Lesn. Cas. For. J. 62 (2016) 39–47

Lesnícky časopis - Forestry Journal
http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Test of airborne laser scanning ability to refine and streamline growing stock estimations by yield tables in different stand structures

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Abstract
Even if stand inventories based on growth tables have been widely discussed over the last years, this method of forest mensuration is still widely applied due to favourable ratio between costs and achievable precision of stand growing stock estimation. The aim of the study was to verify the potential of airborne laser scanning data (ALS) for direct estimation of mean stand height and mean stand density (stocking) as fundamental inputs for forest mensuration based on yield tables. The material from two reference plots with substantially different stand structure was processed by REFLEX software, and confronted with the results of the precise terrestrial inventory. The number of detected tree tops decreased from 100% in the case of super-dominant trees to 30% and 5% in the case of supressed trees at the homogeneous and heterogeneous plot, respectively. The correlation of ALS heights with terrestrially measured heights was R = 0.88 at the homogenous plot, and R = 0.77 at the heterogeneous plot. The tendency to underestimate dominant and to overestimate suppressed trees was revealed at both plots, but was more pronounced at the heterogeneous one. Nevertheless we justified that the mean ALS height calculated from the heights of the detected trees represented the biometric mean stand height linked to the stem with the mean basal area quite well. The stocking estimated by REFLEX software according to delineated crowns´ area was also closer to the real value of stocking than the one obtained by the routine mensuration procedure. The results indicate promising potential of the ALS data processed by REFLEX software to rationalise forest mensuration based on yield tables in even-aged forest structures.

Key words: lidar; stand height; stand density; forest mensuration

Editor: Bohdan Konôpka

Introduction

Yield tables have been developed for a number of tree species and regions across Europe promoting traditional even-aged forest management (Wiedemann 1949;, Assmann & Franz 1963; Bradley et al. 1966; Marschall 1975, etc). Depending on site conditions, such tables forecast mean stand development (mean diameter at breast height – dbh, mean height) and stocking (basal area, volume and stem number) per hectare for pure even-aged forests. Yield tables operate at a stand level, and therefore only stand level estimation is relevant for simple even-aged forests. Due to the change in silviculture from clear-cuts to an uneven-aged, mixed, small-scale and/or individual tree selective management system, existing yield tables will become increasingly unreliable as the main forest management tool (Hasenauer 2006). However, traditional stand-wise forest mensuration based on yield tables is still widely applied because the costs are substantially lower compared to other inventory methods. Despite the fact that according to the results of the national forest inventory (NFI) more than a half of all forests in Slovakia are more or less uneven-aged, stand inventory using growth tables is currently applied at 88% of the forested area. In Slovakia the national yield tables are used (the last edition by Halaj & Petráš 1998). The required inputs for these growth tables, representing also the subject of stand inventories are: stand age, stand height, site index, stocking, and tree species composition. The accuracy of the growing stock estimation is ±20% at 95% confidence level, and strongly depends on the precision of the determination of input values. Currently the underestimation of the growing stock – 23% obtained by forest mensuration compared to NFI in Slovakia 2005–2006 is under discussion (Šmelko et al. 2008; in the same source Austria – 40%, Czech Republic – 33%).

Remote sensing (RS) is considered one of the promising ways to refine and streamline the acquisition of data on the forests. Especially airborne laser scanning (ALS), which can be combined with aerial photography can provide large amounts of fairly accurate characteristics of the three dimensional structure of a forest in a relatively short time, from which it is possible to derive tree or stand characteristics. Existing practices can be summarised into two categories: individual-tree detection approaches (ITD), and area-based approaches (ABA). Within the first group, tree height is the best directly detectable dendrometric parameter, and the accuracy of its detection is ±9 – 33% (Packalén et al. 2007; Akkay et al. 2009). The resulting growing stock is calculated as the sum of individual trees volumes, using additional inputs derived directly (number of trees) or indirectly (tree diameters) from RS data with lower accuracy than tree height, therefore its detection accuracy is only 10 – 42% (Rossman et al. 2007; Heurich 2008; Maltamo et al. 2009). In the second group of methods, timber stock is estimated using the regression equation between a dendrometric parameter measured in the field, and a specific ALS parameter (e.g. point clouds

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Corresponding author. Ladislav Kulla, e-mail: kulla@nlcsk.org, phone: +421 902 895670 density). The accuracy of growing stock estimates by this approaches reaches ±20 – 33% (Maltamo et al. 2006; Vastaranata et al. 2011).

In this study we applied ITD approach to analyse ALS data by REFLEX software, and subsequently we used the results for the calculation of mean stand values for the purpose of yield estimations on the stand level by yield tables. The aims of the study were:

1) To verify the accuracy of direct determination of mean stand height and mean stand density (stocking) by our own newly developed algorithms of ALS data processing.
2) To assess the usability of ALS data processed in this way for the estimation of the growing stock using domestic yield tables in two different stand structures.

