The objective of this paper is to evaluate a new approach for the automatic delineation of forested areas based on airborne laser scanning (ALS) and national forest inventory (NFI) data. In the Austrian NFI a forest area is mainly defined with four fundamental criteria. One of these criteria, the so called “crown coverage”, is the most complex variable and therefore the main focus of this paper is on defining and implementing this criterion in an automatic process to delineate forested areas. Based on Austrian NFI data functions were determined for two different test sites in Austria, describing the criterion crown coverage as a relation between tree height and the distance between trees. Based on the ALS data an automatic method on the basis of adapting α-shapes was developed to link these functions to the ALS data. The approach was tested for two different test sites in Austria. For the first test site a tree species independent function was applied. The results of the delineated forest mask are validated with a reference forest mask which was manually delineated based on orthophotos. The derived forest mask differ less than 1.6% from the reference forest mask and shows a very high accuracy. For the second test site tree species dependent functions were applied for the assessment of the crown coverage. The presented approach shows promising results and shows the high potential for the automatic forest area delineation based on ALS data.

1. INTRODUCTION

Acquiring topographic data of the Earth's surface is widely realized with airborne laser scanning (ALS). Especially for forestry applications height information is a fundamental input to derive different forest parameters (Means et al., 2000). There are several economical and ecological applications like e.g. the estimation of tree heights (Næsset and Bjerknes, 2001), growing stock estimations (e.g. Hollaus et al., 2009b) or forest condition monitoring (Rutters et al., 1992). The determined results of these applications are highly correlated with the fundamental input parameters size and position of the delineated forest areas. Related to forest condition monitoring, the increasing need of a regional and global monitoring of e.g. deforestation requires an automatic determination of forested areas by means of remote sensing data since a manual delineation is a very time- and cost-intensive task.

In the past mainly aerial images were used for manual or semi-automated extraction of forested areas. Shadowing effects limit this task especially for the detection of small forest clearings and the exact delineation of forest borders. Additionally the quality of the results of
a manual delineation is highly correlated with the experience of the human analyzer and may lead to inhomogeneous, maybe even incorrect datasets. However, an automated method for forest delineation based on ALS data can overcome these limitations in most instances and shows objective and reproducible results at short evaluation times. Both, manual and automated methods to delineate forested areas require an exact geometric forest definition. Depending on the different locations worldwide many different national forest definitions are available (Lund, 2010) beside a global definition of Food an Agriculture Organization of the United Nations (FAO) (Zhu and Waller, 2003). The forest definition of the Austrian national forest inventory (NFI) is mainly based on the four criteria (1) minimum height depending on an in situ reachable tree height, (2) minimum crown coverage, (3) minimum area size and (4) minimum area width (Gabler and Schadauer, 2006). Additionally the criterion of land use has to be considered. The criteria of minimum area and minimum tree height can easily be considered, whereas the parameter crown coverage is not clearly defined in the NFI. Therefore, this study aims at developing a generic, automated approach for delineating forested areas from ALS data using these three criteria with the focus on defining and implementing the crown coverage. The remaining parts of this paper are organized as follows: Section 2 describes the selected study areas and the used data. Section 3 describes the methodology and implementation whereas Section 4 shows results and their discussions. Finally, concluding remarks are given in Section 5.

2. STUDY AREA AND DATA SET

In this contribution the approach for an automated delineation of forested areas is applied for two different study areas in Austria. For the first study area Ötscher an approach depending on tree species (coniferous and deciduous trees) is applied. The tree species are automatically extracted from full-waveform ALS data. For the second study area Zillertal a tree species independent approach is applied to discrete ALS data. A manual delineated forest mask is used for validation purposes within the study area Zillertal.

2.1. Study area Ötscher

The study area Ötscher covers an area of 2.2 x 1.5 km and is located in the southern part of the federal state of Lower Austria (Figure 1b). The predominant tree species are red beech (Fagus sylvatica), spruce (Picea abies) and larch (larix decidua) and cover about 80% of the trees in this area. For a previous study the BFW has installed a local forest inventory (FI) for this region. The tree species information from the sampled trees is used as reference for the validation of the derived tree species map. Further information about this study area can be found in (Hollaus et al., 2009a). The used full-waveform ALS data was acquired using a RIEGL LMS-Q560 full-waveform laser scanner during a flight campaign in January 2007 under leaf-off conditions. The mean flying height above ground was 620 m. The mean point density is about 30 echoes/m². For a knowledge-based classification of coniferous and deciduous trees the 3D point cloud with their observables echo width and the calibrated quantity backscatter cross section (Briese et al., 2008) as well as the distribution of the echoes in vertical direction were used. The achieved overall accuracy was 83% (Hollaus et al., 2009a).
2.2. Study area Zillertal

