The Influence of Cross-Section Thickness on Diameter at Breast Height Estimation from Point Cloud

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Abstract: Circle-fitting methods are commonly used to estimate diameter at breast height (DBH) of trees from horizontal cross-section of point clouds. In this paper, we addressed the problem of cross-section thickness optimization regarding DBH estimation bias and accuracy. DBH of 121 European beeches (Fagus sylvatica L.) and 43 Sessile oaks (Quercus petraea (Matt.) Liebl.) was estimated from cross-sections with thicknesses ranging from 1 to 100 cm. The impact of cross-section thickness on the bias, standard error, and accuracy of DBH estimation was statistically significant. However, the biases, standard errors, and accuracies of DBH estimation were not significantly different among 1–10-cm cross-sections, except for oak DBH estimation accuracy from an 8-cm cross-section. DBH estimations from 10–100-cm cross-sections were considerably different. These results provide insight to the influence of cross-section thickness on DBH estimation by circle-fitting methods, which is beneficial for point cloud data acquisition planning and processing. The optimal setting of cross-section thickness facilitates point cloud processing and DBH estimation by circle-fitting algorithms.

Keywords: terrestrial laser scanning; DBH; circle fitting; forest inventory; LiDAR

1. Introduction

Circle-fitting methods are efficient algorithms of tree diameter at breast height (DBH) estimation from point clouds obtained by terrestrial laser scanning (TLS), close-range photogrammetry, and depth-images. These algorithms search for the parameters of the circle that optimally fit to the set of points in a horizontal cross-section of the point cloud representing a horizontal slice of the measured trunk [1].

Cross-section thickness is defined as the interval of z-coordinates around a given cross-section’s height in which points are extracted from the point cloud. The thickness of extracted cross-sections varies across studies. A cross-section thickness in the range of 2–10 cm is common in studies focused on accuracy of derived tree characteristics [2–8], while cross-sections of several 10s of centimeters are used for low-density point clouds, tree identification purposes, cylinder fitting, and 3D trunk modelling [4,9–13].

Recently, the influence of local environmental conditions, forest stand characteristics, scanning scheme, and scanner technical settings on tree identification and measurements from point clouds has been intensively studied. Slope, distance to scanner, plot size, stem density, understory, tree dimensions, wind speed, and occlusions reduce the accuracy of tree detection, estimation of branch parameters and DBH, basal area, and above ground biomass [11,14–18]. However, few studies have addressed cross-section thickness optimization for DBH estimation from TLS point clouds, i.e., cross-section
thickness has been partly investigated in conjunction with the influence of TLS settings and point clouding processing on the accuracy of derived tree characteristics [8,19].

The optimization of cross-section thickness for DBH estimation is vital for data volume reduction, effective point cloud processing, and appropriate setting of scanning parameters. Therefore, this paper studies the influence of cross-section thickness on the accuracy of DBH estimation from point cloud data. For beech and oak forest stands, DBH was estimated by an optimal circle-fitting algorithm to cross-sections of 1–100 cm thickness and differences among DBH estimations and their errors from cross-sections of different thickness were statistically tested.

2. Materials and Methods

2.1. Research Plots and Field Measurements

The study was carried out on two research plots established on the territory of the University Forest Enterprise of the Technical University in Zvolen, central Slovakia. The first research plot was set in a European beech (Fagus sylvatica L.) forest stand and the second in a sessile oak (Quercus petraea (Matt.) Liebl.) forest stand (Figure 1).

![Figure 1. Research plots in (a) European beech and (b) sessile oak forests.](image)

The first research plot was a square (50 × 50 m) and the forest stand was 80 years old. In addition to European beech, four European hornbeams (Carpinus betulus L.) and one European silver fir (Abies alba Mill.) grew on the research plot. Only beech trees with DBH > 9 cm were considered for the purpose of this study (Table 1). Tree DBH was measured by digital caliper (Masser Oy, Finland) on the first research plot and calculated as the arithmetic mean of two measurements, i.e., in the direction of the terrain slope and in the perpendicular one.

| Plot Number | Date of Scanning | Tree Species       | Number of Trees | DBH (cm) |
|-------------|------------------|--------------------|-----------------|----------|
|             |                  |                    |                 | Min  | Max  | Avg  | Std   |
| 1           | 23 October 2012  | European beech     | 121             | 9.1  | 62.3 | 28.4 | 11.9  |
| 2           | 4 July 2017      | Sessile oak        | 43              | 17.9 | 42.5 | 37.8 | 5.6   |

Note: Min, minimum; Max, maximum; Avg, arithmetic mean; Std, standard deviation.

The sessile oak research plot was a circle (r = 16 m) and the forest stand was 115 years old. Two European hornbeams (DBH < 20 cm) were also found on the research plot but were excluded from measurements and processing. DBH of trees on this plot was measured using a diameter tape.

Both research plots were scanned using a Faro Focus3D 120 (Faro Technologies, Inc., Lake Mary, FL, USA). The maximum measuring distance of the scanner was 120 m (accuracy, ±2 mm; 976,000 points/second). The scanner’s angular rotation was 360° horizontally and 300° vertically.
The European beech and sessile oak research plots were scanned from 22 and 7 positions, respectively (Figure 2). Both research plots were scanned with quality set at 3× and a resolution of 6 mm/10 m. The time for one scan was approximately 8 min. The central scan was used as a reference for point cloud registration on both research plots. The point clouds were registered by using 18 and 15 standard reference spheres of diameter 14.4 cm on the European beech and sessile oak research plot, respectively.

