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ORIGINAL PAPER

Influence of the correction method of CHM-based Individual Tree Detection results on the estimation of forest stand characteristics

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ABSTRACT

Information on stand characteristics is of great importance for forest inventory, management and conservation. For more than two decades, Airborne Laser Scanning (ALS) data have enabled remotely sensed estimation of forest stand attributes. Two main approaches are used to estimate biometric forest attributes using Airborne Laser Scanning (ALS): the area-based approach (ABA) and individual tree detection (ITD). So far, the ABA method has been much more commonly used in forestry, as it requires only point cloud metrics. However, with the requirement for precise height information and the development of ITD methods, it is increasingly used to estimate tree biometric characteristics and stand attributes. With this in mind, this study assessed the impact of an ITD correction method based on the Canopy Height Model (CHM) on the estimation of forest characteristics such as tree density and average tree height. The three-step correction method first classifies erroneous segments from ITD methods, which are then refined. In this study, two ITD methods were tested and their results subsequently corrected on a diverse forest area within Białowieża Forest in Poland. In general, more accurate estimates of stand attributes were obtained using the Local ITD method developed in this study area, while correction procedure produced greater improvement using the basic ITD method, which is a marker-controlled watershed with a kernel size of five pixels (MCWS 5×5). Both ITD methods were reliable for estimating tree density for deciduous trees. The correction worked most reliably for estimating tree density with both methods for the area consisted of deciduous trees, while it was most reliable for estimating average tree height with the Local method for the deciduous trees and with the MCWS 5×5 for the conifers. The results indicate that correction improved ITD estimates of stand characteristics, but this varied with species groups, tree height and amount of height variation. Therefore, further development of ITD methods is advisable, as estimating stand attributes using ALS at the individual tree level offers possibilities for improved forest management.

KEY WORDS

Airborne Laser Scanning, average tree height, Individual Tree Detection, parameter estimation, tree density

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Introduction

Information on forest stand attributes is important for forest inventory, management and conservation. Reliable information on characteristics such as tree density (Błaszczak-Bąk *et al.*, 2022), average height (Wang *et al.*, 2019) and growing stock volume (Parkitna *et al.*, 2021) is crucial for improving operational decision-making for sustainable forest management. Estimates of these attributes are fundamental to forest management and silviculture planning (Stereńczak, 2010; Socha *et al.*, 2019).

The first applications of aerial photogrammetry for forestry took place almost 100 years ago (Hugershoff, 1930). For more than two decades, the estimation of stand attributes with continuous spatial information has been possible using remote sensing data, especially by Airborne Laser Scanning (ALS). Using ALS data there are two main approaches for estimating biometric forest characteristics: the area-based approach (ABA) (Nilsson, 1996; Næsset, 1997) and the individual tree detection approach (ITD) (Hyyppä and Inkinen, 1999; Persson *et al.*, 2002). In the ABA approach, statistics describing the horizontal and vertical characteristics of tree canopies are extracted from point cloud data and compared with spatially matched, field-based plot data. The models developed are then used to predict forest attributes on a selected area (defined grid) that are aggregated into forest stands (Vastaranta *et al.*, 2013; White *et al.*, 2015). The alternative to the ABA approach is ITD, which detects and delineates individual tree crowns within a defined area and then estimates from this the tree physical attributes of interest (Straub and Koch, 2011). Values for individual trees can then be generalised to stand- or plot-level estimates for selected attributes, such as tree density or average tree height.

Despite the ABA approach providing less specific information, it is much more commonly used. However, as the need for precise single tree information increases, ITD methods are expected to become more popular, especially because new data provide a better description of individual trees, and improve the results of. i.e. single tree detection algorithms. ITD methods provide a more accurate view of the forest by offering the possibility of describing stand characteristics for single-tree attributes such as height (Stereńczak *et. al.*, 2008; Mielcarek *et al.*, 2018), crown base height and width (Jung *et al.*, 2011), species (Ba *et al.*, 2020) and tree condition (Kamińska *et al.*, 2018), among others. A shortcoming of the ITD method is that many factors influence tree detection rate (Stereńczak, 2013) and some trees will be missed (Lindberg and Holmgren, 2017). In the process of generating a CHM and subsequent tree detection, a leaf-on point cloud faces the problem of the absence of distinct differences between tree tops, which are smoothed during pre-processing, whereas a leaf-off point cloud leads to an excessive number of false tree tops. Nevertheless, methods are being developed that use the entire point cloud, with attempts made to use the distribution of the point cloud to find every tree, even those below the top canopy layer (Wang *et al.*, 2008; Gupta *et al.*, 2013; Huo *et al.*, 2022). However, the accuracy and time required for data processing do not currently allow the general use of such methods, e.g., in national forest inventories. While the performance of ITD depends on the sensitivity and parameterization of the algorithm used, it is probably more affected by the prevailing forest structure than the algorithm or data source (Larsen *et al.*, 2011; Vauhkonen *et al.*, 2012). Therefore, improving ITD methods based on both CHM and the whole point cloud is highly important as this will allow more accurate identification of individual trees, regardless of the type of forest.