2. Material and methods

2.1. Terrestrial data

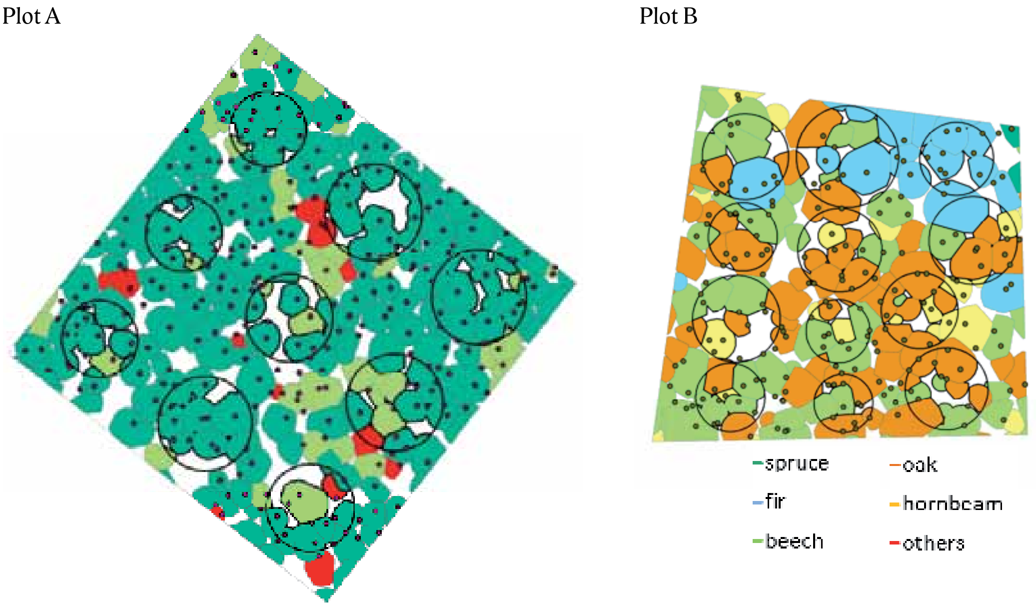
Data from two reference plots established in similar geomorphological and growth conditions of Central Slovakia, but with substantially different stand structure and tree species composition were used (48°37'N, 19°04'E). While plot A with an area of 0.95 ha represents a simpler stand structure of a typical even-aged forest, plot B with an area of 0.65 ha is an example of a complex uneven-aged stand structure (Fig. 1). On both plots, full terrestrial inventory was performed by Field-Map technology (IFER 2012). Tree species detection, diameter at breast height (dbh), tree height, and tree position were measured for each tree. Consequently, the volume of each tree was calculated using volume equations (Petráš & Pajtík 1991). These data were taken as a maximally achievable precise base to assess the accuracy of growing stock estimations by yield tables.

2.2. Remote sensing data

Data of aerial photography and airborne laser scanning (ALS) were obtained for each plot. For technical details see Table 1. The data of aerial photography were used for tree species detection, and pairwise individual tree identification after the overlap with outputs of terrestrial measurements and ALS data manually processed by an operator. REFLEX Software (Sačkov 2014a, b) which is being developed by the National Forest Centre was used to analyse ALS data.

2.3. REFLEX software principles

In the first step the initial procedures are applied to transform the point cloud to a regular mesh and to reduce the number of points in the input file. Thus, a point cloud is produced that is further used for an iterative search for treetops detection and tree crowns delineation. A moving-window analysis is


Plot A

Plot B

Fig. 1. Sample plots with crown projections of trees derived from ALS data with marked real stem positions according to terrestrial measurements, and circular ten-tree sample subplots for simulated mensuration estimations.

Table 1. Technical description of utilised remote sensing data.

Aerial photography		Airborne laser scanning	
Date	18.04.2012	Date	16. 04. 2012
Used aircraft	Cessna 206G	Used aircraft	Cessna 206G
Imaging camera	UltraCamXp	Scanning camera	Riegl LMS-Q680i
Mean height of flight [m]	2000	Mean height of flight [m]	700
Overlay (H/V) [%]	80/60	Scan angle (DEG)	60
GSD (max)	10 cm (7,2 µm)	Point density	20
Format	*.tiff	Format	*.las

applied to search iteratively for the local maxima. Because there are some reasons to assume that a part of the local maxima identified in the previous operation may not be indicative of real treetops, an additional geo-dendrometric test is applied. The geo-dendrometric test consists of two steps. At first, height differences between the local maxima located in the testing area (radius that represents the mean defined crown semi-diameter) are evaluated. At second, horizontal and vertical distances between all local maxima are evaluated. The horizontal distance is tested to eliminate false treetops situated in the crowns of neighbouring trees. The vertical distance is tested to capture the trees situated under the canopy. Finally, all tested local maxima are classified as true treetops or false treetops. The following procedures are applied to delineate tree crowns. At first, each true treetop was assigned its main crown segment. Then, the peripheral crown segments are repeatedly assigned to the main crown segment. Finally, all crown segments assigned to the true treetop are merged to create a single crown object, and the borderline of such an object is smoothed to create a realistic crown shape. When the treetops identification and crown delineation phase is completed, tree heights are recorded and crown coverage is calculated. Finally, the outputs of all procedures are exported to the point and polygon outputs in ESRI format.

