold at multiple angles.

The Tasmanian trees (AUS1, AUS2) have a vertical tree structure, eliminating the need to climb horizontally and thus simplifying the acquisition process. Laser scanning was conducted by three climbers and a laser scanning scientist. The scanner was lifted to the highest accessible position in the tree, and scans were taken every 10–15 m during the descent at multiple angles. Scans were taken at five to six locations within the tree crowns.

Data Processing

Data Filtering

We filtered the single scans on reflectance (−20, − 5 dB) and pulse deviation (≤15). Reflectance is defined as the reflectance of a diffuse Lambertian target filling the laser beam, which would return the same intensity as the actual target at the same distance (Calders et al., 2017). The pulse deviation quantifies the difference between the recorded waveform and the stored reference shapes (Calders et al., 2017).

Data Registration

Single scans were co-registered into a single point cloud using RiSCAN PRO version 2.15 (RIEGL Laser Measurement Systems GmbH, n.d.). For the VZ-400 data, reflective targets were used to co-register the individual scans into a single point cloud. We refined the registration using the multi-station adjustment (MSA) tool, in which the distance between overlapping areas is minimized using planes derived from the single scans. Due to the large distance between canopy and ground scans, they were registered separately and combined using the MSA tool. For the VZ-400i data, reflective targets were not needed due to the scanner's improved sensor integration, and single scans could immediately be co-registered using the Automatic Registration 2 and were further refined using the Multi-station adjustment 2 (MSA2) tool.

Tree Segmentation

Trees were manually segmented. We created two point clouds for each tree: TLS, TLS + CLS and downsampled them to 1 cm (=average laser footprint at ~10 m). This resulted in point clouds with relatively uniform point density, effectively capturing small branches and leaves while maintaining manageable data size. Downsampling was performed using RiSCAN PRO's octree-based method, followed by a significant outlier remover (nn = 6, SD = 10) in CloudCompare version 2.13 to remove floating points (CloudCompare, 2024).

Leaf Wood Separation

We used GBSeparation (Tian & Li, 2022) to extract the trunk and branches from the tree point clouds. The algorithm first constructs a graph from the point cloud, determining the shortest paths to the root point. The point cloud is then segmented into clusters, and clusters with cylindrical characteristics and/or linear characteristics are identified as initial wood points. The initial wood points are then expanded through region growth to form the final wood points, leaving the remaining points as leaf

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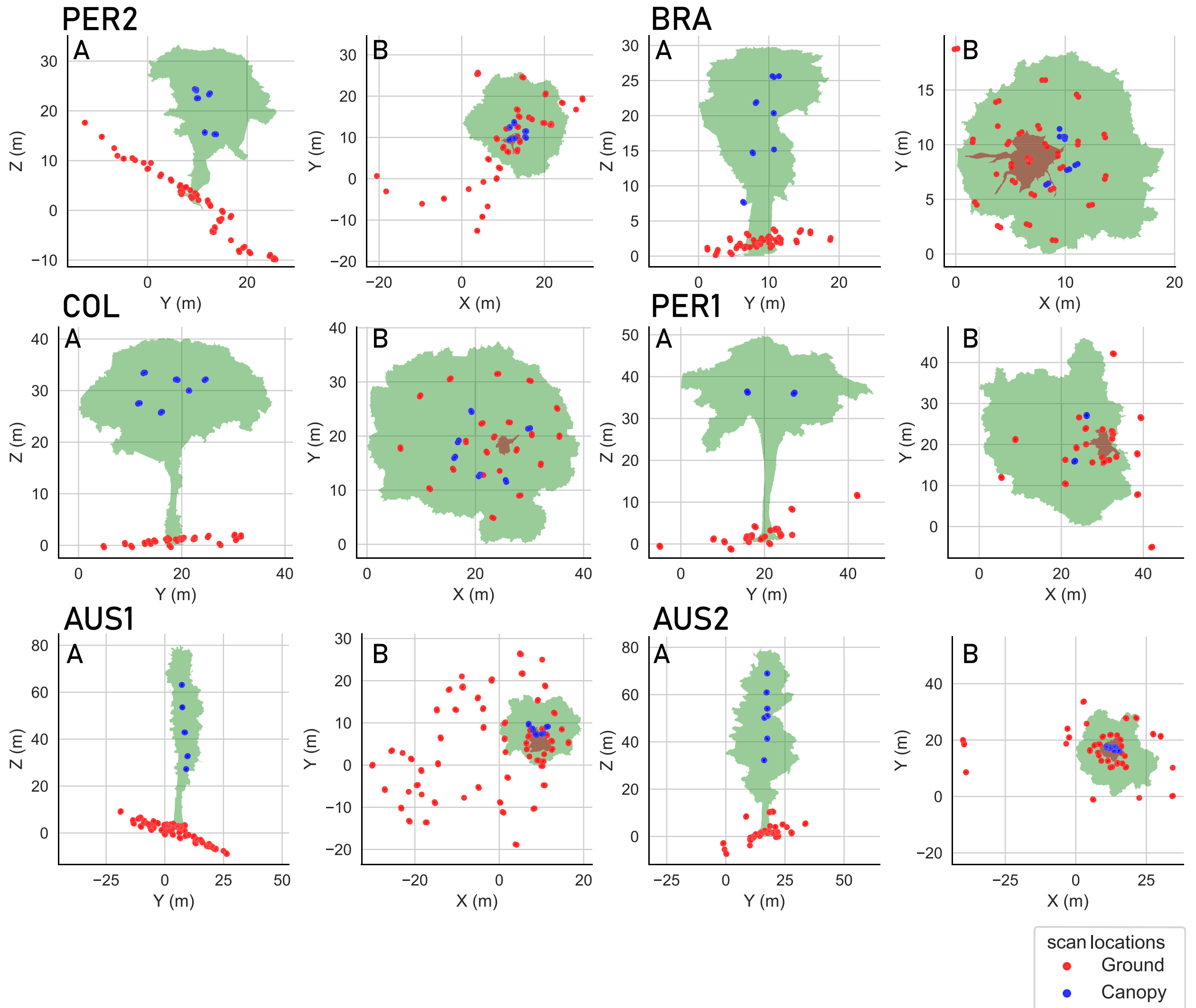

Figure 1. Scanner locations are shown on the vertical (A) and horizontal (B) projections of the trees, which are coloured green. In the horizontal projection, the brown area represents the stem section (first 7 m). Red and blue dots indicate the scanner positions at ground and canopy level, respectively.

points. The algorithm generally does not misclassify leaf points but can overlook some branches. To identify as many branches as possible, we ran GBSeparation several times with varying settings and filters and merged the results (Appendix S3).

