ACCURACY ASSESSMENT OF ALS-DERIVED STEM VOLUME AND BIOMASS MAPS

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ABSTRACT

As an active remote sensing system airborne laser scanning (ALS) is well suited to achieve normalized digital surface models (nDSMs) by subtracting digital terrain models (DTMs) from digital surface models (DSMs). The nDSM represents object heights and is an important data source for the derivation of various forest parameters such as tree height, stem volume or biomass. The validation of the derived results as well as the comparison of the results from different study areas is often a challenging task due to different sampling designs and accuracies of forest inventory data being used as ground truth data.

In this study we use 17 fully callipered samples, covering an area of 4.55 ha in total, to assess the accuracies of stem volume and biomass maps for different Austrian test sites. For the callipered samples all trees with a diameter at breast height ≥10.5 cm were measured. For the calibration of the stem volume and biomass models available national forest inventory (NFI) as well as local forest inventory (LFI) data are used, which are both based on angle count sampling plots. This verification approach guarantees firstly the independency of calibration and validation data and secondly it allows accuracy analyses for different reference units. For the study area *Montafon* the relative differences of stem volume and biomass range between -20.0% and 57.4% and between -16.3% and 56.2% respectively for twelve coniferous dominated sample areas with ~0.25 ha each. For a reference unit with an area of ~3.0 ha the relative differences decrease to 15.7% and 19.3% for stem volume and biomass respectively. For the study area *Tyrol* deciduous and coniferous models were applied. The calculated relative differences of stem volume and biomass vary between -25.8% and -10.3% and -18.5% and 3.1% respectively for the two coniferous dominated sample areas with an area of ~0.38 ha each. For the two deciduous dominated sample areas with an area of ~0.38 ha, both the relative difference of stem volume and biomass vary between -10.0% and 0.6% and -3.3% and 1.1% respectively. The average relative differences for all sample areas of the *Tyrol* study area with a total area of ~1.5 ha is -1.2% and -1.9% for the stem volume and the biomass, respectively. As the estimations of the stem volume and biomass maps are based on federal state wide data sets (ALS and NFI) the findings of this study are of high practical relevance for integrating ALS derived forest parameters into operational forest inventories.

INTRODUCTION

During the last decade airborne laser scanning (ALS) has been developed as a standard method for the acquisition of high precision topographic data. As an active remote sensing system ALS has several advantages in forested areas to construct a digital terrain model (DTM) as well as a digital surface model (DSM) without being influenced by shadows or other varying conditions of the sunlight. The normalized digital surface model (nDSM), calculated by subtracting the DTM from the DSM, represents object heights (i.e. canopy or tree heights) and is an important data source for the derivation of various forest parameters. In recent review papers Næsset (1) and Hyyppä et al. (2) concluded that the retrieval of mean stem volume and tree height from ALS data performs as good as, or better than, common photogrammetric methods and better than other remote sensing methods that use radar or optical data as input. Some researchers even think that ALS provides more accurate data than *in situ* measurement techniques (e.g., (1)). However, the verification of these statements is not easy to achieve due to different sampling designs and accuracies of forest inventory data being used as ground-truth data. For example, in Austria the national forest inventory (NFI) uses angle count sampling plots, so-called Bitterlich plots (3), which do not refer to a fixed sample plot area. This fact makes the combination of the NFI data with any remote sensing data to a challenging task. However, there are some studies that have already investigated the use of angle count sampling plots as reference for regression models. For example Maltamo et al. (4) tested truncated angle count sample plots to construct regression models to predict various forest parameters and found that the accuracy of the stand attributes was almost as good as in the case of using fixed-area plots. Also Hollaus et al. (5,6) demonstrated that angle count sample plots can be used as reference data for assessing stem volume on an operational, district-wide level. Especially, for large area applications the varying properties of ALS data sets (e.g. acquisition time, point density, sensor types and acquisition geometry) influence the accuracy of the derived forest parameters. Further information about this issue can for example be found in Gobakken and Næsset (7) and Næsset (8), who have assessed the effects of different sensors, flying altitudes, pulse frequencies, laser point density, ground sampling intensity, and field sample plot size on biophysical stand properties derived from ALS data.

The aim of this study is to use in addition to the angle count sampling plots fully callipered sample areas to assess the accuracies of stem volume and biomass maps for different Austrian test sites. Within these sample areas single tree parameters (i.e., diameter at breast height, tree height and species) were acquired for more than 1600 trees. For the derivation of the stem volume and the biomass respectively, an area-based semiempirical model (6,9) was applied. In the literature also physical (10-11) and empirical models (e.g., (1,12,13)) can be found. An overview of different algorithms to assess forest attributes from ALS data can be found in e.g. Næsset et al. (14). As shown in the study from Hollaus et al. (6) the results derived from the model of Hollaus et al. (6) are comparable with those from Næsset et al. (1).

