TERRESTRIAL LIDAR MEASUREMENTS FOR ANALYSING CANOPY STRUCTURE IN AN OLD-GROWTH FOREST

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ABSTRACT:

Terrestrial lidar measurements with the Leica HDS 4500 laserscanner (Imager 5003 from Z+F) were executed in a structurally highly diverse, at least 200-year-old natural 11-species forest with typical characteristics of an old growth forest in order to assess the species-specific differences of tree canopy structures growing in a forest stand. Accuracy of the method and completeness of the canopy measurement is evaluated based on independent height measurements and visual inspection of single tree canopies.

While canopy structure could be captured completely in the lower half of the canopies, the upper parts of the virtual canopies exhibited partly gaps along the axis of branches. Virtually executed vertical canopy projections could better represent indentations in the canopy borderline than field measurements – both measurements yielded comparable canopy projection areas (root mean square error, RMSE = 11.1m²). Lidar-derived heights of tree canopy base were in better agreement with field measurements than lidar-derived tree heights.

1. INTRODUCTION

The terms “old-growth forest” and “primeval forest” stand for undisturbed forests that were able to develop all features occurring in a forest within the natural life-span of its constitutive tree varieties, including those unique features that make the forest ecologically valuable as habitat for rare species depending on these features. Therefore, the typical aboveground characteristics of old growth forests comprise (Zenner 2004, Hunter and White 1997):

- large and old trees
- dead trees and wood, standing and on the ground
- standing, leaning, and fallen trees
- trees in all different ages due to natural regeneration
- high spatial complexity, e.g. several layers of vegetation
- naturally high tree species diversity

Out of these, spatial complexity of forests is a difficult and not satisfyingly defined feature that has not yet directly been measured. While it is recognized that species-specific differences in tree canopy structure exist (Hagemeier 2002), are ecophysiologically significant (Fleck et al. 2004), and contribute to structural complexity (Zenner 2004), they have not been quantified due to a lack of reliable and complete structure data of trees growing in competition with other trees in a forest.

Though terrestrial lidar principally provides an efficient tool to measure tree canopies in a forest, old-growth forests belong to the most difficult objects for laser-scanner measurements due to characteristics associated with structural complexity and size:

1. Inaccessibility of the canopy for the instrument leads to an unfavourable scanning geometry with all scanner positions on one side of the scanned object and in a considerable distance from it.
2. Irregularity of the geometrical shapes in old-growth forests (e.g. noncircular stems covered with moss or bulges from wound occlusion and hidden by twigs or epiphytes) limits the utility of semi-automated registration procedures (e.g. Henning and Radtke 2006) based on geometrical features of the scene, resulting in an unfavourable registration geometry with all control points lying on one side of the object.
3. Occlusions depend on the density of canopy elements per canopy volume, which is usually high. They make it difficult to completely capture the structure of the upper part of the forest canopy.
4. Instability of the objects due to wind and growth movements causes additional concerns about reliability and repeatability of the measurements.

This paper presents multiple laser-scanner measurements of single trees standing in a dense, species-rich old-growth forest and evaluates the reliability of these data for further steps in species-specific structure analysis.

2. MATERIAL AND METHODS

2.1. Study site

All measurements were executed on the 10th of March 2006 in a mixed broad-leaved forest in the Hainich national park, study site 3a (51.089° North, 10.523 ° East) of the collaborative research project Graduiertenkolleg 1086 “**The role of biodiversity for biogeochemical cycles and biotic interactions in temperate deciduous forests”** at the University of Göttingen (see http://www.forest-diversity.uni-goettingen.de). Average wind velocity on this sunny day was 11.5 km/h and the main wind direction was west.

The study site is a 65m x 55m fenced section of the natural forest with 11 different tree species inside the fence: small-leaved lime (*Tilia cordata*), large-leaved lime (*Tilia*

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platyphyllos), common ash (*Fraxinus excelsior*), Norway maple (*Acer platanoides*), European hornbeam (*Carpinus betulus*), pedunculate oak (*Quercus robur*), sycamore maple *(Acer pseudoplatanus*), field maple (*Acer campestre*), European beech (*Fagus sylvatica*) European field elm (*Ulmus minor*), and wild cherry (*Prunus avium*) in the order of stem numbers. The total number of 161 trees comprises 9 standing dead trees and equals 392 trees per ha (trees with diameter at breast height (DBH) >7cm). Due to natural regeneration there were trees in all different ages and sizes in the forest: patches of shrub-like young trees (mainly ash and lime trees), suppressed trees in the lowest canopy layer, up to approximately 200-year-old large trees, and large decomposing dead trees lying on the ground. Tree stems in the fenced area had a maximum DBH of 85cm. Leaning stems were inclined to up to 39° from vertical, the average stem inclination was 7°.