![Figure 2. Scanning schemes of (a) European beech and (b) Sessile oak research plots.](image)

### 2.2. Data Processing

Point clouds were registered in Faro Scene software version 5.1 (Faro Technologies, Inc., USA). The software automatically identifies reference spheres, which were visually validated and misplaced reference spheres were deleted. Point clouds were automatically registered and exported for further processing.

The software DendroCloud 1.50 (gis.tuzvo.sk\dendrocloud) was used for point cloud filtration, digital terrain model (DTM) generation, tree identification, cross-section selection, and DBH estimation. The procedure consisted of nine steps (Figure 3).

![Figure 3. Procedure of DBH estimation.](image)

In the first step, the imported point cloud was clipped by a box filter, which removed false laser beam reflections above the research plot and distant points. The size of the box filter was slightly
greater than that of the research plot, so all trees on the research plot were completely captured by the point cloud, i.e. 58 × 58 × 60 m and 44 × 44 × 50 m for the beech and oak research plots, respectively.

DTM of the research plot was constructed by the vertical projection method [20]. The resolution of the output raster was 0.5 m. Because of the flat terrain in the research plots, this raster resolution was suitable for the selection of initial point cloud cross-sections.

Initial cross-sections were selected at 1.275–1.325 m above DTM. The 5-cm cross-sections at breast height above the terrain contained enough points for tree identification and initial estimation of their DBH and positions. The next step was the spatial clustering of cross-section points. Each point was assigned to a spatial group, a clustering of data points whose distance from others was less than or equal to the given threshold (2 cm). Spatial groups with less than 200 points were removed. Finally, the spatial groups were visually verified and the groups representing objects other than trees were removed.

The optimal circle method [1] was used for the initial estimation of tree positions and DBH, and the estimated tree positions were used to derive tree base elevation (more details can be found in [21] on page 57). The points inside the annular cylinder with center at tree position were selected. The inner and outer annulus diameters were 40 and 120 cm larger than tree DBH, respectively, and the base of the annular cylinder was placed at the minimal elevation of the selected points. The annular cylinder height was 50 cm. To avoid terrain extremes and noise, the tree base elevation was estimated as the arithmetic mean of point elevations in range 30–70% above the annulus base.

Finally, cross-sections of different thickness were selected from the point cloud 1.3 m above the estimated tree bases. Two sets of cross-sections were used in the study. The first set consisted of cross-sections 1–10 cm thick in 1-cm steps, which are commonly utilized for accurate tree diameter estimation. The second set contained cross-sections of thickness 10–100 cm in 10-cm steps, which are of interest for tree identification purposes and DBH estimation from low-density point clouds. All cross-sections were visually validated and points corresponding to branches, young trees, and noise were manually removed. DBH was estimated by the optimal circle method [1] from the cleaned cross-sections. The large amount of points in selected cross-sections resulted in computation time of several hours. Therefore, random subsampling was applied to reduce the number of points within the cross-sections. The circle-fitting procedure randomly selected a maximum of 20,000 points from each cross-section for DBH estimation.

The estimated DBHs from different cross-section thickness were exported to the R program. All statistical hypotheses were tested at a significance level of 0.05. Statistical hypotheses were separately tested for all, 1–10 cm, and 10–100 cm cross-sections.

The error \( e_i \) of DBH estimation for the \( i \)-th tree was calculated as the difference between \( DBH_{TLS,i} \), estimated from cross-section, and the measured \( DBH_{M,i} \) over trees included in the study:

\[
e_i = DBH_{TLS,i} - DBH_{M,i}
\]

DBH estimation bias from the cross-section of thickness \( w \) was described by the arithmetic mean of errors \( \bar{e}_w \). Standard error, calculated as standard deviation of errors \( s_w \), was used to characterise the precision of DBH estimation. The overall accuracy of DBH estimation was expressed by the mean square error (MSE\(_a\)), and the root mean square error (RMSE\(_a\)) was also reported so the results can be compared with studies that adopted RMSE for accuracy assessment.

The Shapiro–Wilk test was used to test the normality of data distribution. Homogeneity of variance was tested by the Levene’s test. Permutation one-way repeated measures ANOVA was used to test the significance of cross-section thickness influence on bias and accuracy of DBH estimation [22]. Permutation paired t-tests with Benjamini and Hochberg corrections [22] were used to compare biases and accuracies of the DBH estimation from the cross-sections of different thickness. Permutation and robust tests were preferred when homogeneity of variance or normality of distribution were violated.
3. Results

3.1. DBH Estimations

All trees were identified in the initial 5-cm cross-section of the point cloud on both research plots. The number of points rapidly grew with increasing cross-section thickness (Figure 4). The minimum number of points used in DBH estimation was 79 in a 1-cm cross-section of beech (measured DBH = 9.05 cm), and the maximum number of points in a cross-section was 309,329 for beech (DBH = 40.1 cm) (Table A1). Narrow cross-sections of trees near scanner positions contained a surprisingly large number of points.

![Figure 4. Box-plots of number of points in each cross-section thickness. Red crosses indicate average and the red line connects averages of each cross-section thickness.](image)

The circle-fitting method underestimated minimum DBH of beech trees (9.1 cm) for all tested cross-sections and minimum DBH of oaks (17.9 cm) for cross-sections with thickness up to 70 cm (Figure 5). Maximum DBHs (62.3 and 42.5 cm in beech and oak, respectively) were underestimated for all cross-sections and both species under study (Table A2).

