ACCURACY OF FOREST PARAMETERS DERIVED FROM MEDIUM FOOTPRINT LIDAR UNDER OPERATIONAL CONSTRAINTS

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ABSTRACT:

The objective of this study is to test the feasibility of nation-wide medium footprint airborne laser scanning (ALS) data for derivation of forest parameters. The comparison of canopy closure as one important parameter for many forest functions derived from ALS data and aerial photo interpretation was conducted. The present study was carried out in the framework of the Swiss National Forest Inventory (NFI). Three study areas of different size, topographic and forest characteristics were selected. In a first step, canopy height models (CHM) were obtained by subtracting the interpolated terrain altitudes of LiDAR (Light Detection And Ranging) DTM from the interpolated canopy altitudes (LiDAR DSM). Then a binary forest layer with CHM larger or equal 3 m was calculated according to the Swiss NFI forest definition. The Distinction between deciduous and coniferous forest (degree of composition) was performed using the surface cover classes (broadleaved tree, coniferous tree, larch) of the aerial photo interpretation of the NFI for 7,696 sample plots. In a second step, canopy closure derived from the aerial photo interpretation was compared to canopy closure calculated from binary CHM. The study reveals that the canopy closure is underestimated in the binary CHM from LiDAR data and highlights significant differences between coniferous and deciduous predominated forest plots and significant differences between compared canopy closure from winter and summer data. The study shows limitations of canopy closure derived from national LiDAR data but also stresses its practical relevance for many protective functions of forests in alpine conditions.

1. INTRODUCTION

The present study focuses on a comparison of national medium footprint LiDAR data with aerial photo interpretation for deriving standard forest parameters as required by the Swiss National Forest Inventory.

Forests, as part of the landscape, represent an important natural resource for mankind and other living organisms. Exact information on forest extent, structure and composition is needed for environmental, monitoring or protection tasks (CIPRA, 2001; ALPMON work package 1, 1997). Especially alpine forests play a key role in the protection against natural hazards such as rock fall and avalanches. Furthermore, spatial extent of terrestrial ecosystems such as forests and their composition are a central issue in the discussion of carbon sinks and sources at national and continental level (Turner et al., 1995).

However, estimation of forest parameters for large territories (e.g. for national forest inventories) is either expensive if done in the field or imprecise when accomplished through automated stereophotogrammetry (Lefsky et al., 2001; St.-Onge et al., 2004; Maltamo et al., 2004). Moreover, obtaining tree heights through measuring is often not feasible in dense and impenetrable forest stands (St-Onge and Achaichia, 2001). Especially the mapping of forests and the derivation of forest parameters is challenging when undertaken in alpine environments due to the specific terrain conditions (Hollaus et al., 2006). According to Wang et al. (2004), the costs of forest sampling can be reduced substantially by estimating forest and tree parameters directly from aerial photographs. The measurement of tree heights is one of the tasks that need to be fulfilled for an appropriate estimation of these parameters. Due to the fact that parts of tree crowns are shadowed, it is obvious that not all important forest parameters can be derived from aerial photographs. Especially in dense forest stands and in mountainous regions the shapes of trees are varying with the geometrical position on the stereo images (St-Onge et al. 2004). Because seeing the ground is of critical importance, good results can only be obtained in open forest covers.

Recent progress in three dimensional remote sensing mainly includes digital stereophotogrammetry, radar interferometry and LiDAR (Hyyppä et al. 2000; Lefsky et al. 2001; Naesset 2002). Meanwhile, several LiDAR systems are available on the market (e.g. Baltsavias, 1999; Heurich et al., 2003; Hyyppä et al., 2000), enabling the derivation of DSMs and DTMs from such data as well. Some studies suggest the use of DSM data to detect changes in the forest stands (Schardt et al., 2002; Naesset & Gobakken, 2005). A number of studies reveal the successful use of LiDAR-based techniques to estimate tree and stand attributes such as tree height, crown diameter, basal area and stem volume (Naesset, 1997, Persson 2002; Morsdorf et. al 2004). Combining some of these attributes can be useful to evaluate forest stand parameters, e.g. the percentage of canopy cover (Ritchie et al., 1993).