2.2 Measurement set-up

The measurements were set up in order to cope with the mentioned difficulties for terrestrial lidar measurements in an old-growth forest. 25 scans were performed with a Leica HDS 4500 laser-scanner produced by Zoller + Fröhlich, Germany. Scanning positions about 1.5m above ground level were chosen irregularly in order to take advantage of larger canopy gaps and to increase the measurement density in thickets (Fig. 1). The HDS 4500 scanner measures distances up to 53.5m (ambiguity interval) based on the phase-shift of a frequency modulated laser beam. The laser spot size is 3mm leaving the instrument and 8.5mm in a distance of 25m. Range measurements in a distance of 25m have a root mean square error of 9mm on dark grey surfaces.

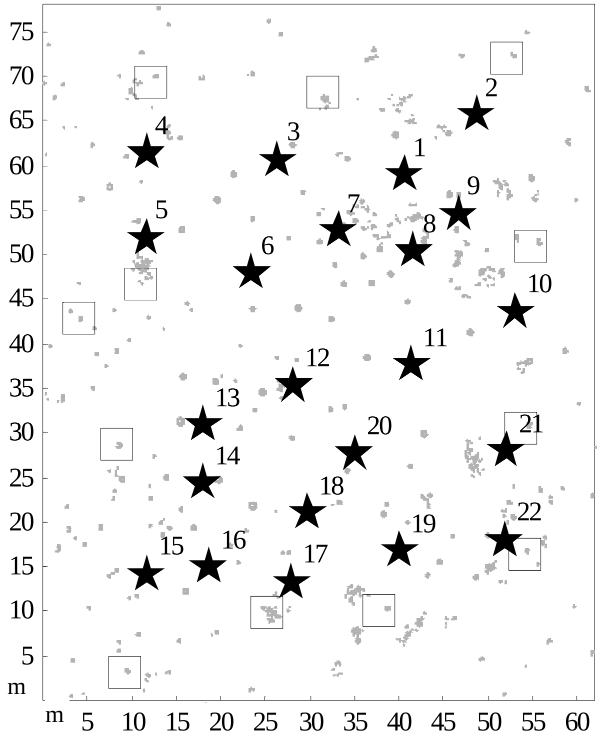

Fig. 1: Horizontal cut through the point-cloud in a height of 2m above ground-level, showing stem positions (grey spots), valid scan positions (filled stars), and the positions of elevated targets providing additional control points for the registration (open squares).

The scanning resolution was set to an angle of 0.036° in both, horizontal and vertical direction and to a total scan angle of 360°, resulting in a point spacing of 15.7mm in a distance of 25m.

The multiple scans were transformed into the same co-ordinate system based on 39 artificial chessboard pattern targets fixed to tree stems in a height up to 2m above the ground. Twelve elevated targets in a height between 8m and 10m on tree stems surrounding the forest stand were added in order to improve the registration geometry. They were directed towards the centre of the plot and fixed using a forest ladder of 10m length, which is equipped for leaning against stem surfaces and for stability on smooth ground. Geometric registration was performed using Z+F-LaserControl 6.8 (Zoller + Fröhlich, Germany). Single trees were extracted based on recognizable canopy elements using Cyclone 5.6.1 software (Leica Geosystems, Switzerland). Virtual canopy projections were performed on 20 trees viewing the single tree point-cloud in z-direction and keeping the actually surveyed part of the canopy in the zenith. Tree height was extracted of 45 single tree point-clouds as the vertical distance between the highest point and stem base (visually selected point at the bottom edge of the stem). A point representing canopy base was selected on 60 trees as the lowest point of the insertion area of the lowest main branch to the stem.

