Tree species classification based on full-waveform airborne laser scanning data

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Abstract

Airborne laser scanning is an evolving operational measurement technique for deriving forest parameters. The objective of the current study was to analyze the potential of full-waveform airborne laser scanning for tree species classification of a mixed woodland. The quantities used were the echo width, backscatter cross section, as well as the distribution of the echoes in vertical direction. Based on segmented tree crowns the mean backscatter cross section of all echoes above the 50th height percentile was computed. Additionally, the canopy density, describing the ratio of the number of all echoes above the 50th height percentile and the total number of echoes, was used for a knowledge-based classification of coniferous and deciduous trees. The achieved overall accuracy was 83%. Furthermore, the standard deviation of the echo widths per crown segment was applied for a separation of spruce and larch. An overall accuracy of the classified tree species red beech, larch and spruce of 75% was obtained. The presented results show that combining geometric information and backscattering properties of full-waveform airborne laser scanning data has a high potential for tree species classification.

Keywords: Waveform; Echo Width; Backscatter Cross Section; Tree Species; Segmentation;

1. Introduction

Small-footprint airborne laser scanning (ALS), also known as light detection and ranging (LiDAR), is increasingly used for forestry applications. The main advantage of ALS compared to aerial photography or multi-spectral imaging is the capability of laser beams to penetrate the forest canopy. Consequently, canopy and terrain heights can be acquired simultaneously, quantitative measures, such as heights, can be measured directly, and the vertical distribution of scatterers can be extracted. In recent review papers (Hyyppä et al., 2008; Lim et al., 2003; Næsset et al., 2004) and on several conferences (see proceedings of Natscan in Freiburg 2004, 3D Remote Sensing in Forestry in Vienna 2006, and previous Silvilaser conferences) the high potential of ALS for forestry applications was emphasized. Therefore, ALS is currently evolving as an operational measurement technique in forest inventory not only for boreal (e.g. Naesset, 2007), but also for alpine forests (e.g. Hollaus et al., 2009).
As stated by Hyyppä et al. (2008) the information about tree species is of particular interest for forestry applications. Until now, the most common way of classifying different tree species is to analyze passive optical remote sensing data. Especially high-spatial-resolution color infrared aerial photography or satellite data (e.g. IKONOS, Quickbird, etc.) are the most valuable data

source to detect different tree species not only for forest stands, but also on single tree levels. As a complimentary data source to the radiometric information of optical remote sensing data, the geometric information of ALS data (e.g. vertical distribution of the scatterers, tree and stand height, tree crown shape) offers promising possibilities for tree species classification. For example Holmgren et al. (2008) described an approach to classify Norway Spruce, Scots Pine and deciduous trees using ALS and multispectral images and achieved an overall accuracy of 96%. Packalén and Maltamo (2007) presented a non-parametric k-MSN method to predict stand attributes for Scots Pine, Norway Spruce and deciduous trees based on height distribution of ALS vegetation hits, spectral values and texture features from aerial photographs. They concluded that especially for coniferous trees the predicted variables were at least as accurate as those from the stand-level field inventory.

In addition to geometric attributes, discrete ALS systems commonly provide intensity information, which seems to be a promising data source for tree species classification. However, as the intensity is influenced by spherical loss, topographic and atmospheric effects, its values should be corrected before being used in forestry applications (Höfle and Pfeifer, 2007). Examples for using the intensity information in forestry applications were published by Holmgren and Persson (2004), Moffiet et al. (2005) and Brandtberg (2007). Since 2004, so-called full-waveform (FWF) ALS systems are available, which allow to record the entire backscattered waveform of the transmitted laser pulses (Mallet and Bretar, 2009). By decomposing the waveforms into a series of echoes (Wagner et al., 2006) the geometric position and further FWF attributes (echo width and amplitude) can be determined for each echo. Using the calibration equation proposed by Wagner et al. (2006), the backscatter cross section can be estimated for each target. Furthermore, Briese et al. (2008) suggested the use of in situ measured reflectance values of natural targets for the radiometric calibration. Wagner et al. (2008) analyzed the scattering characteristics of vegetation and underlying terrain and showed the potential of the radiometric information to classify the laser data into vegetation and non-vegetation echoes. For tree species classification and forest structure parameterization Höfle et al. (2008) analyzed FWF ALS data (i.e. echo width and backscatter cross section) at object level (i.e. crown segments). The results showed that the average segment-based values of echo width and cross section were well suited to separate larch from oak and beech. Furthermore, Reitberger et al. (2008) and Litkey et al. (2007) analyzed FWF ALS data for tree species identification and tree parameter extraction.