Data Analyses

Tree Metrics

We calculated, for all TLS and TLS + CLS point clouds, the functional diameter at 6 m height (fD6m), tree height, crown projected area (CPA) and crown volume (CV) using the R package ItsMe (Terryn et al., 2023). The fD6m was calculated as the diameter of a circle with the same area as the concave hull (concavity = 1) of a 6 cm horizontal slice at 6 m height. We chose this height over the diameter at breast height (DBH) to ensure a fairer comparison between the trees, as some trees have buttresses that could skew measurements at breast height. Functional diameter was used instead of circle fitting, as many trees lacked a round stem. Tree height was calculated as the distance between the highest and the lowest point of the point cloud. Crown points were identified as points above the first major branch bifurcation. The crown area was calculated as the area of a concave hull (concavity = 2) around the *X*/*Y* coordinates of the crown points, and crown volume was estimated using an alpha shape (α = 1) around the crown points.

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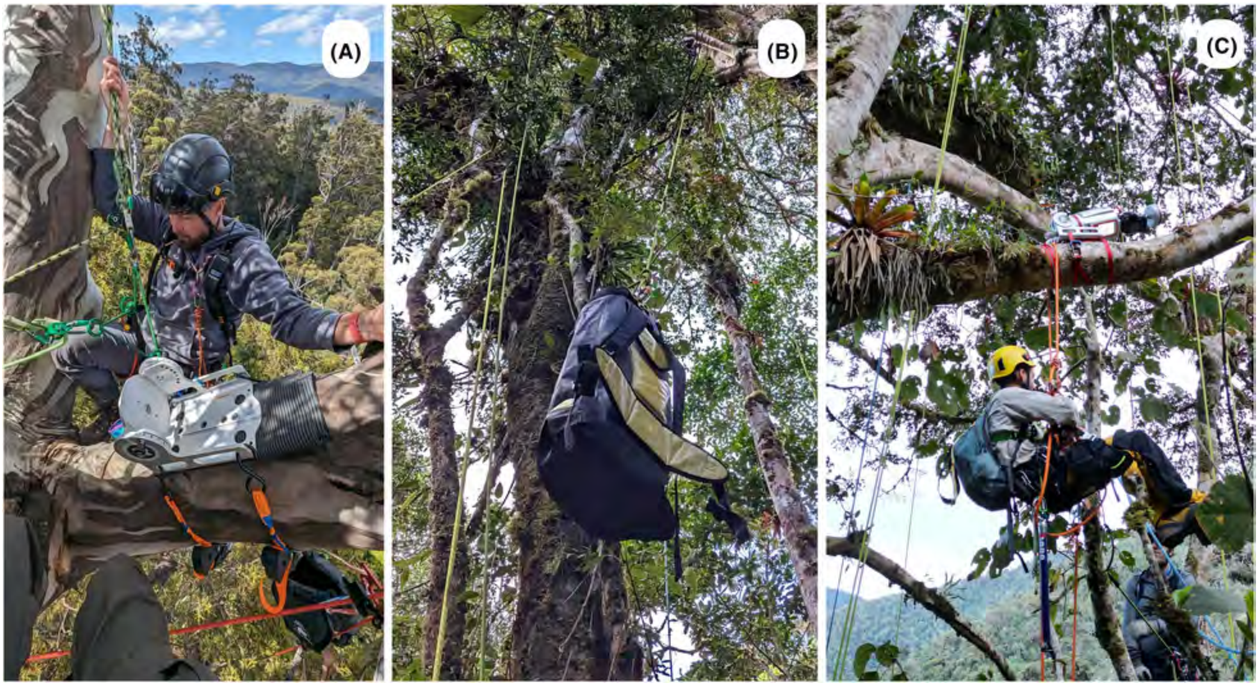

Figure 2. Tilt mount is installed onto a large branch in TAS1 (A). Scanner is lifted inside the tree crown of PER2 (B). After attachment to the tilt mount, the climbers hide and tree PER2 is scanned (C). Photo credits: Steve Pearce (A), Kim Calders (B, C).

Point Cloud Quality

We used the mean Euclidean nearest neighbour distance to compare point cloud density (Wilkes et al., 2017). Euclidean distance was calculated to a point's four closest neighbours. It provides a data agnostic measure of point distribution as it is generally independent of the effects of tree spacing and vegetation clumping (Wilkes et al., 2017). Higher values indicate closer proximity between points. If a point cloud is downsampled to 1 cm and the mean Euclidean nearest neighbour distance is also 1 cm, the 3D space is well sampled. Larger values would indicate under sampling.

We examined the spatial distribution of points using a 10 cm voxel grid. A voxel was considered occupied if it contained at least one point. While we could not determine the number of unsampled voxels in the TLS + CLS point cloud, we could calculate how many fewer voxels were occupied in the TLS point cloud compared to the TLS + CLS point cloud. This highlights occluded 3D space in TLS-only scans, which are resolved by incorporating canopy scans.

Tree Architecture

We used TreeQSM (v2.4) on the wood points to create Quantitative Structure Models (QSMs) to reconstruct the tree architecture (Burt et al., 2021; Gonzalez de Tanago et al., 2018; Raumonen et al., 2013). The algorithm first segments the point cloud, reconstructing the hierarchical branching architecture, and then fits a series of cylinders to these segments. QSMs provide branch lengths, diameters, volumes and other tree parameters. The lower part of the stem up to the first major branch was also modelled with a slice triangulation method to better model the volume of the buttress and the stem parts with a non-circular cross-section (Han et al., 2023).

Epiphyte and Foliage Distribution

To assess to what extent the taxonomic identity, abundance and distribution of epiphytes can be derived from the TLS + CLS point clouds, we manually segmented the bromeliads (members of the plant family Bromeliaceae, the pineapple family) from a 5 × 5 × 5 m^3 subset of the PER2 point cloud that was randomly picked in the upper part of the tree crown. We used a point cloud downsampled to 5 mm (instead of 1 cm) to ensure the downsampling did not impact the level of detail needed to assess the epiphytes. We also explored whether additional organisms could be identified for the BRA tree.

Results

Time and Resources

Scanning the tropical trees from within the canopy required 1–3 h/scan position, with six positions completed over

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Table 2. Time needed to collect and process the data.

