Forest structure and stem volume assessment based on airborne laser scanning

Avaliação da estrutura florestal e do volume de madeira a partir de laser aerotransportado

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Abstract

This paper presents a methodology for the derivation of structural parameters and stem volume in forests based on Airborne Laser Scanning (ALS) data. We describe three different measures of horizontal and vertical canopy structure: (1) tree crown segmentation, (2) compactness of vegetation patches, and (3) vertical layering of vegetation patches and canopy cover. An empirical regression model for the derivation of stem volume from the ALS and forest inventory sample plot data is described and its results are validated with extensive reference data. Different study areas in Austria were used to illustrate the workflows. The presented study demonstrates the applicability of the proposed methods on study sites and ALS data of differing characteristics, as well as it points out the suitability of ALS as a tool for reliable wide area assessment of structural parameters and stem volume for forested areas.

Key words: LiDAR; canopy architecture; crown coverage; forest inventory; canopy cover.

Resumo

Esse artigo apresenta uma metodologia para derivação de parâmetros estruturais e de volume de madeira em florestas baseado em dados de Laser Scanner Aerotransportado (ALS). Nós descrevemos três diferentes medidas da estrutura horizontal e vertical da copa: (1) segmentação da copa da árvore, (2) compacidade das manchas de vegetação, (3) estratificação vertical das manchas de vegetação e cobertura do dossel. Um modelo empírico de regressão para derivar o volume de madeira fazendo uso de dados ALS e dados amostrais obtidos em inventário florestal é descrito e seus resultados são validados com extensivos dados de

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Recebido para publicação em 22/06/2012 e aceito em 11/09/2012

DOI:10.5777/ambiencia.2012.04.03

referência. Diferentes áreas na Áustria foram utilizadas para ilustrar o fluxo de trabalho. O estudo apresentado demonstra a aplicabilidade dos métodos propostos nas áreas de estudo e dos dados ALS de diferentes características, bem como aponta a adequação do ALS como ferramenta confiável para avaliação de parâmetros de estrutura e de volume de madeira de amplas áreas florestais.

Palavras-chave: LIDAR; arquitetura de copa; cobertura de copa; inventário florestal; dossel florestal.

Introduction

Airborne Laser Scanning (ALS) is an active remote sensing technique that is used for a wide range of forestry applications for more than one decade. One of the advantages of ALS compared to aerial photographs or high resolution optical satellite data is a real three-dimensional (3D) data acquisition determined from multiple single polar measurements. Especially in forests this advantage minimizes the probability of shadowing and enables the acquisition of terrain points and the vertical forest structure. Based on the acquired point cloud, topographic models such as the digital terrain model (DTM), the digital surface model (DSM) and the normalized digital surface model (nDSM = DSM - DTM) can be derived. As one of the most important forest parameters, tree heights or the height of a stand can directly be derived from the nDSM or from normalized echoes (i.e. normalizing by subtracting the terrain height from the echo height). For the assessment of forest parameters, such as stem volume or biomass, statistical (e.g. NÆSSET, 1997; NÆSSET, 2002), (semi-) empirical (e.g. HOLLAUS et al., 2009c) or physical (e.g. HYYPPÄ et al., 2001) models are commonly applied. An automated derivation of these forest parameters has already reached an operational status. Thus, it is rather a question of organizing periodic data acquisition cycles and building efficient processing chains that come into the foreground. A severe limitation is often the availability of software tools allowing computations directly on the 3D point cloud. In complex 3D scenarios, such as forests, the point cloud content is often converted to raster data (e.g. DTM, DSM, nDSM) with a notable loss of information. As a result, the information on the vertical structure of the vegetation is irretrievably lost. However, research has shown that the information on structural diversity is one of the most valuable indicators for forest and habitat quality. Diversity of structure indicates diversity of species and also different ecological niches are created (TEWS et al., 2004). ALS provides efficient means for the mapping of the vertical structure, as it is able to penetrate through small gaps in the foliage and depict vertical canopy composition down to the forest ground. It is assumed that the distribution of laser echoes in taller vegetation allows drawing conclusions on its structural complexity. Especially the latest development in ALS, full-waveform digitization (FWF-ALS), is highly suitable for measuring the canopy structure. In comparison to conventional discrete ALS systems, FWF-ALS systems sample the full backscattered pulse information (i.e. waveform) and store it for post-processing. Thus it allows a selection and adaption of the processing algorithms (MALLET; BRETAR, 2009; RONCAT et al., 2011; WAGNER et al., 2006) and consequently, in most cases, a larger number of returns (i.e. echoes) per laser shot. This makes it the preferred measurement technique especially for dense forested areas, such as old unmanaged deciduous forests or tropical rainforests, which feature structurally highly complex scenarios.