Many statistical models and algorithms for forest inventories have been developed based on ABA and ITD (Hyyppä *et al.*, 2008; Peuhkurinen *et al.*, 2011; Vastaranta *et al.*, 2011a; Miścicki and Stereńczak, 2012; 2013; Stereńczak 2012; Apostol *et al*., 2016; White *et al*., 2017). The results of these two approaches are generally consistent when estimating basal area, volume, average height, average diameter, and aboveground carbon volume, but in most cases ITD-based methods have slightly lower accuracy (Yu *et al*., 2010; Peuhkurinen *et al*., 2011; Vastaranta *et al*., 2011; Coomes *et al*., 2017). Nevertheless, ITD looks at the forest from the perspective of individual trees and therefore has the potential to analyse forest structure considering features such as tree species. Consequently, there is a need to develop approaches that improve the accuracy of individual tree methods. In our previous work (Lisiewicz *et al*., 2022a, b), we proposed an automated approach to improve individual tree detection results using different CHM-based ITD methods.

In light of the need for methods that more accurately identify individual tree crowns, this study evaluates the impact of the correction method for improving individual tree detection (described in Lisiewicz *et al*. 2022a) on the estimation of stand attributes such as tree density and average tree height.

Materials and methods

Study area. Białowieża Forest (BF), a remnant of the Central European lowland forests that once occupied much of the Central European lowland plains (Faliński, 1986), covers about 150,000 ha, with 42% of its area in Poland (Fig. 1). The Polish part of the BF (about 62,000 ha) comprises four different spatial units: Białowieża National Park (BNP) and three forest districts. Thanks to several years of protection, part of BF is now preserved in close-to-natural forest conditions.

The BF area comprises a lowland forest complex characteristic of the Central European ecoregion of mixed forests. Overstory tree species composition in the BNP is 20% – black alder *Alnus glutinosa* (L.) Gaertn.; 16% – European hornbeam *Carpinus betulus* L.; 15% – Norway spruce *Picea abies* (L.) H. Karst; 13% – Scots pine *Pinus sylvestris* L.; 12% – lime *Tilia cordata* Mill.; 9% – pedunculate oak *Quercus robur* L.; 6% – silver and downy birches *Betula pendula* Roth., and *Betula pubescens* Ehrh., respectively; and 9% – other species. In comparison, in the part of the BF part situated outside the BNP, overstory species composition is: 23% – Norway spruce; 19% – black alder; 17% – Scots pine; 8% – pedunculate and sessile oaks *Q. robur* and *Q. petraea* (Matt.) Liebl., respectively; 8% – European hornbeam; 7% – lime; 7% – birches; and 11% – other species (Stereńczak *et al*., 2020a).

Field measurement. Field measurements were carried out from July to the end of October 2015. In total 685 circular sample plots with a radius of 12.62 m were surveyed over the entire BF. For this study, 69 plots with different species composition and height variation, totalling 1015 trees of nine tree species, were used. Furthermore, the plots were divided into three groups based on species composition (forest types): coniferous (the share of spruce and/or pine exceeds 90%), deciduous (the share of deciduous trees exceeds 90%) and mixed (the share of deciduous and coniferous trees ranges from 40-60%). The centres of each plot were measured using a real-time kinematic (RTK) receiver or a static geodetic class receiver for global navigation satellite systems. During field measurement, numerous tree-related characteristics, such as tree species, tree height, diameter at breast height (DBH), crown length, tree condition and visibility from above, were recorded.

Airborne laser scanning data. The ALS dataset was acquired on 2-5 July 2015 using the LMS-Q680i full wave-form system (Riegl, Horn, Austria). The acquired point cloud had an average density of 11 points/m^2 with horizontal accuracy =0.20 m and vertical accuracy <0.15 m. The ALS strips were overlapped with a coverage of 40% (field of view =60°). The point cloud