For the calibration of the stem volume and biomass model, available NFI data as well as local forest inventory (LFI) data are used, which are both based on angle count sampling plots. As for the validation the fully callipered sample areas are used it is guaranteed, firstly the independency between calibration and validation data and secondly it allows accuracy analyses for different reference units (i.e. different forest stand sizes). Furthermore, the achievable accuracies for different stand sizes are shown and discussed. These accuracy measures are compared with the output of accuracies derived from cross-validations using the forest inventories. The main factors influencing the accuracies are described and discussed including, for example, the measurement errors of the forest inventory data as well as the applied algorithms to estimate the stem volume and biomass maps from the ALS data.

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the Stand Montafon Forstfonds, Schruns, and (vi) the Amt der Tiroler Landesregierung, Abteilung Forstplanung, Innsbruck.

METHODS

Study areas

The first study area is located in the southern part of the federal state *Vorarlberg*, Austria and covers the *Montafon* region with a total area of about 525 km² (Figure 1a). The elevation ranges between 800 m above sea level in the valley *Illtal* to more than 2700 m above sea level in the *Silvretta* Montain range. The *Montafon* region is covered by alpine meadows, forests, alpine wasteland and agricultural and urban land. Due to the topographic conditions forests have an essential role in the protection of villages and infrastructure against avalanches, rockfalls and landslides. The dominating tree species is Norway spruce (*Picea abies*).

The second study area *Tyrol* is located in the federal state *North-Tyrol*, Austria and covers the districts *Schwaz*, *Kufstein* and *Kitzbühel* with a total area of 3976 km² (Figure 1b). The landscape is characterized by intensely used valley floors and partly forested slopes. Several skiing areas, Alpine meadows and farms characterize the valley slopes. The elevations of the study area vary between ~465 m above sea level in the *Inntal* near the city *Kufstein* and more than ~3400 m above sea level in the *Zillertaler* Alps located in the South-West of the study area. The dominant tree species is Norway spruce (*Picea abies*). In the northern parts of the study area European beech (*Fagus sylvatica*) is the subdominant tree species. Beside the forested areas buildings, cable cars and power lines can be found in the study area.

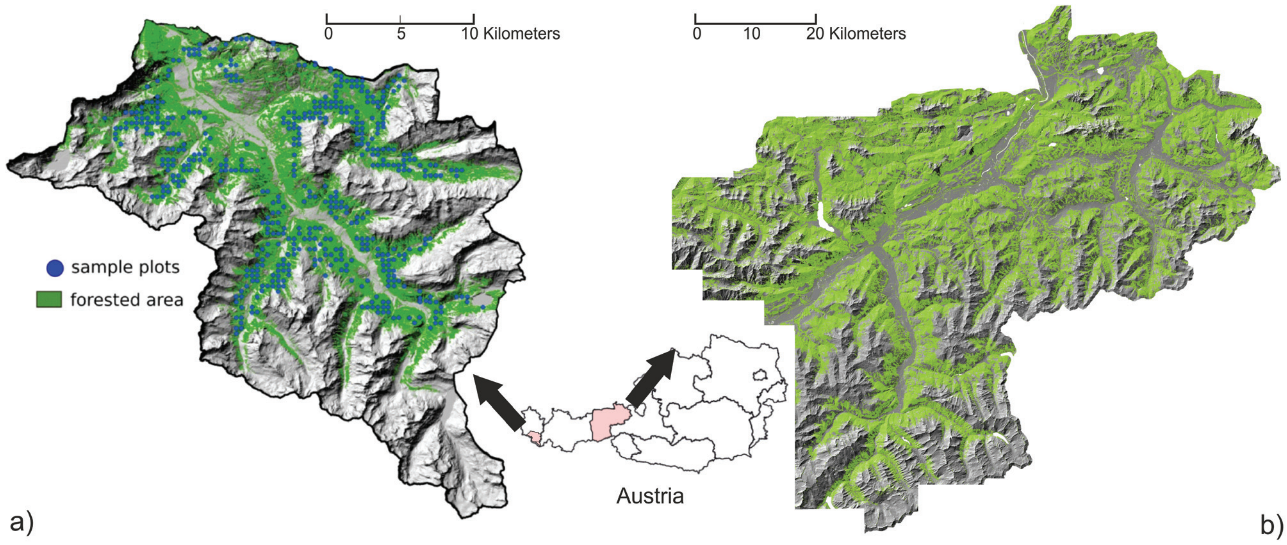

Figure 1: Location of the study area Montafon (a) and Tyrol (b). In the background shaded digital terrain models are shown.

Airborne laser scanning data

For the study area *Tyrol* the used ALS data was acquired using an Optech Inc. ALTM 3100 laser scanner during multiple flight campaigns in 2007 and 2008 under leaf-off and leaf-on canopy conditions. The ALS data was acquired in the framework of a commercial *Tyrol*-wide terrain mapping project. The mean flying height above ground was ~1200 m. The mean point density is about 5 echoes/m^2. The ALS-based DTM in raster format (spatial resolution of 1 m) and the georeferenced 3D points cloud data were provided by the *Amt der Tiroler Landesregierung, Gruppe Landesbaudirektion, Abteilung Geoinformation*.