This article describes methodologies for assessing different forest structure information and stem volume (SV) based on the 3D point cloud and/or rasterized topographic models. We propose a methodology for the derivation of three measures relevant for the description of horizontal and vertical forest structure: (1) crown segmentation based on nDSM, (2) a 3D metric relating to the compactness of a vegetation patch and (3) vertical layer structure (VLS) and canopy cover (CC) derived from the horizontal and vertical ALS echo distribution. For the assessment of the stem volume, the empirical regression model from Hollaus et al. (2009c) is described and applied for different ALS data (i.e. discrete and full-waveform) and for different groups of tree species (i.e. coniferous and deciduous tree species). The regression models are calibrated with forest inventory data and are validated with independent in-situ measurements. The presented approaches combine processing steps directly in the 3D point cloud and in the raster domain.

The following section describes the investigated study areas and data. In section "Methods" the used methods and workflows for forest structure assessment and stem volume assessment are presented followed by the "Result and Discussion" section. Finally, conclusions and an outlook are given.

Study Area and Data

Different study areas located in Austria are used to illustrate the workflows for assessing the forest structure, as well as the stem volume. For each study area different types of ALS data (discrete or full-waveform) are available. Table 1 shows a summary of the investigated study areas and used ALS data sets. For all study areas the georeferenced point clouds as well as the rasterized DTMs were provided by the local authorities.

Table 1. Summary of the investigated study areas and used ALS data sets

Tabela 1. Sumário das áreas investigadas e série de dados ALS utilizados

	Study areas			
	Montafon	**Tyrol**	**Ötscher**	**Leithagebirge**
Location	Federal state of Vorarlberg, Austria	Federal state of North-Tyrol, Austria	Federal state of Lower Austria	Leithagebirge mountain, Austria
Size	525 km^2	3976 km^2	3.3 km^2	0.48 km^2
Sea level	800 to 1900 m a.s.l.	465 to ~1950 m a.s.l.	431 to ~1893 m a.s.l.	~240 to ~260 m a.s.l.
Landscape	alpine meadows, forests, wasteland, agricultural and urban land	valley with partly forested slopes; Alpine meadows and farms	varying landscape featuring steep slopes, deep valleys and basins	complex landscape composed of forest, vineyards and fields
Tree species	Coniferous	Coniferous dominated	Mixed forest	Deciduous dominated
ALS sensor	Optech Inc. ALTM 1225 & 2050, Leica ALS-50	Optech Inc. ALTM 3100	RIEGL LMS-Q560 FWF laser scanner	RIEGL LMS-Q560 FWF laser scanner
Point density	0.9 to 2.7 echoes/m^2	5 echoes/m^2	2 to 50 echoes/m^2	18 echoes/m^2
Time of acquisition	2002 to 2004, leaf-off / leaf-on	2007 and 2008, leaf-off / leaf-on	January 2007, leaf off	March 2007, leaf-off

The Montafon study area is used to investigate the assessment of the VLS and the CC. As a reference, local forest inventory (LFI) data from the forest administration Stand Montafon Forstfonds are available. These LFI data include 455 permanent sample plots. For each sample plot a wide range of forest parameters is available, whereas for this study the forest structure information (e.g. CC for three defined height layers 1.3-4.0 m, 4.1-10.0m, >10.0 m) is used as reference data source. Further details on these LFI data, as well as on the ALS data can be found in Hollaus et al. (2009a; 2009c).