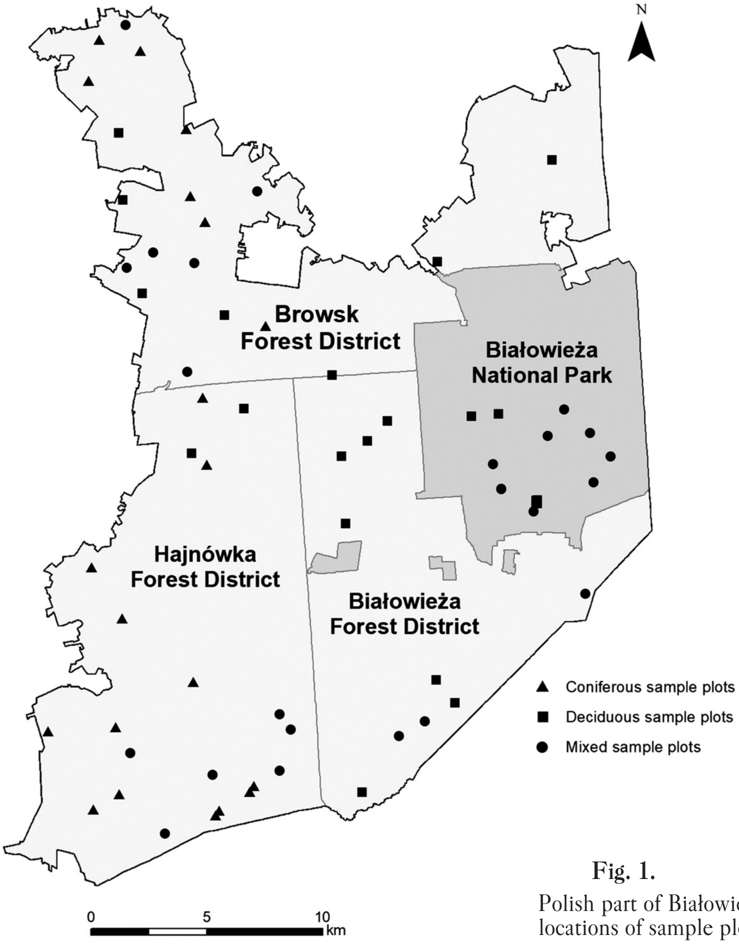

Fig. 1.
Polish part of Białowieża Forest showing the locations of sample plots used in this study

was acquired with a maximum scan angle of ±30°. To cover the entire study area, 135 individual flight lines were performed. Flight altitude of 500 m resulted in a laser beam footprint of 0.25 m. Data from ALS were used to generate the digital terrain model (DTM) and digital surface model (DSM) with a spatial resolution of 0.5 m. These models allowed the elaboration of a Canopy Height Model, on the basis of which the segmentation of individual trees was carried out.

Individual tree detection algorithms and correction method.

Individual tree detection algorithms. In our work, two automatic individual tree detection methods were used to identify trees on a raster in the form of a CHM. The first method used is the algorithm described in Stereńczak *et al.* (2020b), hereafter referred to as the 'Local method', as it was developed using data from Białowieża Forest. This method is based on finding local maxima and subsequently extracting tree crowns by outlining minimum valleys in the CHM with additional segmentation parameterisation in three height ranges. For each height range, the CHM is filtered with different settings to find the optimal parameters. After filtering, a hierarchical segmentation is performed starting from the top canopy layer using the pouring algorithm (Soille, 1999). Subsequently, the resulting segments are adjusted using the five-step procedure. The second method used, hereafter referred to as 'MCWS 5×5', consists of two steps. In the first step, the method implements a tree detection algorithm based on a local maximum filter to search for potential tree tops (Popescu and Wynne, 2004). The window size can be fixed or variable and the algorithm can work with both raster and point cloud. In this study, we defined the window size as fixed with a kernel size of five pixels. In the second step, the method applies the watershed function (Meyer and Beucher, 1990) to segment (*i.e.*, outline) crowns from a CHM. The segmentation is based on the position of the potential tree crowns determined in an earlier step.

Correction method. In order to evaluate the feasibility of estimating stand characteristics we used improved results of individual tree detection based on the method whose algorithm was described by Lisiewicz *et al*. (2022a). The three-step approach for segmentation improvement consisted of first extracting segmentation errors by classifying segments into correct and erroneous segments (Lisiewicz *et al*., 2022b). Using the Random Forest algorithm and a set of selected predictors, it was possible to identify under-segmentation and over-segmentation errors, as well as to identify segments that correctly included living trees, dead trees and snags. High accuracies were achieved for both, training data (OA=87.0% and κ=0.794) and test data (OA=85.3% and κ=0.641). Once the erroneous segments had been extracted during the classification process, segments from the under-segmentation class (where several trees are combined into one segment) were selected for further refinement. The correction of errors in this class were addressed by performing a re-segmentation based on a defined window size, to search for local maxima within these segments, with the goal of extracting additional tree crowns within the input segment. The final step merged segments from the over-segmentation class (where one tree is divided into several segments), with segments classified as correct contained the tree stem, based on four conditions indicative of similar intensity values or a common segment boundary. The correction method provides a possible solution to reduce segmentation errors by considering different forest types and different CHM-based ITD methods for identifying individual trees. The algorithm is particularly useful in mixed stands, where the largest improvement in accuracy has been reported.

Parameter estimation at sample plot level. The influence of correction method applied to CHM-based ITD algorithms on estimates of stand characteristics was investigated using the 69 field measurement plots. Plots were chosen to provide ranges of species diversity and tree height. In addition, the plots were grouped into three forest types based on species composition: coniferous, deciduous and mixed. Two characteristics describing forest stands at the plot level were evaluated: tree density (number of trees per hectare) and average stand height. Tree density was calculated by summing the segments that contained the centroid within the sample plot and then converting them into trees per hectare. Average tree height was estimated by calculating the average height of segments whose centroids were within the boundaries of the sample plot. The values estimated of each attribute were compared with the values determined using algorithms from ITD and their subsequent correction. This made it possible to determine the influence of the correction method on the estimation of each attribute. Due to the use of methods based only on CHM, the analyses were only carried out for trees that were determined to be visible from above during field measurements. In addition to the overall interpretation of the corrected results, height groups and tree height variations across sample plots were also determined. Height groups were obtained by dividing the sample plots into those where median tree height was ≤25 m and >25 m. For height variability, we divided sample plots into those where the coefficient of variation of tree height was ≤15% and >15%. Thresholds were set as close as possible to the mean for both average height and tree height variability.