2.3 Forest Inventory data

8-point canopy projections were performed in January 2006 using a sighting tube equipped with a 45° mirror and cross-hairs to ensure vertical view of specified canopy elements from the ground (Johansson 1985). Eight points along the border of the canopy where chosen in order to approximate the canopy projection with a polygon and markers were set on the ground at each polygon corner point. Distance and direction of each point from the stem base were measured with a compass and a meter tape.

Height measurements in the stand were performed with the Vertex sonic clinometer and transponder (Haglöf, Sweden), aiming first to the stem at breast height (transponder height 1.30m a.g.l.) and then to the base and top of the canopy. Base of canopy was defined as the origin of the lowest main branch. Main branches were defined as branches with at least 10% of the cross-sectional area of the stem at this position.

3. RESULTS

3.1 Registration and Segmentation

Three scans were excluded from the evaluation due to target positions with offsets of more than 5cm in comparison to the grid of target positions represented by the other scans. The maximum positional deviation of control points in the remaining 22 scans was 2.1cm.

The extraction of single tree canopies based on visual recognition of canopy elements was safely possible for all branches with diameters of 4cm or more, but also smaller branches were usually well distinguishable due to the possibility to look at the point-cloud from many different viewpoints. Though the knowledge of species-specific tree habit accelerated the process of visual segmentation, this knowledge was not essential to distinguish tree canopies from each other.

Branches of adjacent tree canopies were visibly apart with gaps of more than 20cm between them. Gaps between canopies could in less than 10% of all cases not safely be distinguished from the gaps between measured points on a branch. For these cases it was necessary to separate the tree point-clouds by an equidistant plane to those branches of the trees that could safely be identified. It cannot be excluded that this had a smoothing effect on the irregular form of the canopy surface due to wrongly assigned points filling indentations of a neighbouring canopy. The result of this segmentation may be inspected in Fig. 2, 3, and 4. The point-clouds had up to 2 million points per tree. Point densities along branches were lower in the uppermost part of the canopy, but branches could still be identified.

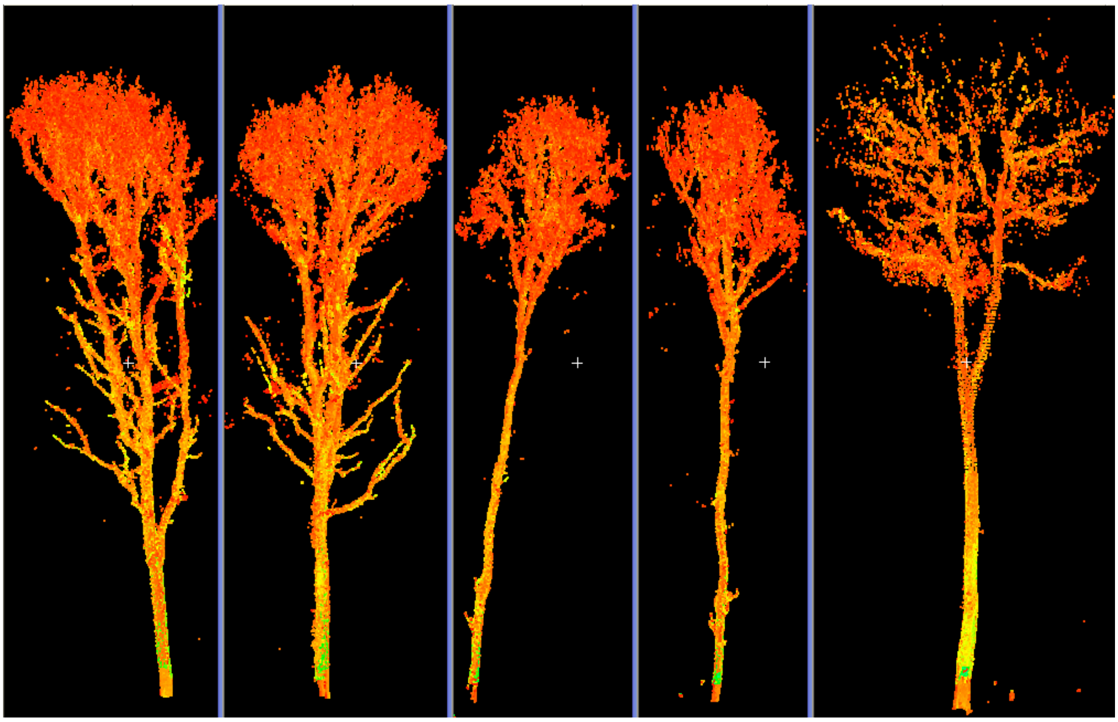

Fig. 2: Single tree point clouds of pedunculate oak #1 (south and east view), sycamore maple #2 (south and east), and common ash #3 (south view)