![Figure 5. Scatter plots showing trees with their reference (y-axis) and estimated (x-axis) DBH. Color distinguish the cross-sections thickness. Lines above graphs are marginal density plots.](image)
The variance of DBH estimations was homogeneous on both research plots for all cross-sections (Levene’s test, $p$-values = 1.0).

The relationship between measured and estimated DBH was modelled by linear regression without intercept (Appendices B and C). Correlation coefficients and regression slopes were close to 1.0 for each cross-section thickness and species under study.

### 3.2. DBH Estimation Errors

The errors of oak DBH estimation were normally distributed for most cross-sections, except 100-cm cross-section ($p_{SH}$ in Table 2). Contrastingly, the errors of beech DBH estimation were not normally distributed for more than half of the tested cross-section thicknesses ($p_{SH}$ in Table 2).

**Table 2. Errors of DBH estimation.**

| Cross–Section Thickness $w$ (cm) | European Beech | Sessile Oak |
|----------------------------------|----------------|-------------|
|                                  | Min  | Max  | $\bar{e}_w$ | $s_w$ | $p_{SH}$ | Min  | Max  | $\bar{e}_w$ | $s_w$ | $p_{SH}$ |
| 1                                | -2.26 | 1.08 | -0.32       | 0.46  | 0.01     | -2.08 | -0.09 | -1.15       | 0.44  | 0.48     |
| 2                                | -2.43 | 0.95 | -0.33       | 0.47  | <0.01    | -1.85 | -0.20 | -1.15       | 0.40  | 0.51     |
| 3                                | -1.96 | 0.79 | -0.32       | 0.45  | 0.13     | -1.95 | -0.30 | -1.15       | 0.43  | 0.50     |
| 4                                | -2.33 | 1.02 | -0.33       | 0.46  | <0.01    | -2.00 | -0.30 | -1.16       | 0.39  | 0.96     |
| 5                                | -1.88 | 0.99 | -0.31       | 0.45  | 0.27     | -1.88 | -0.10 | -1.15       | 0.43  | 0.33     |
| 6                                | -2.26 | 0.89 | -0.33       | 0.46  | 0.04     | -2.03 | -0.10 | -1.15       | 0.41  | 0.88     |
| 7                                | -2.43 | 1.12 | -0.33       | 0.47  | <0.01    | -1.92 | -0.21 | -1.14       | 0.40  | 0.95     |
| 8                                | -2.16 | 0.73 | -0.31       | 0.44  | 0.03     | -1.93 | -0.28 | -1.17       | 0.39  | 0.79     |
| 9                                | -2.19 | 0.61 | -0.33       | 0.44  | 0.01     | -1.82 | -0.22 | -1.14       | 0.42  | 0.25     |
| 10                               | -2.08 | 0.93 | -0.31       | 0.44  | 0.06     | -1.97 | -0.13 | -1.13       | 0.47  | 0.52     |
| 20                               | -2.05 | 0.89 | -0.29       | 0.44  | 0.06     | -1.95 | -0.12 | -1.12       | 0.44  | 0.89     |
| 30                               | -2.09 | 0.72 | -0.24       | 0.44  | <0.01    | -1.90 | -0.12 | -1.09       | 0.42  | 0.33     |
| 40                               | -2.32 | 1.21 | -0.16       | 0.47  | <0.01    | -1.83 | -0.20 | -1.07       | 0.42  | 0.25     |
| 50                               | -2.33 | 1.97 | -0.08       | 0.58  | <0.01    | -1.86 | -0.19 | -1.03       | 0.46  | 0.08     |
| 60                               | -2.20 | 2.97 | 0.03        | 0.72  | <0.01    | -1.75 | -0.18 | -0.99       | 0.47  | 0.09     |
| 70                               | -1.96 | 4.21 | 0.14        | 0.87  | <0.01    | -2.28 | 0.20  | -0.92       | 0.56  | 0.83     |
| 80                               | -2.34 | 5.29 | 0.24        | 1.04  | <0.01    | -2.85 | 0.33  | -0.85       | 0.63  | 0.13     |
| 90                               | -2.30 | 5.72 | 0.38        | 1.17  | <0.01    | -3.19 | 0.65  | -0.79       | 0.69  | 0.06     |
| 100                              | -2.54 | 6.05 | 0.50        | 1.33  | <0.01    | -3.54 | 0.97  | -0.71       | 0.77  | 0.01     |

Note: $w$, cross-section thickness; Min, minimum; Max, maximum; $\bar{e}_w$, arithmetic mean of errors; $s_w$, standard deviation of errors; $p_{SH}$, $p$-value of the Shapiro-Wilk test of DBH estimation errors normality.

Mean DBHs were underestimated for all cross-sections of oaks and for the cross-sections thinner than 60 cm of beech trees (Table 2). Oak DBH estimations were biased for all cross-section thicknesses (Student’s $t$-test, $p < 10^{-6}$). Meanwhile, beech DBH estimations were unbiased for 50, 60, and 70 cm cross-sections ($p$-values of Student’s $t$-test 0.16, 0.65, and 0.08, respectively).