Statistical analysis. Stand characteristics at the sample plot level obtained using segmentation algorithms and their subsequent corrected estimates were analysed in comparison to field-surveyed values. The results were evaluated using Mean Bias Error (MBE%), Root Mean Square Error (RMSE%) and Mean Absolute Percentage Error (MAE%) according to the following formulas:

$$MBE\% = \frac{MBE}{\overline{y}} \cdot 100 \tag{1}$$

where:

$$MBE = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \tag{2}$$

$$RMSE\% = \frac{RMSE}{\overline{y}} \cdot 100 \tag{3}$$

where:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \tag{4}$$

$$MAE\% = \frac{MAE}{\overline{y}} \cdot 100 \tag{5}$$

where:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}| y_i - \hat{y}_i | \tag{6}$$

where:

n – number of observations,
y_i – reference stand characteristic,
$\hat{y}_i$ – estimated forest characteristic,
$\overline{y}$ – mean observed stand characteristic.

Stand characteristics for the ITD methods evaluated and their subsequent correction data were also compared using the R^2 coefficient:

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i - \overline{y})^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2} \tag{7}$$

Results

General results. In the present study, the Local ITD method performed better than the general method (MCWS 5×5). Table 1 and Figs. 2 and 3 show the summarised results for all analysed plots for two attributes (tree density and average tree height) for the two ITD methods tested and their subsequent correction. In addition, Table 2 provides detailed results for three species groups: coniferous, deciduous, and mixed. Based on the results for all plots, both ITD methods improved the accuracy of parameter estimation and reduced errors after applying the ITD correction (Table 1). Comparing the Local and MCWS 5×5 methods, the latter method yielded weaker evaluation metrics, but the correction procedure provided greater improvement in segmentation results for MCWS 5×5.

For the MCWS 5×5 method, the accuracy of tree density estimates increased 12% based on R^2 (Fig. 2), and errors decreased by 15-17%. The estimate of average tree height by MCWS

5×5 improved 4% based on R^2 (Fig. 3) and individual errors decreased by 2-3% (Table 1). For the Local method, tree density estimates increased by 4% (Fig. 2) and errors in all metrics decreased by 1%. There was a 1% improvement in R^2 using the Local method for estimation of average tree height (Fig. 3).

Three species groups – coniferous, deciduous and mixed – were evaluated to assess the influence of the correction method on the estimation of plot level stand characteristics (Table 2). For the Local method, correction most improved results in the deciduous group, with a 6% increase in R^2 and a 3% decrease in errors for tree density. Similarly, when average tree height

Table 1.

General accuracy and error levels for two stand characteristics before and after undergoing correction

Parameter	Method	R^2	RMSE%	MAE%	MBE%
Tree density	Local method	0.80	20	16	11
	Local method post-correction	0.84	19	15	10
	MCWS 5×5	0.59	48	41	41
	MCWS 5×5 post-correction	0.71	32	26	24
Average height	Local method	0.91	5.8	4.3	–1.8
	Local method post-correction	0.92	5.5	4.3	–1.6
	MCWS 5×5	0.80	11.0	8.4	–7.7
	MCWS 5×5 post-correction	0.90	8.6	6.1	–4.6

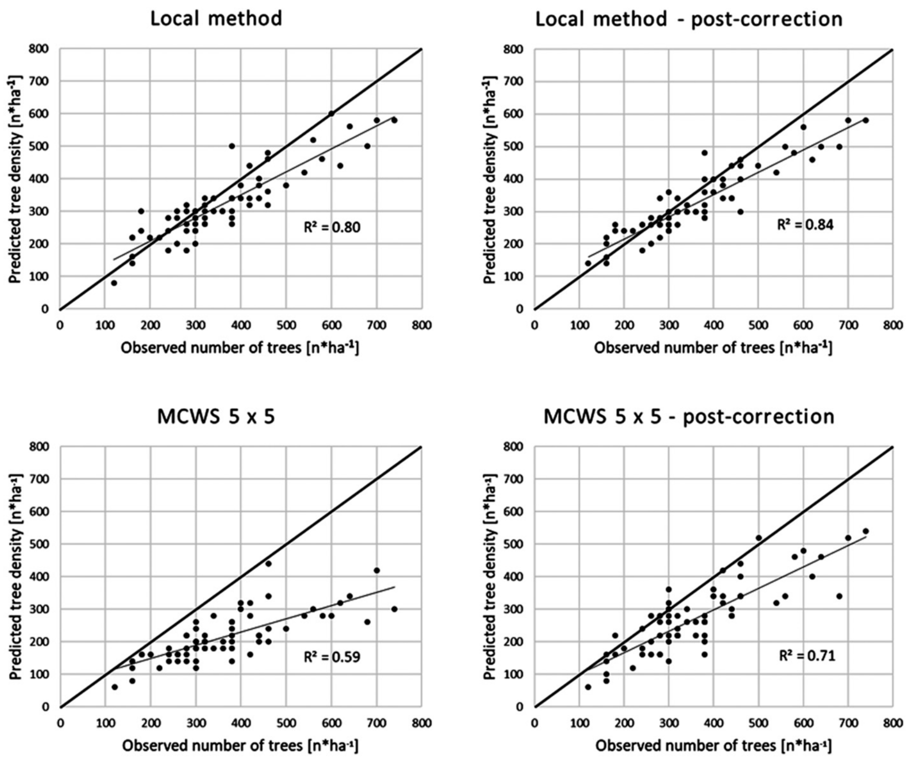

Fig. 2.

