APPLICATION

Analysing individual 3D tree structure using the R package ITSMe

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Funding information
Bijzonder Onderzoeksfonds

Handling Editor: Paul Galpern

Abstract

1. Detailed 3D quantification of tree structure plays a crucial role in understanding tree- and plot-level biophysical processes. Light detection and ranging (LiDAR) has led to a revolution in tree structural measurements and its 3D data are increasingly becoming publicly available. Yet, calculating structural metrics from LiDAR data can often be complex and time-consuming and potentially requires expert knowledge.

2. We present the R package Individual Tree Structural Metrics (ITSMe), a toolbox that works with LiDAR tree point clouds and quantitative structure models (QSMs) derived from LiDAR point clouds to obtain individual tree structural metrics. It serves as a robust synthesis framework for researchers who want to readily obtain structural information from 3D data of individual trees.

3. The package includes functions to determine basic structural metrics (tree height, diameter at breast height, diameter above buttresses, projected crown area, 3D alpha crown volume) from individual tree point clouds, as well as more complex structural metrics (individual tree component volumes, branch angle-, radius- and length-related metrics) from QSMs.

4. The ITSMe package is an open-source package hosted on GitHub that will make the use of 3D data more straightforward and transparent for a range of end-users interested in exploiting tree structure information.

KEYWORDS
LiDAR, quantitative structure models, R package, tree structural metrics

1 | INTRODUCTION

Measurements of tree structure, defined as the 3D size and spatial arrangement of the basic components of a tree (e.g. twigs, branches, leaves), play a crucial role in understanding tree- and plot-level biophysical processes (e.g. photosynthesis and evapotranspiration; Lau et al., 2018). In the past, tree structure quantification was limited to metrics that are easily measurable in the field, for example, the diameter at breast height (DBH) and the tree height (H). Yet, even these metrics are sometimes difficult to measure, for example, in tropical forests due to buttressed trees and dense canopies (Terryn et al., 2022). More complex structural metrics that are, for instance, based on branching angles, lengths and radii are practically impossible to measure manually in the field for more than a handful of trees (Wilkes et al., 2021). Therefore, studies linking a tree's complex structure with, for example, its functionality or, biotic or abiotic environment, have remained limited (Verbeeck et al., 2019).

The emergence of light detection and ranging (LiDAR, also called laser scanning) and more specifically terrestrial laser scanning (TLS) in forestry has led to a revolution in tree structural measurements (Calders et al., 2020; Malhi et al., 2018; Newnham et al., 2015). TLS is an active remote sensing technique that can accurately measure distances by transmitting laser pulses and analysing the returned energy as a function of time (Calders et al., 2015). Using laser scanners mounted on unoccupied aerial vehicles (UAV-LS) is also an interesting tool to monitor forest structure as it can cover larger areas in a fraction of the time compared to TLS (Terryn et al., 2022). Calders et al. (2020) have shown that laser scanning data will play a critical role in understanding fundamental ecological questions about tree size and shape, allometric scaling, metabolic function and plasticity of form.

In the last decade, TLS and UAV-LS have been used to quantify the structural complexity of forest stands (Atkins et al., 2018; Ehrbrecht et al., 2017; Terryn et al., 2021) and there has also been significant progress in the development of algorithms for individual tree detection, segmentation and reconstructive modelling which allows detailed quantification of individual tree structure. Several semi-automatic tree segmentation algorithms enable the user to quickly obtain individual tree point clouds from laser scanning data acquired at the plot level (Burt et al., 2019; Krisanski et al., 2021; Raumonen et al., 2021). From these individual (leaf-on) tree point clouds, tree structural metrics (e.g. the DBH, H, etc.) have been reliably measured (Calders et al., 2015; Terryn et al., 2022). To infer volumes and complex structural metrics of trees, algorithms that model the tree point cloud using geometric shapes (often cylinders) have been developed (Åkerblom et al., 2017; Hackenberg et al., 2014; Pfeifer et al., 2004; Raumonen et al., 2013). TreeQSM (https://github.com/InverseTampere/TreeQSM) by Raumonen et al. (2013), a freely available quantitative structure model (QSMs) method, has been used for purposes such as the non-destructive estimation of AGB (Calders et al., 2015), tree species classification (Åkerblom et al., 2017; Terryn et al., 2020) and the quantification of branch architecture (Lau et al., 2018).

Increasingly, more datasets with tree point clouds and QSMs are becoming publicly available for a broader group of scientists that are not specifically trained in processing LiDAR point clouds (Calders et al., 2020; Weiser et al., 2022). Moreover, laser scanning and 3D tree data are more frequently used by governments to upgrade their national forest inventories (Kükenbrink et al., 2022; Puletti et al., 2021), and can help to manage our natural capital through the evaluation of nature-based solutions projects that focus on carbon sequestration (Girardin et al., 2021). Hence, there is a growing need for accessible tools that translate the calculations of structural metrics into easy-to-use and well-documented functions. The open-source software environment R, which ecologists widely use, is free, does not require a specific licence and can be used across many platforms with shared compatibility (Atkins et al., 2022). Thus, it is a suitable environment to develop and share 3D forest structure-related packages to stimulate forest structure-related research. Several of these packages in R already exist (Atkins et al., 2018, 2022), yet most focus on stand structure from airborne laser scanning. Of the TLS-related R packages, Atkins et al. (2022) identified, only the FORTLS package of Molina-Valero et al. (2022) allows for the determination of individual tree attributes from point clouds (DBH and H), but mainly focuses on providing these metrics and variables at stand level. Both the VoxR (Lecigne et al., 2017) and rTLS package (Guzmán et al., 2019) allow to determine the H, DBH and some volume and crown characteristics from tree point clouds but lack flexibility in the DBH measurement for different types of trees (e.g. buttressed trees) and a comprehensive user manual. Moreover, no R package supporting the calculation of individual tree structural metrics from QSMs appears to be available (Figure 1).

In this paper, we present the R package Individual Tree Structural Metrics (ITSMe), a toolbox that works with tree point clouds and QSMs in the TreeQSM format (Calders et al., 2015; Raumonen et al., 2013), to obtain individual tree structural metrics efficiently (Figure 1). It serves as a synthesis framework for a range of end-users (e.g. researchers, foresters, etc.) who want to easily obtain structural information from individual tree point clouds and/or TreeQSMs. More specifically, with the ITSMe package, you can easily calculate (i) the tree height (H), DBH, the diameter above buttresses (DAB), the projected crown area (PCA), and the 3D alpha crown volume (ACV) from multiple individual tree point clouds and (ii) the structural metrics defined by Åkerblom et al. (2017) and Terryn et al. (2020) from multiple TreeQSMs.