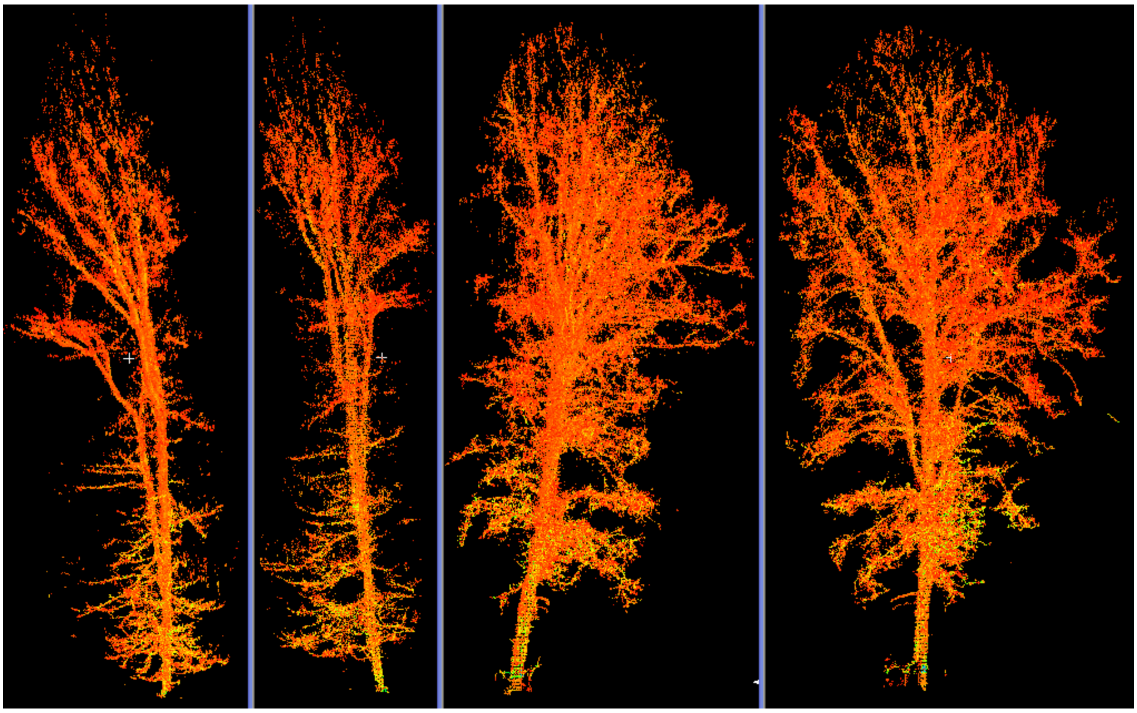

Fig.3: Single tree point clouds of European hornbeam #5 (south and east view) and small-leaved lime #12 (south and east view).