The Tyrol study area is used to validate the derived SV maps based on independent reference data (i.e. fully callipered sample areas with more than 600 measured trees). Additional information about this data can be found in Hollaus et al. (2012). For calibrating the SV model, 237 sample plots from the Austrian national forest inventory (NFI) from the assessment period 2007/2009 were used. More information about the used NFI data can be found in Hollaus et al. (2009a). For each sample plot the statistically derived SV expressed as m^3/ha is used. The calculation of the SV per sample plot is based on the formulas published in Gabler and Schadauer (2008).

To demonstrate the potential of FWF-ALS for a tree species dependent SV calculation and forest structure assessment, the study areas Ötscher and Leithagebirge are investigated. For the Ötscher study area a LFI (i.e. 87 angle gauge sample plots) is available. This dataset is used as reference data source for tree species classification and for calibrating tree species dependent SV models. Further details on the Ötscher study area can be found in Hollaus et al. (2009b) . The study area Leithagebirge is used to assess additional forest structure parameters. Details on this study area can be found in Mücke et al. (2010).

Methods

In the following section the pre-processing of the ALS data and the assessment of the forest structure information, as well as the estimation of SV is described.

Pre-Processing of the ALS Data

For all study areas the ALS data (point clouds) were already georeferenced. For the calculation of the DTM the hierarchic robust filtering approach described in Kraus and Pfeifer (1998) is applied, which is implemented into the software (SCOP++, 2012). The DSM is calculated based on a land cover dependent approach described in Hollaus et al. (2010). Finally the nDSM is derived by subtracting the DTM from the DSM. The spatial resolution of all topographic models is 1x1 m^2 for the Montafon, Tyrol and Ötscher study areas and 0.5x0.5 m^2 for the Leithagebirge study area. For the study areas Ötscher and Leithagebirge a Gaussian decomposition (WAGNER et al., 2006) is applied to the FWF-ALS data to extract the echo width and amplitude in addition to the 3D position of each echo from the backscattered waveforms. Furthermore, the backscatter cross section (BCS) was computed during the calibration process (WAGNER, 2010).

OPALS

For the forest structure and SV assessment the software package Orientation and Processing of Airborne Laser Scanning data (OPALS) was used. OPALS is a scientific software project developed at the TU Vienna (MANDLBURGER et al., 2009). The aim of OPALS is to provide tools for processing large ALS projects with focus on the following topics: processing of raw sensor data, quality control, georeferencing, modelling of structure lines, filtering of ALS point clouds, DTM interpolation, and subsequent applications like city modelling, forestry, hydraulics etc. OPALS is a modular system consisting of small units (modules), each covering a well-defined task. For the assessment of the forest structure as well as the SV, Python modules of OPALS have been used to build a workflow in Python which also opened the possibility to use additional Python side-packages such as e.g. OGR / GDAL (GDAL, 2012).

Forest Structure Assessment

In the following we describe three approaches for the derivation of structurally relevant parameters from ALS data, namely (1) crown segments (2) compactness of vegetation (3) vertical layer structure (VLS) of vegetation and (4) canopy cover (CC). These parameters exploit the information collected by ALS to describe vegetation structure and how different patches of vegetation are inter-connected in terms of vertical structure of the plants building the patches.

The main aim of the crown segmentation is to extract individual trees in forested areas. In the approaches described here, the segments are also used as reference unit for the calculation of structural parameters based on the 3D point cloud. To create the tree crown segments, an edge-based segmentation procedure is applied on the nDSM (HÖFLE et al., 2008). It delineates convex shapes in the nDSM by finding concave edges between them. The main criterion for the edge detection is a minimal curvature in the direction perpendicular to the direction of the maximum curvature.