Observed vs. predicted tree density before and after undergoing correction. The grey line shows the calculated correlation while the bold black line is the 1:1 line

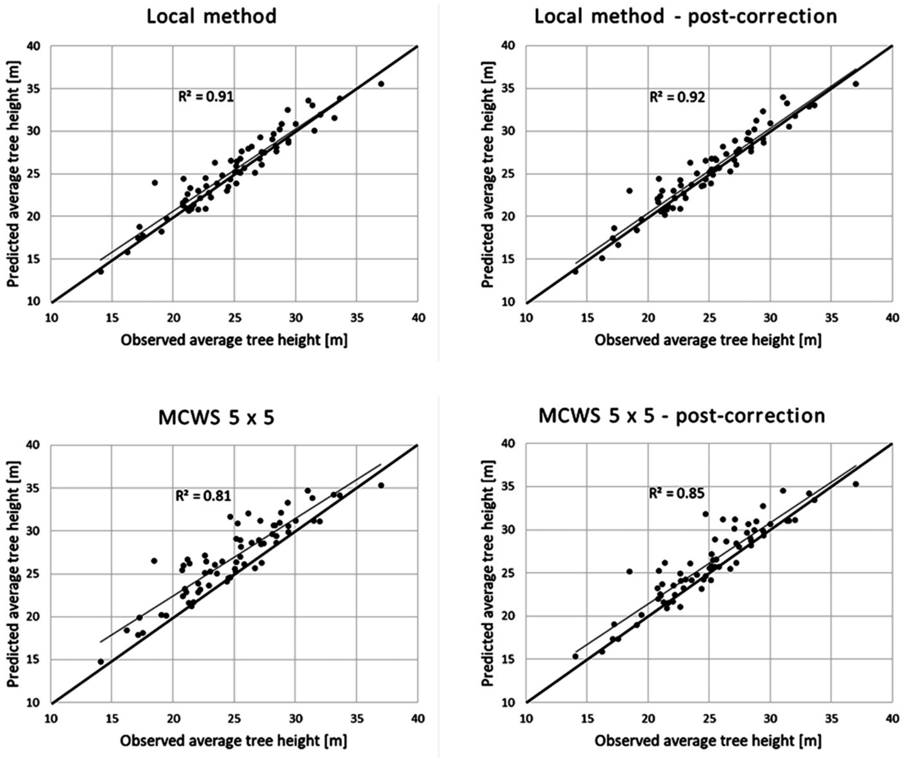

Fig. 3.

Observed vs. predicted average tree height before and after undergoing correction. The grey line shows the calculated correlation while the bold black line is the 1:1 line

was considered, R^2 increased by 3%, while errors decreased by 0.3-0.8%. The case of tree density of the coniferous group is noteworthy, as error increased 2-3%, but there was a 3% improvement in R^2. For the average tree height for conifers there was a 2% improvement in R^2 and slight improvements in errors (0.3-0.4%). Using the MCWS 5×5 method, considering tree density, the improvement in results was greatest for the deciduous group, with R^2 increasing 20% and of other stand attributes in the range of 14-19%. Interestingly, for the mixed group, a notable decrease in R^2 of 7% was observed with a concomitant decrease in errors of 16-23%. For average tree height, improvement of R^2 was greatest for the coniferous group (5% increase) and for other attributes R^2 increased by about 4-5% for the mixed group.

Results with height groups. To more closely examine the performance of the correction method, sample plots were divided into height groups of ≤25 m or >25 m (Table 3). The correction results using the Local method differed slightly between height groups. In terms of tree density, the increase in accuracy was the same (3% in R^2), but the decrease in error was larger for taller trees. This also led to greater improvement in the estimation of average tree height for this height class. When analysing the results for MCWS 5×5, it is important to note that R^2 for estimating tree density decreased by 6% when assessing taller trees, but with a large reduction in error (20% or more). Although R^2 improved by 11% when assessing low trees, RMSE%, MAE% and MBE% improved less than for the taller trees. Considering average tree height, the correction was more reliable in plots with taller trees (R^2 increased by 5% and errors decreased by 3.1-4.6%).