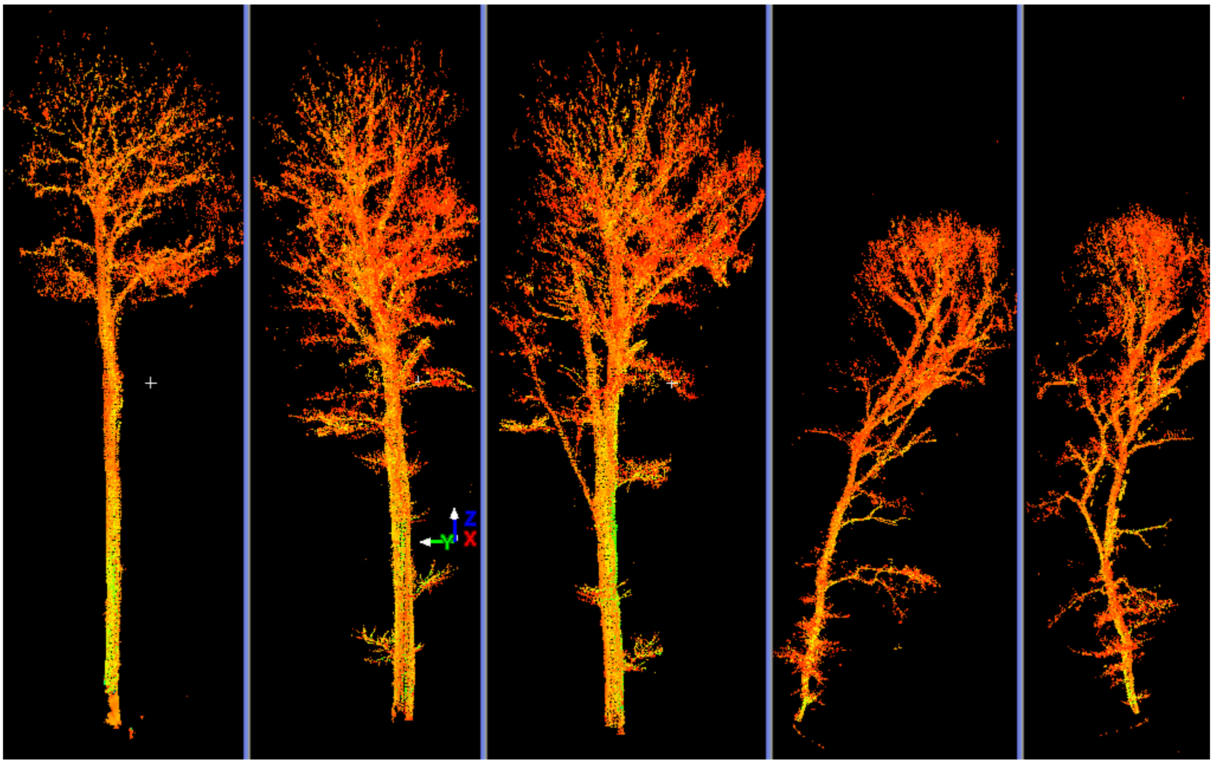

Fig. 4: Single tree point clouds of common ash #3 (east view), European beech #2 (south and east view), and field maple #15 (south and east view).

3.2 Virtual canopy projections

The 8-point canopy projections of 3 trees could not be evaluated due to obvious deviations from the virtual canopy projections. The area of 8-point canopy projections of 17 more trees ranged from 9m² to 112m² (mean = 47m²). The area of virtual canopy projections was well correlated with this measurement, yielding an r^2 of 0.90 and a root mean square error of 11.1m².

It was obvious from the measurement procedure that virtual canopy projections may capture indentations of the projected canopy surface line much better due to the higher number of polygon corner points, which were between 100 and 150.

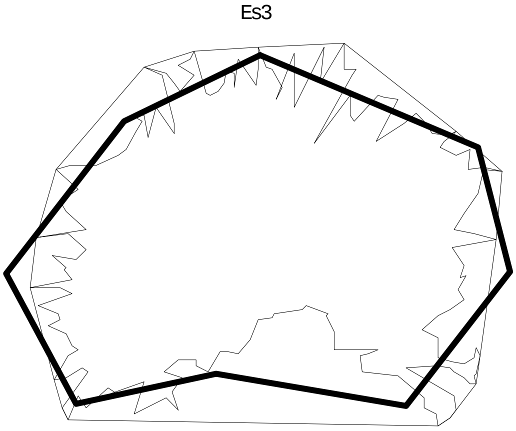

Fig. 5: Canopy projections of common ash #3: Contour lines of the 8-point canopy projection (thick line), the virtual canopy projection (inner thin line), and convex hull of the virtual canopy projection (outer thin line).

Both sorts of canopy projection were therefore compared to the area of their 2-dimensional convex hull (Fig.5): While 8-point-canopy projections were practically identical to their convex hull with an average area of 97% of their convex hull area (range: 87% - 100%), virtual canopy projections had on average 69% of the area that their convex hull would have (range: 56% to 79%). Virtual canopy projections were, thus, better suited for the representation of indentation-rich canopy shapes. While all virtual canopy projections represented a significant amount of canopy indentations, 53% of the 8-point projections did not.

The correlation of the 8-point-canopy projection area with the convex hull area of virtual canopy projections was even better than in the direct comparison of both projections (r^2=0.95, RMSE=11.1m²).