In both research plots, DBH estimation variance ($s_w^2$ in Table 2) was not constant across cross-section thickness (Levene’s test for homogeneity, $p$-values < 0.001). Homogeneity of variance was rejected for both species and cross-sections 10–100 cm thick (Levene’s test for homogeneity, $p$-value = $2.6 \times 10^{-15}$ and 0.02 for beech and oak, respectively), whereas Levene’s test failed to reject homogeneity of variance for both species and cross-sections < 10 cm thick (Levene’s test for homogeneity, $p$-value 1.0 and 0.996 for beech and oak, respectively).

DBH bias trend was similar for both research plots (Figure 6). DBH estimation bias was practically constant for cross-section thickness up to 10 cm on both research plots, whereas it noticeably increased with cross-section thickness above 10 cm. The influence of cross-section thickness on DBH estimation bias was statistically significant on both research plots (permutation one-way repeated measures ANOVA, $p$-values < $2.2 \times 10^{-16}$). The pairwise $t$-test confirmed the trend visible on Figure 6. DBH estimation biases from cross-sections up to 10 cm were not significantly different for both species under study (Tables A3 and A4, Figure A39).
Figure 6. Box-plots of error of DBH estimation for each cross-section thickness separated by tree species. Red crosses indicate average and red line is connecting averages of each cross-section thickness. The line is clearly showing the increment of average (bias) from 10–100 cm thickness.

DBH estimation bias from 20-cm cross-section of beech forest stand was similar to that from thinner cross-sections, but it was significantly different in some cases (Table A3). However, DBH estimation bias from 20-cm cross-section of oak was not significantly different to that from thinner cross-sections (Table A4). The 20-cm point cloud cross-sections represented almost ideal oak trunks as well as thinner ones.

Square errors of DBH estimation were not normally distributed for any point cloud cross-section thickness on both research plots, except 7-cm cross-section of oak ($p_{SH}$ in Table 3). The influence of cross-section thickness on $MSE_W$ was significant for both species under study (permutation one-way repeated measures ANOVA, $p$-values $< 2.2 \times 10^{-16}$).

Table 3. DBH estimation accuracy. Conditional formatting ranges from lowest (green) to highest (red).

| Cross-Section Thickness $w$ (cm) | European Beech | Sessile Oak |
|----------------------------------|----------------|-------------|
|                                  | $MSE_W$ | $RMSE_W$ | $p_{SH}$ | $MSE_W$ | $RMSE_W$ | $p_{SH}$ |
| 1                                 | 0.31    | 0.56     | <0.01    | 1.51    | 1.23     | <0.01    |
| 2                                 | 0.32    | 0.57     | <0.01    | 1.48    | 1.22     | 0.02     |
| 3                                 | 0.3     | 0.55     | <0.01    | 1.51    | 1.23     | 0.01     |
| 4                                 | 0.32    | 0.57     | <0.01    | 1.48    | 1.22     | 0.03     |
| 5                                 | 0.3     | 0.55     | <0.01    | 1.49    | 1.22     | 0.02     |
| 6                                 | 0.32    | 0.57     | <0.01    | 1.49    | 1.22     | 0.02     |
| 7                                 | 0.32    | 0.57     | <0.01    | 1.46    | 1.21     | 0.08     |
| 8                                 | 0.29    | 0.54     | <0.01    | 1.5     | 1.23     | 0.01     |
| 9                                 | 0.3     | 0.54     | <0.01    | 1.47    | 1.21     | 0.01     |
| 10                                | 0.29    | 0.54     | <0.01    | 1.5     | 1.22     | 0.01     |
| 20                                | 0.28    | 0.53     | <0.01    | 1.44    | 1.2      | 0.01     |
| 30                                | 0.25    | 0.5      | <0.01    | 1.35    | 1.16     | <0.01    |
| 40                                | 0.25    | 0.5      | <0.01    | 1.32    | 1.15     | <0.01    |
| 50                                | 0.34    | 0.58     | <0.01    | 1.26    | 1.12     | 0.01     |
| 60                                | 0.51    | 0.71     | <0.01    | 1.19    | 1.09     | <0.01    |
| 70                                | 0.77    | 0.88     | <0.01    | 1.16    | 1.08     | <0.01    |
| 80                                | 1.13    | 1.06     | <0.01    | 1.1     | 1.05     | <0.01    |
| 90                                | 1.51    | 1.23     | <0.01    | 1.08    | 1.04     | <0.01    |
| 100                               | 2       | 1.41     | <0.01    | 1.08    | 1.04     | <0.01    |

Note: $w$, cross-section thickness; $MSE_W$, mean square of errors; $RMSE_W$, root mean square of errors; $p_{SH}$, $p$-value of the Shapiro-Wilk test of DBH estimation square errors normality.
MSE_w approximately followed the trend of the bias absolute values (Table 2). MSE_w of beech DBH estimation slightly decreased with cross-section thickness up to 50 cm and increased relatively fast with thicker cross-sections. MSE_w of oak DBH estimation slightly decreased with increasing cross-section thickness. The differences between most beech DBH estimation accuracies for cross-sections up to 10 cm were not statistically significant (Table A5). Moreover, all accuracies of oak DBH estimation for cross-sections up to 10 cm were not significantly different among them (Table A6, Figure A40).

4. Discussion

Liu G. et al. [4] demonstrated the application of TLS for DBH and tree height estimation on mixed forests, using random Hough transform to estimate DBH from the cross-section of point cloud. A multiple cross-section approach was used to select the most suitable thickness for DBH estimation, and RMSE and tree identification rate for cross-sections of thickness 1 to 10 cm were evaluated. They considered the thickness of cross-section with the smallest RMSE and the greatest tree identification rate to be optimal. However, significance of differences between DBH estimations was not reported.