The package can be freely downloaded from GitHub and is accompanied by a documentation website. The ITSMe package will lower the threshold for researchers to use forest and tree 3D data for various purposes (e.g. tree monitoring, linking tree structure to tree functionality or environmental factors).

2 | MATERIALS AND METHODS

2.1 | ITSMe availability

The current version (1.0.0) of the package ITSMe requires R version 2.10 or above and is distributed under the MIT licence. The package can be downloaded from GitHub at https://github.com/lmterryn/
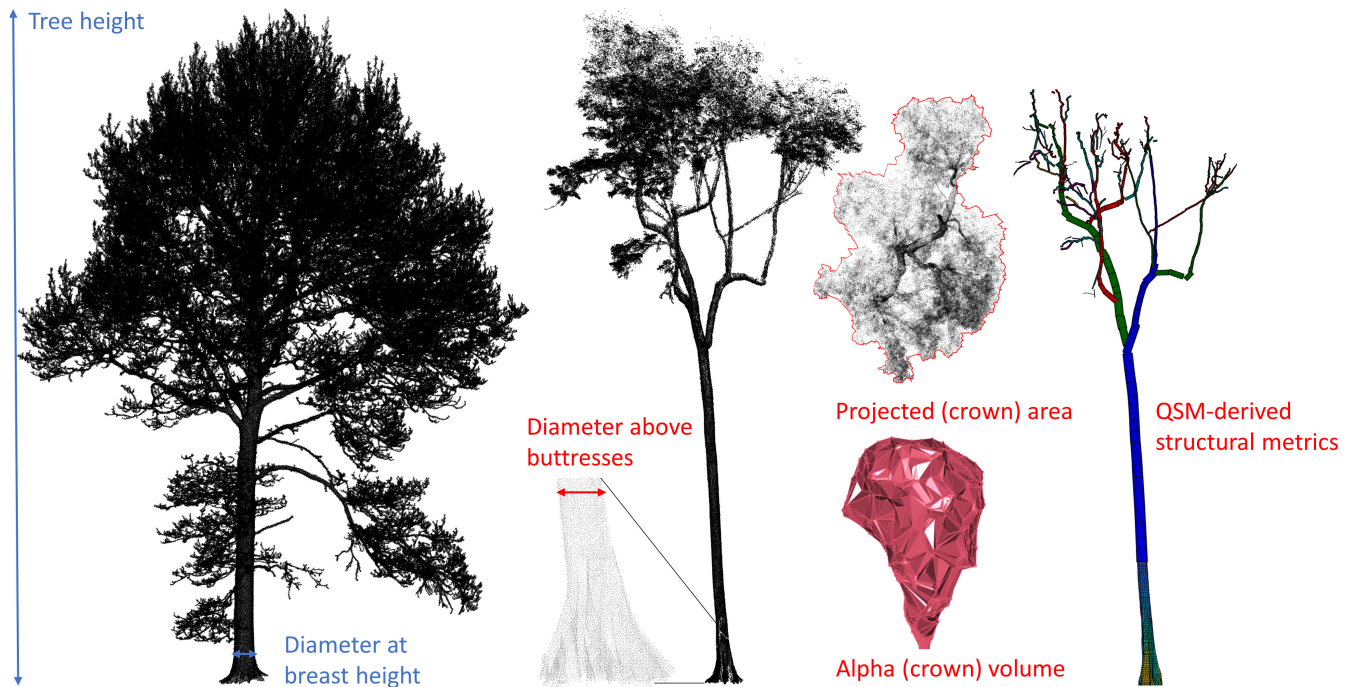
FIGURE 1 Illustration of structural metrics that can already be determined using the packages available at the moment (blue) and those that the Individual Tree Structural Metrics (ITSMe) package offers additionally (red).

TABLE 1 List of essential support functions available in the ITSMe package

Support function	Description
read_tree_pc	Reads a tree point cloud file of txt, las or ply format
classify_crown_pc[a]	Identifies and returns the tree points belonging to the crown
diameter_slice_pc[b]	Returns the fitted diameter of a point cloud slice at a chosen height
extract_lower_trunk_ pc	Identifies and returns the tree points belonging to the first 1.5 m of the trunk without branches
read_tree_qsm	Reads a TreeQSM Matlab file (.mat)

[a]The crown is defined as the leaves and the woody part above the start of the lowest branch. Plot for all tree point clouds in a folder with the *plot_crown_classification_pcs* function.
[b]Plot for all tree point clouds in a folder with the *plot_circle_fit_pcs function*.

ITSMe. The current and future versions of the package will also be hosted at Zenodo (https://doi.org/10.5281/zenodo.6769105). The ITSMe website is available at https://lmterryn.github.io/ITSMe/ and includes documentation of a complete workflow to help the user get acquainted with the package.

2.2 | Structural metrics

To determine individual tree structural metrics with the ITSMe package you only require tree point cloud files (txt, ply or las format with the x, y and z coordinate attributes of the points) and/or TreeQSM files (mat format). The package provides two read functions, one to read the tree point cloud file and one to read the TreeQSM file, that transform those files to the required input format for the other functions in the package (Table 1). Figure 2 presents a flowchart, illustrating the input, functions and output of the ITSMe package.

2.2.1 | Tree point cloud-based metrics

The ITSMe package includes functions to obtain the H, DBH, DAB, PA and AV from individual tree point clouds (Table 2). H is calculated as the height difference between the highest and the lowest point of the tree point cloud. In case, the lower part of the tree is not sampled (e.g. with low point density UAV-LS or in dense forests), a digital terrain model (DTM) can be provided and is used to estimate the lowest point of the tree.