	Tropical trees	Tasmanian giants
Data collection	2 days	½ day
Data registration[a]	2 h (automatic—VZ-400i), 1 day (manual—VZ-400)	2 h (automatic)
Quality control registration	5 h	5 h
Tree segmentation[a]	4–8 h (~complexity)	5–1 h
Leaf wood separation[b]	1 day (automatic)	1 day (automatic)
QSMs[a]	1–2 h	1–2 h

[a]Intel(R) Xeon(R) E-2276M CPU@2.80 GHz, 2808 MHz, 6 Core(s), 12 Logical Processor(s), 32 GB RAM.
[b]Intel(R) Xeon(R) W-2295 CPU@3.00GHz, 3000 MHz, 18 Core(s), 36 Logical Processor(s), 195 GB RAM.

2 days. The Tasmanian giants were simpler to scan, as climbers only moved vertically, requiring 3–4 h/tree. Ground scans were acquired much faster, taking between 5 and 20 min/scan location depending on the difficulty of the terrain. Data registration was automatic with the RIEGL VZ-400i and manual with the RIEGL VZ-400. Tree segmentation was performed manually, taking 30 min in open environments but up to a full day for complex cases. The most time-intensive step was leaf wood separation, conducted semi-automatically. In total, it took an average of 2 days to process a tree (Table 2).

Point Cloud Dimensions

The studied trees vary in tree structure: Tasmanian trees (AUS1, AUS2) have monopodial branching, forming tall trees with relatively small crown projection areas, while tropical trees, especially COL and PER1, show wide, complex crowns. When CLS scans were added to the TLS point cloud, the point clouds contained 2.7–4.1 times more points (subsampled to 1 cm). The additional points were predominantly located in the tree crown (Fig. 3). In tropical trees, the increase in the number of points began at the start of the crown. Tasmanian trees maintained a consistent point density for the first 10–15 m of the crown, meaning this lower part of the tree was not occluded when using TLS only.

Compared to only using ground scans, calculated crown volume was 3–9% greater for the Tasmanian trees (AUS1, AUS2) and the Ficus trees (PER2, BRA) when adding canopy scans. Crown volume was 16 and 29% larger for the complex, large tropical trees (PER1, COL). Other tree dimensions (tree height, fD6m, CPA) differed by less than 1% (Table D.1 in Appendix S4).

Point Cloud Quality

When CLS scans were added to the TLS point cloud, point cloud density increased, especially in the top part of the tree crowns (Fig. 4, Fig E.1–6 in Appendix S5). While the mean nearest neighbour distance was greater than 4 cm at the top of the tree crown using TLS scans only, the point density remained constant (around 1 cm) when combined with canopy scans. Given the downsampling to 1 cm resolution, this implies there is a uniform coverage and little to no occlusion (though this metric cannot account for hidden structures). Upon closer qualitative examination of the point clouds (Fig. 5), the improved precision and detail became evident: epiphytes were distinguishable within tree crowns, small branches were visible and branch bifurcations were better captured. Because the mean nearest neighbour metric cannot fully account for occlusion (i.e. parts of the tree crown may still be hidden from view), we also examined the spatial distribution of the points using a 10 cm voxel grid (Fig. 6). A voxel is considered occupied if it contains at least one point. There was a noticeable decrease in occupied voxels for the tropical trees when using ground scans only compared to both ground and canopy scans: −31% for BRA, −38% for PER2, −37% for ABI and −52% for COL. For the Tasmanian trees, the difference in occupied voxels was noticeably smaller, with a 15–16% decrease for AUS1 and AUS2. The difference in occupied voxels occurred in the tree crowns, with the largest differences occurring in the upper part of the crown.

Branch Architecture

We selected three structurally diverse trees (AUS2, PER2 and COL) to discuss the tree architecture. The leaf wood separation and the QSMs demonstrate the added value of canopy scans. The improved point cloud quality allowed the leaf-wood separation algorithm to correctly identify more woody points, particularly in the top part of the tree crowns, resulting in QSMs with considerably more branches. Compared to the TLS QSM, the branch length for AUS2 was 47% larger when adding canopy scans. The branch length for a smaller tree like PER2 was 28% larger.