The ALS data for the study area *Montafon* was acquired during several flight campaigns in the framework of a commercial *Vorarlberg*-wide terrain mapping project using Optech Inc. ALTM systems (ALTM 1225, ALTM 2050) and a Leica ALS-50 scanner. For the study area the flight campaigns recorded first and last echoes and took place under snow-free conditions in the years 2002 to 2004. The ALS data was acquired at an average flying height of 1100 m above ground. The average point density varies between 0.9 and 2.7 echoes/m^2 within the study area. The georeferenced 3D point clouds as well as the rasterized DTM were provided by the *Landesvermessungsamt Feldkirch* in Gauß-Krüger coordinates (reference meridian M28). More details about the ALS data can be found in Hollaus et al. (5,6).

For both study areas the DSMs were calculated based on the 3D point clouds applying the method described in Hollaus et al. (15) and have a spatial resolution of 1 m. This approach makes use of the strengths of different algorithms for generating DSMs by using surface roughness information to combine DSMs, which are calculated based (i) on the highest echo within a raster cell and (ii) on moving least squares interpolation (i.e. moving planes interpolation). The used algorithms are implemented in the scientific software package OPALS (16). The nDSMs were calculated by subtracting the DTMs from the DSMs and provide the basic input for the stem volume and the biomass estimation.

Forest inventory data

The Austrian national forest inventory (NFI) data from the assessment period 2007/2009 was used for calibrating the stem volume and the biomass model for the study area *Tyrol*. The sampling design of the NFI is based on a permanent sampling grid pattern, where clusters consisting of four angle count sampling plots are regularly distributed in a grid of 3.89 km over Austria. The positions of the sample plot centres are permanently marked in the field. Unfortunately, the real centre coordinates of this regular grid can have inaccuracies in the range of ±20 m. To improve the spatial accuracy of the sample plots, each centre coordinate was measured with a non-differential Global Positioning System (GPS) during the last assessment period 2007/2009. Within a sample plot the azimuth and distance to the sample plot centre of each selected tree were measured using a compass and an ultrasonic range instrument, respectively. More information about the used NFI data can be found in Hollaus et al. (5). In total 237 NFI sample plots could be co-registered to the ALS data using the methodology described in Dorigo et al. (17). This approach assumes that the measured polar coordinates (azimuth and distance) from a sample plot centre to the sampled trees have a high accuracy. Therefore, the pattern of the sampled tree positions is used to search for the best match between the ALS-based nDSM and the tree position and height. The errors of the co-registered sample plot centre coordinates are expected to lie at the sub-pixel level (i.e. <1.0 m). For this study statistically derived stem volumes and biomass are used as reference data, expressed as cubic metres per hectare and tons per hectare, respectively. The calculation of the stem volume per sample plot is based on the formulas published in Gabler and Schadauer (18). For coniferous trees the biomass contains the dry biomass of the stems, branches and needles whereas for larch the biomass of the needles is not included. The biomass of deciduous trees contains the stems and the branches without leafs. The used methods to calculate the biomass per sample plot from the NFI data are described in Ledermann and Gschwantner (19,20).

For the study area *Montafon* local forest inventory (LFI) data, operated by the forest administration *Stand Montafon Forstfonds*, is available from the assessment year 2002. This LFI is based on permanent angle count sample plots distributed in a 350 m grid. Similar to the NFI plots the LFI sample plot centre coordinates and the azimuth and distance to the sample plot centre of each selected tree are measured. Further details of this LFI data can be found in Hollaus et al. (6) and Jochem et al. (9). The co-registration of the LFI data to the ALS data was done by the approach described in Dorigo et al. (17), whereas 455 sample plots could clearly be co-registered. For the calculation of the stem volume per sample plot the “form height concept” was applied that transforms the conical shape of a stem to a cylinder, whereas the diameter at breast height (dbh) was not modified. The calculation of the form heights the formulas of Pollanschütz (21) were applied and the statistical calculation of the stem volume per sample plot is based on the formulas of Sterba (22). The biomass estimation is based on tree specific expansion factors of the stem volume, whereas in a first step the dry stem biomass is calculated based on the formulas of Weiss et al. (23) and in a second step the total tree biomass is estimated by using tree specific factors described in Körner et al. (24).

For both study areas additional sample areas were fully callipered to obtain independent reference data for validating the estimated stem volume and biomass maps. Within the *Tyrol* test site four circular sample areas with a radius of 35 m were callipered in the year 2010. These sample areas are located in the district *Schwaz* (Figure 2a). Two sample areas are covered by coniferous trees whereas the remaining two areas are dominated by deciduous tree species. In total more than 600 trees were callipered with a minimum dbh of 10.5 cm. The spatial positions of the individual trees were measured with a Garmin GPSMAP® 60CSx (expected accuracy ±3-5 m) in combination with a compass and an ultrasonic range instrument. For each sample area the centre point was measured with the GPS and relative coordinates (in relation to the centre point) were measured with the compass and the ultrasonic range instrument for each tree. In post-processing the measured tree positions were manually adjusted to the detectable tree positions in the nDSM, which leads to a relative accuracy between both data sets of ±1.0 m. The stem volume as well as the biomass for each individual tree is estimated based on the same approach that is applied for the NFI data. For the study area *Montafon* 12 sample areas were fully callipered with a minimum dbh of 7.5 cm (Figure 2b). Ten of the 12 sample areas were callipered in the year 2002 and the remaining two areas in 2010. In total the tree specific parameters were measured for about 900 trees. All samples have an area of ~50×50 m^2 each. The stem volume is calculated based on the methods used for the LFI.