The impact of two circle-fitting methods, range and angular errors, angular steps, DBH, distance to scanner, and cross-section thickness on DBH estimations was simulated in the work of Wang, P. et al. [19]. They used point cloud cross-sections (10, 15, 20, and 25 cm thick) to analyze the influence of cross-section thickness on DBH estimation and expressed DBH estimation accuracy by the relative error of DBH estimations. In the numerical experiments, increase in cross-section thickness resulted in better accuracy for wider angular steps of laser scanning, which is consistent with our findings. Wang, P. et al. [19] hypothesized that the increase in the relative error of DBH estimation is related to the larger number of points in cross-sections.

In the field, the trunk outer diameter is measured by caliper and diameter tape. Contrastingly, irregularities on trunk perimeter and bark fissures are recorded by dense and accurate TLS data. Thus, greater bias and RMSE of DBH estimations may originate in trunk bumpiness and bark roughness. In our study RMSEs of DBH estimation from thick cross-sections of beech trees with smooth bark were noticeably smaller than ones of oaks with deeply fissured bark (Table 3). Slant and uneven beech trunks might be associated with rapid increase of bias and RMSE of DBH estimation with increasing cross-section thickness (Figure 7). However, only two tree species were included in this study and further research with other species would be needed to corroborate this.

(a) Leaning beech (DBH 36.8 cm)  (b) Straight oak (DBH 35.8 cm)

**Figure 7.** Orthogonal projection of 100 cm cross-sections of (a) a leaning beech and (b) a straight oak.

The advantage of thicker cross-section is not only a larger number of points available for tree identification and measurements, but also the reduction of cross-section height error. Cross-section height above ground is usually derived from DTM. The incorrect determination of cross-section height above ground can result in systematic errors of DBH estimation. Thicker cross-sections more likely overlap with breast height (1.3 m). To the best of our knowledge, the accuracy of cross-section height above ground determination and its impact on DBH estimation have not been studied yet. Moreover, the mean estimated DBH slightly increased with cross-section thickness, which implied decreased
DBH underestimation and better DBH estimation accuracy of some cross-section thickness. Thicker cross-sections contain larger parts of a tree under and above breast height than thinner ones. Owing to tree slenderness, the diameter of the lower part of a cross-section is greater than that at the upper part of a cross-section in most cases. Therefore, it can be assumed that the lower part of a cross-section contains a larger number of points than its upper part. Consequently, a larger number of points placed around a greater perimeter of the cross-section’s lower part would result in a greater estimated DBH. The vertical distribution of points in trunk cross-sections should also be addressed by further research.

5. Conclusions

In this paper, we addressed the problem of optimal cross-section thickness for DBH estimation from point cloud data. The results indicated marginal differences between biases and accuracies of DBH estimations from cross-sections of thickness up to 10 cm, and that overall accuracy of DBH estimation may increase to some level with cross-section thickness. Furthermore, trunk irregularities and bark roughness of the tree species under study should be considered when determining cross-section thickness. The proper setting of cross-section thickness facilitates point cloud processing, tree identification, and DBH estimation by circle-fitting algorithms. Moreover, better understanding the influence of cross-section thickness on DBH estimation from point clouds will improve TLS applications in forestry.

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Appendix A

| Cross-Section Thickness (cm) | European Beech | Sessile Oak |
|-----------------------------|----------------|-------------|
|                             | Min | Max | Avg | Std | Min | Max | Avg | Std |
| 1                           | 79  | 3132| 709.8| 581.9| 161 | 2492| 539.4| 424.3|
| 2                           | 151 | 6244| 1424.4| 1165.1| 343 | 4996| 1081.9| 847.5|
| 3                           | 212 | 9457| 2135.4| 1750.6| 532 | 7476| 1614.8| 1266.0|
| 4                           | 276 | 12,594| 2843.8| 2332.0| 666 | 10,003| 2158.6| 1696.2|
| 5                           | 353 | 15,684| 3556.0| 2910.4| 861 | 12,421| 2697.8| 2108.9|
| 6                           | 429 | 18,845| 4267.6| 3495.0| 1066| 14,946| 3239.4| 2531.5|
| 7                           | 506 | 21,971| 4980.2| 4075.1| 1226| 17,379| 3779.2| 2950.3|
| 8                           | 591 | 25,128| 5692.3| 4658.5| 1398| 19,867| 4317.9| 3372.7|
| 9                           | 668 | 28,249| 6402.6| 5239.9| 1604| 22,359| 4860.9| 3794.1|
| 10                          | 746 | 31,353| 7111.3| 5819.1| 1794| 24,780| 5396.8| 4205.1|
| 20                          | 1639| 62,652| 14,204.0| 11,635.9| 3534| 49,611| 10,800.2| 8425.7|
| 30                          | 2507| 93,705| 21,302.8| 17,430.6| 5352| 74,453| 16,202.7| 12,639.4|
| 40                          | 3359| 124,978| 28,391.9| 23,225.7| 7090| 98,972| 21,608.2| 16,824.7|
| 50                          | 4171| 155,980| 35,447.9| 28,989.3| 8844| 123,219| 26,986.4| 20,974.0|
| 60                          | 5044| 187,014| 42,466.5| 34,734.4| 10,659| 147,211| 32,351.9| 25,092.0|
| 70                          | 5835| 217,860| 49,416.7| 40,415.8| 12,438| 171,021| 37,714.1| 29,186.4|
| 80                          | 6607| 248,505| 56,321.5| 46,093.0| 14,244| 194,517| 43,059.1| 33,246.2|
| 90                          | 7438| 278,968| 63,189.8| 51,725.1| 16,033| 217,687| 48,398.0| 37,261.4|
| 100                         | 8213| 309,329| 69,978.5| 57,314.7| 17,813| 239,948| 53,712.1| 41,186.0|