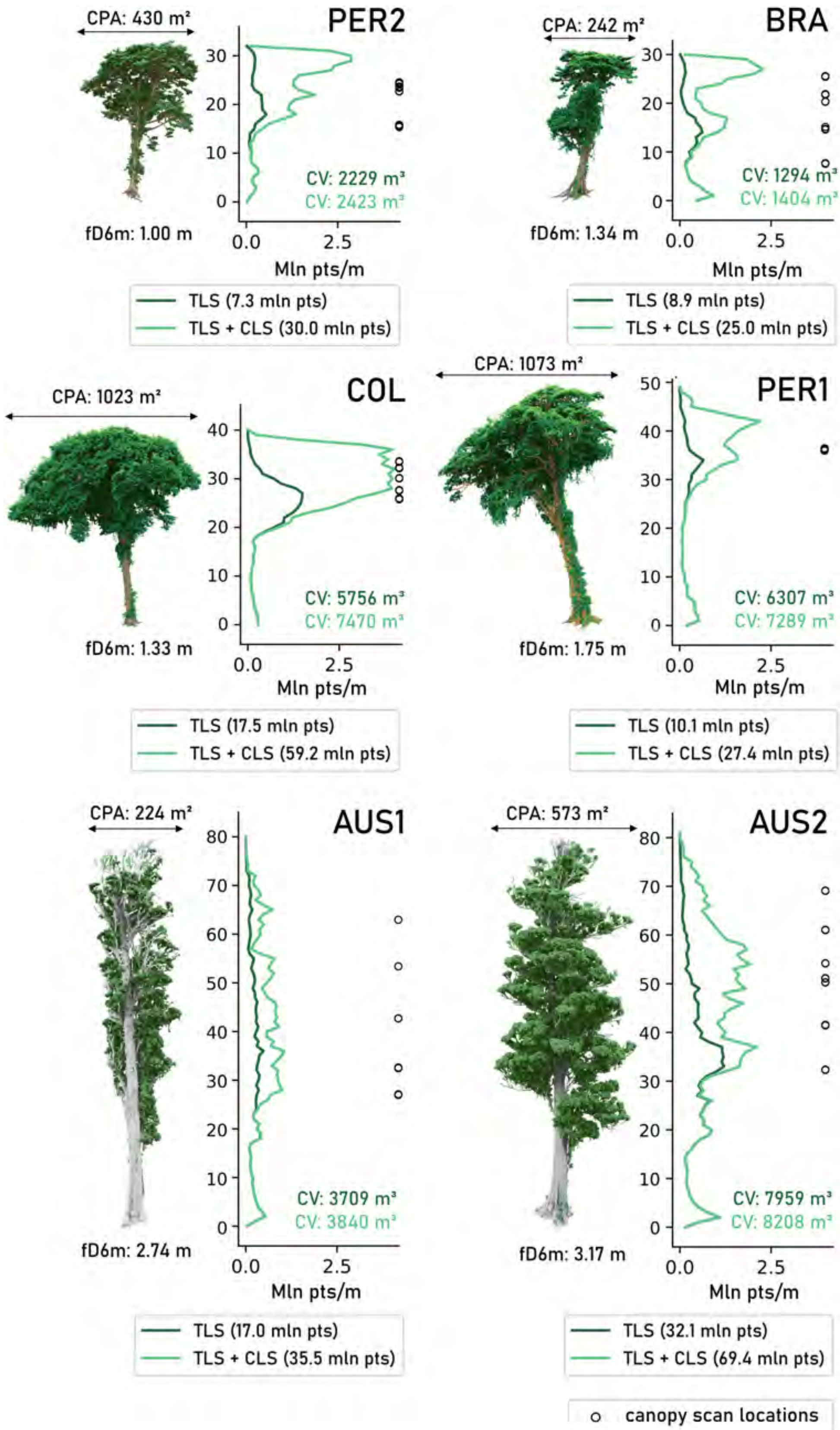

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Figure 3. Tree structural metrics and vertical point distribution. For each tree (and host tree in the case of the *Ficus* trees), we displayed the TLS + CLS point cloud and calculated functional diameter at 6 m height (fD6m), crown projected area (CPA) and tree height from the TLS + CLS point clouds (left). The amount of points in the point clouds with (TLS + CLS) and without (TLS) canopy scans, calculated per 1 m height bin, is displayed in million points per metre (right). Estimated crown volume (CV), with and without canopy scans, is also displayed on the right. Black circles indicate the different heights at which the canopy is scanned. CLS, canopy laser scanning; TLS, terrestrial laser scanning.

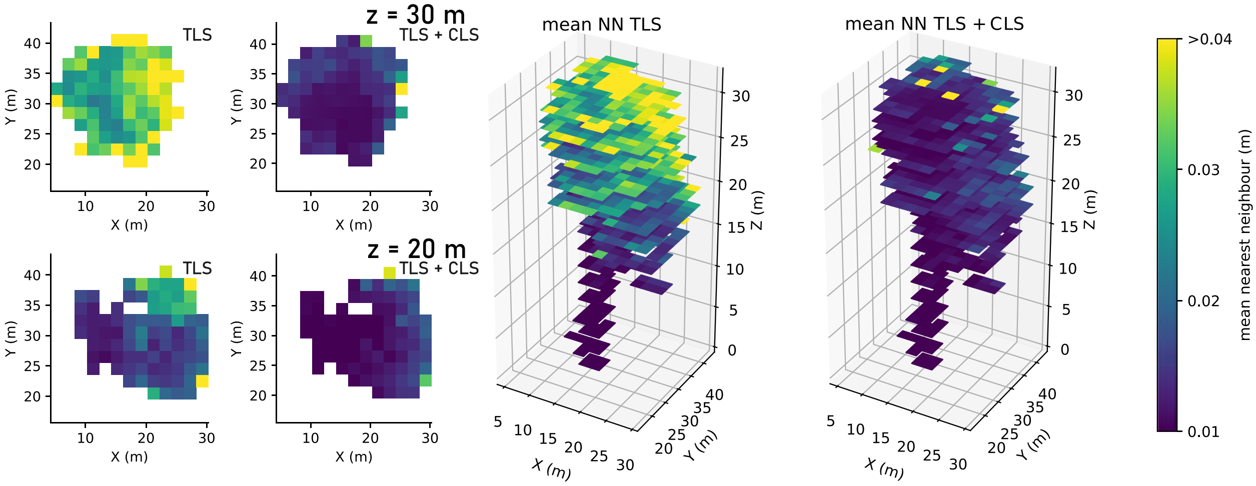

Figure 4. We calculated the mean nearest neighbour distance of each point to its four closest neighbours. We averaged this value within 2 m × 2 m voxels for the PER2 tree.

The COL tree, an extremely complex tree with branches covered with moss, epiphytes and canopy humus, showed reduced accuracy in QSM reconstruction. However, the difference in branch length is similar (+33%). The largest differences occur above 40 m in tree height for AUS2, above 30 m for COL and above 20 m for PER2 (Fig. 7).

Differences in estimated woody volume also reflect the impact of canopy scans. The estimated woody volume of AUS2 was 8.5% larger when canopy scans are included (TLS + CLS: 322 m^3, TLS: 296 m^3). For tropical trees, the estimated woody volume was 20.7% larger for PER2 and 31% for COL. The volume differences started to be noticeable at a lower height than the cylinder length differences. For AUS2, the main differences occurred between 10–20 m and 60–70 m. For COL and PER2, the largest differences appeared above 20 m and 10 m, respectively (Fig. 7).

Epiphyte and Foliage Distribution

In the TLS + CLS leaf points of the GBS leaf wood separation, we could clearly distinguish between plants located on the branches (epiphytes, such as bromeliads) and leaves from the tree (Fig. C.2 in Appendix S3). Certain plants were, however, misclassified as woody points due to their smooth texture. We therefore manually delineated the bromeliads. We segmented 38 bromeliads in a 5 × 5 × 5 m^3 selection of the PER2 TLS + CLS point cloud. The smallest distinguishable bromeliads had a diameter of 10 cm and a height of 8.5 cm (Fig. 8). Using only TLS scans, we could detect 23 bromeliads (smallest diameter 26 cm) and missed four larger bromeliads. In the BRA tree, which likely contains a very high species richness of epiphytes, taxonomists could not robustly identify specimens to genus and species in the TLS + CLS point cloud without adequate reference images produced from vouchered specimens (Fig. F.1 in Appendix S6).

Discussion

Improvements in Point Cloud Quality

By lifting a high-end laser scanner into the canopy of large old trees, we addressed two key issues of ground-based laser scanning: the relatively low point precision of the canopy and occlusion. Canopy scans improved point densities in tree crowns, which typically decline with height in TLS-only data. We achieved a uniform point spacing throughout the tree (downsampled to 1 cm).