The study area Zillertal is located in the eastern part of the federal state of Tyrol and covers an area of 2.5 x 2.5 km (Figure 1a). The lowest elevation of the study area is 620 m above sea level up to 1500 m above sea level at the highest point. The dominant tree species is spruce (*Picea abies*). Beside the forested areas buildings, cable cars and power lines can be found in the study area. The used ALS data was acquired using an Optech Inc. ALTM 3100 laser scanner during multiple flight campaigns in 2008 under leaf-off and leaf-on canopy conditions. The mean flying height above ground was 1200 m. The mean point density is about 5 echoes/m². For the validation of the delineated forest areas a forest mask, which was manually derived from orthophoto interpretations, is used as reference. This forest mask was provided by the Amt der Tiroler Landesregierung, Abteilung Forstplanung.

![Figure 1: Observed study areas (a) orthophoto of the study area Zillertal (b) orthophoto of the study area Ötscher (sources: Bing maps).](source)

2.3. Derived base products

For both study areas the ALS data has been processed and filtered using the hierarchic robust filtering approach (Kraus and Pfeifer, 1998). As a digital terrain model (DTM) and a digital surface model (DSM) was derived. By subtracting the DSM from the DTM a normalized digital surface model (nDSM) was created as a fundamental base product for delineating forested areas. Additionally a slope adaptive echo ratio (*sER*) map, as a measure for local transparency and roughness, was derived (section 3.1). The derived products have a spatial resolution of 1 x 1 m.
3. METHODOLOGY AND IMPLEMENTATION

As described in section 1 the criteria of the Austrian NFI (area, height and crown coverage) are used for the delineation of forested areas in this study. Based on the NFI the minimum area is defined with 500 m² and is applied by using GIS tools. The minimum height was set to 3.0 m and is considered by applying a height threshold on the nDSM heights. Artificial objects i.e. buildings, power lines and cable cars, which have similar objects heights as forests, are removed from the nDSM in a pre-processing step (section 3.1). The parameter crown coverage defines the projected crown area of trees within a reference area. Current automatic methods calculating crown coverage maps are commonly based on a moving window approach. The kernel size of the moving window, which defines the reference area, is a fundamental parameter. Since there is no exact definition of the size and the shape of the reference area available in the NFI, different results are derived if different kernel sizes and shapes (square, circle, and irregular polygons e.g. forest stands) are applied. Another limitation of the moving window approach is, that especially with circle- or square-shaped kernels smoothing effects occur at the border of a forest and at small clearings. To overcome these problems a method is investigated, which is currently used for the manual delineation of forested areas at the BFW. This method describes the crown coverage by the relation between the tree crown size and the distance between trees (section 3.2) and is originally based on the work of (Hasenauer, 1997). The transfer of this approach to the ALS data is described in section 3.3. For the derivation of the final forest mask all previously describe processing steps are combined, the minimum area criterion is applied and a final check of the crown coverage within each delineated forest polygon is done (section 3.4).

3.1. Removing artificial objects

As all elevated objects e.g. buildings, forests, power lines and cable cars are present in the nDSM a pre-processing step is required to extract a vegetation mask that represents the potential forested area. As shown in previous studies (Höfle et al., 2009; Hollaus et al., 2009a) the slope adaptive echo ratio (sER) can be used to differentiate between buildings and forested areas. The sER is defined as the ratio between 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). An sER value of 100% means, that the echoes within the 2D search radius describe a planar surface (e.g. roofs), whereas a sER value <100% means that the echoes are vertically distributed within the 2D search area and thus indicating transparent objects i.e. forests, building borders and power lines. An empirically determined sER threshold of sER less than 85% is used to extract the vegetation mask. Finally, morphological operations (open, close) are applied to remove the remaining building borders and power lines from the vegetation mask.

3.2. Crown coverage calculation based on NFI data

Based on the defined minimum crown coverage the maximum distances between trees are calculated, which are used as weights for the adapting α-shapes (see section 3.3). To derive the maximum distance the following two steps are necessary:
A statistical relationship between tree height and crown radius and a mathematical relation between crown radii and the maximum distance between two neighboring trees to fulfill the crown coverage threshold.