However, some studies also show an underestimation of tree and canopy height, a result also found by scanning LiDAR studies (e.g. Magnussen et al. 1999; Means et al. 2000; Gaveau & Hill 2003). Estimations of the mean tree height are sensitive to forest structure and shape of the canopy (Nelson 1997; Schardt et al. 2002). Often a narrow tree apex is missed by LiDAR hits or the top of a small tree is covered by branches of a tall tree. However, for large monitoring programs or national

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forest inventories there is a growing need to develop new remote sensing techniques that allow deriving quantitative forest parameters more directly.
The objective of this study is to compare national medium footprint LiDAR data with aerial photo interpretation as applied in the Swiss National Forest Inventory (NFI) for the derivation of the degree of composition and canopy closure. Canopy closure is one of the most important parameters to determine the protective functions of forest in alpine conditions, in particular against avalanches (Meyer-Grass and Schneebeli, 1992). To ensure that the results are of practical relevance, only data and methods which are already applied and serve as operational applications are used (national LiDAR data and stereo image interpretation of NFI sample plots).

2. MATERIAL AND METHODS

2.1 Study area

Switzerland is divided into 26 cantons. For this study three cantons with different topographic and forest characteristics are used as test sites. An overview is given in figure 1.
The first study area is located in the northern part of Switzerland (approx. 47°23' N and 8°2' E, 350-900 m a.s.l.) and covers the area of the canton Aargau (AG) with approx. 14,000 km^2. The highly fragmented landscape is characterized by a smooth terrain, forests, agricultural and urban areas. The forest covers 35 % of the area (4,930 km^2) according to the second NFI (Brassel and Brändli, 1999). The forest consists of mixed deciduous trees (*Fagus sylvatica* as dominant tree species) and coniferous trees (*Picea abies* as dominant tree species).
The second study area is located in the pre-alpine zone of central Switzerland (approx. 47°1' N and 9°4' E, 400-3600 m a.s.l.) and covers the area of the canton Glarus (GL) with approx. 7,000 km^2. The tree line in the area is around 1750-1800 m a.s.l. The landscape is characterized by steep slopes with the exception of the main valley and its plane, forests, pastures, few agricultural areas and settlements. The forest covers 29 % of the area (2,050 km^2) (Brassel and Brändli, 1999). The forest is characterized by mixed deciduous trees (*Fagus sylvatica* as dominant tree species) in the lower parts and coniferous trees (*Picea abies* as dominant tree species) in the upper parts.

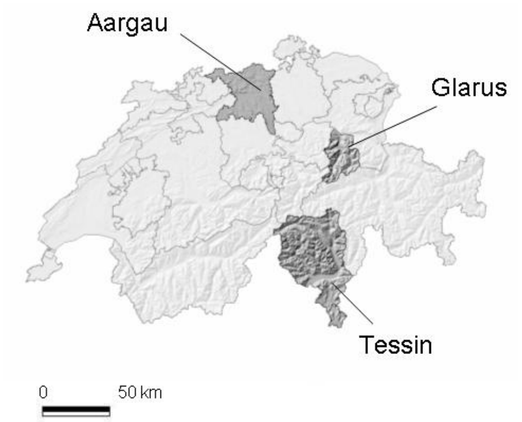

Figure 1. Overview of the three test sites: Cantons Aargau, Glarus and Tessin.

The third study area is located in the southern part of Switzerland (approx. 46°11' N and 9°1' E, 200-3400 m a.s.l.). It covers the area of the canton Tessin (TI) with approx. 28,100 km^2 whereas 49.4 % (13,900 km^2) are forests (Brassel and Brändli, 1999). The landscape is mainly characterized by complex terrain with steep slopes, many valleys and forests (figure 2). The tree line in the area is around 2100-2150 m a.s.l. The forest consists of mixed deciduous trees (*Castanea sativa* as dominant tree species) and coniferous trees (*Picea abies* as dominant tree species).