2.4. Determination of stand height

The first step was the pairwise identification of individual trees using the overlap of terrestrially measured positions of trees with the treetops and crown projections derived from ALS data. The orthophotomap and the data on tree height were additionally used for unique detection of the trees. Only the data pairs with no doubt about the identity of the tree were considered as identified. Using these pairs, the correlation between the terrestrially measured heights and heights derived from ALS data was analysed, and the systematic error (BIAS) was examined by t-test. Consequently, the ALS average height (h_{als}) was computed from z-coordinates (heights) of treetops derived from ALS data, and was compared with different types of mean stand height derived from terrestrial measurements. These types of stand height were compared: mean height (h_m) computed as a simple arithmetic mean of heights obtained from terrestrial measurements, Lorey´s height (h_L) computed as a weighted mean of measured heights with basal area used as the weight [Eq. 1], and the upper height ($h_{10}\%$) computed as a mean height of 10% of thickest trees in the examined set of trees.

$$h_L = \frac{\sum_{i=1}^{n} h_i g_i}{\sum_{i=1}^{n} g_i} \qquad [1]$$

Where h_i is the height of tree i, g_i is basal area of tree i, and n is number of trees in the examined set.

To simulate real forest mensuration procedures (Bavlšík et al. 2009), virtual sample subplots each comprising 10 trees were selected within the reference plots (Fig. 1). This approach enabled us to reproduce the variability within the plots for the purpose of the statistical comparison, and it was applied generally for all calculations. Nine subplots were established in the relatively homogenous plot A, and twelve in the heterogeneous plot B.

2.5. Determination of stand density

Stand density (stocking) was estimated from ALS data (st_{als}) as a ratio of the cumulated area of crown projections delineated by REFLEX software to the whole investigated area (in our case to the area of circular subplots) after dissolving of tree crown overlaps. This stocking was compared with the stocking obtained by traditional procedure of forest mensuration based on the estimation of the potential number of missing trees (st_{num}) [Eq. 2], as well as with the precise value of stocking calculated as a ratio of real stand basal area derived from the inventory to the potential maximal basal area according to yield tables (st_{ba}).

$$st_{num} = \frac{n}{n+m} \qquad [2]$$

Where n is number of trees in the examined set (in our case always 10), and m is estimated number of missing trees which would be needed to cover empty space in the set of assessed trees (in our case a circular subplot).

2.6. Growing stock estimation

Finally, the deviations of growing stock estimated by yield tables using either remote sensing (V_{als}) or simulated terrestrial mensuration data (V_{men}) from the accurate growing stock based on full inventory of all trees on the plots (V_{inv}) were assessed. The accurate growing stock represents the sum of individual tree volumes calculated using the set of volume equations $v=f(dbh, h)$ derived for individual tree species, and applied in the National Forest Inventory of Slovakia (Petráš & Pajtík 1991).

The standard national 2-parameter yield tables (Halaj & Petráš 1998) were used for the estimation of growing stock by yield tables. The procedure applied to obtaining two from five necessary inputs for the tables (stand height and stocking) is described above. Regarding the other inputs, the age was taken from the forest management plan, the site index was determined as a function of the age and the stand height, and tree species composition was assessed by visual interpretation of aerial photographs (orthophotomap) in the case of V_{als}, in the case of V_{men} it was calculated from the number of trees, and in the case of V_{inv} it was a relative proportion of a tree species from the basal area of the virtual subplots.

3. Results

3.1. Accuracy of ALS detection of individual tree heights

The pairwise analysis of tree height detection was performed only for identified trees. The proportion of the identified tree crown peaks with the real terrestrially recorded and measured positions of trees strongly depends on the social status of the tree (Fig. 2), and varies from 100% in the case of super-dominant trees to 5 – 35% for supressed trees. The proportion of unrecognised under-storey trees is even more pronounced in the multi-layered plot B (Fig. 3). The two factors: the type of stand structure (single- or multi-layered), and the tree species were examined by the analysis of variance, and none of them could be proved to be statistically significant by F-test. The correlation of ALS heights with terrestrial heights was higher at the more homogenous plot A (R = 0.88) than at the heterogeneous plot B (R = 0.77). A tendency to underestimate dominant and to overestimate suppressed trees was observed at both plots, but was more apparent at plot B. This tendency is expressed by the deviation of the dotted line with the intercept equal to zero from the solid line representing the linear regression that fitted the data best (Fig. 4). The distribution of the differences with the results of the test on BIAS is shown in Fig. 5. The values of broadleaved tree species and from the more complex stand structure were more sensitive to BIAS. Generally, dominant trees tended to be underestimated while suppressed ones were significantly overestimated. The positive systematic error (BIAS) of h_{als} in the case of dominant coniferous trees detected at both plots (A + 0.4 m, B + 0.9 m) is difficult to explain.