Table 2.
Accuracy and error levels of species groups for two stand characteristics before and after undergoing correction

Parameter	Group	Method	R^2	RMSE%	MAE%	MBE%
Tree density	Coniferous	Local method	0.84	15	11	9
		Local method post-correction	0.87	17	13	12
		MCWS 5×5	0.51	43	37	37
		MCWS 5×5 post-correction	0.75	28	24	24
	Deciduous	Local method	0.79	24	19	11
		Local method post-correction	0.85	21	16	8
		MCWS 5×5	0.69	52	42	42
		MCWS 5×5 post-correction	0.89	33	28	28
	Mixed	Local method	0.66	22	18	12
		Local method post-correction	0.68	19	16	9
		MCWS 5×5	0.39	50	44	44
		MCWS 5×5 post-correction	0.32	34	25	21
Average height	Coniferous	Local method	0.90	4.5	3.6	0.7
		Local method post-correction	0.92	4.1	3.3	0.4
		MCWS 5×5	0.88	5.6	4.3	–2.8
		MCWS 5×5 post-correction	0.93	4.0	2.8	–0.8
	Deciduous	Local method	0.83	7.7	5.7	–3.4
		Local method post-correction	0.86	7.1	5.4	–2.6
		MCWS 5×5	0.73	12.1	8.9	–8.3
		MCWS 5×5 post-correction	0.76	10.3	7.3	–5.9
	Mixed	Local method	0.96	4.5	3.8	–2.5
		Local method post-correction	0.95	5.1	4.3	–2.6
		MCWS 5×5	0.86	14.4	12.3	–12.3
		MCWS 5×5 post-correction	0.85	10.5	8.0	–7.2

Table 3.
Accuracy and error levels for two tree height classes for two stand characteristics before and after undergoing correction

Parameter	Variant	Method	R^2	RMSE%	MAE%	MBE%
Tree density	h>25 m	Local method	0.85	22	17	15
		Local method post-correction	0.88	20	15	13
		MCWS 5×5	0.76	53	45	45
		MCWS 5×5 post-correction	0.70	33	26	25
	h≤25 m	Local method	0.76	18	15	7
		Local method post-correction	0.79	18	14	7
		MCWS 5×5	0.61	43	36	36
		MCWS 5×5 post-correction	0.72	30	25	24
Average height	h>25 m	Local method	0.71	7.1	4.9	–1.4
		Local method post-correction	0.74	6.7	5.0	–0.8
		MCWS 5×5	0.56	13.3	9.6	–9.3
		MCWS 5×5 post-correction	0.61	9.6	6.5	–4.7
	h≤25 m	Local method	0.81	5.0	4.0	–2.0
		Local method post-correction	0.83	4.8	3.9	–2.1
		MCWS 5×5	0.59	9.6	7.7	–6.7
		MCWS 5×5 post-correction	0.63	7.9	5.7	–4.5

Results with different levels of variation in height. Results for height variation provide information on how the ITD and correction method performs in stands with an undifferentiated tree height structure and in stands where there is considerable height variation among trees (Table 4). Using the Local ITD method, greater improvement in determining tree density was obtained when there was greater variation in tree height (increase of R^2 by 6%, decrease of RMSE% and MAE% by 2%). For average tree height, there were no notable differences in the improvement of accuracy between the Local and MCWS 5×5 method. For tree density, using MCWS 5×5, there was improved estimation for stands with greater tree height variation (R^2 by 20%). Nevertheless, the decrease in error values was larger when there was less tree height variation (18-21%), with a concomitant decrease in R^2 of 1%. Greater improvement in the estimation of average tree height was obtained when there was less variation in tree height. It is worth noting that both ITD methods underestimated tree density and overestimated average tree height, taken over all stand height and height variation groups and MBE% values.

Discussion

In this study, we evaluated the impact of the CHM-based ITD results correction method described in Lisiewicz *et al.* (2022a) in estimating stand parameters such as tree density and average tree height. The ITD methods were evaluated by examining stand characteristics estimated for forest areas differentiated according to tree species, height classes and tree height variation. Overall, more accurate estimates of stand characteristics were obtained using the Local ITD method, while there was a greater improvement of results following correction for the MCWS 5×5 method. Both ITD methods worked most reliably for deciduous species when estimating tree density, while estimates of average tree height were most reliable using the Local method for deciduous trees and with MCWS 5×5 for conifers. This study was conducted in one of the most diverse forest communities in Europe, making tree identification and thus estimation of basic stand attributes for individual trees a major challenge.

Table 4.

Accuracy and error levels for stands with higher or lower coefficient of variation in height for two stand characteristics before and after undergoing correction

Parameter	Variant	Method	R^2	RMSE%	MAE%	MBE%
Tree density	CV_h>15%	Local method	0.79	21	17	9
		Local method post-correction	0.85	19	15	9
		MCWS 5×5	0.62	46	38	38
		MCWS 5×5 post-correction	0.82	31	26	25
	CV_h≤15%	Local method	0.81	19	15	12
		Local method post-correction	0.81	19	14	11
		MCWS 5×5	0.57	51	45	45
		MCWS 5×5 post-correction	0.56	33	25	24
Average height	CV_h>15%	Local method	0.92	4.9	3.9	–1.2
		Local method post-correction	0.93	4.7	3.7	–1.0
		MCWS 5×5	0.91	6.6	5.1	–4.0
		MCWS 5×5 post-correction	0.91	5.5	4.0	–2.1
	CV_h≤15%	Local method	0.85	7.0	5.1	–2.5
		Local method post-correction	0.87	6.6	5.2	–2.4
		MCWS 5×5	0.76	15.9	13.2	–13.2
		MCWS 5×5 post-correction	0.77	12.1	9.0	–8.2