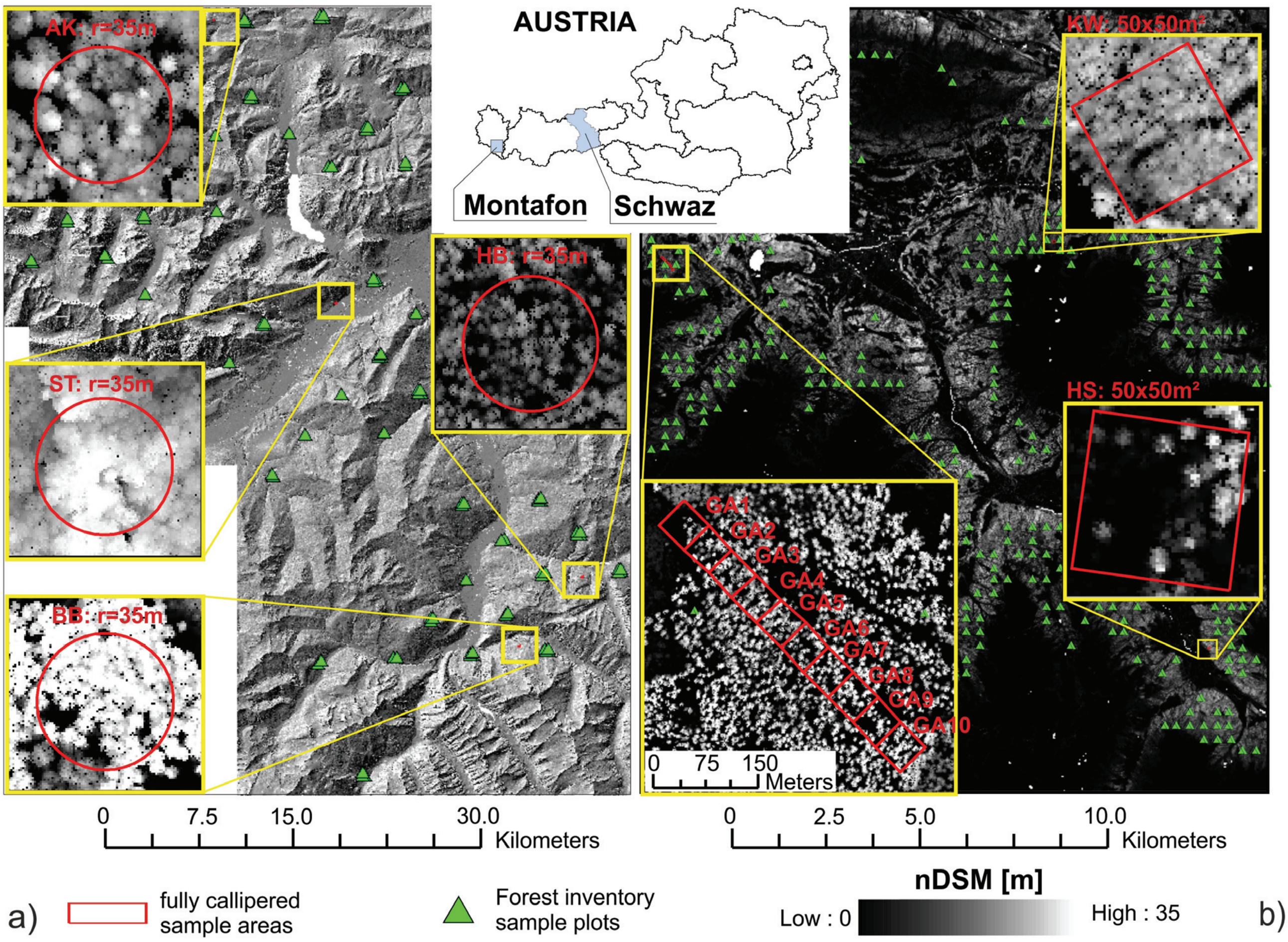

Figure 2: Location of the fully callipered study area within the test site (a) Tyrol and (b) Montafon. For the fully callipered study areas the nDSM is shown. The background image for the Tyrol test site shows a shaded digital terrain model, for the Montafon test site an nDSM.

Stem volume and biomass model

For assessing the stem volume and the biomass from the ALS data the method described in Hollaus et al. (6) is applied. This method assumes a linear relationship (Eq. 1) between the stem volume and the biomass respectively, and ALS derived canopy volume, stratified according to four canopy height classes to account for height dependent differences in canopy structure.