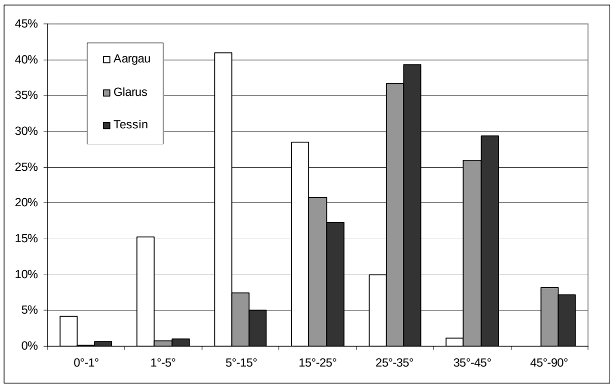

Figure 2. Distribution of the deciduous forest area in relation to the terrain slope for cantons Aargau (left), Glarus (middle) and Tessin (right). For test site Aargau most of the deciduous forest area is located in relatively flat topography, contrary to Tessin and Glarus where most of the forest area is located in steeper terrain.

2.2 National Forest Inventory Data (NFI)

In the Swiss NFI continuous parameters are assessed by aerial photo interpretation at each sample plot belonging to a regular 500 m grid. 25 raster points are distributed regularly (distance 10 m) on the sample plot. For each raster point height and surface cover information is gained and a forest boundary line is measured. The layout of a sample plot is illustrated in figure 3.

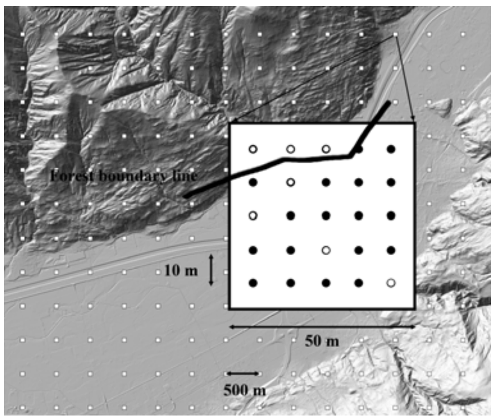

Figure 3. Design of the 50 x 50 m sample plot area with 25 raster points and a forest boundary line. Canopy closure is obtained by calculating the number of points falling on trees with a minimum height of 3 m (black points) within the forest boundary line in relation to the total number of raster points within the forest boundary line.

Each sample plot comprises an interpretation area of 50 x 50 m. The discrimination of forest and non-forest areas is one of the most important attributes resulting from aerial photo interpretation. This requires a non-ambiguous and reproducible forest definition. Summarised the following aspects are crucial: (1) the width of the stocked part of the interpretation area has to measure at least 25 m, (2) the crown coverage of the stocked part of the interpretation area has to be larger or equal 20 %, (3) the stocking has to have a dominant stand height of 3 m.

Stereo-measured variables were gathered on the aerial imagery at each of the 25 raster points within each sample plot. The analogue true colour photos were taken between 1998 and 2005 covering all of Switzerland at a scale of ~1:30,000 and where scanned at a resolution of 14 µm. The digitised photos have a ground resolution of ~0.45 m and a RMS error after aerial triangulation of < 1 m. A photo interpreter assigned each raster point to one of eleven thematic surface cover classes (broadleaved tree, coniferous tree, larch, shrub, grass vegetation, rock, bare soil, paved surface, construction object, water, glacier) using a 3D stereo softcopy station (Socet Set 5.0, BAE Systems).

In addition to surface cover, canopy height information was attributed to each raster point based on the difference between the surface elevation measured by the interpreter and the interpolated (Socet Set 5.0, BAE Systems) terrain elevation from an existing terrain model (25 m grid) provided by swisstopo (Swiss Federal Office of Topography). Finally, in cases with a forest border, a forest boundary line is digitised in addition to the raster points.