3.2. ALS stand height versus mean heights applied in forest mensuration

The stand height computed as the mean from all treetops identified by REFLEX software in ALS data generally best responded to terrestrially measured Lorey´s height (Fig. 6). This tendency was even more pronounced in single-layered structure at plot A. The differences between the various types of terrestrially measured stand height were clearly visible. Their values decreased in the following order: top height – Lorey´s height – mean height. The only exception was hornbeam at plot B, where Lorey´s height was the lowest due to the strongly left-skewed diameter distribution of under-story hornbeam population, and ALS height was even higher than the top height because of the overestimation of suppressed tree heights by ALS method as stated before. The variability of terrestrial heights at plot B with the multi-layered stand structure was two to three times higher than at the sinle-layered plot A.

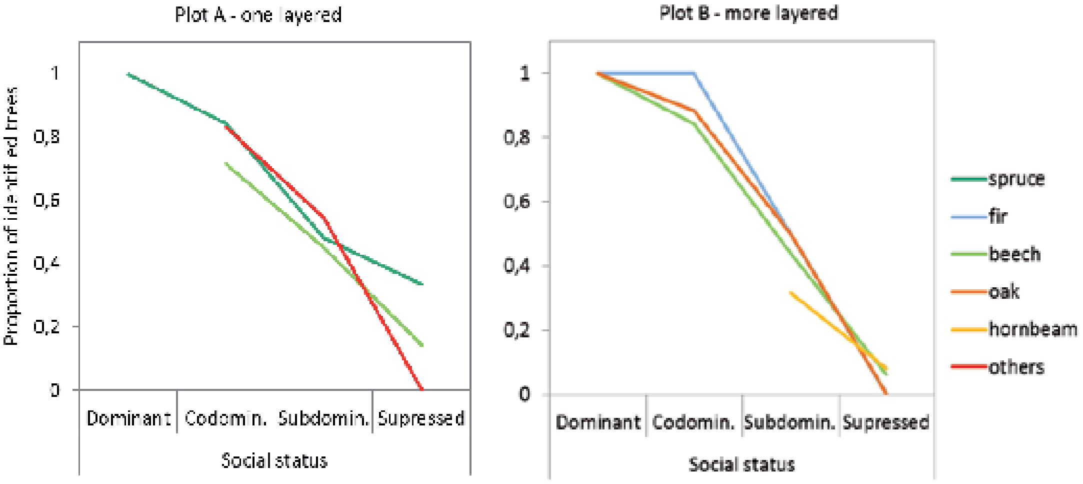


Fig. 2. Proportion of ALS identified trees from all terrestrially recorded trees.

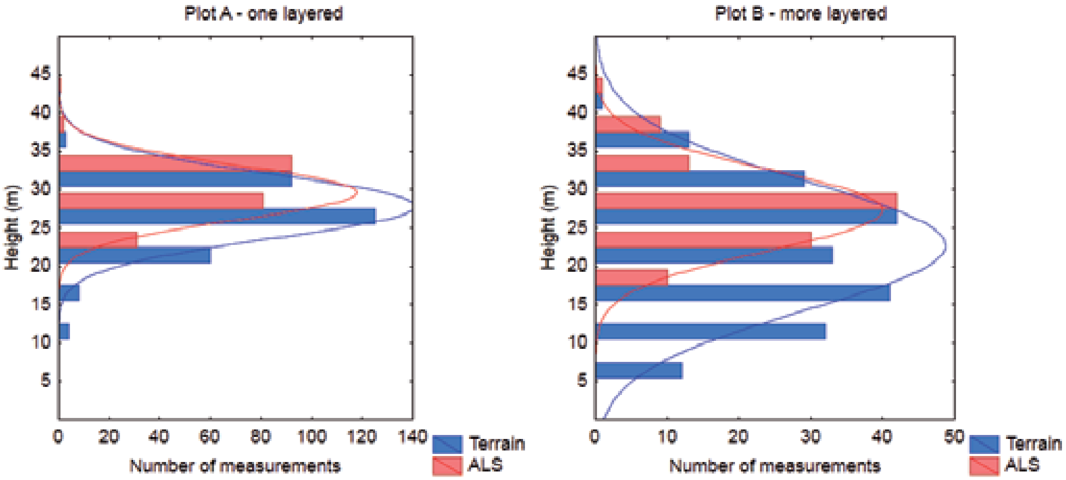


Fig. 3. Height distribution of all ALS identified and terrestrially measured trees fitted with normal distribution.