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

where v_{FI} represents the stem volume (m^3/ha) and the biomass (AT/ha) respectively, 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 Eq. 2.

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

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 $ch_{\mathrm{mean},i}$ 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 the *Montafon* study area one stem volume and biomass model is calibrated using the coniferous dominated LFI data as reference. Due to the fact that coniferous trees are dominating in this region no differentiation between coniferous and deciduous ones was done. For the *Tyrol* study area species depended stem volume and biomass models were calibrated using the NFI as reference data. The classification into coniferous and deciduous dominant NFI sample plots is based on the basal area applying a 50% threshold. Additionally, a species independent stem volume and biomass model was calibrated.

Finally, the calibrated models are applied for both study areas resulting in stem volume and biomass maps with a spatial resolution of 1 $\times$ 1 m^2.

Validation

For each calibrated model a leave-one-out cross-validation is carried out. The cross-validation comprised the calculation of the statistical parameters minimum, maximum, mean and standard deviation of the residuals derived by subtracting the forest inventory derived stem volumes and biomass values respectively, from the ALS estimated ones. In addition to the statistics scatter plots are generated. The fully callipered sample areas are used as independent reference data to validate the generated stem volume and biomass maps. For each sample area the ALS-based total stem volume and biomass is calculated and compared to the quantities derived from the *in situ* measurements. The differences are statistically analysed and discussed.

RESULTS AND DISCUSSIONS

For each study area stem volume and biomass models were calibrated using the forest inventory data as reference. As the number of deciduous dominated forest inventory sample plots is low for the *Montafon* study area, only stem volume and biomass models could be calibrated for coniferous dominated LFI plots. For the *Tyrol* study area models for coniferous and deciduous dominated sample plots were calibrated. Furthermore, species independent models were calibrated. In Table 1 the derived results are summarized and show similar results for both study areas. For the study area *Tyrol* the species independent models were calibrated based on 237, the coniferous dominated ones based on 188 and the deciduous ones based on 49 NFI sample plots. For the *Montafon* study area all 452 coniferous dominated LFI sample plots were used for calibrating the stem volume as well as the biomass model.

In overall the results show comparable results for both study areas, whereas for the estimated stem volume the relative standard deviations (rSD) derived from cross-validations vary between 35.2% and 37.3% for the coniferous dominated plots from the *Tyrol* and *Montafon* study area respectively. For the *Tyrol* study area the rSDs for the deciduous dominated models are 49.8% and 45.8% for the estimated stem biomass and biomass respectively. The coefficients of determination (R^2) vary between 0.64 and 0.81 where the highest values could be achieved for the coniferous stem volume model for the *Tyrol* study area. In Figure 3 the corresponding scatter plots are shown.

The relative high standard deviations can be explained by the fact that the forest inventory sample plots are based on the angle count sampling method, which is a probability-proportional-to-size sampling method, meaning that not all trees within a defined sample plot area are callipered (3). As shown in Figure 4 over- and underestimations occur due to the mismatch between the area covered by an angle count sample plot and the area that is used for assessing the stem volume and the biomass from the ALS data. Furthermore, Table 1 shows the differences of the applied methods to calculate biomass based on stem volume due to different calculation methods of biomass. Thus, the absolute biomass values are not comparable between the study area *Tyrol* and *Montafon*. Therefore, the relative accuracy measures have to be used to compare the results. A further aspect of evaluating the derived accuracies is the accuracy of the forest inventory data itself. For example Weiss et al. (23) have estimated the uncertainties of the estimated biomass with ±14%. This uncertainty of the reference data used for calibrating the regression models explains the relative low R^2-values (Table 1).

Table 1: Summary of the calibrated stem volume and biomass models for the study areas Tyrol and Montafon. Furthermore, the statistics of the used reference forest inventory data and of the ALS-based estimates are summarized. [1]) stem volume (SV) in m³/ha, [2]) biomass (BM) in AT/ha, [3]) standard deviation of the residuals (SD) and [4]) the relative standard deviation (rSD).

	Study area							
	Tyrol						*Montafon*	
	species independent		*Coniferous dominated*		*Deciduous dominated*		*Coniferous dominated*	
	SV[1)] (m³/ha)	BM[2)] (AT/ha)	SV (m³/ha)	BM (AT/ha)	SV (m³/ha)	BM (AT/ha)	SV (m³/ha)	BM (AT/ha)
Reference data								
Nr. of samples	*237*		188		49		452	
Minimum	3.3	2.3	3.3	2.3	3.8	2.9	1.1	3.0
Maximum	1220.5	534.5	1220.5	534.5	729.2	454.0	1544.7	426.3
Mean	252.2	144.8	261.5	141.2	218.3	160.0	482.6	133.5
SD[3)]	197.5	105.6	201.5v	100.4	177.4	122.8	296.7	81.8
ALS derived data								
Minimum	1.1	0.0	0.1	0.0	9.0	5.5	1.1	0.3
Maximum	812.5	437.9	962.6	458.5	556.0	378.3	1224.5	338.0
Mean	248.7	141.7	259.9	138.7	215.6	155.7	464.2	128.4
SD	173.0	93.9	183.2	89.1	152.1	109.4	270.9	74.6
Model calibration								
R²	0.72	0.71	0.81	0.72	0.70	0.70	0.65	0.64
RMSE	103.9	56.6	89.3	53.5	99.9	68.7	178.2	49.2
rel. RMSE (%)	41.2	39.1	34.1	37.9	45.8	41.9	36.9	36.8
Cross validation								
SD	107.2	57.7	92.0	54.5	109.0	73.6	180.2	49.8
rSD (%)[4)]	42.5	39.9	35.2	38.7	49.8	45.8	37.3	37.3