DBH is calculated as the diameter of the optimal circle fitted through a horizontal slice of a chosen thickness (default 6 cm) around 1.3 m from the lowest point of the tree point cloud. To fit the circle, a least-squares circle fitting algorithm was applied (Calders et al., 2015). If there are branches at breast height (indicated by the residuals of the circle fit, or the estimated diameter is larger than 2 or larger than the diameter at 15 cm above ground), the lower trunk (up to 1.5 m) without the branches is extracted and a new circle fitting
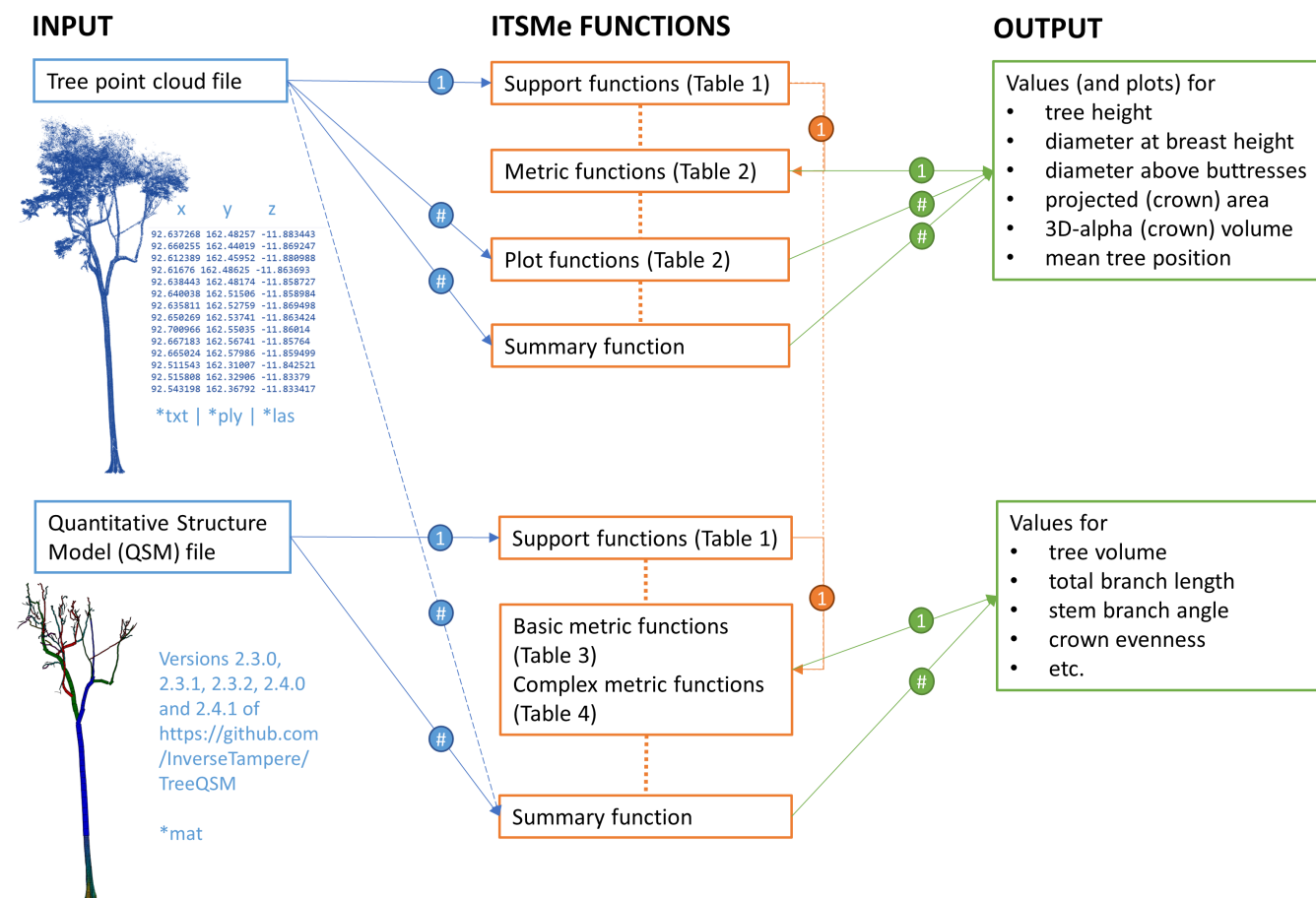
INPUT

Tree point cloud file

x	y	z
92.637268	162.48257	-11.883443
92.660255	162.44019	-11.869247
92.612389	162.45952	-11.880988
92.61676	162.48625	-11.863693
92.638443	162.48174	-11.858727
92.640038	162.51506	-11.858984
92.635811	162.52759	-11.869498
92.650269	162.53741	-11.863424
92.700966	162.55035	-11.86014
92.667183	162.56741	-11.85764
92.665024	162.57986	-11.859499
92.511543	162.31007	-11.842521
92.515808	162.32906	-11.83379
92.543198	162.36792	-11.833417

*txt | *ply | *las

Quantitative Structure Model (QSM) file

Versions 2.3.0, 2.3.1, 2.3.2, 2.4.0 and 2.4.1 of https://github.com /InverseTampere/ TreeQSM

*mat

ITSMe FUNCTIONS

Support functions (Table 1)

Metric functions (Table 2)

Plot functions (Table 2)

Summary function

Support functions (Table 1)

Basic metric functions (Table 3)
Complex metric functions (Table 4)

Summary function

OUTPUT

Values (and plots) for
- tree height
- diameter at breast height
- diameter above buttresses
- projected (crown) area
- 3D-alpha (crown) volume
- mean tree position

Values for
- tree volume
- total branch length
- stem branch angle
- crown evenness
- etc.

FIGURE 2 Flowchart illustrating the input, functions and output of the ITSMe package.

TABLE 2 List of the point cloud-based structural metrics and their respective functions in ITSMe

Structural metric	Abbreviation	Metric function[a]	Plot function[b]
Mean x, y, z tree positions	—	*tree_position_pc*	—
Diameter at breast height (m)	DBH	*dbh_pc*	*plot_dbh_fit_pcs*
Diameter above buttresses (m)	DAB	*dab_pc*	*plot_dab_fit_pcs*
Tree height (m)	H	*tree_height_pc*	*plot_tree_height_pcs*
Projected (crown) area (m^2)	PA, PCA	*projected_area_pc*	*plot_pa_pcs*
3D alpha (crown) volume (m^3)	AV, ACV	*alpha_volume_pc*	*plot_av_pcs*

[a]The metric function is the function with which the metric is determined for a single tree.
[b]The plot function is the function with which the metric is determined for multiple trees in a folder and the accompanying figure is produced.

is done. This trunk extraction is based on an iterative method which combines k-means clustering and circle fitting. Also the functional DBH (fDBH) is calculated by determining the area of the concave hull (concavity = 4) constructed on the slice at breast height and deriving the diameter of a circle with the same area (Disney et al., 2020).

For buttressed trees, the diameter needs to be determined above the buttresses (DAB). In this case, an iterative approach was implemented to determine the height above buttresses. Starting at 1.27 m to 1.33 m from the lowest point of the tree point cloud, the average residual between the points and the fitted circle is calculated. When the average residual exceeds a value of a user-defined

parameter (*thresholdbuttress*, default = 0.001) times the radius, indicating a non-circular (irregular) stem shape and presumably buttresses, the process is repeated with a new slice 6 cm higher than the previous one until a slice above the buttresses is reached. When the maximum buttress height (user-defined parameter) is exceeded, the iterative process is restarted with a higher *thresholdbuttress*. Similar as with the fDBH, also a functional DAB (fDAB) is determined on the slice above buttresses.