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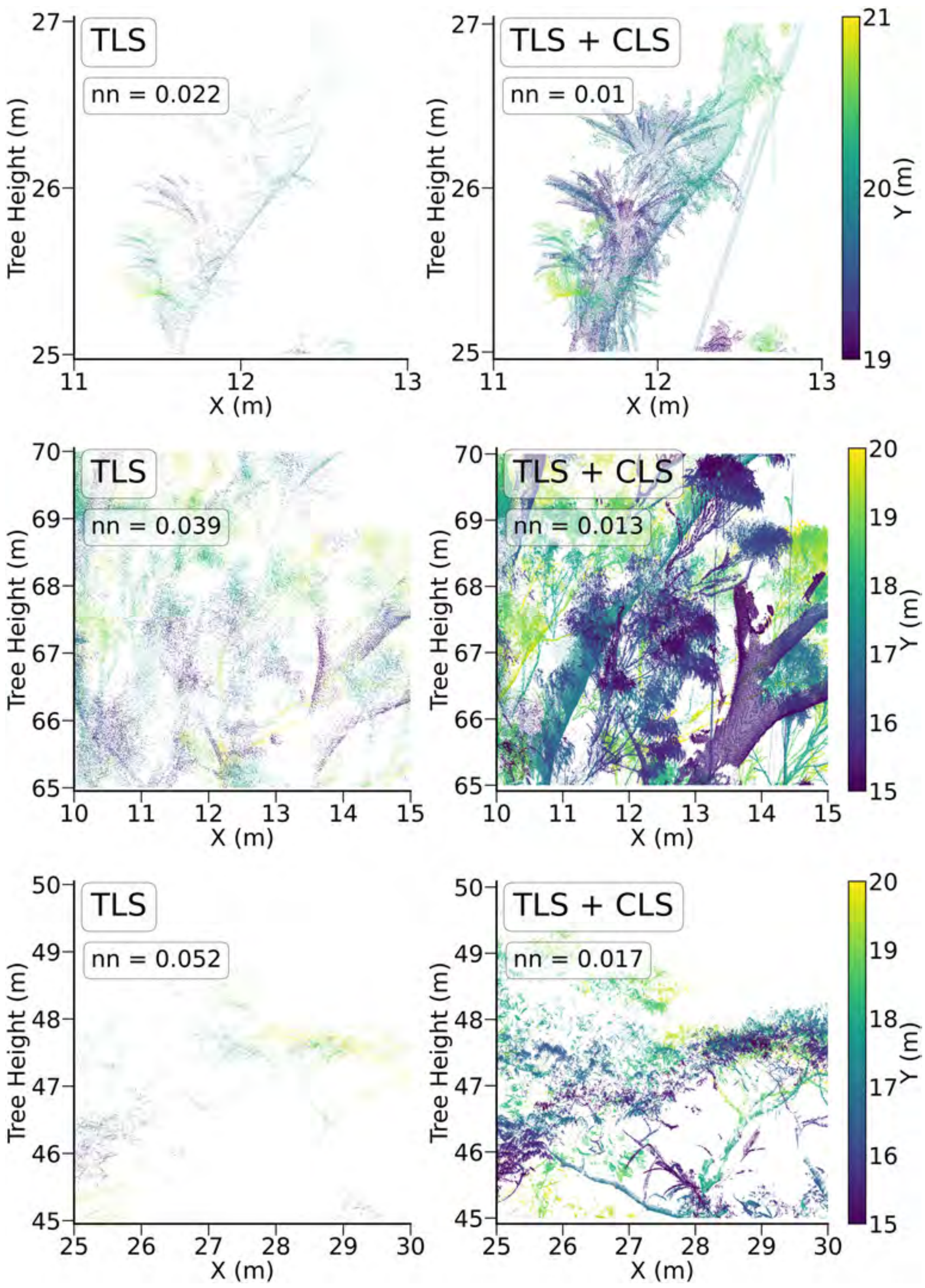

Figure 5. Three subsets of tree crowns showing point cloud detail using only ground-based scans (left) versus combined ground and canopy scans (right). A 2 × 2 × 2 m^3 volume is shown for tree PER2, and 5 × 5 × 5 m^3 volumes for trees AUS2 and PER1. Point clouds are coloured by their *Y*-coordinate, which is oriented perpendicular to the tree height axis, to highlight lateral structural detail.

By calculating the number of occupied voxels, we identified 3D space that was unsampled using TLS only (i.e. occluded regions). Due to the complementary perspective from within the canopy, more 3D space was sampled. The difference was particularly high in the dense tropical forests, with 31–52% fewer voxels occupied using ground scans only. For the Tasmanian trees, located in a more open environment, fewer voxels were unsampled using TLS alone (15–16% less). The true coverage, however, remains unknown, as accurately quantifying occlusion is

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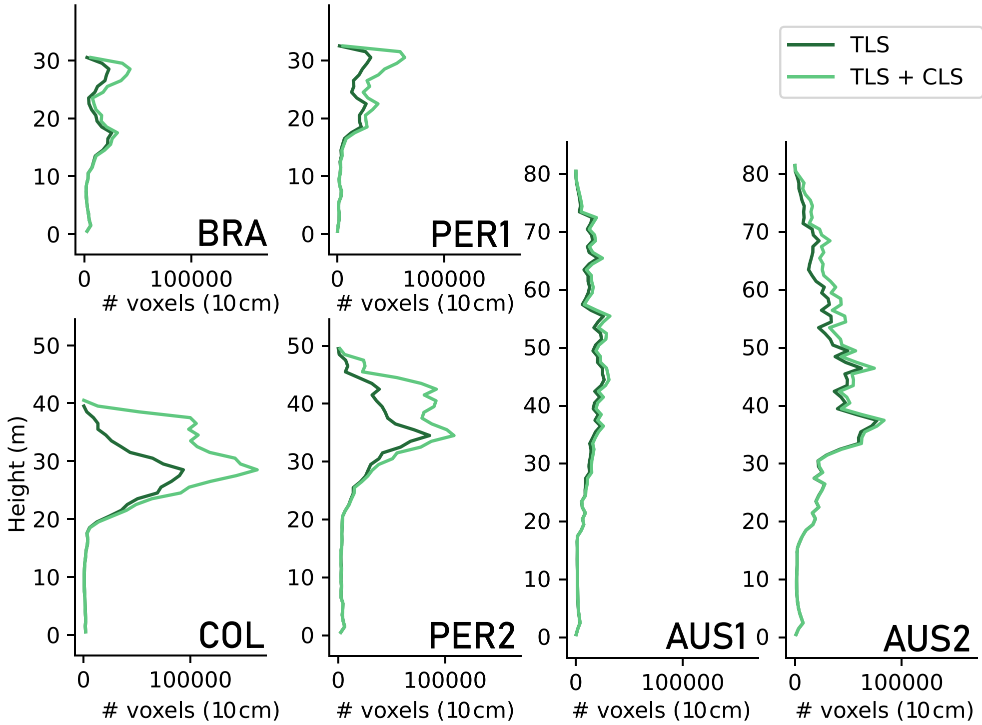

Figure 6. Number of voxels occupied as a function of tree height, using a voxel grid of 10 cm. A voxel is occupied when at least one point of the point cloud is located inside the voxel. The number of voxels is displayed per metre height.

challenging. Schneider et al. (2019) explored occlusion reduction in TLS point clouds with an additional canopy tower scan, showing a decrease in occluded voxels but not complete resolution. We did not use their algorithm but opted to compare occupied voxel counts because their ray-tracing-based algorithm has limitations, particularly in open environments.