Note: Min, minimum; Max, maximum; Avg, arithmetic mean; Std, standard deviation.
Table A2. DBH estimation from cross-sections.

| Cross-Section Thickness (cm) | European Beech | Sessile Oak |
|-----------------------------|----------------|------------|
|                             | Min  | Max  | Avg  | Std  | Min  | Max  | Avg  | Std  |
| 1                           | 8.09 | 61.59| 28.07| 11.97| 16.93| 40.42| 30.64| 5.56 |
| 2                           | 8.04 | 61.47| 28.06| 11.98| 17.00| 40.65| 30.64| 5.57 |
| 3                           | 8.08 | 61.49| 28.07| 11.99| 17.04| 40.64| 30.64| 5.56 |
| 4                           | 7.91 | 61.59| 28.06| 12.00| 17.01| 40.70| 30.64| 5.57 |
| 5                           | 7.87 | 61.52| 28.08| 12.01| 16.92| 40.63| 30.65| 5.59 |
| 6                           | 8.00 | 61.37| 28.06| 11.99| 16.82| 40.47| 30.64| 5.57 |
| 7                           | 8.01 | 61.66| 28.06| 11.99| 16.99| 40.58| 30.65| 5.57 |
| 8                           | 8.13 | 61.58| 28.08| 11.99| 16.99| 40.72| 30.63| 5.56 |
| 9                           | 8.02 | 61.56| 28.06| 11.99| 16.91| 40.72| 30.65| 5.56 |
| 10                          | 8.09 | 61.60| 28.08| 12.00| 16.82| 40.53| 30.66| 5.56 |
| 20                          | 8.43 | 61.39| 28.10| 11.96| 17.04| 40.55| 30.67| 5.53 |
| 30                          | 8.49 | 61.49| 28.15| 11.92| 17.10| 40.75| 30.71| 5.52 |
| 40                          | 8.59 | 61.51| 28.23| 11.85| 17.26| 40.67| 30.72| 5.48 |
| 50                          | 8.68 | 61.43| 28.31| 11.76| 17.59| 40.83| 30.76| 5.47 |
| 60                          | 8.63 | 61.56| 28.42| 11.68| 17.71| 40.91| 30.80| 5.46 |
| 70                          | 8.97 | 61.61| 28.53| 11.57| 18.10| 40.79| 30.87| 5.43 |
| 80                          | 8.83 | 61.70| 28.63| 11.50| 18.18| 41.09| 30.95| 5.39 |
| 90                          | 8.82 | 61.72| 28.77| 11.41| 18.44| 40.97| 31.00| 5.37 |
| 100                         | 8.95 | 61.80| 28.89| 11.33| 18.87| 41.27| 31.08| 5.36 |

Note: Min, minimum; Max, maximum; Avg, arithmetic mean; Std, standard deviation.

Appendix B

Figure A1. Linear regression of measured on estimated DBH (cm) for European beech 1-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A2. Linear regression of measured on estimated DBH (cm) for European beech 2-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
**Figure A3.** Linear regression of measured on estimated DBH (cm) for European beech 3-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

**Figure A4.** Linear regression of measured on estimated DBH (cm) for European beech 4-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

**Figure A5.** Linear regression of measured on estimated DBH (cm) for European beech 5-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A6. Linear regression of measured on estimated DBH (cm) for European beech 6-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A7. Linear regression of measured on estimated DBH (cm) for European beech 7-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A8. Linear regression of measured on estimated DBH (cm) for European beech 8-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A9. Linear regression of measured on estimated DBH (cm) for European beech 9-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A10. Linear regression of measured on estimated DBH (cm) for European beech 10-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A11. Linear regression of measured on estimated DBH (cm) for European beech 20-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A12. Linear regression of measured on estimated DBH (cm) for European beech 30-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A13. Linear regression of measured on estimated DBH (cm) for European beech 40-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A14. Linear regression of measured on estimated DBH (cm) for European beech 50-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A15. Linear regression of measured on estimated DBH (cm) for European beech 60-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A16. Linear regression of measured on estimated DBH (cm) for European beech 70-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A17. Linear regression of measured on estimated DBH (cm) for European beech 80-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A18. Linear regression of measured on estimated DBH (cm) for European beech 90-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A19. Linear regression of measured on estimated DBH (cm) for European beech 100-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Appendix C