The projected area (PA) is calculated as the area of a concave hull (with *concavity* as a user-defined parameter) constructed for the points of the tree point cloud. The 3D alpha volume (AV) is

calculated as the volume of the 3D alpha shape (with *alpha* as a user-defined parameter) generated for the points of the tree point cloud. The crown is defined as the leaves and the woody part above the start of the lowest branch. The crown points can be identified and extracted using the *classify_crown_pc* function and given as the input point cloud to calculate the PCA and 3D ACV (Table 1). More details on how these metrics are calculated can be found in the individual function help files.

The performance of the functions and default parameters can be visually assessed with figures, which can be produced for each tree separately with the metric functions for H, DBH, DAB, PA and CV or with the plot functions for all tree point clouds in a folder (Table 2). There are also plot functions *plot_circle_fit_pcs* and *plot_crown_classification_pcs* that can be used to check the results of *diameter_slice_pc* and *classify_crown_pc* for multiple tree point clouds in a folder. Using these plot functions, you can visualise the effect of parameter values and you can optimise them for specific trees. All point cloud-based structural metrics can be obtained at once for a group of tree point clouds in a folder using the *summary_basic_pointcloud_metrics* function.

2.2.2 | QSM-based metrics

The ITSMe package includes functions to extract structural metrics from TreeQSMs (Table 3). These include the H, DBH, tree volume, trunk volume, total branch volume, total branch length and total cylinder length. The functions work for QSMs with and without triangulation of the stem.

The ITSMe package also provides functions to extract more complex structural metrics from TreeQSMs (Table 4). The metrics that can be obtained with the package are those defined in Terryn et al. (2020). These metrics were adapted from Åkerblom et al. (2017) except for the branch angle ratio and the relative volume ratio which were new metrics. Normalisation (e.g. dividing a feature, by for example DBH or H, to remove the size dependency of the feature) according to Terryn et al. (2020) as well as Åkerblom et al. (2017) is possible through the normalisation parameter. If the tree point cloud is provided along with the TreeQSM as an input in the functions,

DBH or DAB and tree height values are based on the point clouds instead of the QSMs.

These metrics can be calculated for a group of QSMs in a single folder using *summary_qsm_metrics*. Because TreeQSM uses a random seed to start the reconstruction process, there are likely differences between the resulting models. Therefore, multiple TreeQSM iterations are often made for a single tree. When multiple QSMs are provided for one tree in the input folder, *the summary_qsm_metrics* function additionally returns the mean and standard deviation for each structural metric of each tree (the tree point cloud files need to follow the naming conventions specified in the help files).

2.3 | Demonstration data

To demonstrate the applicability of the package, we discuss its use on a total of 1030 tree point clouds at three different sites (Table 5). Robson Creek (RC) is a wet tropical rainforest site situated in Queensland, Australia. We use 57 tree point clouds extracted by Terryn et al. (2022) from TLS and UAV-LS of a one-hectare plot at RC. Litchfield (LF) is a tropical savanna site situated in Darwin, Australia. We use 283 tree point clouds extracted from TLS and UAV-LS data from a one-hectare plot in LF by Brede et al. (2022). Wytham Woods (WW) is an ancient semi-natural woodland, situated in Oxford, United Kingdom. We use 690 tree point clouds and their respective QSMs extracted from TLS data from a 1.4-hectare plot in Wytham Woods by Calders et al. (accepted). In all the sites, TLS data were collected with a RIEGL VZ-400 terrestrial laser scanner (RIEGL Laser Measurement Systems GmbH) at a pulse repetition rate of 300 kHz. In RC and LF, the UAV-LS data were collected with a RIEGL RiCOPTER equipped with the RIEGL VUX-1UAV laser scanner combined with an Applanix AP-20 Inertial Measurement Unit (RIEGL LaserMeasurement Systems GmbH). The flight speed was 2.5 m/s. Full details on the sites, data collection and tree segmentation for RC, LF and WW can be found in Terryn et al. (2022), Brede et al. (2022) and Calders et al. (accepted), respectively.

3 | RESULTS AND DISCUSSION

3.1 | Point cloud metrics

3.1.1 | Tree height

Determining H (*tree_height_pc*) as the difference in the z-value between the highest and lowest point is possible for all TLS and UAV-LS tree point clouds in RC, LF and WW. However, for UAV-LS point clouds, the lower parts of the tree are often not sampled, and thus H is underestimated with this method (Figure 3a vs. 3b). In this case, the *tree_height_pc* function offers the option to additionally provide a DTM to estimate the lowest point and improve the H

TABLE 3 List of the basic metrics extracted from the TreeQSM and their respective functions in ITSMe

Structural metric	Metric function
x, y position of tree trunk	*tree_position_qsm*
Diameter at breast height (m)	*dbh_qsm*[a]
Tree height (m)	*tree_height_qsm*
Tree volume (L)	*tree_volume_qsm*[a]
Trunk volume (L)	*trunk_volume_qsm*[a]
Total branch volume (L)	*total_branch_volume_qsm*
Total branch length (m)	*total_branch_length_qsm*
Total cylinder length (m)	*total_cyl_length_qsm*

[a]Automatically takes into account triangulated stems.

TABLE 4 List of the TreeQSM metrics defined by Terryn et al. (2020) and Åkerblom et al. (2017) and their respective functions in ITSMe

Structural metric	Abbreviation	Metric function
Stem branch angle (degrees)	sba	*stem_branch_angle_qsm*
Stem branch cluster size	sbcs	*stem_branch_cluster_size_qsm*
Stem branch radius (–/m)[a]	sbr	*stem_branch_radius_qsm*
Stem branch length (–/m)[a]	sbl	*stem_branch_length_qsm*
Stem branch distance (–/m)[a]	sbd	*stem_branch_distance_qsm*
DBH H ratio	dhr	*dbh_height_ratio_qsm*
DBH tree volume ratio (m^{-2})	dvr	*dbh_volume_ratio_qsm*
Volume below 55	vb55	*volume_below_55_qsm*
Cylinder length volume ratio (m^{-2})	clvr	*cylinder_length_volume_ratio_qsm*
shedding ratio	sr	*shedding_ratio_qsm*
Branch angle ratio	bar	*branch_angle_ratio_qsm*
Relative volume ratio	rvr	*relative_volume_ratio_qsm*
Crown start height	csh	*crown_start_height_qsm*
Crown height	ch	*crown_height_qsm*
Crown evenness	ce	*crown_evenness_qsm*
Crown diameter crown height ratio	cdhr	*crown_diameterheight_ratio_qsm*
DBH minimum tree radius ratio	dmr	*dbh_minradius_ratio_qsm*

Abbreviation: DBH, diameter at breast height.