The nearest neighbour analysis provided insight into point cloud quality on a smaller scale: maintaining a constant nearest neighbour value around 1 cm (the value to which we downsampled) indicates highly detailed point clouds. The canopy scans indeed revealed detailed views of branches and their bifurcations. The canopy biome, including bromeliads and other epiphytes, became visible as a micro-ecosystem, allowing us to clearly distinguish leaves and wood of the tree itself and of epiphytes.

Branch Architecture

The quality of the QSMs considerably improves when using canopy scans, particularly in the upper canopy, where QSMs from TLS + CLS point clouds contained substantially more branches. According to Burt et al. (2021), who studied the AGB distribution of 10 large trees, a large part of AGB (and thus tree volume) is concentrated in the tree crown (42–62% AGB). This underscores the need for precise and detailed mapping of branches in tree crowns. For in-depth canopy research, improved leaf-wood separation algorithms can further improve the quality of the branch architecture in QSMs. However, for tropical trees with wide and complex crowns (e.g. PER1, COL), the main branches are covered and occluded due to plant material and canopy soil, making it impossible to derive their true wood dimensions from the point cloud, regardless of the LiDAR technique. The suboptimal quality of QSMs for these trees highlights the difficulty in accurately quantifying tree volume and derived above-ground biomass (AGB) for the oldest and largest trees of the forest without destructively harvesting the tree. To get an indication, only using TLS ground scans, previous research reported an RMSE of 23.7% when estimating AGB compared to destructive harvest measurements for large tropical trees (Gonzalez de Tanago et al., 2018). Note that all trees in that study had volumes <30 m^3, with only one tree exceeding 40 m^3.

Epiphyte and Foliage Distribution

The high precision of the TLS + CLS point clouds enables mapping epiphytes such as bromeliads and

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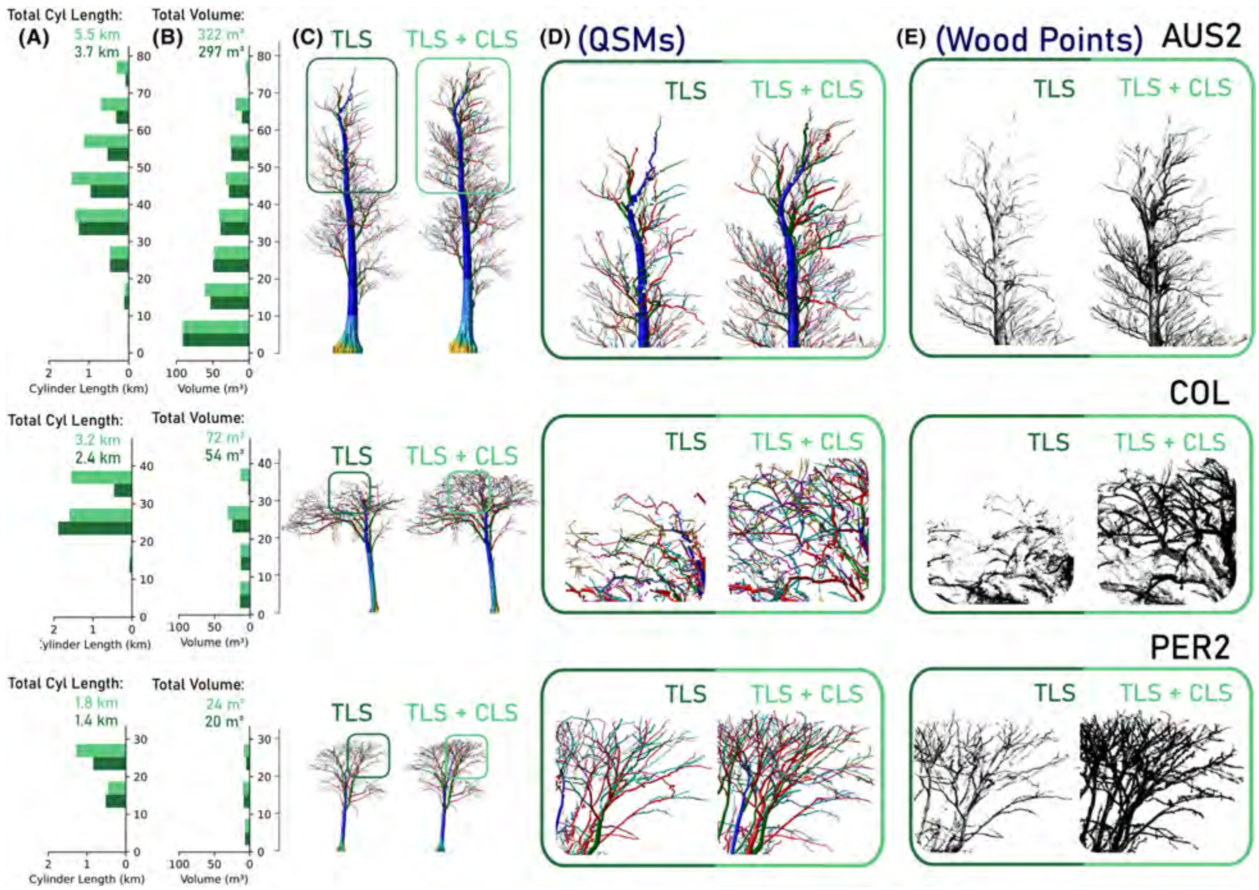

Figure 7. (A) cylinder length and (B) volume per 10 m height interval of the Quantitative Structure Models (QSMs) (average values of 10 generated QSMs). (C) an example of a QSM model. (D) A zoomed-in view of the QSMs and the wood points (E) on which the QSM is based.

observing their distribution within the canopy. For a $5 \times 5 \times 5$ m^3 grid, we identified 38 bromeliads manually, with the smallest measuring 10 cm in diameter. The scanner's distance to a branch within the canopy can still reach up to 20 m, resulting in a laser footprint of ~1.4 cm for the RIEGL VZ-400(i), making the identification of epiphytes smaller than 10 cm challenging, as well as larger individuals whose diagnostic features (such as spines along the margins of bromeliad leaves characteristic of certain genera). Scans could be supplemented with photographs to enhance identification in future work to lower taxonomic levels. Further research could focus on developing algorithms to automatically detect, segment and classify various types of leaf material within the tree canopy—such as bromeliads, other epiphytes and tree leaves—using deep learning, machine learning or mechanistic models. Image data could be integrated to enhance recognition, potentially using image recognition and classification algorithms under a supervised machine learning approach.