Figure A20. Linear regression of measured on estimated DBH (cm) for sessile oak 1-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A20. Linear regression of measured on estimated DBH (cm) for sessile oak 1-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A21. Linear regression of measured on estimated DBH (cm) for sessile oak 2-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A22. Linear regression of measured on estimated DBH (cm) for sessile oak 3-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A23. Linear regression of measured on estimated DBH (cm) for sessile oak 4-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A24. Linear regression of measured on estimated DBH (cm) for sessile oak 5-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A25. Linear regression of measured on estimated DBH (cm) for sessile oak 6-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A26. Linear regression of measured on estimated DBH (cm) for sessile oak 7-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A27. Linear regression of measured on estimated DBH (cm) for sessile oak 8-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A28. Linear regression of measured on estimated DBH (cm) for sessile oak 9-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A29. Linear regression of measured on estimated DBH (cm) for sessile oak 10-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A30. Linear regression of measured on estimated DBH (cm) for sessile oak 20-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A31. Linear regression of measured on estimated DBH (cm) for sessile oak 30-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A32. Linear regression of measured on estimated DBH (cm) for sessile oak 40-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A32. Linear regression of measured on estimated DBH (cm) for sessile oak 40-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A33. Linear regression of measured on estimated DBH (cm) for sessile oak 50-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A34. Linear regression of measured on estimated DBH (cm) for sessile oak 60-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A35. Linear regression of measured on estimated DBH (cm) for sessile oak 70-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
Figure A36. Linear regression of measured on estimated DBH (cm) for sessile oak 80-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A37. Linear regression of measured on estimated DBH (cm) for sessile oak 90-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).

Figure A38. Linear regression of measured on estimated DBH (cm) for sessile oak 100-cm cross-section (a, regression slope; r, correlation coefficient; RSE, residual standard error).
### Table A3. *p*-Values of pairwise comparison between DBH estimation bias for European beech from different cross-section thickness.

| w   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2   | 0.441 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 3   | 0.963 | 0.442 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 4   | 0.532 | 0.937 | 0.513 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 5   | 0.706 | 0.182 | 0.684 | 0.231 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 6   | 0.500 | 0.961 | 0.500 | 0.996 | 0.218 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 7   | 0.501 | 0.965 | 0.442 | 0.930 | 0.137 | 0.956 | -   | -   | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 8   | 0.791 | 0.288 | 0.808 | 0.323 | 0.867 | 0.252 | 0.164 | -   | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 9   | 0.513 | 0.965 | 0.455 | 0.996 | 0.138 | 0.963 | 0.963 | 0.160 | -   | -   | -   | -   | -   | -   | -   |     |     |     |
| 10  | 0.761 | 0.230 | 0.711 | 0.293 | 0.963 | 0.270 | 0.234 | 0.867 | 0.148 | -   | -   | -   | -   | -   | -   |     |     |     |
| 20  | 0.106 | 0.006 | 0.093 | 0.025 | 0.230 | 0.011 | 0.006 | 0.121 | 0.011 | 0.188 | -   | -   | -   | -   | -   |     |     |     |
| 30  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.006 | 0.003 | 0.003 | 0.003 | -   | -   | -   | -   |     |     |     |
| 40  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | -   | -   | -   |     |     |     |
| 50  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | -   | -   | -   |     |     |
| 60  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | -   |     |     |     |
| 70  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | -   |     |     |
| 80  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | -   |     |
| 90  | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 |     |
| 100 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 |

Note: Highlighted, significantly different.
| $w$ | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2   | 0.967 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 3   | 0.973 | 0.960 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 4   | 0.898 | 0.957 | 0.976 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 5   | 0.957 | 0.805 | 0.824 | 0.805 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 6   | 0.947 | 0.957 | 0.986 | 0.960 | 0.775 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 7   | 0.805 | 0.733 | 0.805 | 0.715 | 0.926 | 0.657 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 8   | 0.520 | 0.561 | 0.599 | 0.701 | 0.466 | 0.705 | 0.306 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 9   | 0.775 | 0.657 | 0.660 | 0.607 | 0.899 | 0.717 | 0.969 | 0.305 | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 10  | 0.575 | 0.599 | 0.599 | 0.558 | 0.694 | 0.597 | 0.805 | 0.317 | 0.845 | -   | -   | -   | -   | -   | -   | -   | -   |
| 20  | 0.218 | 0.265 | 0.311 | 0.203 | 0.326 | 0.159 | 0.326 | 0.067 | 0.470 | 0.679 | -   | -   | -   | -   | -   | -   |
| 30  | 0.017 | 0.008 | 0.047 | 0.014 | 0.014 | 0.017 | 0.017 | 0.008 | 0.014 | 0.085 | 0.158 | -   | -   | -   | -   | -   | -   |
| 40  | 0.017 | 0.005 | 0.023 | 0.005 | 0.017 | 0.005 | 0.014 | 0.005 | 0.023 | 0.047 | 0.042 | 0.617 | -   | -   | -   | -   |
| 50  | 0.008 | 0.008 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.017 | 0.005 | 0.138 | -   | -   | -   | -   |
| 60  | 0.008 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.032 | 0.187 | -   | -   |
| 70  | 0.005 | 0.008 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.008 | 0.008 | 0.008 | 0.011 | 0.020 | 0.011 | -   | -   |
| 80  | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.008 | 0.008 | 0.008 | 0.008 | 0.005 | 0.005 | 0.011 | -   |
| 90  | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.008 | 0.008 | 0.008 | 0.005 | 0.005 | 0.005 | 0.050 | -   |
| 100 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.008 |

Note: Highlighted, significantly different.
Figure A39. Bias of DBH estimations using cross-section thickness of (a) 1–10 and (b) 10–100 cm.
### Table A5.
P-values of pairwise comparison between DBH estimation $\text{MSE}_W$ for European beech from different cross-section thickness.