[a]The unit depends on the chosen normalisation (could be unitless or in meter).

TABLE 5 Site details of the three sites used for the package demonstration

Site	Forest type	Reference	LiDAR	TLS scanning pattern[a]	# trees	DBH range
Robson Creek (AUS)	Wet tropical rainforest	Terryn et al. (2022)	TLS, UAV-LS	10×10m	57	0.11–0.94m
Litchfield (AUS)	Tropical savanna forest	Brede et al. (2022)	TLS, UAV-LS	25×25m	283	0.05–0.49m
Wytham Woods (UK)	Deciduous forest (leaf-off)	Calders et al. (accepted)	TLS	20×20m	690	0.05–1.41m

Abbreviations: DBH, diameter at breast height; LiDAR, Light detection and ranging; TLS, terrestrial laser scanning; UAV-LS, laser scanners mounted on unoccupied aerial vehicles.

[a]In each site, the TLS scanning was done in a regular grid to ensure the best possible data quality.

measurement (Figure 3c vs. 3b). Terryn et al. (2022) showed that in RC this DTM-based H measurement for (multiple returns) UAV-LS tree point clouds resulted in a root mean squared error (RMSE) of 0.38m. For the open savanna site (LF), a DTM is not necessary as there is much less occlusion and the lower part of the stems are sampled with UAV-LS. Comparing H from TLS with those of UAV-LS measured with and without DTM in LF, results in an RMSE of 0.36 and 0.35m, respectively.

3.1.2 | DBH and DAB

The DBH measurement (*dbh_pc*) for different TLS tree point clouds is illustrated in Figure 4. The DBH fitting was successful (resembling Figure 4a–c) for 100%, 99.6% and 96% of the TLS tree point clouds (non-buttressed, DBH ≥ 5 cm) of RC, LF and WW, respectively.

Compared to the DBH census data of these trees, the DBH was measured with an RMSE of 2.3 cm for RC and WW, and 1.7 cm for LF. For the unsuccessful 4% of the trees in WW, low branches hampering the DBH measurement could not be extracted automatically from the tree point cloud and DBH was not (correctly) measured. This is typically the case for very small (DBH ≤ 0.05 m), slanted trees (Figure 5a) and trees with diverting stem growth (the angle at which the tree grows changes below 1.5 m, Figure 5b). In these cases, an improved DBH measurement can be achieved by manually removing branches or vegetation below 1.5 m. Also, DBH measurement from the trees' QSM could be a solution in situations where the fitting fails.

In the case of buttressed trees, the diameter needs to be measured above the buttresses. This is implemented in the *dab_pc* function and illustrated in Figure 6. An RMSE of 4.8 cm is achieved for the buttressed trees in RC compared to the census data.
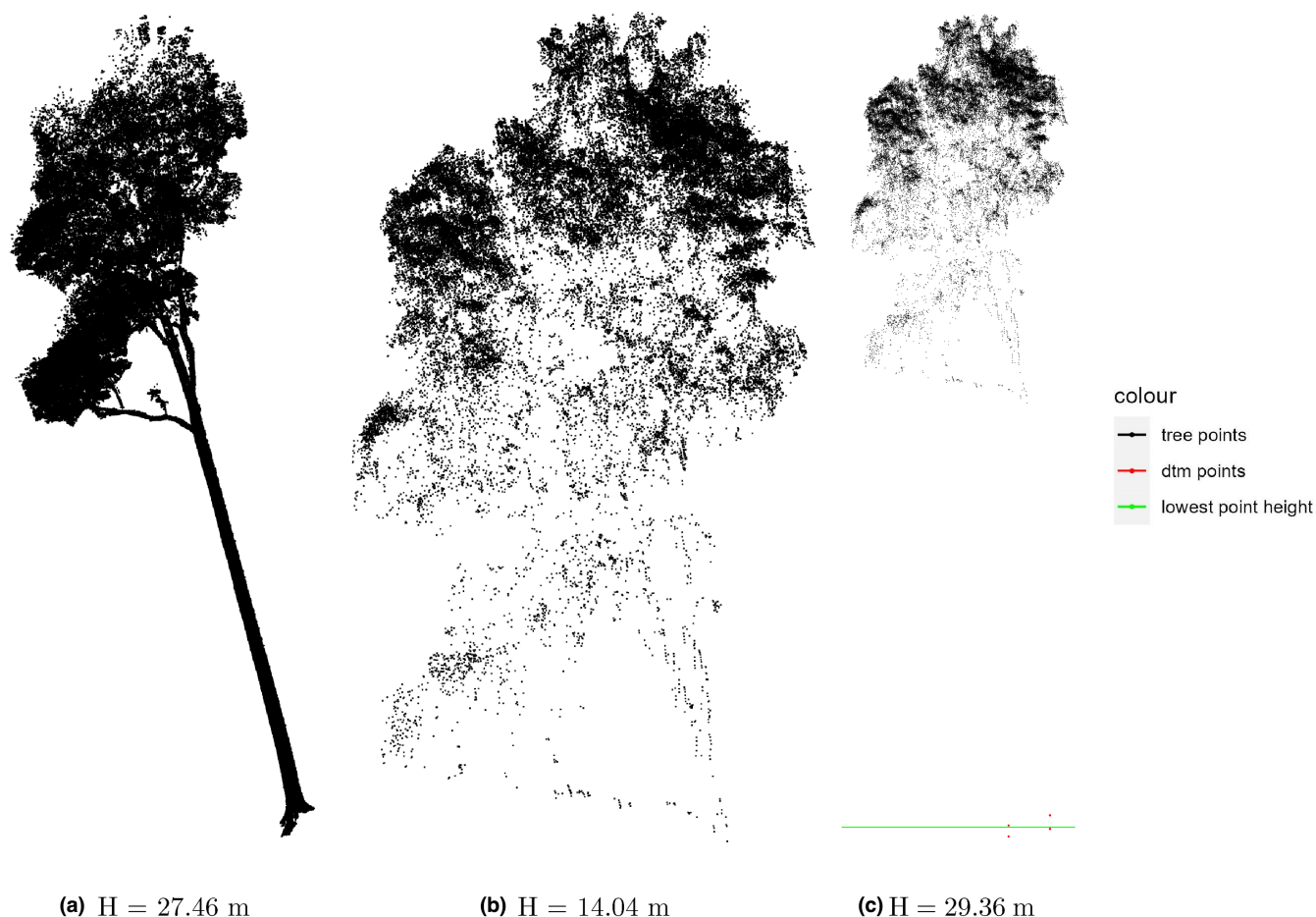
(a) H = 27.46 m   **(b)** H = 14.04 m   **(c)** H = 29.36 m