Biodiversity and Microclimate

The abundance and distribution of organisms on a tree is influenced by both the tree's structure and its microclimate. Although not directly investigated in this study, we believe that the high-quality TLS + CLS point cloud enables detailed analysis of these factors. Future research should explore radiative transfer modelling (RTM) to quantify the light environment within the canopy. RTM could particularly benefit from CLS, as CLS excels at capturing the upper canopy where light interception is critical. The high-quality point clouds might allow 3D-explicit tree reconstruction as input for RTM, which is not possible with TLS leaf-on data due to occlusion (Liu et al., 2024). We can then map the different microclimates in the tree crown by combining RTMs with temperature and humidity loggers inside the tree (see, e.g. the MicroClimate Database hosted by the Microclimate Ecology & Biogeography network; http://meb-network.com). Species distributions can then be correlated with

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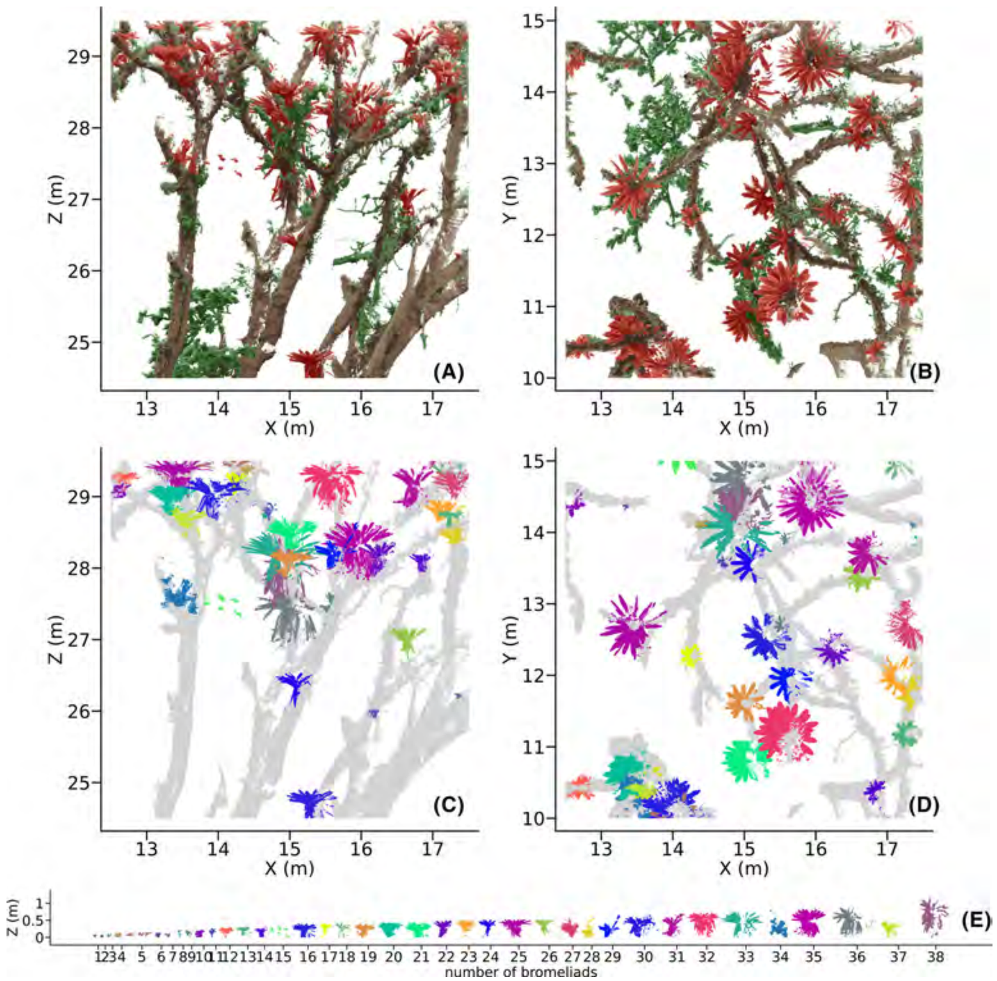

Figure 8. A 5 × 5 × 5 m^3 selection of the PER2 point cloud (TLS + CLS). (A, B) We manually segmented the bromeliads from the point cloud (red). The brown and green represent the remaining wood and leaf points, respectively, that were labelled by the automatic leaf-wood separation. (C, D) We counted 38 bromeliads and coloured each bromeliad specimen differently. (A, C) Side view. (B, D) Top view. (E) Bromeliads are ordered from small to large.

these environmental metrics and other tree characteristics, such as branching angles and thickness (derivable from QSMs). If data are collected at multiple timestamps, this approach could also enhance our understanding of ecological dynamics by capturing temporal changes in canopy structure, species distributions and microclimatic conditions. If the canopy is scanned with limited disturbance (using a scaffold, tree tower or canopy; see, e.g. https://treefoundation.org/), the tree can be monitored by scanning at ecologically meaningful intervals, and the growth, productivity, turnover and movement of species and individual specimens can be monitored.

Practical Considerations

We employed two techniques to scan inside canopies: climbing the tree and using scaffolds. When already in place, the scaffold method does not require specialist climbers, speeds up the acquisition process and allows us to scan the canopy with limited disturbance. However, multiple scaffolds are needed to cover the tree from various horizontal viewpoints. Scanning through scaffold holes also introduces point deviations and additional noise near the scanner, likely due to diffraction, partial reflection, or multipath effects of the laser beam (Figs G.1 and G.2 in Appendix S7). Climbing avoids scaffold construction and is effective for very large and/or wide crowns, allowing ample vertical and horizontal movement. It, however, requires a specialist climbing team and involves handling numerous ropes inside the canopy that can affect branch stability and disrupt the canopy biome. Movement within the canopy can also be slow and complex, especially when moving horizontally. Depending on the position, it took 1–3 h to safely set up the scanner in

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the chosen location, and 2 days were needed to scan 6 locations. The Tasmanian trees, where a vertical rope was sufficient, could be scanned in one go and took only half a day. CLS is thus time-consuming but still manageable for individual tree research—especially if other canopy research is already being conducted on site that requires tree climbers. It is, however, not suitable for forest-scale studies.