The compactness of vegetation refers to the relation of a vegetation patch's surface, defined as the area of its enveloping canopy, to the volume enclosed by it. Thus, it is called the surface-to-volume ratio in the following. The parameter basically relates to the 3D shape of a vegetation patch and how the patch is inter-connected with other patches. It is calculated on the basis of a so-called difference DSM (DSMdiff), which comprises the height difference of the highest and lowest occurring ALS echo in a grid cell without consideration of terrain echoes. The DSMdiff is a measure of vertical vegetation extent, its multiplication by the grid width results in the vegetation volume. The vegetation surface is derived as the sum of the area of all visible lateral faces, the top and the bottom face of a cell column in the DSMdiff. Finally, the ratio of the surface and the volume are computed for each raster cell and assigned to the vegetation segments (MÜCKE et al., 2010).

For the derivation of the VLS and the CC we exploit the capability of ALS to penetrate the foliage and provide direct height measurement of canopy and sub-canopy strata, as well as the forest ground. A so-called penetration index for different vegetation height intervals is calculated based on the 3D point cloud as a measure of penetrability and geometric structure. The definition of the height intervals can either be done in an absolute (i.e. a-priori fixed heights for each level) or in a relative way (i.e. percentage of maximum occurring height). In the following, we give an example for both ways. To enable a comparison of the layer structure information assessed by the forest inventory (FI) and the ALS data, the ALS data within the FI sample plots were extracted. At the GPS measured positions of 455 sample plot centres the ALS data were selected with a 12 m radius to account for border effects during the following raster calculations. The DTM was used to calculate the normalized echo heights of the single ALS echoes, which were subsequently needed for the selection of the echoes belonging to the respective height levels as defined in the FI (see section "Study areas and data"). For every defined height level, a 1 m resolution raster map was created containing the number of ALS echoes in each cell. If a cell contained ALS echoes, it was counted as covered. The sum of all overgrown cells per height level results in the total CC of a single height level.

Additionally, an area-wide forest structure map was derived on the basis of relative height intervals (i.e. 0 33%, 34 66% and 67 100% of the maximum relative height per each before derived crown segment). For each segment the number of points per height layer and the total number of vegetation points are determined. Finally, the ratio of these quantities (penetration index) is computed (MÜCKE et al., 2010). For the generation of the forest structure map a decision tree based classification approach is used to classify the segments and determine the number of vertical forest layers based on the penetration index.

Stem Volume Assessment

The SV is estimated for the study areas Tyrol and Ötscher using the method described in Hollaus et al. (2009c). This method assumes a linear relationship (Equation 1) between the SV and the ALS derived canopy volume, stratified according to four canopy height classes to account for height dependent differences in canopy structure.

$$v_{FI} = 10^4 \cdot \sum_{i=1}^{m} \beta_i \cdot v_{\mathrm{can},i} \qquad (1)$$

where v_{FI} represents the stem volume (m^3/ha), calculated from the forest inventory data, m is the number of canopy volumes and is set to four and β_{i} are the unknown model coefficients. The canopy volumes ($v_{\mathrm{can,i}}$) are calculated based on equation 2.

$$v_{\mathrm{can},i} = p_{\mathrm{fe},i} \cdot ch_{\mathrm{mean},i} \qquad (2)$$

where $p_{\mathrm{fe,i}}$ represents the relative proportion of nDSM pixels within the corresponding canopy height class to the total number of nDSM pixels within a circular sample plot area with a radius of 10 m and chmean,i is the mean height of the nDSM pixels within the corresponding canopy height class. For the current analyses the nDSM height limits are for ch_1 2 m to 12 m, for ch_2 12 m to 22 m, for ch_3 22 m to 32 m, and for ch_4 >32 m. For both study areas species depended SV models are calibrated using the NFI and the FI data respectively. The classification into coniferous and deciduous dominant NFI/FI sample plots is based on the basal area applying a 50% threshold. All calibrated SV models are calibrated based on a cross validation. Within the study area Tyrol an extensive validation is done using the fully callipered reference areas.