FIGURE 3 Tree height estimation for a tropical tree (RC) based on: (a) TLS tree point cloud (b) UAV-LS tree point cloud, and (c) UAV-LS tree point cloud and DTM. RC, Robson Creek; TLS, terrestrial laser scanning; UAV-LS, laser scanners mounted on unoccupied aerial vehicles; DTM, digital terrain model.
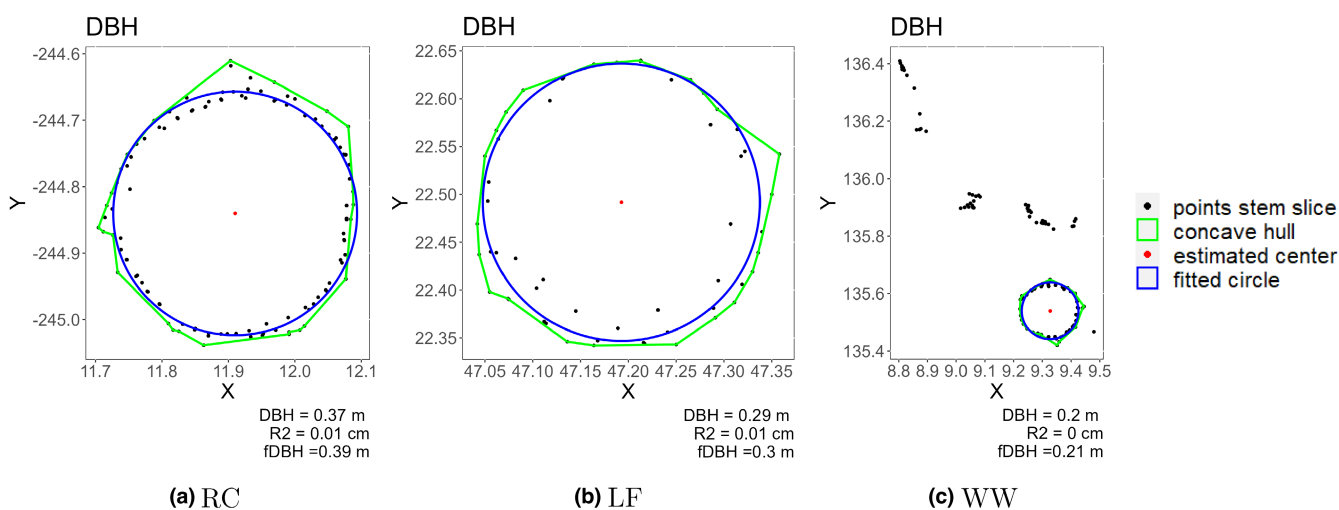

(a) RC   **(b)** LF   **(c)** WW

FIGURE 4 Stem slice at 1.3 m height above the lowest point of the tree point cloud (black) for a point cloud of a tree at (a) RC, (b) LF, (c) WW. The circle fit (blue), estimated centre (red), and concave hull for fDBH measurement (green), based on the 6 cm thick stem slice at breast height are also shown. RC, Robson Creek; LF, Litchfield; WW, Wytham Woods; fDBH, functional diameter at breast height.

In a dense tropical forest, ALS and even UAV-LS might not penetrate the canopy sufficiently to sample the base of the tree and there are no stem points at breast height to measure DBH. Terryn et al. (2022) showed that DBH and DAB measurement from UAV-LS-based tree point clouds in RC is impossible for the majority of the trees due to this lack of sampled stem points. But, in an open savanna
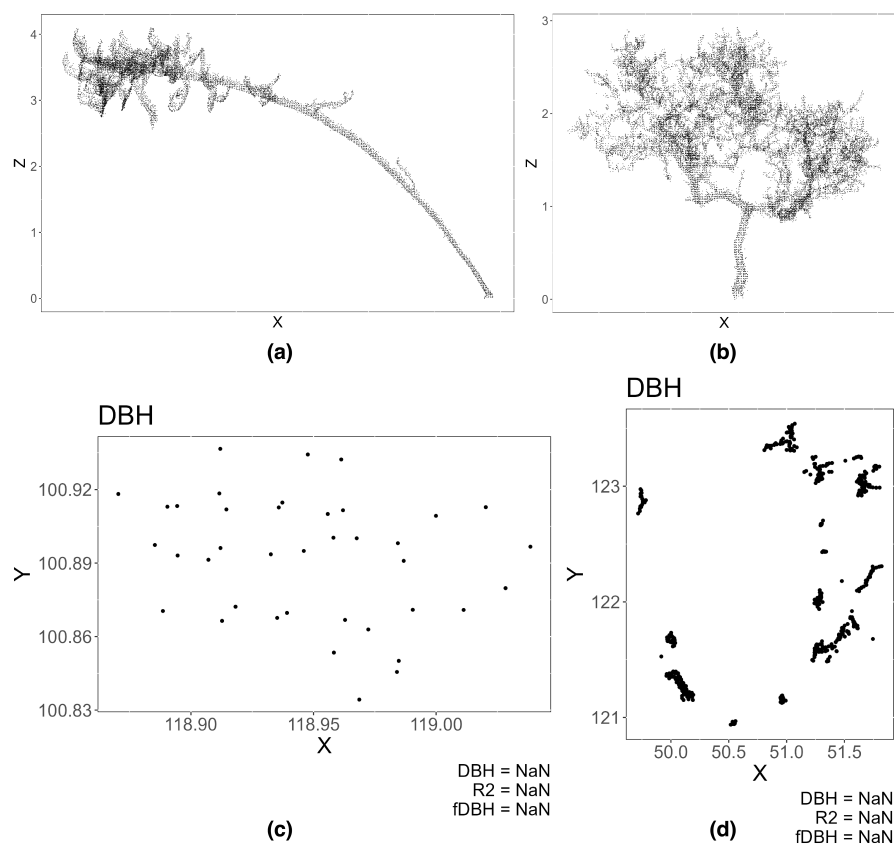
FIGURE 5 Tree point clouds (top) and its respective stem slice at 1.3 m height above the lowest point of the tree point cloud (bottom). (left) Slanted tree and (right) tree with diverting stem growth below 1.3 m (a) Tree point cloud of a slanted tree, (b) Tree point cloud of a tree with diverting stem growth below 1.3 m, (c) Stem slice at 1.3 m height above the lowest point of the tree point cloud of the slanted tree, and (d) Stem slice at 1.3 m height above the lowest point of the tree point cloud of the tree with diverting stem growth.

forest, UAV-LS could sample the stem sufficiently (depending on the UAV-LS system and scanning pattern). To calculate the DBH with *dbh_pc* from UAV-LS tree point clouds, which have inherently fewer stem points than those from TLS, the slice thickness parameter can be increased (e.g. to 0.2 m), to increase the number of points used for the circle fitting. For LF, even though wind slightly hampered the registration of the flight lines the DBH measurement was successful for 82% of the UAV-LS tree point clouds. For trees with a DBH larger than 10 cm, the fitting was successful for 94% of the trees. The trees with smaller DBHs are more influenced by the wind and the DBH measurement failed for 24% of the trees. Compared to the census data in LF, the DBH is measured from UAV-LS with an RMSE of 5.7 cm.