For the study area *Tyrol* four fully callipered sample areas with an area of 0.38 ha each are available to assess the accuracy of the estimated stem volume and biomass. As summarized in Table 2 the differences of the stem volume calculated from field measurements of the fully callipered sample areas and the estimated stem volumes differ for the coniferous sample areas (HB, BB) between -25.8% and -10.3%, those of the deciduous dominated ones (AK, ST) between -10.0% and 0.6%. The relative high difference for the sample area HB can be explained by the dominance 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 for the HB sample area, which leads to the underestimation of the stem volume as well as the biomass. This means that the aggregation of spruce and larch trees into one strata is critical and should be changed, if enough samples for calibrating an individual larch model are available. For the deciduous dominated sample areas AK and ST the differences of stem volume and biomass vary between -10.0 and 0.6% and indicate a very high accuracy. For all four *Tyrolean* fully callipered sample areas the accuracy of the estimated biomass is higher than those from the stem volume. Therefore, it can be stated that the applied semiempirial model is better suited for biomass than for stem volume estimation. This can be explained by the fact that the input parameters "canopy volumes" for the regression models describe the entire tree volume and reflect the biomass better than the stem volume.

For the *Montafon* study area the validation using the 12 fully callipered sample areas with an area of ~0.25 ha each shows a large range of the differences between the field measured and the estimated quantities. For stem volume and biomass the differences vary between -20.0% and 57.4%, and -16.3% and 56.2% respectively. The large accuracy range can partly be explained by the different acquisition dates for the field measurements of the LFI data and the fully callipered sample areas as well as the ALS data acquisitions. However, there are still analyses required to investigate also other factors influences the accuracy e.g. varying growing conditions within the study area.

Concerning different reference sizes the results for the *Montafon* study area show a decrease of the differences of stem volume and biomass to 15.7% and 19.3% respectively (see Table 2) if the average of all sample areas is calculated, which increases the reference area from ~0.25 ha to 3.0 ha. For the study area *Tyrol* the averaging of the coniferous dominated sample areas leads to a decrease of the difference to -13.7% and -2.4% for the stem volume and biomass respectively with an increase of the reference area to 0.77 ha. A similar trend can be observed for the deciduous dominated sample areas where the differences decrease to -3.8% and -2.4% and reference area increases to 0.77 ha. For the study area *Tyrol* the applied species independent stem volume and biomass models lead to a difference between the field measured and the estimated quantities of -1.2% and -1.9% respectively. These accuracies are valid for all four sample areas with a total area of ~1.5 ha.

Especially, for small reference units (e.g. 0.25 ha) effects of borders become relevant as shown in Figure 5. Finally, there are still some errors in the field measurements as for example missing trees (Figure 5) or inaccuracies in the measurement of the tree positions. This fact clearly shows that the measurement of exact positions in forests is still a big challenge if limited economics resources are available. A possible way to improve the accuracy of field measured tree positions could be to identify e.g. dominant trees in the field with their corresponding ones within a reference map that contain the extracted single tree positions from ALS data. Based on such information each sample plot can be locally adjusted to the ALS data applying a 2D transformation. On this way expensive geodetic measurements could be minimized.

Finally, the used discrete ALS data sets (max. two returns per transmitted laser shot) can limit the achievable accuracy of the derived stem volume and biomass maps. As found by Tonolli et al. (25) the second return from multi-return ALS data can significantly improve the estimate of stem volume for forests with complex structure. Therefore, it is expected that the use of e.g. full-waveform ALS data can improve the accuracies of the assessed stem volume and biomass maps due to the fact that the vertical structure of trees can be described in more detail.