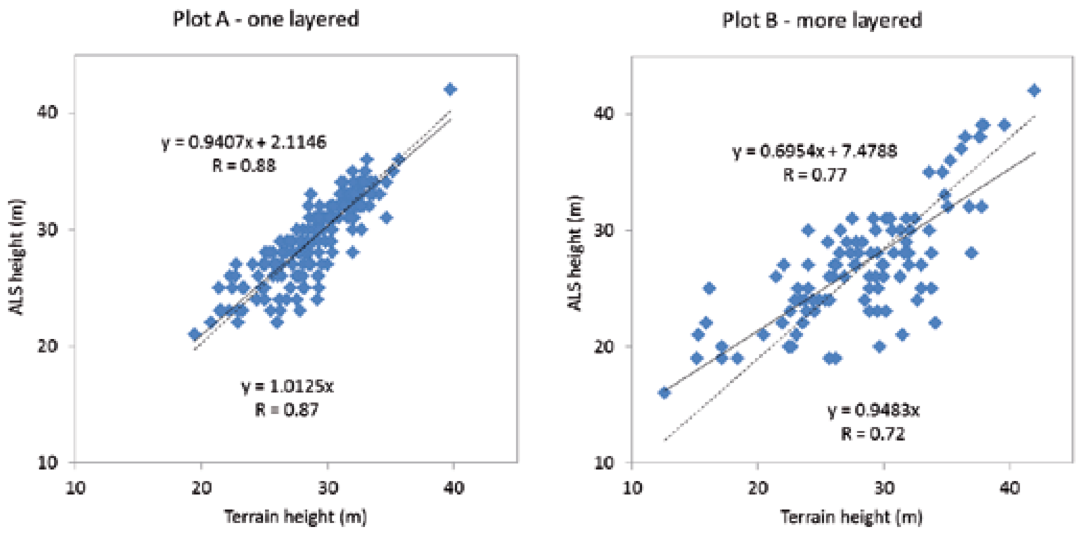


Fig. 4. Pairwise correlation of tree height derived from ALS data and tree height measured terrestrially for identified trees.

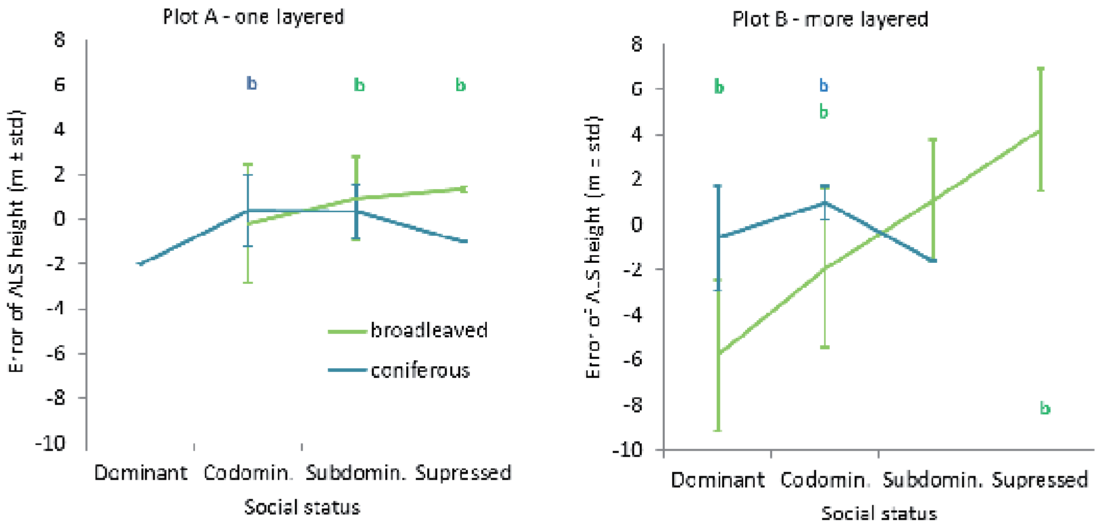


Fig. 5. Distribution of pairwise differences of ALS tree heights from terrestrially measured tree heights of identified trees (standard deviations and BIAS indicated).