Thus, to (accurately) estimate the DBH with the *dbh_pc* function, sufficient points need to be sampled from the stem, co-registration of multiple scan locations (or flight lines for UAV-LS) needs to be accurate and the tree point cloud should not contain any vegetation that does not belong to the tree (segmentation quality). Visualising the point cloud slice at breast height is a good way to check the tree point cloud quality and possibilities for accurate measurements.

3.1.3 | PA and 3D AV

Contrary to the DBH, DAB and tree height of a tree, there is no way to measure the projected (crown) area and alpha (crown) volume

with any reasonable accuracy in the field. The PA and AV of a tree point cloud can be calculated with the *projected_area_pc* and *alpha_volume_pc* functions and different concavity and alpha values can be applied (Figures 7 and 8).

Using the *classify_crown_pc* function allows one to first extract the crown points before calculating the PCA and ACV (Figure 8). The crown classification is, however, only possible for tree point clouds where DBH or DAB measurement is also possible. This means that for the UAV-LS tree point clouds of RC, the PA and 3D AV can only be determined from the complete tree point cloud and not of the crown, as a crown classification is not possible.

3.2 | QSM metrics

The *summary_qsm_metrics* function results in a matrix with each row representing a tree and each column representing a structural metric derived from the trees' QSM. These structural metrics matrices can be used for a range of purposes such as supporting tree species classification (Terryn et al., 2020), evaluating a plant structural economics spectrum (Verbeeck et al., 2019), or exploring the link between tree structure and the environment. It can be used to monitor the structural dynamics within a plot or between plots.

Similar to the more complex point cloud-based metrics (PCA and ACV), a lot of complex QSM-derived metrics have not been validated. However, the QSM-derived tree volume was validated using destructive data (Calders et al., 2015; Lau et al., 2018).

FIGURE 6 Stem slice at 1.3 m height above the lowest point of the tree point cloud (grey) and above buttresses (black) for four tree point clouds of buttressed trees at Robson Creek. The circle fit and estimated centre based on the 6 cm thick stem slice above buttresses are also shown (a) Buttressed tree 1, (b) Buttressed tree 2, (c) Buttressed tree 3, and (d) Buttressed tree 4.
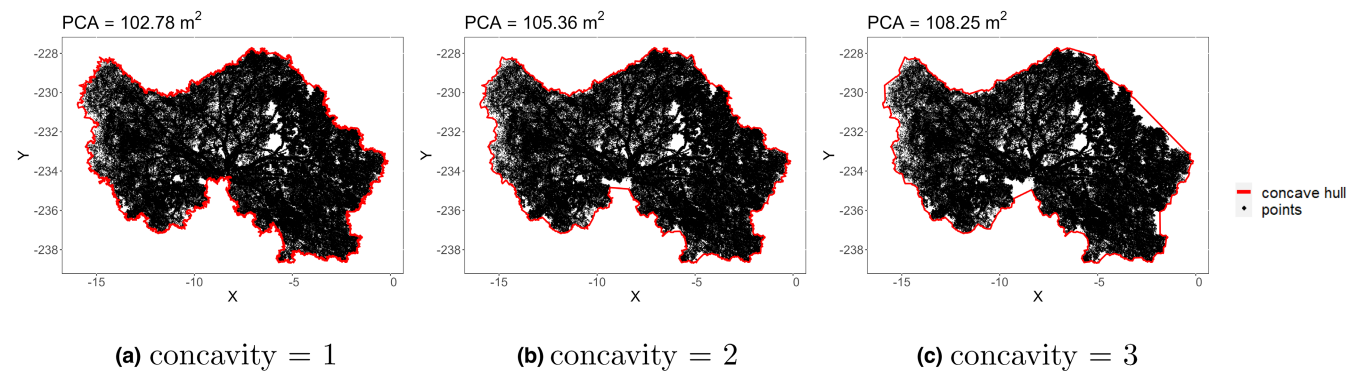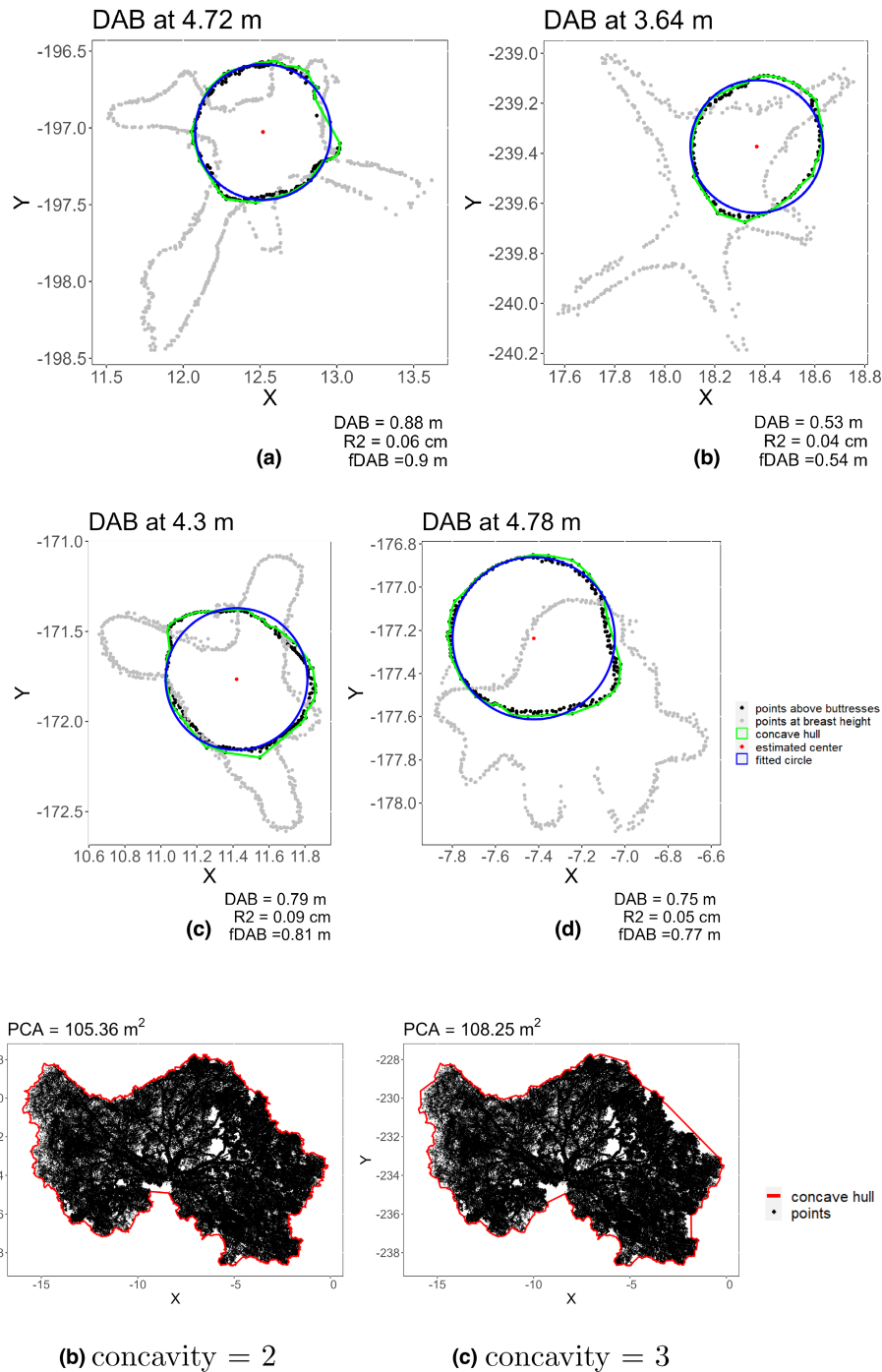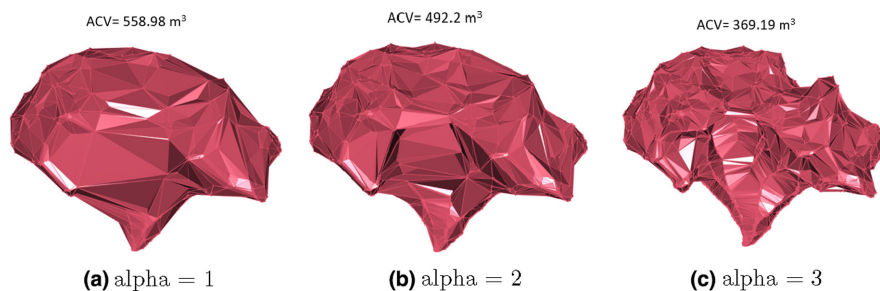