To derive a stem volume map for the entire study areas the classification into coniferous and deciduous dominated areas is required. The classification can be based on different remote sensing data such as aerial images, high resolution satellite images or FWF-ALS data. For the Ötscher study area, the FWF-ALS data (i.e. average BCS, echo width and geometric quantities describing the vertical distribution of the ALS echoes within the crown segments) are used for tree species classification.

Results and Discussion

Forest Structure Assessment

Generally it can be stated that the delineation of single trees or tree crowns in dense deciduous forests is a challenging task. As the applied segmentation algorithm detects convex objects separated by concave areas, it works very well for single trees with clearly distinct crowns. But especially older or larger deciduous trees often develop large crowns with multiple maxima which results in multiple convex areas and these are therefore represented by more than one segment. A further limitation occurs in very dense young deciduous forest, characterised by a smooth canopy surface leading often to segments that include multiple trees.

The vegetation surface-to-volume ratio can be seen as a proxy for the compactness of a particular landscape element. Changing compactness along a geometric element implies a change in structure and consequently permeability. This permeability is of significance for certain species, e.g. highly adapted birds, whose requirements do not allow structural changes within their habitats. In figure 1a the computed vegetation surface-to-volume ratio is shown. A high voltage power line runs right through the study area crossing several vegetation corridors. It is clearly visible in the ratio image that the character of the vegetation structure is changing significantly below the power line. For evaluation of the results, visual examination of the 3D point cloud had to be used, because of the lack of an adequate ground truth measurement method for the proposed surface to volume ratio. A profile view is given in figure 1b. It can be seen that the changing of the corridor vegetation character, as indicated by the ratio, is supported by the 3D point cloud. In this case the power line acts as a natural barrier, which is a disturbance in this particular habitat or corridor.

In figure 2 the canopy cover maps of individual a-priori fixed height levels (V1, V2 and V3) are shown. The total CC is shown in V4. For quantitative evaluation of the results of the derived layer structure and CC on plot level, scatterplots were derived (see Figure 3). All three single levels V1 to V3, as well as the total CC represented by level V4 exhibit significant scattering. The upper levels V3 and V4 reveal a linear relationship of FI- and ALS-derived CC.

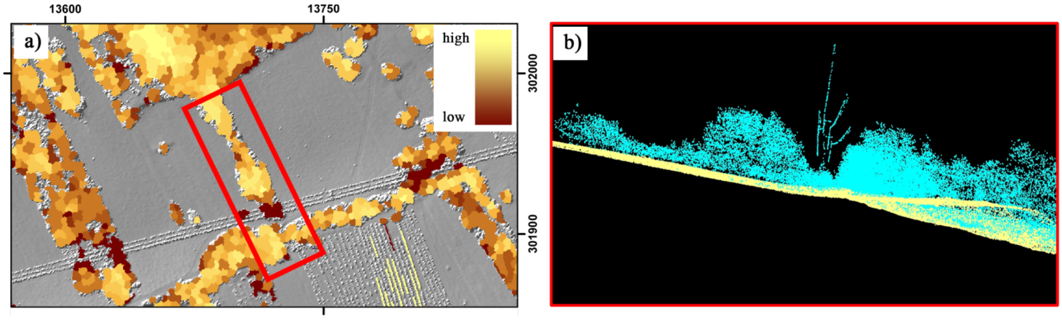

Figure 1. (a) surface-to-volume ratio calculated on segment basis, (b) vertical profile of the point cloud showing the differing character of vegetation in an area where also the surface-to-volume ratio significantly changes (adapted from MÜCKE et al., 2010). Terrain points are in yellow, vegetation points are in turquoise.