3.3 Height of canopy base and tree height

Vertex measurements and lidar-measurements of height of canopy base were well correlated (r^2=0.99), with a root mean square error of 0.52m, the mean height of canopy base being 9.18m.

The correlation of both measurement methods for absolute tree height was with an r^2 of 0.82 a bit weaker, RMSE being 2.41m and average tree height was 24.88m.

4. DISCUSSION

The segmentation of point clouds representing dense forest canopies into sub-clouds for each tree was visually not possible without a certain amount of insecurity at the canopy contact zones that lead to partly smoothed canopy surfaces.

The indentation-rich, irregular canopy surface of trees is on the other hand mostly well represented in its visual appearance (compare Figs. 2, 3, and 4).

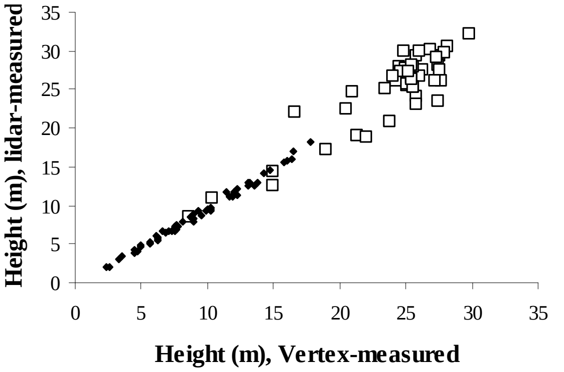

Fig. 7: Height measurements of top of the tree (open squares, n=45) and canopy base (black dots, n=60) as measured with the Vertex instrument (x-axis) and by terrestrial lidar (y-axis).

The low ratio of virtual canopy projection area to their convex hull area shows that this feature of tree canopies is well represented in lidar-measured point-clouds, while it cannot be captured by 8-point canopy projections.

Since 8-point canopy projections are a cheap and frequently used method to characterize forest composition, it needs to be specified that the arbitrary choice of corner points with the goal to approximate the projected canopy surface line with straight lines is essential for the accuracy of the method: The alternative use of the outermost points of the canopy projection would in many cases result in the convex hull area, which overestimates canopy cover up to 79% when compared with lidar data.

The slighter overestimation (23%) that was found comparing 8-point projections and virtual canopy projections may rather be explained by canopy indentations not represented than by branches that were not scanned due to occlusions or wrong segmentation, since the general shape of projected canopies was similar between both methods (compare Fig. 5) and completely missed branches would have been visible as gaps between canopies in the segmentation process. This interpretation is also supported by the better correlation of 8-point projection areas with the convex hull areas than with virtual canopy projections themselves.

A big practical advantage of virtual canopy projections is the possibility to view canopy contact zones from all necessary viewpoints before decisions on point-cloud segmentation are taken. This possibility does not exist when measuring projections with a vertical sighting tube which may have contributed to the deviation between both methods.

The agreement between Vertex measurement and lidar measured tree heights was much better for height of canopy base than for total tree height. This may have several causes: First, the canopy base is easily visible for both, the laser-scanner as well as the operator of the Vertex instrument. Second, canopy base and stem base are more probably in the same horizontal distance to the operator than the top of the tree would be. Though stems may be inclined a few degrees, same horizontal distance is a presupposition for correct measurement with the Vertex instrument. The highest point of the tree not necessarily has to be on the elongation of the stem axis. Third, branches in the uppermost part of the canopies had lower densities of lidar-measured points than below the canopy. It may, therefore, be that the tree top and its neighbouring points directly beneath have not been detected in some cases, though this is not likely in the visual representations. Since both measurement methods may have contributed to these errors, it is difficult to judge the accuracy of tree height measurements without independent measurements. The data do show a reasonable agreement where the error sources for both methods are less severe, i.e., for measurements of height of canopy base.

5. CONCLUSIONS

(1) Not yet developed automated segmentation procedures for tree canopies in a forest will likely have the same problems as the visual segmentation of trees in a point-cloud with the consequence of partly smoothed canopy surfaces, unless the point density is even higher than in this example. (2) Terrestrial lidar measurements provide a tool to validate the performance of canopy projection methods. The arbitrary choice of border points of canopy projections leads to more accurate results than using the outermost points. (3) The validation of lidar-derived tree height measurements in a forest is not possible based on Vertex measurements, since these depend too much on visibility limitations.

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