The current paper describes an approach to classify tree species using geometric information (e.g. roughness images, echo width) and radiometric properties (e.g. backscatter cross section) extracted from full-waveform ALS data. The advantage of this approach is that the used measures are derived from a single measurement and therefore no positional inaccuracies exist between the geometric and the radiometric information. Furthermore, ALS as an active remote sensing system is not affected by varying sunlight conditions. Especially in mountainous regions the effect of shadows limits automatic tree species classification based on orthophotos and therefore ALS data provide a promising data source instead of orthophotos. Starting with an exploratory data analysis characteristic FWF point cloud attributes are assessed for different tree species, which provide the input for the proposed knowledge-based classification of forests. Local forest inventory data are used as reference. The analyses are done for a mixed woodland in the eastern part of Austria.

2. Study area and datasets

2.1 Study area

To study the potential of FWF ALS data for tree species classification an investigation area with a size of 2.2 x 1.5 km located in the federal state of Lower Austria was selected. As part of the northern Limestone pre-Alps the region is characterized by a varying landscape featuring steep slopes, deep valleys and basins. The densely forested area, which is owned by the Austrian Federal Forests (ÖBf AG), stretches from the Ötscher mountain (1893 m a.s.l.) northwards to the small town of Gaming (431 m a.s.l.). The predominant tree species are red beech (*Fagus sylvatica*), spruce (*Picea abies*) and larch (*Larix decidua*) and cover about 80% of the trees in the study area. Therefore, further investigations and tree species classification concentrated on these three species.

2.2 Forest inventory data

In the study area a local forest inventory was performed by BFW[1]. In total 15 sample plots were distributed in a regular grid of 100 m. The field measurements took place in October and November 2007 and April 2008. Based on angle count sampling (Bitterlich, 1984) trees were selected using a basal area factor of four. For each sampled tree the species was determined and position, diameter at breast height, tree height and crown diameter parallel and perpendicular to the slope line were measured. A summary of the forest inventory data is given in Table 1. To guarantee that the measured tree positions match the ALS data, the co-registration as described in Dorigo et al. (2009) was applied.

Table 1: Summary of the forest inventory data for the 15 sample plots located in the study area. The number of the sampled trees of the dominant tree species are given. Furthermore, the means and standard deviations of tree heights (*h*) and crown diameters (*cd*) are shown.

Tree Species	No. trees	h_{mean} [m]	h_{stddev} [m]	cd_{mean} [m]	cd_{stddev} [m]
Spruce	42	27.05	6.23	2.55	1.06
Larch	23	25.07	3.9	2.72	1.19
Beech	76	23.41	5.55	3.54	1.29

2.3 Full-waveform ALS data

The analyzed ALS data were acquired during a flight campaign in January 2007 under leaf-off conditions. The acquisition was carried out by the company Diamond Airborne Sensing GmbH[2] using a RIEGL LMS-Q560 full-waveform laser scanner mounted on a fixed wing aircraft. The LMS-Q560 operates at wavelengths of 1500 nm generating laser pulses with a typical width of 4 ns (full width at half maximum). The mean flying height was 620 m above ground, which in combination with a laser beam divergence of 0.5 mrad, resulted in an average footprint size of 0.3 m on the terrain. Decomposition of the backscattered waveforms was done with the software RiAnalyze[3]. In principle, FWF laser scanning offers an unlimited number of detectable echoes. Therefore, a higher number of echoes per laser shot can be achieved. For the current test site 95 million echoes were available and densities ranging from 2 to 50 echoes/m² could be observed. Georeferencing and strip adjustment of the 3D point data was based on the method proposed by Kager (2004)..

The observables derived from the backscattered waveform (i.e. echo width and amplitude) are affected by a number of different parameters like flying height, energy of the emitted pulse and the reflectance of the illuminated surface (Wagner et al., 2006). Therefore, the backscatter cross section (BCS) was computed, which is as a quantity that simultaneously accounts for all these

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influences. This task is also referred to as calibration (Wagner et al., 2006). The calculation of the BCS was done as stated in Briese et al. (2008) and carried out for every laser echo. Subsequently, models that were needed for further analysis and processing were derived from the point data. A digital surface model (DSM) was calculated using the highest points within grid cells of 1.0 m resolution and the digital terrain model (DTM) was computed with robust filtering (Kraus and Pfeifer, 1998) using only the last echoes as input data. A normalized digital surface model (nDSM) was obtained by subtracting the DTM from the DSM. All models were generated with a resolution of 1.0 m.