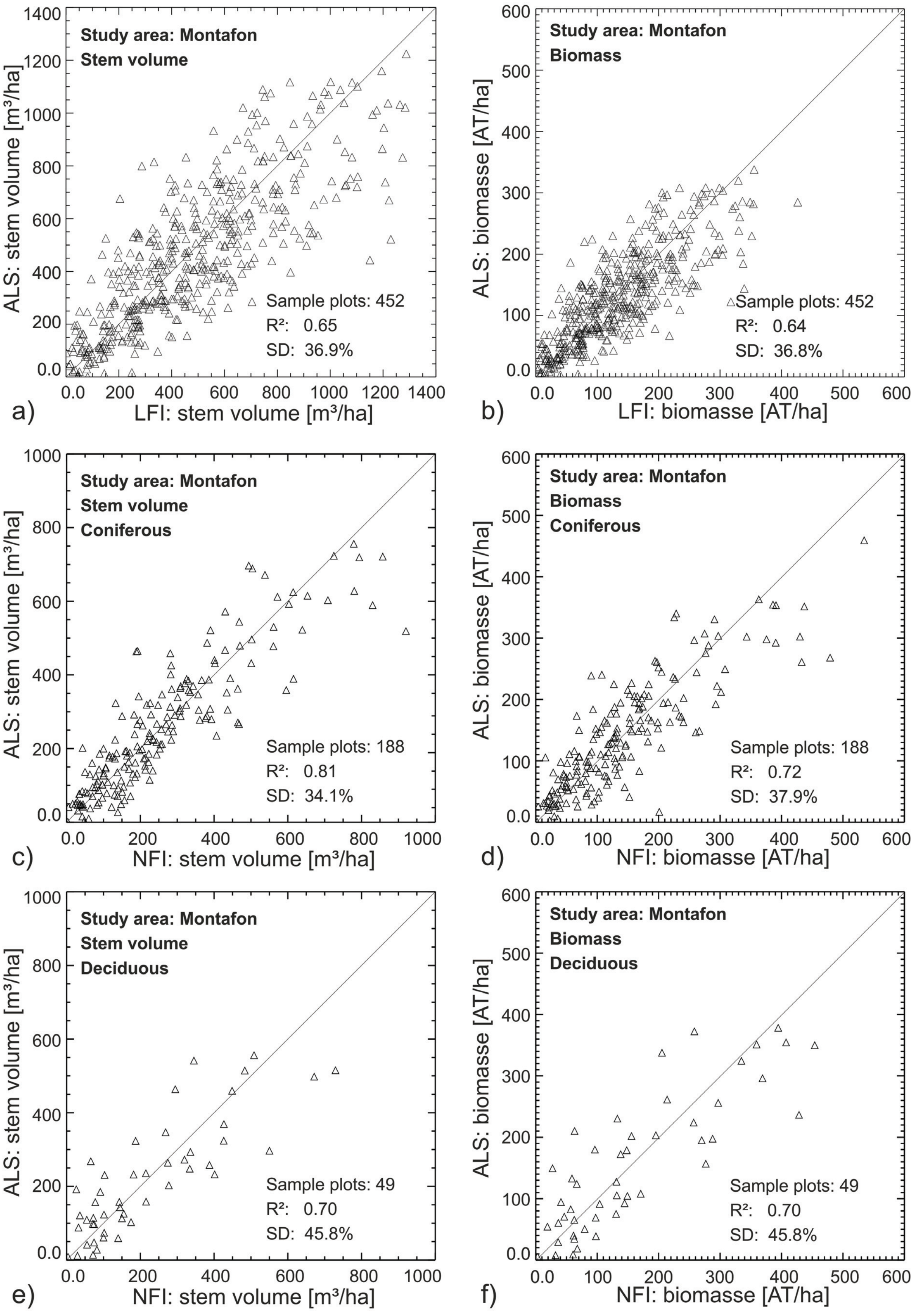

Figure 3: Scatter plots of the calibrated stem volume (a,c,e) and biomass (b,d,f) models for both study areas. For the Montafon study area species independent models and for the Tyrol study area species dependent models were calibrated.

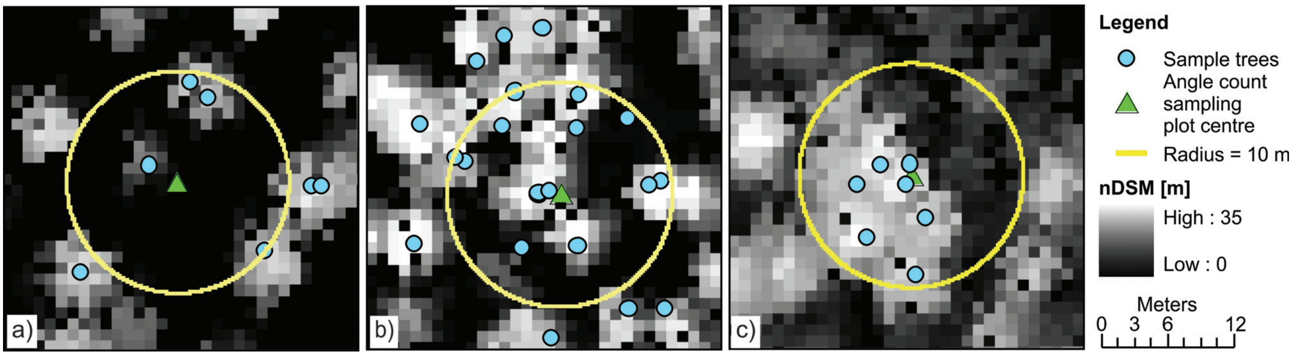

Figure 4: Examples of angle count sampling plots for the study area Montafon. Shown are the centres of the sample plots, the sample plot area with a radius of 10 m used for calibrating the stem volume and biomass models, and the position of the sampled trees.