For the first step measurements of crown radii from the Austrian NFI were used. A subsample of measured trees was chosen for describing the crown radii for trees with low competition according to a border situation. Thus dense stands and trees of lower social classes according to (Kraft, 1884) were excluded. A short description of the data used is given in table 1.

<table>
<thead>
<tr>
<th></th>
<th>Coniferous trees</th>
<th>Deciduous trees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>mean</td>
</tr>
<tr>
<td>Crown radius (m)</td>
<td>1972</td>
<td>3.14</td>
</tr>
<tr>
<td>Tree height (m)</td>
<td>26.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>1137</td>
<td>426</td>
</tr>
</tbody>
</table>

Table 1: NFI data description used for the statistical models between crown radius, tree height and elevation.

For the second step a simple linear approach is chosen leading to the following model:

\[ C_r = a + b \times H + c \times E \]

Eq. (1)

whereas \( C_r \) is the crown radius (m), \( H \) is the tree height (m), \( E \) is the elevation above sea level (m) and \( a, b, c \) are factors that are different for coniferous and deciduous trees.

The mathematical relation between crown radii and the maximum distance between the trees to fulfill the crown coverage threshold of the forest definition is a complex problem. For our study a simple solution is to restrict the problem to two trees and define the forest area of these two trees as the area between the trees including the crown projections as shown in figure 2a. The mathematical derivation of the forest area is simplified (figure 2c) by neglecting the exact solution as shown in figure 2b. According to this approximated solution the relation between the maximum distance and the crown radii for variable crown coverage thresholds can be derived as:

\[ d = f \times (C_{r1}^2 + C_{r2}^2) / (C_{r1} + C_{r2}) \]

Eq. (2)

whereas \( f \) is a constant for different crown coverage thresholds.

Figure 2: Forest area of two neighboring trees at the borderline. \( d \) is the distance between the trees, \( r_1, r_2 \) are crown radii. (a) General solution, (b) exact solution and (c) approximated solution for the area between the trees.
3.3. Crown coverage calculation based on ALS data

The determined relation between tree height, sea level, main tree species and crown diameter as well as the relation between crown diameter and crown coverage, both derived from NFI data (section 3.2), are applied to the ALS data.

In the first processing step the tree species specific crown diameters are assessed for the coniferous and deciduous trees. The input parameters are the tree height, the sea level and the tree species (see section 3.2). For the study area Zillertal only coniferous trees and for the Ötscher test site both coniferous and deciduous trees are considered. The derivation of the tree species map for the Ötscher test site is described in section 2.1. For the extraction of the tree heights the positions of single trees have to be determined. This is done by using a local maxima filter based on a circular kernel with a diameter of three pixels. Furthermore, the criterion of the minimum tree height is considered. For each detected tree position the sea level is determined by the DTM and the tree height is extracted from the pre-processed nDSM (see section 3.1). Applying Eq. (1) the crown diameter for each tree is computed.

In the second processing step adapting $\alpha$-shapes are used to consider the maximum allowed distance between trees taking into account the required minimum crown coverage of 30%, which is defined in the NFI. In detail the distances between trees are calculated using a Delaunay triangulation of the detected tree positions. The Delaunay triangulation is calculated using the Open Source software CGAL. The $\alpha$-shape of a set of 2D-points is a "shape" following the outline of the given points. Depending on the value of $\alpha$, the shape follows cavities or displays inner holes to a larger or lesser extent (Edelsbrunner and Mücke, 1994). In our case, the length of the maximum allowed distance between trees (see equation 1) defines the value $\alpha$ and is adapted for each tree pair, depending on tree species and crown diameter. Each triangle is validated if all edges are shorter than the maximum length calculated based on Eq. (1). If this criterion is not fulfilled the triangle is deleted. The remaining triangles are combined to connected areas and provide a potential forest mask.

3.4. Forest area delineation

For the delineation of the final forest mask, additional post-processing steps on the derived potential forest mask (section 3.3) are required. As the borderlines of the derived potential forest mask represent the tree stem axis, the potential forest mask is buffered by the half of the maximum available crown diameter found in the study area. In order to prevent an overestimation of the derived forest mask the buffered area is intersected with the vegetation mask (section 3.1). The expanded forest mask is vectorized and the minimum area criterion is applied by deleting single polygons and by filling forest gaps with an area less than 500 m².
4. Results and discussion

4.1. Removing artificial objects

The results of the method described in section 3.1 are shown in figure 3 for the study Area Zillertal. Figure 3a shows the original sER-map with colored markers pointing to selected artificial objects. Figure 3b shows the processed sER-map without the artificial objects. The method shows suitable results for the elimination of artificial objects and deriving a vegetation mask. Buildings, power lines, etc. are removed from the sER-map in most instances while vegetated areas with a sER value <85 are retained within the processing. The so derived vegetation mask is used to eliminate the nDSM heights from the artificial objects.