3. Methods

The concept of tree species classification is based on the laser light backscattering mechanisms of the forest canopy. As the investigated laser data were acquired in January, we focused on characterizing the scattering mechanisms of different tree species (spruce, larch, beech) under leaf-off conditions. For example, the canopy surface of a spruce consists of thousands of needles, each representing a small scatterer for the near infrared laser pulses. In total, the surface of a spruce is similar to an extended target and therefore, the backscatter cross section is expected to be high. Contrary to a spruce, a beech consists of leafless branches and consequently of small scatterers. Already single branches can lead to a detectable echo in the full-waveform and thus the cross section is expected to be small. To analyze these physical properties in more detail, the extracted ALS quantities are described, followed by an exploratory data analysis for the tree species spruce, larch and beech. The ALS quantities were computed both on raster and segment level (i.e. tree crown). The field measured forest inventory data were used as reference data. Based on the findings a rule set for a knowledge-based fuzzy classification of tree species was derived.

3.1 ALS measures

An edge-based segmentation approach (Höfle et al., 2008) was applied to generate tree crown segments. This segmentation approach assumes that a tree crown is represented as a convex surface surrounded by concave areas which are detected in a first step. The derived potential crown edges are delimited to areas with an nDSM height >2.0 m and a slope-adaptive echo ratio (*sER*) <60%. The nDSM threshold is used to exclude bushes and rocks from the tree crown segmentation, whereas the *sER* threshold is used to differentiate between buildings and trees, which have both nDSM heights >2.0 m. The *sER* is the ratio of the number of neighboring echoes in a fixed search distance of 1.0 m measured in 3D (a sphere) and all echoes located within the same search distance in 2D (a cylinder) (Höfle et al., 2009; Rutzinger et al., 2008) and is calculated for each echo separately. The derived *sER* values are aggregated into regular cells of 1.0 m using the average value. A *sER* value of 100% means that the echoes within the 2D search radius describe a planar surface (e.g. street, roofs, short grass areas, etc.), whereas a *sER* value <100% means that the echoes are vertically distributed within the 2D search area and thus indicate forests.
For the quantitative description of the vertical distribution of the laser echoes, the canopy density (d_{50}) was computed as described for example in Næsset (2002). For the current analysis the d_{50} was calculated for raster cells of 1.0 m and for crown segments, respectively. In detail, the d_{50} is the ratio of the number of all echoes above the 50th height percentile (median) and the number of all echoes. The height percentile is derived from the nDSM. The 50th height percentile was chosen to exclude the influence of echoes backscattered from the terrain, rocks, bushes and understory. High d_{50} values are expected for dense coniferous forests, whereas lower values are expected for

deciduous forests under leaf-off conditions. Furthermore, the mean echo widths (EW_{mean}), the standard deviation of the echo widths (EW_{std}) and the mean backscatter cross sections (BCS_{mean}) were calculated for all echoes above the 50th height percentile for raster cells of 1.0 m and crown segments, respectively. Figure 1 shows a real color orthophoto (1a), the *sER* (1b) and the nDSM overlaid with the derived crown segments (1c). Furthermore, figures 1d-f show mean values per crown segment of EW_{mean}, BCS_{mean} and d_{50}.

3.2 Exploratory data analysis

For each sampled tree in the field inventory the measured position and the averaged diameter of the two measured tree crown diameters were used to extract the 3D points. For further exploratory data analysis 50% of the sampled trees were used, while the remaining 50% were intended for validation. To minimize overlapping tree crown areas and positional inaccuracies between the ALS and the forest inventory data the crown diameters were reduced by 10% for selecting the 3D points. For the derivation of the mean values of the attributes EW_{mean} and BCS_{mean} only points above the median of the tree heights were selected. Additionally, the mean d_{50} was computed by dividing the total number of points per tree above the median height by the number of all points belonging to a tree. Finally, scatterplots of BCS_{mean} versus EW_{mean}, BCS_{mean} versus d_{50} and EW_{std} versus d_{50} were generated as shown in Figure 2.