Figura 1. (a) razão superfície-volume calculada nos segmentos-base, (b) perfil vertical da nuvem de pontos mostrando o diferente caráter da vegetação em uma área onde a razão superfície-volume também se altera significantemente (adaptado de MüCKE et al., 2010). Pontos representativos do terreno estão em amarelo e aqueles de vegetação em turquesa.

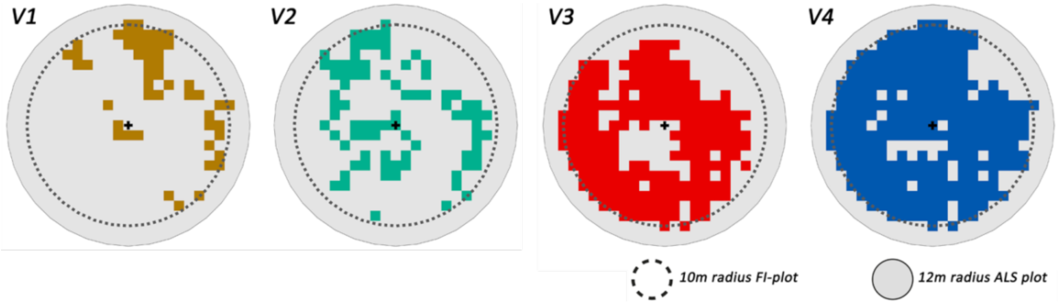

Figure 2. Example of canopy cover derivation based on ALS echo distribution. Levels V1 (brown) and V2 (green) clearly show an under-representation of the respective vertical layers due to the lack of echoes.

Figura 2. Exemplo de cobertura de dossel baseado na distribuição de eco do ALS. Níveis V1 (marrom) e V2 (verde) mostram claramente uma sub-representação das respectivas camadas verticais decorrentes da falta de ecos.

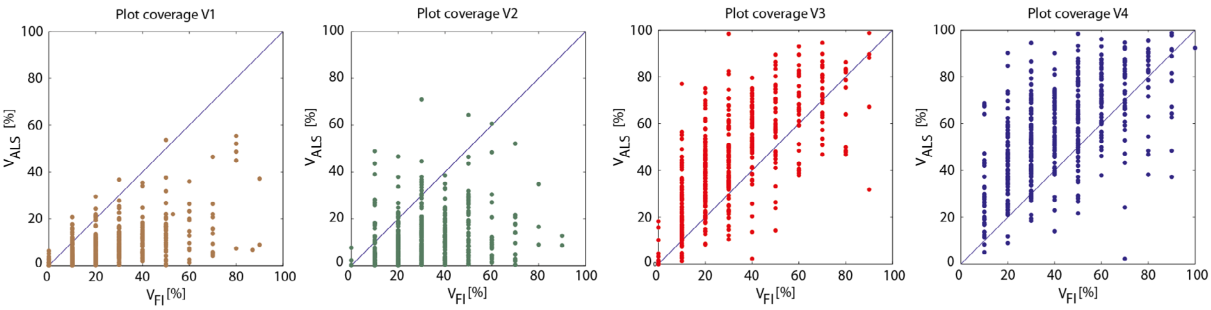

Figure 3. Comparison of FI- and ALS-estimated canopy cover.

Figura 3. Comparação de FI – e ALS da cobertura de dossel estimada.

However, linear relation is only weakly distinguished in the lower levels V1 and V2, clearly showing an underestimation by the ALS-based method because of the absence of echoes in this canopy strata. This indicates that future research on this topic will need to concentrate on the development of a predictive model describing the relationship of FI- and ALS-based layer structure and CC, and considering the drawback of missing echoes in any stratum.

Figure 4 shows the resulting forest structure map for the chosen study area and two profiles of the 3D point cloud, which are meant to display the structural diversity. Four dominant types of vegetation structure could be identified: L1 + L3 > 80% (red), L2 + L3 > 80% (light green), L3 > 80% (dark green) and equally distributed structure (yellow). Below the profiles the corresponding lines from the forest structure map are given. They demonstrate that the classification result corresponds very well with the actual structure of the forest. Deviations could be observed in areas with high local variations, which cannot be accounted for by using the proposed method because inner segment variations are not considered.