![Image of figure 3: Preliminary mask of vegetated areas: (a) Echo ratio map and (b) adjusted Echo ratio map with eliminated man-made objects of the study area Zillertal. The red arrow shows a power line, the blue arrow shows a building and the green arrow shows a cable car station.](image)

**4.2. Crown coverage calculation based on NFI data**

Eq. (1) was calibrated for coniferous and deciduous trees, whereas the crown radii, tree heights and elevations were taken from NFI sample trees (see table 1). The following equations for calculating the crown radii were found:

\[
\text{Coniferous trees: } C_r = 1.02 + 0.0625\times H + 0.000416\times E \\
\text{Deciduous trees: } C_r = 1.34 + 0.1331\times H + 0.000164\times E
\]

Based on Eq. (2) the constant \( f \) was calculated for coniferous and deciduous trees and is 29.8 and 8.9 for a crown coverage of 10% and 30% respectively.

**4.3. Crown coverage calculation based on ALS data**

Because of the small kernel size of 3 x 3 pixels multiple local maxima were found within the area of single tree crowns. Especially within dense forested areas the detected local maximums do not represent the exact tree stem positions. Therefore, the amount of detected local maximums is highly correlated with the kernel size. In the case of multiple local maxima within one tree crown the error of the distance between trees could be the crown diameter at the maximum. However this limitation plays a minor role for the delineation of forests along the timberline or along the forests borderlines, where sparse forests and clear separable single trees are present. For the detected local maxima the corresponding tree crowns were calculated based on the calibrated formulas (see section 4.2) and serve an input for the adapting $\alpha$–shape method. As shown in figure 4, triangles with edges larger than the maximum possible distance between trees are reliably eliminated from the final triangulation result.

![Figure 4: result of the tree species specific adapting $\alpha$–shape method](image)

4.4. Forest area delineation

In Figure 5 the results for the automatic delineation of the forested areas are presented for the study areas Zillertal (figure 5a) and Ötscher (figure 5b). Single trees at the forest’s border as well as small forest clearings within a sparse forest are considered as forested area if the maximum possible tree distance is not exceeded (figure 5b). Due to the applied area criterion small forest patches with an area less than 500 m² are removed and forest clearings (<500 m²) are assigned to the forest area. As the preliminary output of the $\alpha$–shape approach represents the forests borderline along the tree axis the expanded forest area delineate the real forest area with high accuracy (figure 5). The final validation of the crown coverage, which is averaged for each forest polygon, fulfills the required threshold of 30%.

For the study area Zillertal the automatically delineated forest mask was visually validated with the manual delineated forest mask, which is based on an orthophoto interpretation. As shown in figure 5b and 5c the high potential of the ALS based forest delineation is especially within shadowed areas. Based on the clearly defined geometric criteria the result is objective and repeatable. This can be shown in figure 5b where the manual delineation of single trees near the forests border is not comprehensible. Finally the areas of the manually and automatically detected forests were calculated and show a very good agreement. For example for the Zillertal study site the total forest area is 316.375 ha and 311.327 ha for the manual and the automatic detected forest area respectively.
5. Conclusion and Outlook

The results of the presented approach show the high potential of an automatic delineation of forested areas based on ALS- and NFI-data. The presented method delivers repeatable and objective results with high accuracy along the forests borderline. Since fragments of artificial objects remain in the vegetation mask further steps on eliminating these fragments need to be done. Three criteria of the NFI were used and therefore additionally the two criteria minimum area width and land use need to be considered in further investigations.

Acknowledgements

The ALS data for the test area Ötscher was kindly provided by the Amt der Niederösterreichischen Landesregierung, Gruppe Baudirektion, Abteilung Vermessung und Geoinformation and for the test area Zillertal by the Amt der Tiroler Landesregierung, Gruppe Landesbaudirektion, Abteilung Geoinformation. This study is done within the project LASER-WOOD (822030), funded by the Klima- und Energiefonds in the framework of the program "NEUE ENERGIEN 2020".
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