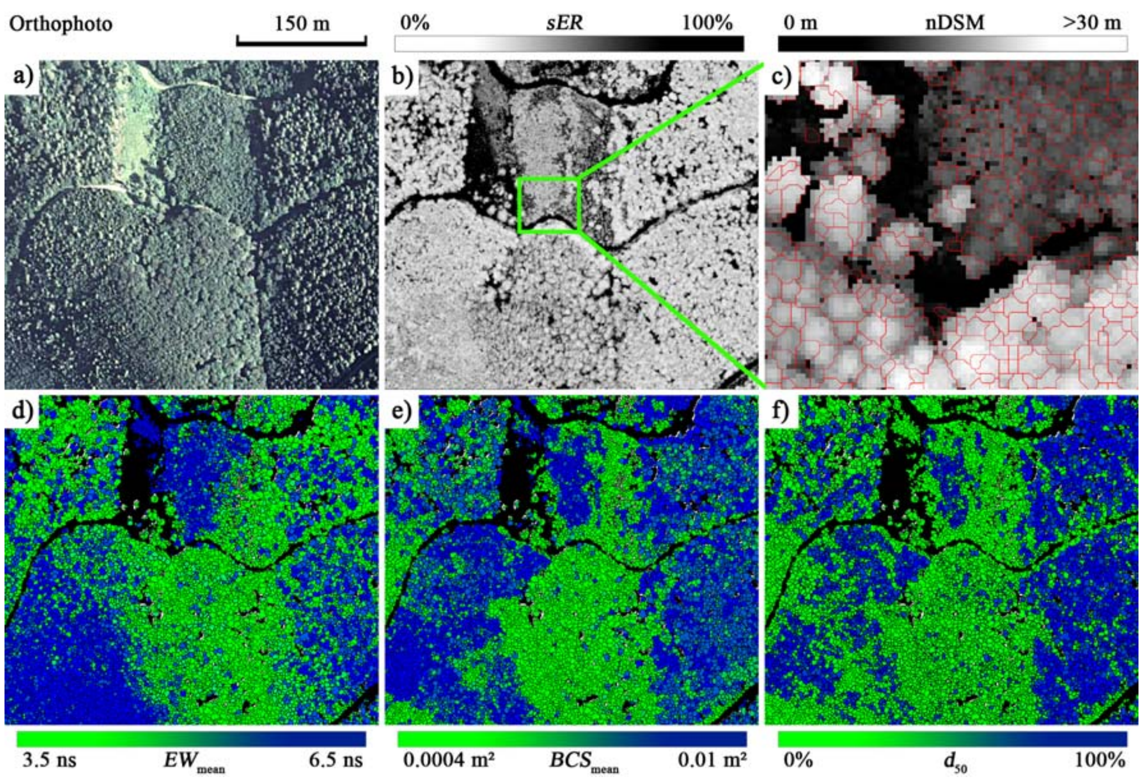

Figure 1: a) Real-color orthophoto (© http://maps.live.de), b) *sER*, c) nDSM overlaid with segmentation result and mean values per segment of the d) echo width (EW_{mean}), e) backscatter cross section (BCS_{mean}) and f) canopy density (d_{50}).

Besides the analysis based on single trees, a segment based investigation was carried out. The points inside each polygon derived in the segmentation process were used to calculate the quantities already described above in the point based analysis. Finally, scatterplots of the investigated mean values per segment were produced for those segments that contained one or more forest inventory reference trees of a single species (Figure 3). For these analyses 50% of the segments were randomly selected from each tree species, whereas the remaining segments were used to validate the derived classification result.