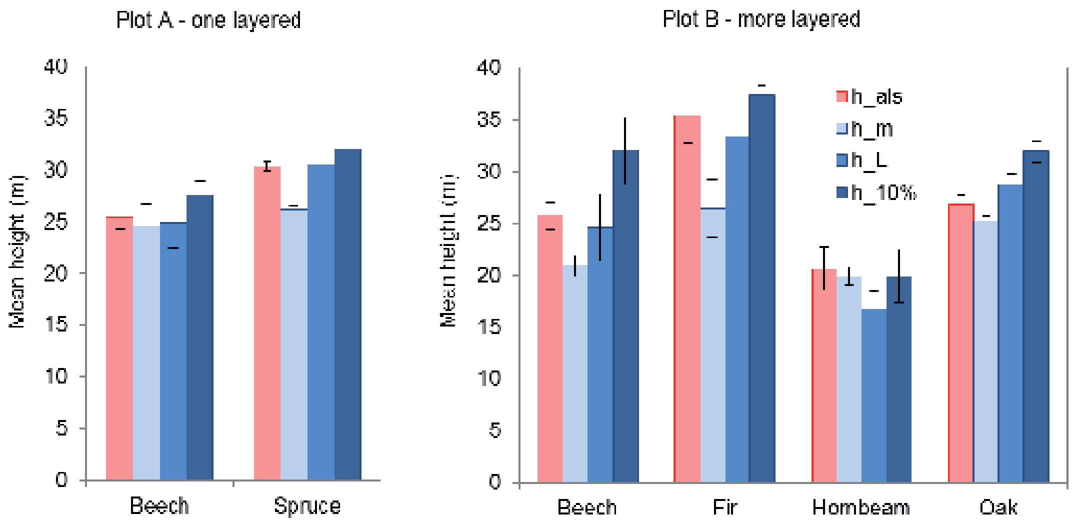


Fig. 6. Comparison of mean stand heights derived from ALS with different types of stand heights computed from terrestrial data (with standard errors at 95% confidence level).

3.3. ALS stocking versus stocking detected by conventional methods

The stocking value assessed from ALS data as a proportion of canopy built from crown projections delineated by REFLEX software was between the values of the other two examined methods at both plots (Fig. 7). We found an interesting (though not statistically significant) tendency to underestimate stocking by nearly 5% using the traditional procedure based on the number of missing trees, when compared with the exact value of stocking calculated from basal area. The variability was highest in the case of stocking calculated from basal area.

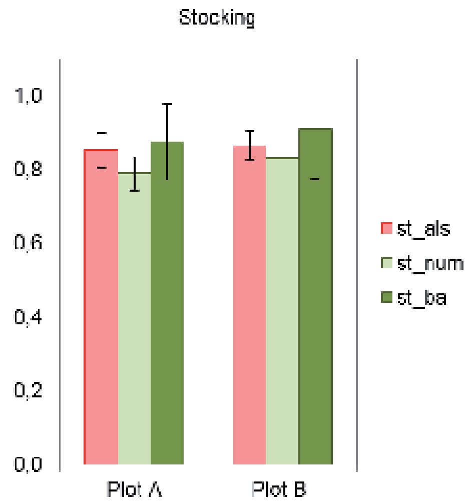


Fig. 7. Comparison of mean stand density (stocking) derived from ALS data with stand densities computed by different ways from terrestrial data (with standard errors at 95% confidence level).

3.4. Impact of remote sensing inputs on growing stock estimation

The results of comparison of remote sensing supported with traditional terrestrially supported estimation of growing stock by yield tables are summarised in Table 2. Finally, confrontation of both methods based on the yield tables with exactly determined growing stock by field measurements of all trees is given. The observed differences are presented in Fig. 8. The results showed good conformity between the estimates of the total growing stock by all examined methods, what is surprising especially in the case of the multi-layered plot B. The differences in the growing stock were −3% and −2% for terrestrially, and +7% and +9% for ALS supported yield table estimates at plots A and B, respectively. Much higher differences (about ±40%) were observed in the case of individual tree species growing stock estimates. Here partial errors of such inputs as the tree species proportion and the tree species mean height played a more pronounced role. Generally, the error of tree species proportion and the error of stocking affect the growing stock estimated by yield tables linearly as a multiplier, while the error of mean height influences the estimated growing stock indirectly through

Table 2. Estimates of stand growing stock based on yield tables derived from remote sensing inputs and from conventional terrestrial inputs, and from fully measured terrestrial data.

Method	Stand	Tree species	Proportion [ratio]	Mean height [m]	Stocking [ratio]	Age [years]	Site index [m]	Volume [m^3 ha^{-1}]
Yield tables – remote sensing inputs	plot A	beech	0.16	25.4	0,85	85	28	58.8
		spruce	0.84	30.3			32	479.1
		total						537.9
	plot B	beech	0.38	25.7	0.87	105	26	155.1
		fir	0.15	35.4			34	111.3
		oak	0.38	26.9			26	131.9
		spruce	0.02	42.0			42	19.2
		hornbeam	0.07	20.6			20	22.5
		total						440.0
Yield tables – terrestrial inputs	plot A	beech	0.24	24.8	0.79	85	28	81.1
		spruce	0.76	30.5			34	419.8
		total						500.9
	plot B	beech	0.27	24.6	0.83	105	24	100.8
		fir	0.16	33.4			32	104.2
		oak	0.46	28.7			28	162.1
		spruce	0.03	29.2			28	17.7
		hornbeam	0.07	16.7			16	17.5
		total						402.3
Terrestrial measurements of all trees	plot A	beech	0.19	23.4	0.88	—	—	95.4
		spruce	0.81	29.2			—	415.5
		total						510.9
	plot B	beech	0.21	20.0	0.91	—	—	108.6
		fir	0.20	33.5			—	104.6
		oak	0.31	28.3			—	157.6
		spruce	0.04	28.2			—	20.5
		hornbeam	0.03	16.4			—	17.1
		total						408.4