2.3 Airborne laser scanner data

National LiDAR data was acquired between 2001 and 2004 by swisstopo, the leaves partly off (figure 4). The project was realised with different companies so very little metadata are available. No detailed information on instruments or platforms is available. Average flight height above ground was between 1000 m and 1500 m. The footprint on ground varies between 0.8 m and 1.2 m. From the raw data, both a DTM and DSM are generated (as raw irregularly distributed points) The average density of the DSM data is 0.5 points / m^2 and the height accuracy (1 sigma) 0.5 m for open areas and 1.5 m for vegetation and buildings (Artuso et al. 2003). The DTM has an average point density of 0.5 points / m^2 and height accuracy (1 sigma) of 0.5 m (Artuso et al. 2003).

Figure 4. LiDAR data acquisition time of the three test sites. White areas were flown between November and March (leaves-off) and black areas during the vegetation season between April and October (mostly leaves-on).

2.4 Interpolation: DTM and DSM

The interpolation is based on the initial triangulation of all raw data points into a TIN. Depending on the expected point density of 0.5 points/m^2, a conservative grid size of 2.5 m has been chosen. The interpolation of raw data revealed that the measured point density varies more than expected. Initial results show, that 20 % of the test area in the canton Tessin has less than 0.4 points/m^2.

2.5 Canopy height model (CHM)

The Canopy height model (CHM) was obtained by subtracting the interpolated terrain altitudes from the interpolated canopy altitudes. Because only first and last pulse data is available, no further processing of pulse information was possible.

2.6 Derivation of forest parameters

According to the NFI forest definition the CHM was reclassified to a binary layer, where values >= 3 m are assigned to forest (1) and values < 3 m to non-forest (0). The sample plot area (50 x 50 m) was reduced to the actual forest area on the sample plot, if a forest boundary line was digitised in the aerial photo interpretation (see figure 5).

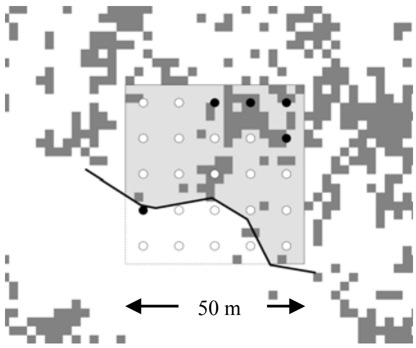

Figure 5. Binary CHM and the reduced sample plot area, with a forest boundary line and 25 raster points of the aerial photo interpretation.

As first forest parameter, the degree of composition was determined. The surface cover classes of the aerial photo interpretation were used to distinguish between plots dominated by deciduous trees and plots dominated by coniferous trees (degree of composition). Plots with more than 90 % of broadleaved tree raster points are assigned to the class 'deciduous forest' and plots with less than 10 % of broadleaved tree to the class 'coniferous forest'. Mixed plots where not used further in this study.

As second forest parameter, canopy closure was calculated as the sum of pixels of the binary CHM in the corresponding sample plot area. Canopy closure from aerial photo interpretation is obtained by calculating the number of points falling on trees with a minimum height of 3 m within the forest boundary line in relation to the total number of raster points (see figure 3).

3. RESULTS

3.1 Degree of composition

In total, in all three test sites 7,696 sample plots were classified into four classes of degree of composition using the raster points of the aerial photo interpretation (Table 1).

Fraction of deciduous trees on forest plots		Number of plots AG (n=1,998)	GL (n=701)	TI (n=4,997)
Coniferous Plots (< 10%)		***151***	***228***	***1565***
Mixed Plots	*10-50%*	*429*	*145*	*355*
Mixed Plots	*50-90%*	*673*	*165*	*486*
Deciduous Plots (> 90%)		***745***	***163***	***2591***

Table 1. Degree of composition for the three test sites.