| $w$ | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|     | 0.577 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 3   | 0.571 | 0.352 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 4   | 0.779 | 0.778 | 0.385 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 5   | 0.535 | 0.385 | 0.780 | 0.385 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 6   | 0.802 | 0.772 | 0.399 | 0.903 | 0.296 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 7   | 0.596 | 0.982 | 0.411 | 0.802 | 0.334 | 0.820 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 8   | 0.112 | 0.024 | 0.339 | 0.044 | 0.671 | 0.013 | 0.027 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 9   | 0.370 | 0.130 | 0.780 | 0.161 | 0.937 | 0.119 | 0.094 | 0.555 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 10  | 0.211 | 0.127 | 0.399 | 0.110 | 0.576 | 0.056 | 0.096 | 0.970 | 0.596 | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 20  | 0.044 | 0.013 | 0.091 | 0.030 | 0.315 | 0.021 | 0.046 | 0.475 | 0.279 | 0.519 | -   | -   | -   | -   | -   | -   | -   | -   |
| 30  | 0.006 | 0.006 | 0.010 | 0.006 | 0.006 | 0.006 | 0.013 | 0.010 | 0.027 | 0.024 | -   | -   | -   | -   | -   | -   | -   | -   |
| 40  | 0.010 | 0.006 | 0.080 | 0.010 | 0.135 | 0.006 | 0.006 | 0.106 | 0.070 | 0.182 | 0.234 | 0.904 | -   | -   | -   | -   | -   | -   |
| 50  | 0.711 | 0.863 | 0.565 | 0.776 | 0.530 | 0.780 | 0.835 | 0.370 | 0.508 | 0.474 | 0.321 | 0.091 | 0.017 | -   | -   | -   | -   | -   |
| 60  | 0.098 | 0.110 | 0.491 | 0.151 | 0.068 | 0.114 | 0.130 | 0.062 | 0.100 | 0.059 | 0.046 | 0.010 | 0.006 | 0.013 | -   | -   | -   | -   |
| 70  | 0.017 | 0.027 | 0.013 | 0.041 | 0.030 | 0.013 | 0.017 | 0.017 | 0.017 | 0.010 | 0.010 | 0.006 | 0.010 | 0.006 | 0.006 | 0.006 | 0.006 | -   |
| 80  | 0.006 | 0.010 | 0.013 | 0.006 | 0.006 | 0.006 | 0.006 | 0.010 | 0.010 | 0.006 | 0.006 | 0.006 | 0.010 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | -   |
| 90  | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | -   |
| 100 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 |

Note: Highlighted, significantly different.
Table A6. $p$-Values of pairwise comparison between DBH estimation $MSE_w$ for sessile oak from different cross-section thickness.

| w  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2  | 0.820 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 3  | 0.978 | 0.854 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 4  | 0.891 | 0.958 | 0.891 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 5  | 0.913 | 0.913 | 0.910 | 0.923 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 6  | 0.910 | 0.913 | 0.913 | 0.917 | 0.923 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 7  | 0.754 | 0.903 | 0.769 | 0.891 | 0.785 | 0.767 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 8  | 0.958 | 0.811 | 0.956 | 0.891 | 0.913 | 0.923 | 0.610 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 9  | 0.820 | 0.913 | 0.767 | 0.913 | 0.913 | 0.913 | 0.913 | 0.810 | -   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 10 | 0.923 | 0.909 | 0.917 | 0.913 | 0.923 | 0.986 | 0.754 | 0.963 | 0.811 | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 20 | 0.349 | 0.734 | 0.580 | 0.725 | 0.572 | 0.481 | 0.910 | 0.320 | 0.910 | 0.441 | -   | -   | -   | -   | -   | -   | -   | -   |
| 30 | 0.065 | 0.023 | 0.056 | 0.084 | 0.031 | 0.041 | 0.056 | 0.041 | 0.041 | 0.041 | 0.041 | 0.041 | 0.041 | 0.041 | 0.041 | 0.041 | 0.041 | 0.041 |
| 40 | 0.041 | 0.039 | 0.041 | 0.078 | 0.039 | 0.041 | 0.039 | 0.041 | 0.041 | 0.078 | 0.041 | 0.041 | 0.078 | -   | -   | -   | -   | -   | -   |
| 50 | 0.031 | 0.023 | 0.041 | 0.041 | 0.041 | 0.041 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 |
| 60 | 0.041 | 0.023 | 0.023 | 0.023 | 0.031 | 0.031 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 |
| 70 | 0.083 | 0.031 | 0.031 | 0.041 | 0.051 | 0.045 | 0.031 | 0.041 | 0.023 | 0.041 | 0.103 | 0.221 | 0.349 | 0.548 | 0.903 | -   | -   | -   |
| 80 | 0.121 | 0.070 | 0.060 | 0.045 | 0.084 | 0.112 | 0.078 | 0.065 | 0.045 | 0.088 | 0.178 | 0.308 | 0.483 | 0.636 | 0.913 | 0.807 | -   | -   |
| 90 | 0.180 | 0.150 | 0.084 | 0.162 | 0.149 | 0.178 | 0.164 | 0.150 | 0.141 | 0.138 | 0.224 | 0.481 | 0.610 | 0.785 | 0.913 | 0.913 | 0.917 | -   |
| 100| 0.278 | 0.300 | 0.239 | 0.279 | 0.296 | 0.284 | 0.349 | 0.278 | 0.229 | 0.278 | 0.447 | 0.736 | 0.810 | 0.891 | 0.923 | 0.913 | 0.978 | 0.926 |

Note: Highlighted, significantly different.
Figure A40. RMSE of DBH estimations using cross-section thickness of (a) 1–10 and (b) 10–100 cm.

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