Table 2: Summary of the calibrated stem volume and biomass models as well as of the accuracy assessment using the independent sample areas for the study areas Tyrol and Montafon. Furthermore, the statistics of the used reference data and of the ALS-based quantities are shown.

Sample areas	Area (m^2)	*In situ* measurements		ALS-based quantities		Differences *in situ* minus ALS		Number of trees
		Stem volume (m^3/ha)	Biomass (AT/ha)	Stem volume (m^3/ha)	Biomass (AT/ha)	Stem volume (%)	Biomass (%)	Conif/dicid
Study area *Tyrol*								
AK	3848	397	269	357	266	-10.0	-1.1	30/71
ST	3848	569	409	572	396	0.6	-3.3	31/119
HB	3848	272	139	202	113	-25.8	-18.5	226/0
BB	3848	990	410	888	423	-10.3	3.1	122/0
AK + ST	7696	483	339	465	331	-3.8	-2.4	61/190
HB + BB	7696	631	275	545	268	-13.7	-2.4	348/0
all	15392	557	307	550	301	-1.2	-1.9	409/190
Study area *Montafon*								
GA1	2499	160	49	192	57	-20.0	-16.3	18/0
GA2	2503	555	171	495	147	10.8	14.0	56/0
GA3	2507	670	206	654	192	2.4	6.8	77/0
GA4	2502	703	217	624	183	11.2	15.7	72/0
GA5	2497	633	195	689	202	-8.8	-3.6	63/0
GA6	2496	593	182	529	157	10.8	13.7	43/0
GA7	2510	809	249	558	166	31.0	33.3	49/0
GA8	2508	845	260	578	171	31.6	34.2	40/0
GA9	2503	531	164	376	110	29.2	32.9	23/0
GA10	2497	885	273	637	186	28.0	31.9	51/0
KW	2524	860	267	951	279	-10.6	-4.5	290/0
HS	2558	423	130	180	57	57.4	56.2	108/0
GA1-10	25022	639	197	533	157	16.5	20.1	492/0
KW + HS	5082	640	198	563	167	12.0	15.5	398/0
all	30104	639	197	538	159	15.7	19.3	890/0

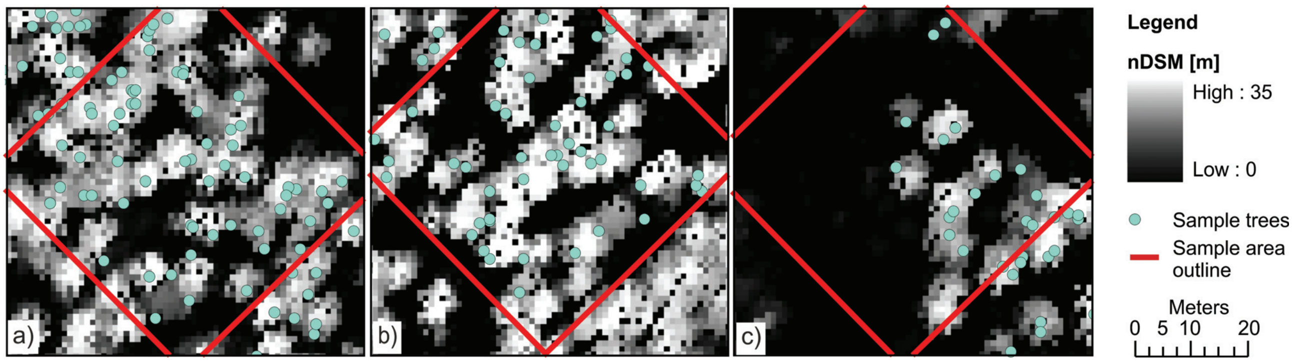

Figure 5: Examples of fully callipered sample areas within the study area Montafon. In all three examples missing trees can be identified as well as border effects are evident.

CONCLUSIONS

This study shows the high potential of ALS data for assessing forestry relevant parameters such as stem volume and biomass. For the study area *Tyrol* the analyses have shown that the higher accuracies can be achieved for the estimated biomass than for the stem volume. It could also be shown that the differences between stem volume and biomass estimated from field measurements and ALS data are less than 2.0% for an area of ~1.5 ha. It could also be shown that a stratification of the sample plots into groups representing main tree species increases the accuracies for smaller reference areas e.g. 0.25 ha. The available national and local forest inventory data sets, both based on the angle count sampling method, have the advantage that they are available, but there are still some limitations for combining them with ALS data due to the fact that an angle count sample plot does not contain all trees within a defined reference circle. Therefore, in future studies, we will analyse if the achievable accuracies can be increased by using fully callipered sample areas for calibrating the stem volume and biomass models. Furthermore, the partly occurring relative large differences of stem volume and biomass for the sample areas in the study area *Montafon* will be analysed in more detail in future. The analyses have also shown that the measurement of tree positions in dense forests is still a challenge, especially if limited economic resources are available.

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