Table 1 shows that Aargau is characterised by mixed forests (55 %) and followed by deciduous forests (37 %) whereas Tessin is characterised by either predominant coniferous plots or predominant deciduous plots (83 %). In Aargau only 8 % are dominant coniferous forest plots. In Glarus most of the forest plots are mixed forest (44 %) followed by coniferous (33 %). In the following results only predominant coniferous and deciduous forest plots (n=5,443) are taken into account.

3.2 Canopy closure

The focus of this study lies on canopy closure obtained by means of aerial image interpretation and data derived from LiDAR.

3.2.1 Canopy closure obtained from aerial photo interpretation

Table 2 shows that canopy closure obtained from aerial photo interpretation is high in all test sites. Three quarters of the plots have a canopy closure between 75 % and 100 %. Deciduous plots are generally denser than coniferous plots. Only 0.7 % of deciduous plots and 6.8 % of coniferous plots are less dense than 30 %.

	Canopy closure from aerial photo interpretation					
	Number of deciduous forest plots			*Number of coniferous forest plots*		
Canopy Closure %	*AG n=745*	*GL n=163*	*TI n=2,591*	*AG n=151*	*GL n=228*	*TI n=1,565*
<30	*7*	*1*	*19*	*9*	*15*	*109*
30-50	*10*	*4*	*78*	*3*	*31*	*239*
50-75	*44*	*17*	*284*	*12*	*65*	*429*
75-100	*684*	*141*	*2210*	*127*	*117*	*788*

Table 2. Canopy closure as obtained by aerial photo interpretation. Deciduous forest plots are denser than coniferous forest plots. Three quarter of the plots is denser than 75 %.

Mean, median and standard deviation of canopy closure for both deciduous and coniferous forest plots are given in table 3. For deciduous trees the mean canopy closure varies between 89.7 % (TI) and 93 % (AG). Coniferous forest plots are less dense and vary between 70.8 % (TI) and 88.1 % (AG).

	Canopy closure from aerial photo interpretation (%)					
	deciduous forest plots			*coniferous forest plots*		
	AG n=745	*GL n=163*	*TI n=2,591*	*AG n=151*	*GL n=228*	*TI n=1,565*
Mean	*93.0*	*90.2*	*89.7*	*88.1*	*71.2*	*70.8*
Median	*100.0*	*96.0*	*96.0*	*100.0*	*76.0*	*76.0*
Std	*13.9*	*15.0*	*15.7*	*23.1*	*23.7*	*23.6*

Table 3. Mean canopy closure from aerial photo interpretation on deciduous forest plots and forest coniferous plot respectively.

3.2.2 Canopy closure obtained from LiDAR (binary CHM)

Table 4 shows the canopy closure obtained from LiDAR data and table 5 summarizes the canopy closure for deciduous and coniferous forest plots. For deciduous trees the mean canopy closure varies between 50.9 % (GL) and 62.7 % (AG). In contrary to aerial photo interpretation, coniferous forest plots obtained from LiDAR are denser than deciduous forest plots – with the exception of Tessin. They vary between 53.7 % (GL) and 67.1 % (AG).

	Canopy closure from LiDAR (CHM)					
	Number of deciduous forest plots			*Number of coniferous forest plots*		
Canopy Closure %	*AG n=745*	*GL n=163*	*TI n=2,591*	*AG n=151*	*GL n=228*	*TI n=1,565*
<30	*59*	*40*	*132*	*21*	*43*	*312*
30-50	*139*	*37*	*344*	*16*	*56*	*355*
50-75	*301*	*53*	*1153*	*32*	*77*	*546*
75-100	*246*	*33*	*962*	*82*	*52*	*352*

Table 4. Canopy closure from LiDAR (binary CHM). Deciduous forest plots are denser than coniferous forest plots. Only 30 % of the plots are denser than 75 %.