The estimation of stand attributes varied according to forest type, ITD method (Local *vs.* MCWS 5×5) and the influence of the ITD correction method. The ITD method developed in the study area, i.e., the Local method, has high accuracy in estimating both tree density and average tree height, with R^2 of 0.80 and 0.92, respectively. The correction method improved these results to values of 0.84 and 0.93, respectively, with a simultaneous decrease in errors for RMSE%, MAE% and MBE%. The Local ITD method was expected to be very accurate as it was developed in this study area. Nevertheless, applying the correction approach showed that there is room for improvement in this ITD method, which argues, among other things, for a more accurate estimation of stand parameters. The other ITD method used, MCWS 5×5, which can be described as a baseline method, had considerably lower accuracy than the Local method in estimating both tree density and average tree height, R^2 of 0.59 and 0.81, but correction method improved R^2 to 0.71 and 0.85, respectively. ITD correction reduced errors in estimating tree density by more than ten percent and estimates of average tree height improved by several percent. Both ITD methods underestimated tree density and overestimated average tree height. In many cases this was due to the lack of detection of suppressed trees, which are absorbed by the dominant trees during segmentation, reducing estimates of tree density and increasing average height estimates.

The estimation of stand parameters has been addressed in several studies. Packalén *et al.* (2008) used a low-density (0.7 pts/m^2) ALS point cloud to achieve an RMSE% of 49.1% in estimating tree density in managed coniferous-dominated boreal forest in eastern Finland. In another study, Simula *et al.* (2022), using ordinary ALS data and a watershed segmentation method, achieved an R^2 of 0.58 and an RMSE% of 32.3% in estimating tree density for all species in southern boreal forests in Finland. They obtained their best results for deciduous trees with much poorer results for conifers, especially spruce. In our study, we obtained an R^2 of 0.84 and an RMSE% of 19% using the Local ITD method and its subsequent correction. However, it is important to note that since we had field data that indicated trees visible from above, we only used such data. When looking at species groups, our results differed depending on ITD method. For the Local method, the accuracy of tree density estimation was higher for conifers, while for MCWS 5×5 it was higher for deciduous trees. The poorest results were obtained for mixed species, which tend to have higher segmentation errors than homogeneous conifer stands (Kankare *et al.*, 2013). This can be explained by mixed forests specificity: diverse species with different heights and crown characteristics are present, especially in mixed stands in Białowieża Forest. In evaluating the effects of different ITD methods, it is valuable to consider several accuracy indices when evaluating accuracy, as some measures of accuracy are more sensitive to outliers, *e.g.*, R^2, which automatically underestimates accuracy and at the same time decreases errors (as was the case for the mixed species group, see Table 2).

In our work, we did not predict average tree height directly, but determined it from segmentation results. However, the findings of this study are in line with other studies on this issue. Yu *et al.* (2020) achieved an R^2 of 0.95 and an RMSE% of 6.73% for the prediction of average tree height in southern Finland. Wästlund *et al.* (2018) achieved an R^2 of 0.96 and an RMSE% of 6.1% in semi-boreal forests in southern Sweden using the ABA method. Simula *et al.* (2022) obtained an R^2 of 0.95 and an RMSE% of 6.4% in their best case. In our study, considering the Local ITD method after the correction method was applied, we obtained an R^2 of 0.92 and RMSE% of 5.5%, a result consistent with the studies mentioned above. The correction results particularly improved the results of the MCWS 5×5 method, where R^2 increased from 0.81 to 0.85 and RMSE% decreased from 11.0% to 8.6%.

These results indicate that the correction method has a notable effect on improving the results of ITD in estimating stand attributes, when considering features such as species groups, tree height and height variation; the results obtained after correction, especially for the Local ITD method, are consistent with the current literature. Nevertheless, the ABA approach is so far considered fully operational (Næsset, 2014), while ITD methods are still operationally problematic (Kaartinen *et al.*, 2012; Vauhkonen *et al.*, 2012). The difficulty facing ITD methods is segmentation errors, which can seriously affect forest management planning calculations since such errors can misrepresent the number of trees and tree height and cause errors in tree diameter predictions (Vastaranta *et al.*, 2011b). Correctly identifying the number of trees is extremely important, as this influences the calculation of stand volume. As a result, further development of ITD methods is needed, as estimating stand parameters at the individual tree level offers the opportunity for more precise forest management and for taking into account additional factors, such as species composition, tree health and growth. Moreover, accurate ITD results allow for estimation of stand parameters by measuring attributes of individual trees, without the need to create special models, which often depend on local conditions and specific characteristics of the forest. Our research has confirmed that errors still occur both in the accuracy of individual tree identification and in the estimation of stand parameters. For this reason, we believe that aspects of tree species and stand height diversity should be given special consideration in the further development of ITD methods, as forest managers increasingly spread the risk of carrying out silviculture over as many tree species as possible that are adapted to changing and increasingly challenging forest environments.