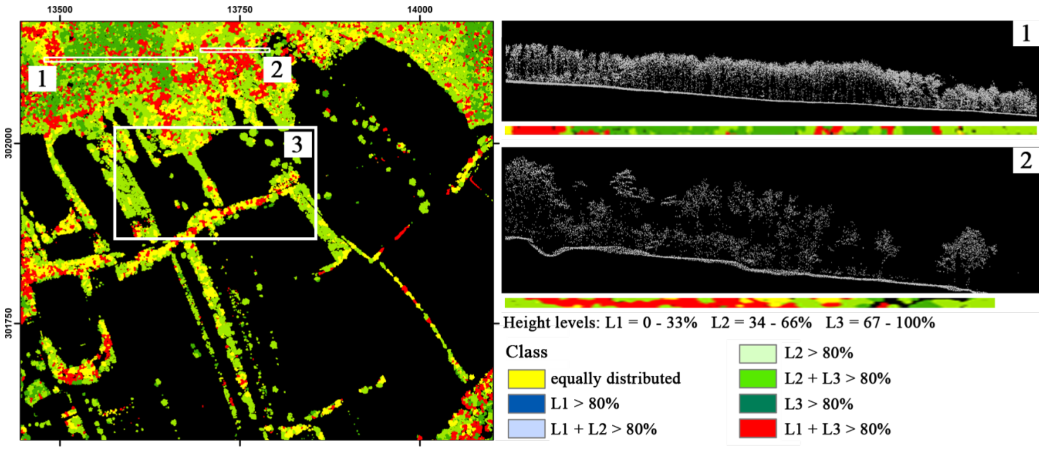

Figure 4. Left: Forest structure map calculated on segment basis (white lines show profile locations, white rectangle Nr.3 shows location of detailed Figure 1). Right: Profile views of the ALS point cloud. Below the profiles the corresponding lines from forest structure map are given (adapted from MÜCKE et al., 2010).

Figura 4. Esquerda: Mapa da estrutura florestal calculada nos segmentos-base (as linhas brancas mostram a localização do perfil, enquanto o retângulo branco Nr3 ilustra a localização da Figura 1 em detalhe). Direita: Vista dos perfis da nuvem de pontos ALS. Abaixo, são apresentados os perfis das linhas correspondentes do mapa de estrutura florestal (adaptado de MÜCKE et al., 2010).

Stem Volume Assessment

For the study area Tyrol the SV models for coniferous and deciduous dominated trees could be calibrated with an R^2=0.81 and R^2=0.70 respectively. The relative RMS errors are 34.1% and 45.8% respectively. These accuracy values are based on sample plots with an area of 0.031 ha and a leave-one-out cross validation. Using the independent fully callipered reference data, the validation of the estimated SV shows different accuracy values. For the two coniferous dominated test sites with a total area of 0.77 ha an underestimation of the SV of 13.7% could be observed. Also for the two deciduous dominated test sites with a total area of 0.77 ha an underestimation of 3.8% was found. The increase of the accuracies clearly shows the influence of the reference area for which the SV is averaged, meaning with increasing size of the reference area for which the estimated SV is averaged the accuracy increases. The underestimation can be explained by different acquisition times of the ALS and FI data as well as the validation data. On average the ALS data were acquired two years before the validation data. The relatively large underestimation of the coniferous dominated test areas can be explained by the presence of Larch trees. It is assumed that the canopy volume is underestimated due to the loss of needles during the winter season where the ALS flights took place, which lead to the underestimation of the estimated SV. This means that the aggregation of spruce and larch trees into one stratum is critical and should be avoided, provided that enough FI samples for calibrating individual SV models are available. Further details about this accuracy analyses can be found in Hollaus et al. (2012).