	Canopy closure from LiDAR (%)					
	deciduous forest plots			*coniferous forest plots*		
	AG n=745	*GL n=163*	*TI n=2,591*	*AG n=151*	*GL n=228*	*TI n=1,565*
Mean	*62.7*	*50.9*	*66.2*	*67.1*	*53.7*	*53.8*
Median	*66.3*	*53.0*	*69.5*	*78.0*	*53.1*	*55.5*
Std	*21.0*	*26.9*	*18.6*	*28.7*	*24.6*	*24.1*

Table 5. Mean canopy closure from CHM from LiDAR on deciduous plots and coniferous plot respectively

3.2.3 Aerial photo interpretation versus LiDAR

Overall, canopy closure is underestimated in all three test sites by the LiDAR CHM in comparison to the aerial photo interpretation. For the statistical analysis the plots were grouped into plots predominated by coniferous trees or deciduous trees respectively. Then a Kolomogorov-Smirnov-Test (alpha=0.05) as implemented in SAS's UNIVARIATE procedure was applied on the dataset. This test revealed that the plot wise calculated differences in canopy closure measurements from the aerial photo interpretation and the LiDAR measurement are not normally distributed. Therefore a non-parametric test, the Wilcoxon two-sample test as implemented in SAS's NPAR1WAY Procedure (SAS, 2000), was chosen to account for significant differences. A significant difference (alpha=0.05) between the calculated differences in canopy closure measurements for coniferous forest plots and deciduous forest plots (p<0.0001) was found. Finally, table 6 reveals that this underestimation is higher at deciduous than at coniferous plots.

	Difference of canopy closure (%)	
	deciduous forest plots	*coniferous forest plots*
Mean	*25.7*	*17.4*
Median	*24.0*	*15.0*
Std	*16.9*	*19.2*

Table 6. Mean differences of canopy closure from CHM and aerial photo interpretation on predominated deciduous plots and predominated coniferous plot respectively

3.2.4 LiDAR data acquisition: leaves-off versus leaves-on

For this analysis the plots were grouped into plots predominated by coniferous trees or deciduous trees and the flight date (in vegetation season yes or no). Again the calculated differences are not normally distributed. Therefore, the Wilcoxon two-sample Test was chosen, to account for significant differences of the canopy closure measure for the two datasets. A significant difference (alpha=0.05) between the flight dates in both cases, coniferous forest plots (p=0.0007) and deciduous forest plots (p=0.0316) was found.

4. DISCUSSION AND CONCLUSION

ALS data covering large country wide areas is becoming more and more popular and is available for many countries. However, these data sets suffer from some limitations: First, in most cases these data are medium to large footprint ALS and do not meet the requirements for single tree detection and accurate derivations of relevant forest parameters as performed in many case studies. Second, although the acquisition time is not focused on single specific questions the data has to serve for different purposes.

The present study reveals that large area application of national LiDAR data for derivation of canopy closure as one important forest parameter is challenging since time of data acquisition varies. Therefore the accuracy of the obtained parameters is only partly satisfactory. Especially in predominated deciduous forest plots the differences of canopy closure obtained by aerial photo interpretation and LiDAR measurements are high. Therefore, the obtained information on canopy closure is reliable, since most protective functions of alpine forests are limited to coniferous forests (lower underestimation than for deciduous forests) in higher regions. Nevertheless, the influence of data acquisition time remains evident, in deciduous and in coniferous cases.

For a further quality assessment there is a strong need for more information on exact date of acquisition for each single LiDAR measurement. Summarized metadata for organizational units, like map sheets, are not appropriate. Furthermore, since both forest parameters strongly depend on the quality of the CHMs a more extensive quality check of the CHMs has to be performed. Further reference data (e.g. tree heights) will be obtained using stereo photogrammetry and field measurements.

To summarize, the need to develop new remote sensing techniques for large NFIs is evident. The use of nation wide available LiDAR data is obvious, but further studies are needed to obtain more information on quality and characteristics of the data for forest specific questions.

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