DAB at 4.72 m

DAB = 0.88 m
R2 = 0.06 cm
fDAB =0.9 m

(a)

DAB at 3.64 m

DAB = 0.53 m
R2 = 0.04 cm
fDAB =0.54 m

(b)

DAB at 4.3 m

DAB = 0.79 m
R2 = 0.09 cm
fDAB =0.81 m

(c)

DAB at 4.78 m

DAB = 0.75 m
R2 = 0.05 cm
fDAB =0.77 m

(d)

- points above buttresses
- points at breast height
- concave hull
- estimated center
- fitted circle

PCA = 102.78 m^2

PCA = 105.36 m^2

PCA = 108.25 m^2

concave hull
points

(a) concavity = 1

(b) concavity = 2

(c) concavity = 3

FIGURE 7 Results of the projected crown area (PCA) calculation for different concavity values (1, 2, 3 from left to right). (a) PCA calculation with concavity = 1, (b) PCA calculation with concavity = 2, and (c) PCA calculation with concavity = 3.

ACV= 558.98 m^3

ACV= 492.2 m^3

ACV= 369.19 m^3

(a) alpha = 1

(b) alpha = 2

(c) alpha = 3

FIGURE 8 Results of the alpha crown volume (ACV) calculation for different alpha values (1, 2, 3 from left to right). (a) ACV calculation with alpha = 1, (b) ACV calculation with alpha = 2, and (c) ACV calculation with alpha = 3.

Moreover, Lau et al. (2018) compared and validated QSM-derived branch lengths and diameters of nine trees with length and diameter measured after the trees had been felled. Yet, it should be kept in mind that the accuracy of QSM-derived metrics depends on the quality of the TreeQSMs which also depends on the quality of the tree point clouds and how well it was processed. For example, evergreen tropical forests (like RC) cannot be scanned in leaf-off conditions like deciduous forests (WW), and an extra leaf-wood separation step is required before the QSMs can be built. This introduces an extra step where errors can occur and the resulting QSM will be less accurate, which results in less accurate structural metrics.

3.3 | Outlook

At the moment, the QSM-based functions can only be used for QSMs reconstructed with TreeQSM (Raumonen et al., 2013). Yet, in the future, we aim to expand the package and also include the use of other popular methods like those developed by Pfeifer et al. (2004) and Hackenberg et al. (2014). Moreover, new point cloud and QSM-based structural metrics can be integrated in the future versions of the package as new research on tree structure develops. This is particularly easy as the code is publicly hosted on the collaborative GitHub platform.

4 | CONCLUSION

Here we present the ITSMe package which offers a synthesis framework for researchers who want to easily obtain structural information from 3D data of individual trees. The package allows the determination of structural metrics that are often difficult or even impossible to measure in the field, from individual tree point clouds and QSMs reconstructed using the TreeQSM method from different types of forests. Future versions of the package will also include other QSMs and new structural metrics. We believe that the open-source ITSMe package, hosted on GitHub, will make the use of LiDAR data more straightforward for a range of end-users and further our understanding of tree structure.

AUTHOR CONTRIBUTIONS

Louise Terryn and Kim Calders conceived the ideas and designed the methodology; Louise Terryn, Kim Calders, Harm Bartholomeus, Mathias Disney, Shaun Levick and Niall Origo collected the data; Louise Terryn and Kim Calders analysed the data; Louise Terryn led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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How to cite this article: Terryn, L., Calders, K., Åkerblom, M., Bartholomeus, H., Disney, M., Levick, S., Origo, N., Raumonen, P., & Verbeeck, H. (2022). Analysing individual 3D tree structure using the R package ITSMe. *Methods in Ecology and Evolution*, *00*, 1–11. https://doi.org/10.1111/2041-210X.14026