Optimal scanning conditions include no wind and a consistent tree status (wet or dry). This consistency is crucial for canopies with water-retaining material such as bryophytes, orchid roots and bromeliads. Post-rain tree architecture can change considerably, especially in cloud forests, where the weight of the wet material can shift branch positions. In addition, ropes and climbers add extra weight, potentially shifting branch architecture. While multiple tilts and scans at one location can increase spatial detail, it can also increase noise, particularly in windy conditions. We advise to visually check each scan for a good alignment to maintain point cloud quality.

During registration with the VZ-400 scanner, reflective targets placed inside the tree proved ineffective to co-register scan locations due to the large distance between the canopy and the ground. Coarse manual registration was needed, which was time-consuming but yielded the desired results. For future research, we advise not to place reflectors in the canopy, but to align canopy scans manually. For the VZ-400i, we put a GNSS base station close by to get RTK (real-time kinematic) corrections, which facilitated the point cloud registration.

The study is limited by the small sample size (six trees) and the fact that true tree dimensions remain unknown. The primary goal is to evaluate the comparative improvement of combining CLS with TLS versus TLS alone. While the Tasmanian trees are exceptionally tall, the tropical trees included here are not unusually large by tropical standards. Many tropical trees are thus likely to face similar measurement constraints when scanned only from the ground.

UAV-LS Alternative

A UAV-LS flight is a non-disruptive alternative to capture tree crowns and can be conducted below and/or above the canopy, or by spiralling around the canopy. While flights conducted below the canopy also tend to undersample the upper crown (Hyyppä et al., 2020), flights above the canopy do capture the upper crown well but can undersample lower parts (Terryn et al., 2022). Spiral flights around the tree can improve coverage but are challenging in dense tropical forests. If crowns are large, data gaps could also still persist in the centre of the tree. In situations where the tree stands out, spiral flights may offer an alternative to CLS. A spiral UAV-LS flight around AUS1 showed excellent coverage without occlusion but lower precision than TLS + CLS, with more noise (Fig. H.1 in Appendix S8). This noise complicates detecting fine structures like cavities and epiphytes and can bias measurements like branch dimensions. Mobile systems have been shown to overestimate volumes in QSMs (Brede et al., 2019; Vandendaele et al., 2024) but produce more contiguous point clouds than TLS (Terryn et al., 2022). The choice between TLS + CLS and UAV-LS depends on the application. Future improvements in stabilizers, co-registration and low-divergence scanners may enhance UAV-LS precision, potentially enabling high-quality LiDAR data collection in dense canopies.

Conclusion

We mapped the canopies of large, old trees using CLS. These trees are invaluable components of ecosystems; they sustain a rich and unique biodiversity, play key ecological roles and are the main drivers of AGB. Due to their complexity, they are challenging to map accurately using TLS. CLS addresses the two key limitations of TLS: high occlusion levels in the canopy and the reduced point cloud precision. Combining CLS and TLS resulted in more uniform point densities, higher point cloud quality, less occlusion and larger crown volume estimates compared to using TLS scans alone. Moreover, derived QSMs exhibited branch length and volume that were, on average, 20% larger, primarily located at the upper portion of the crown. The consistent high point cloud quality enabled detailed examination of both the tree structure and the canopy vegetation. While bromeliads larger than 10 cm could effectively be mapped, plant identification remains challenging at low taxonomic levels (species and genera). Taxonomic precision could increase through pre-surveys that map common or structurally distinguishable species in particular habitats.

Applications of CLS extend across disciplines, offering new opportunities in biodiversity assessments, forest biomass estimation, and ecological modelling. CLS data can lead to improved carbon estimates of large old trees (that are not heavily covered with canopy soil). It can also help understand microhabitat distributions and species interactions within tree canopies. Beyond research, the high-quality LiDAR visualizations from single tree biodiversity projects can engage the public, fostering awareness of the ecological importance of large old trees and inspiring stronger conservation efforts and strategies.

Despite its promise, CLS currently requires significant resources, including professional climbers, specialized and

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expensive equipment, and considerable investment of time and labour. Future innovations, such as lightweight, autonomous scanning technologies or UAVs capable of high-resolution canopy scans, could reduce costs and improve accessibility. Overall, CLS enhances individual tree research across diverse scientific disciplines, advancing our understanding of canopy structure, biodiversity and ecosystem functions.

Author contributions

Barbara D'hont: Conceptualization; methodology; data curation; writing – original draft; writing – review and editing; formal analysis; visualization; investigation; funding acquisition. **Kim Calders:** Conceptualization; methodology; data curation; writing – review and editing; funding acquisition. **Alexandre Antonelli:** Conceptualization; methodology; writing – review and editing; funding acquisition. **Thomas Berg:** Writing – review and editing. **Wout Cherlet:** Data curation; writing – review and editing. **Karun Dayal:** Writing – review and editing. **Olivia Jayne Fitzpatrick:** Writing – review and editing. **Leonard Hambrecht:** Data curation; writing – review and editing. **Maurice Leponce:** Conceptualization; methodology; data curation; funding acquisition; writing – review and editing. **Arko Lucieer:** Data curation; writing – review and editing. **Olivier Pascal:** Conceptualization; methodology; funding acquisition; writing – review and editing. **Pasi Raumonen:** Methodology; writing – review and editing. **Hans Verbeeck:** Conceptualization; methodology; writing – review and editing.

Acknowledgements

We particularly thank the tree climbing teams: without them, the canopy would remain unexplored territory. Specifically, we thank Noui Baiben, Charlie Delhumeau, Jean-Yves Serein, Laurent Grosman, Matias Loubes, Benjamin Rebreyend and Matthieu Audoin for their unabated climbing of the trees in Peru and Colombia; tree climbers Steve Pearce, Toni Sterai, Jack O'Hare, Sam Hardingham, Shaun Green and Jan Corigliano for their amazing assistance with the climbing and guidance in Tasmania. We also thank Alexandre Salino, Igor Kessous and Gerhard Zotz for discussions on the potential of LiDAR data for studying and identifying epiphytes on the Brazilian tree; and the anonymous reviewers for their insightful suggestions. This study was partly conducted in the framework of the 'Life on Trees' (www.lifeontrees.org) Program, a joint initiative of the Royal Belgian Institute of Natural Sciences and the Fonds de Dotation Biotope pour la Nature in partnership with the Museo Historia Natural de la Universidad Nacional Mayor de San Marcos, Peru, the Servicio Nacional de Áreas Naturales Protegidas por el Estado (SERNANP, Peru), the Instituto de Investigación de Recursos Biológicos Alexander von Humboldt (Colombia).

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.15880856.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used Chat-GPT in order to improve the readability of the paper. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published paper.

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