3.3 Tree species classification

Based on the findings of the exploratory data analysis a fuzzy rule set in combination with a decision tree was defined for classifying the tree species spruce, larch and red beech. In a first step deciduous and coniferous trees were separated based on linear probability functions where probabilities (p) range between 0.05 and 0.95. As seen in Figure 3b, the BCS and the d_{50} are appropriate measures to differentiate between deciduous and coniferous species. For the linear probability functions the minimum BCS_{mean} was set to 0.0017 m^2 ($p_{\mathrm{dec,BCS}}$=0.95, $p_{\mathrm{con,BCS}}$=0.05) and the maximum BCS_{mean} to 0.0023 m^2 ($p_{\mathrm{dec,BCS}}$=0.05, $p_{\mathrm{con,BCS}}$=0.95). The minimum d_{50} was set to 0.55 (p_{dec},d_{50}=0.95, $p_{\mathrm{con,d50}}$=0.05) and the maximum to 0.65 ($p_{\mathrm{dec,d50}}$=0.05, $p_{\mathrm{con,d50}}$=0.95). The averaged probabilities for deciduous and coniferous species were used to assign the class to each tree crown segment. For the differentiation between spruce and larch the classified coniferous segments were subclassified using a threshold of the EW_{std}. Segments with $EW_{\mathrm{std}} > 0.7$ ns were assigned to larch and the remaining segments were classified as spruce. For the validation only those classified crown segments were used that contained one or more reference trees of one species, which were not used for the signature analyses. The validation was done for the tree species red beech, larch and spruce separately, as well as for the class coniferous (i.e. containing spruce and larch), and deciduous trees.

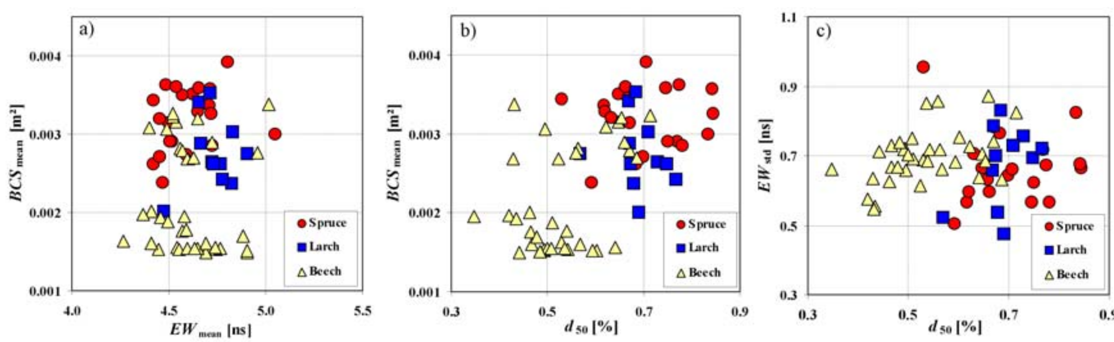

Figure 2: Mean values of point cloud attributes per field measured crown areas for different tree species. a) backscatter cross section (BCS_{mean}) vs. echo width (EW_{mean}), b) (BCS_{mean}) vs. canopy density (d_{50}) and c) standard deviation of echo widths (EW_{std}) vs. d_{50}.

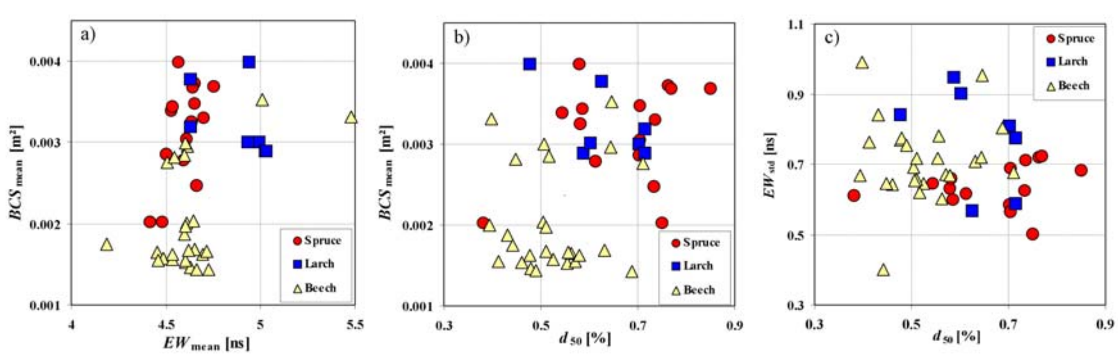

Figure 3: Mean values of point cloud attributes per segmented tree crowns for different tree species. a)

backscatter cross section (BCS_{mean}) vs. echo width (EW_{mean}), b) (BCS_{mean}) vs. canopy density (d_{50}) and c) standard deviation of echo widths (EW_{std}) vs. d_{50}.