For the Ötscher test site a classification into coniferous and deciduous dominated tree species on a tree crown level was done based on FWF-ALS data (Figure 5b).

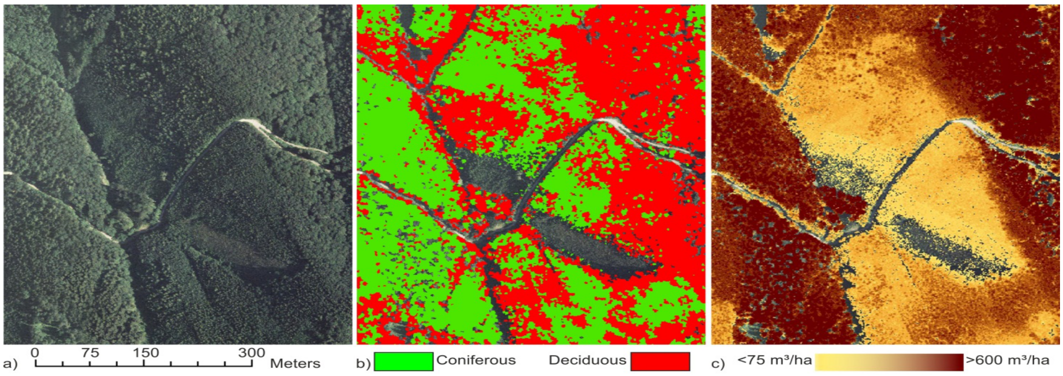

Figure 5. (a) Orthophoto © bing maps, (b) classified tree species map and (c) tree species dependent stem volume map.

Figura 5. (a) Ortofotos © bing maps, (b) mapa de espécies de árvores classificadas e (c) mapa de volume das espécies de árvores.

The achieved overall accuracy for these two classes was 83% (HOLLAUS et al., 2009b). For each class a SV model was calibrated with an $R^2=0.68$ and $R^2=0.64$ for deciduous and coniferous model respectively. The corresponding relative standard deviations derived from leaf-one-out cross validation were 29.4% and 30.7%. Finally, the calibrated models were applied to the whole study area depending on the tree species classification. In figure 5c the final SV map with a spatial resolution of 1 x 1 m^2 is shown and provides an excellent basis for different forestry applications (e.g. optimize harvesting approaches, environmental studies).

Conclusion

In this paper methodologies for the derivation of structural forest parameters and stem volume are presented. Through its application on a number of study areas with mixed species composition and different characteristics of the ALS data at hand, we conclude that the proposed techniques can be easily adapted and that ALS data can be used for a variety of forestry applications. However, we found that for the derivation of canopy cover based on the described approach additional investigations are necessary. Future research on this topic will concentrate on this matter to increase the quality of the result. This research will be done within the project NEWFOR financed by the European Territorial Cooperation "Alpine Space".

Acknowledgements

The authors would like to thank (i) Prof. Michael Doneus, Department for "Ur- und Frühgeschichte, environmental- and landscape archaeology" at the University of Vienna, for providing the Leithagebirge dataset, (ii) the Amt der Tiroler Landesregierung, Gruppe Lndesbaudirektion, Abteilung Geoinformation for providing the ALS data for the Tyrol study area, (iii) the Landesvermessungsamt Feldkirch for providing the ALS data from the Montafon study area and (iv) the Amt der Niederösterreichischen Landesregierung, Gruppe Baudirektion, Abteilung Vermessung und Geoinformation for providing the ALS data for the Ötscher study area. The forest inventory data is kindly provided by the Stand Montafon Forstfonds, Schruns, Austria, the Department of Forest Inventory at the Federal Research and Training Center for Forests, Natural Hazards and Landscape, Vienna, Austria and the Amt der Tiroler Landesregierung, Abteilung Forstplanung. Parts of this study were funded by the TransEcoNet project implemented through the CENTRAL EUROPE Program co-financed by the ERDF and the project NEWFOR financed by the European Territorial Cooperation "Alpine Space".

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