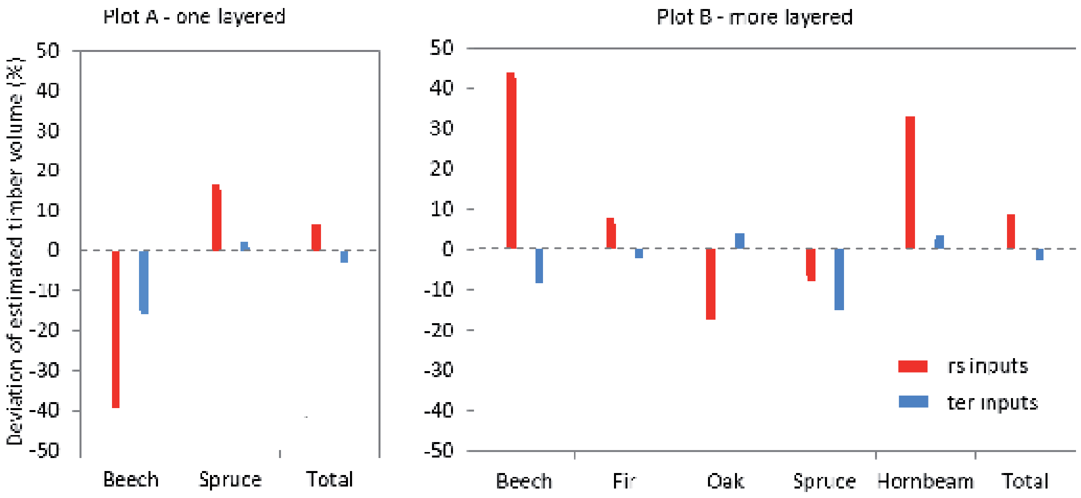


Fig. 8. Differences of stand growing stock estimated by yield tables using remote sensing inputs (rs) and terrestrial inputs (ter), from the real growing stock obtained by full measurement of all trees.

the classification in site index class with a span of 2 m. Hence, a small change of height might sometimes cause relatively substantial differences in the estimated growing stock.

4. Discussion

According to numerous studies focused on individual tree detection using the ALS data it can be stated that in single-layered forest stands individual tree detection results are better than in multi-layered ones. When testing different detection methods in the area of Berner Jura, Eysn et al. (2015) obtained best results in old forest stands with high trees and no understory vegetation. The lowest detection result was obtained in a multi-layered forest with a high amount of trees in different height layers. Only 15% of trees smaller than 10 m could be correctly extracted by the best performing method. Vega et al. (2014) reported an overall performance of 58% for mixed multi-layered mountainous forests in the French Alps, with a 75% detection rate in the dominant tree layer. Between the single-layered coniferous and mixed class, a considerable difference in the matching rates as well as in the commission rates is noticeable (Vauhkonen et al. 2011). Higher commission rates for multi-layered mixed forests can be linked to more complex crowns of broadleaved trees that can have several possible treetops, which results in over performing detection results, while coniferous trees have, in most cases, a clearly defined tree crown shape, and the tree top appears as a clear peak in the canopy height model.

In our study, the detection of 71% of all trees was obtained within the single-layered forest stand, while in the multi-layered stand structure it was only 52%. In both cases, the detection of dominant trees exceeded 80%, and the detection of supressed trees continually decreased with the decreasing relative tree height. Only 6% of trees with their relative height below 1/2 of the main canopy height was detected within the multi-layered structure. No problem with the overestimation of broadleaved crown tops was detected, what might indicate good ability of REFLEX software to delineate also problematic crowns of deciduous trees.

It should be noted that LiDAR studies, similar to other remote sensing studies of individual tree properties, are sensitive to the positional error of both field data and remote sensed data. Potential sources of errors derived from ground-based survey measurements, scanning configuration, position of the tree within the canopy, ground slope effects and crown shape and spacing might affect the predictors extracted from LiDAR, e.g. height (Saremi et al. 2014). Some of these facts might have been reasons for the unexplainable positive BIAS of dominant trees´ heights derived from ALS data when compared with precise terrestrial measurements in our study. Generally, negative BIAS has been documented for ALS height of dominant trees, and positive bias for suppressed trees (Hollaus et al. 2006). Our approach tries to avoid these biometric complications related to individual tree detection method (ITD) by deriving mean stand parameters – mean height, mean stocking directly from ALS data, and using them for growing stock estimations by yield tables at a stand level.