4. Results and discussion

Due to the local forest management practice (natural reproduction, shelterwood method) the forest in the study area is very densely grown and trees overgrowing each other or overlapping branches are very common. This fact becomes crucial for mixed woodland and single segments falsely representing more than one tree and of different tree types. As shown in Figures 2a and 3a, the distribution of beeches shows two clusters. Below a BCS_{mean} of 0.002 m² the beeches form a significant cluster, well separated from the coniferous species. The BCS_{mean} values of those beeches located above the threshold are mainly derived from areas where different tree species and hence the signatures overlap. In general, the assumed higher BCS_{mean} values for coniferous than for deciduous trees could be confirmed in this study. The second parameter for differentiating coniferous and deciduous trees was the d_{50}. As can be seen in Figures 2b-c and Figures 3b-c the d_{50} values are higher for coniferous than for deciduous trees corresponding to a more dense canopy surface of coniferous trees. However, the overlap between coniferous and deciduous trees is larger for d_{50} than for BCS_{mean}. The separation of larch and spruce is even more challenging and on the basis of the available dataset harder to achieve. However, the EW_{std} seems to be a valuable measure. This can be explained by the physical backscattering properties of the canopy surface. A spruce consists of a dense, homogenous surface of needles, resulting in lower standard deviations of the echo widths describing the height variation of the scatterers within the laser footprint. During leaf-off conditions the surface of a larch is much more heterogeneous than those of a spruce and therefore the height variation of the scatterers within the laser footprint is higher.

In Figure 4b the result of the classification is displayed. Generally, the applied method works quite well on the underlying dataset. Delineations of stands of the different tree species are clearly visible. Apart from that, the classification result in the mixed woodland matches the impression from the true color orthophoto. Along the forest roads small bands of deciduous trees can be recognized. These are correctly classified deciduous bushes on slopes or in roadside ditches. The validation of the classified red beech, larch and spruce through half of the sampled forest inventory trees produced an overall accuracy of 75% and a κ-value of 0.62. The confusion matrix is shown in Table 2. For the aggregated classes coniferous and deciduous trees the overall accuracy increased to 83% and the κ-value to 0.67.

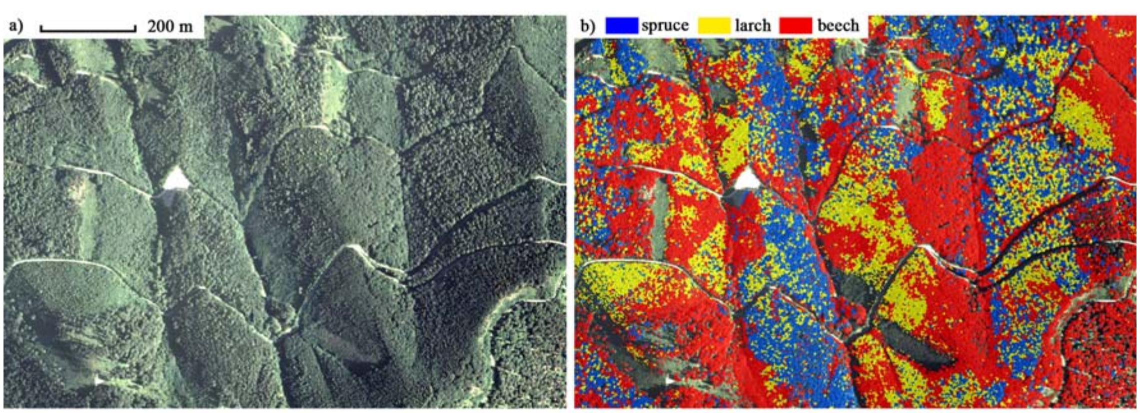

Figure 4: a) Orthophoto b) Result of tree species classification.

Table 2: Confusion matrix for the classified tree species spruce, larch and beech.

	Reference				
Classified data	Spruce	Larch	Beech	Total	User's accuracy (%)
Spruce	11	1	2	14	78.6
Larch	3	7	6	16	43.8
Beech	0	0	18	18	100.0
Total	14	8	26	48	
Producer's accuracy (%)	78.6	87.5	69.2		
Overall accuracy: 85.0%		Kappa: 0.62			

5. Conclusions

The current study shows the high potential of FWF ALS data for tree species identification. Especially the usage of complementary data sources of FWF data containing geometric information and backscattering properties yielded a more detailed result. The averaged backscatter cross section and the canopy density per tree crown are well suited for classifying coniferous and deciduous trees. Additionally, the standard deviation of the echo widths turned out to be a valuable discriminator for subdividing coniferous trees into larch and spruce. Further research will concentrate on the integration of the derived results into tree species based stem volume estimation.

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