Conclusions

In this study we evaluated the effect of a correction method applied to two CHM-based ITD methods to consider their ability to improve the estimation of stand parameters such as tree density and average tree height. For the two ITD methods evaluated, in general, more accurate estimates of stand parameters were obtained using the Local ITD method, while applying the ITD correction method produced greater improvement for the results from the MCWS 5×5 ITD method. The results indicate that the ITD correction method improves the performance of ITD methods in estimating stand parameters. In this context, correction method can help implement ITD algorithms in practice. The improvement in results for particular species groups, tree height classes and levels of height variation led, in most cases, to meaningful increases in accuracy and reduced error. Nevertheless, we believe that ITD methods need further development to improve their ability to be used operationally and accurately in forestry.

Authors' contributions

M.L. – performed the literature review, conceptual planning, formal analysis, validation, visualization, original draft preparation, text writing and editing; A.K. – contributed to the conceptual plan, validation, text writing and editing; K.S. – contributed to the conceptual plan, text writing and editing and funding acquisition.

Conflicts of interests

Authors declare there is no conflict of interest.

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STRESZCZENIE

Wpływ metody korekcji wyników algorytmów detekcji pojedynczych drzew opartych na Wysokościowym Modelu Koron na szacowanie parametrów drzewostanowych

Informacje o parametrach drzewostanowych mają kluczowe znaczenie dla inwentaryzacji lasu, zarządzania i ochrony obszarów leśnych. Dokładne informacje o takich parametrach jak gęstość drzew (Błaszczak-Bąk i in. 2022), średnia wysokość (Wang i in. 2019) czy zasobność drzewostanu (Parkitna i in. 2021) są kluczowe dla podejmowania strategicznych decyzji w zakresie zrównoważonej, a coraz częściej precyzyjnej gospodarki leśnej. Co więcej, szacowanie tych parametrów jest podstawowym kryterium przy opracowywaniu wytycznych dla urządzania i hodowli lasu (Stereńczak 2010; Socha i in. 2019).

Pierwsze próby zastosowania fotogrametrii lotniczej w leśnictwie podjęto już blisko 100 lat temu (Hugershoff 1930). Od ponad dwóch dekad dane teledetekcyjne, zwłaszcza dane lotniczego skanowania laserowego (z ang. ALS), umożliwiają nieinwazyjne szacowanie parametrów drzewostanowych. Na podstawie danych ALS można wyróżnić dwie główne metody szacowania biometrycznych parametrów lasu: metodę obszarową (z ang. ABA) (Nilsson 1996; Næsset 1997) oraz metodę wykrywania pojedynczych drzew (z ang. ITD) (Hyyppä i Inkinen 1999; Persson i in. 2002). Dotychczas w praktyce leśnej znacznie częściej stosowano metodę ABA. Jednak wraz z rozwojem metod ITD wzrasta tendencja do wykorzystywania tych danych w szacowaniu podstawowych parametrów drzewostanowych.

Celem niniejszej pracy była ocena wpływu metody korekty ITD opartej na Wysokościowym Modelu Koron (Lisiewicz i in. 2022a) na szacowanie parametrów drzewostanu, takich jak zagęszczenie drzew oraz średnia wysokość drzew. Trzyetapową metodę korekcji rozpoczęto od sklasyfikowania błędnych segmentów z metod ITD, które następnie zostały poddane poprawie. W pracy przetestowano dwie metody ITD, które następnie skorygowano na danych pochodzących ze zróżnicowanego pod względem wysokościowym i gatunkowym obszaru leśnego, jakim jest Puszcza Białowieska (ryc. 1).

Przy szacowaniu parametrów drzewostanowych dokładniejsze wyniki uzyskano metodą lokalną (Stereńczak i in. 2020b), opracowaną na bazie danych z tego obszaru badawczego, natomiast metoda korekcji miała większy wpływ na poprawę wyników dla jednej z podstawowych metod ITD, jaką jest MCWS 5×5 (tab. 1, ryc. 2 i 3). W odniesieniu do gatunków drzew i szacowania zagęszczenia drzew metoda korekcji dla obu metod przynosi najlepszą poprawę dla grupy drzew liściastych, natomiast przy uwzględnieniu średniej wysokości drzew dla grupy drzew liściastych w metodzie lokalnej oraz dla grupy drzew iglastych metodą MCWS 5×5 (tab. 2). Aby szczegółowo zbadać działanie metody korekcji, powierzchnie próbne podzielono również na warianty wysokościowe oraz zmienności wysokości (tab. 3 i 4). Szczegółowe wyniki zastosowania algorytmów ITD i metody korekcji w wymienionych podgrupach pokazały wydajność metody korekcji w tym kontekście.

Uzyskane wyniki sugerują, że metoda korekcji ma znaczący wpływ na poprawę wyników metod ITD w szacowaniu parametrów drzewostanowych z uwzględnieniem grup gatunków, wysokości drzew i zróżnicowania wysokości. Z tego względu wskazany jest dalszy rozwój w zakresie metod ITD, gdyż perspektywa szacowania parametrów drzewostanowych na poziomie pojedynczego drzewa daje większe możliwości precyzyjnego zarządzania lasem, także z uwzględnieniem takich aspektów jak skład gatunkowy, zdrowotność czy wzrost drzew.