Stand growth tables utilise different types of stand heights to determine site index. Slovak yield tables are based on the mean stand height representing the height of a mean stem, or top height representing the mean height of 10% of the thickest trees in the stand (Halaj & Petráš 1998). The best mean stand height used for this purpose is the height of the stem with mean diameter, mean basal area, or Lorey´s height. These heights are very similar, and are all consistent with the so called Weise´s height widely applied in forest mensuration (for the description of Weise´s rule see Sedmák et al. 2015). In the case of most frequent left-skewed diameter distribution in even-aged stands, they are always higher than the simple arithmetic mean height (Šmelko 2007). Our results showed good consistency of ALS height with Lorey´s height. The decreasing ability of ALS to detect the tops of lower trees has been compensated by the fact that the “mensuration” mean stand height does not represent the arithmetic mean of all heights in the stand, but it is linked to the mean, i.e. a thicker stem.

Numerous automatic algorithms for detecting and delineating individual tree crowns from ALS data are routinely presented with improving performance and computational efficiencies (e.g. Li et al. 2012; Kania et al. 2014; Strimbu et al. 2015). As we documented in our previous studies (Sačkov 2014a, b), the ratio of crown projections delineated by REFLEX software, dissolved, aggregated and related to the whole stand area differed from routine stocking estimates applied in forest mensuration by +6% on average. The results presented in this study are in accordance with previous findings. At both plots, ALS stocking was higher than the stocking obtained by the traditional procedure of forest mensuration, but was lower than the exact value of stocking calculated as a ratio of real stand basal area to potential basal area from yield tables. The recorded tendency to underestimate stocking by routine practice of forest mensuration could be one of the reasons of underestimation of growing stock estimates when compared with forest inventory results.

Stand inventories based on growth tables have been widely discussed over the last years. Nevertheless, this method is still commonly applied not only in Central-Eastern Europe, but also in countries with developed forestry. The main reason is the ratio between the costs and the achievable precision regarding uncertainty (Haara 2005). A mean error of ±20% is declared for stand growing stock estimates by yield tables. A mean error of ±5% is achievable when all trees are measured and individual tree volume functions are applied (Šmelko 2007). Our growing stock estimates obtained from yield tables using remote sensing inputs met the declared accuracy for the whole stand, but not for individual tree species. At plot A, the main reason was the overestimation of the proportion of the dominant spruce and the underestimation of the proportion of the supressed/shaded beech from aerial photographs. At plot B, the overestimation of height and consequently of site index of mostly suppressed beech and hornbeam populations were the main reasons of the observed deviations. The uncertainty of broadleaved tree species detection from aerial photographs, resulting to mutual shifts in oak, hornbeam and beech proportions might be the next reason. The alternative of estimation supported by terrestrial measurements produced very good results, which indicates good accuracy of the yield table model if correct inputs are used.

5. Conclusions

Our study confirmed the existing knowledge about the limited ability of ALS data-processing tools to detect individual treetops of under-storey trees. Hence, individual tree detection (ITD) becomes problematic in more complex, uneven-aged and multi-layered forest structures, and it is necessary to look for other approaches of using ALS data for biometric purposes in such stands.

The tested REFLEX software showed good ability to detect treetops as well as crown shapes of dominant trees in the stand. Although not all trees were identified, we proved that the mean height calculated from the heights of detected trees represented the biometric stand height, linked to the stem with the mean basal area quite well. This height is used in the calculations of site index, thus ALS average height could be directly utilisable instead of terrestrially measured mean height for forest mensuration based on yield tables. Also the stocking estimated according to REFLEX software delineated crown area of the identified trees was closer to the real value of stocking than that obtained by routine mensuration assessment. Since the study was conducted only at two sample plots, the results cannot be generalised, and should be verified on larger data sets. However, they indicate the potential of the ALS data processed by REFLEX software to rationalise forest mensuration based on yield tables in even-aged forest structures. The risk of possible systematic error (BIAS) can be eliminated by checking field measurements and subsequent correction of the results according to the principles of the two-phase survey.

When using ALS and remote sensing data for stand-wise forest inventories it remains challenging: 1) to determine the proportion of individual tree species in the stand, and 2) to estimate the distribution of trees to diameter classes in multi-layered close-to-nature forests.

Acknowledgments

This research was supported by the Slovak Research and Development Agency (project APVV-0439-12, 50%), by the European Regional Development Fund (project INMEIN - HUSK/1101/1.2.1/0141, 30%), and by the Ministry of Agriculture and Rural Development of the Slovak Republic (item no. 08V0301, project VIPLES, 20%).

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