ASSESSING MOUNTAIN FOREST STRUCTURE USING AIRBORNE LASER SCANNING AND LANDSCAPE METRICS

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ABSTRACT:

Forest structure is a key element to determine the capacity of mountain forests to protect people and their assets against natural hazards. Airborne laser scanning offers new ways for describing forest structure in 3D. This study aimed at developing a generic automated approach for assessing and quantifying forest structure using landscape metrics on height class patches of the normalized crown model (nCM). These patches were built up from objects that were obtained by segmentations. Two separate multi-resolution segmentations were carried out: level 1 objects represented tree crowns and collectives of tree crowns, level 2 objects represented forest stands. Level 1 objects were classified into four height classes and overlaid with level 2 stands in order to calculate landscape metrics as the Shannon Evenness Index (SHEI) and the Division Index (DIVI). The SHEI could not sufficiently represent the vertical layering of the stands. Canopy density values of each height class were used instead. The DIVI proved to be a suitable measure to distinguish between dense and open crown closure. By means of the DIVI and canopy density values, 85% of the forest area could be correctly assigned to one of the six discrete forest structure types. With the approach presented, resource and natural hazard managers can easily assess the structure of different forests and as such can better take into account the protective effect of forests.

1. INTRODUCTION

“Mountain forests provide the most effective, the least expensive and the most aesthetic protection against natural hazards” recalls the first paragraph of the Mountain Forest Protocol of the Alpine Convention. Without mountain forests, the costs of building and maintaining technical protective constructions against rapid mass movements in the Alps would be unaffordable. Forest structure is a key element that determines the protective capacity of mountain forests (Dorren et al. 2004). It can be characterized by the position of trees, the vertical layering and the tree species mixture. Structures of mountain forests differ greatly from those in the lowlands. Mountain forests contain relatively few species, tend to be quite open and consist of a mosaic of tree clusters and gaps (Schönenberger 2001). In mountain forests, particularly, structure is closely related to stand stability, i.e. resistance against storm and snow loads (Bachhofen & Zingg 2001, Brang 2001). Other characteristics that determine structure are crown closure and tree density. These influence forest avalanche risk potential and the protective effect of a forest against rockfall. Consequently, assessing forest structure enables forest managers and natural risk engineers to evaluate whether a forest can fulfil its protective function or not. Reliable and area-extensive data on forest structure is thus a prerequisite for effective resource and risk management in mountainous regions.

Traditional methods for assessing forest structure comprise field inventories (Herold & Ulmer 2001) and aerial photo interpretation (Bebi 1999). The drawback of inventories is that they cannot provide spatially continuous information over a large area. The usefulness of photo interpretation is hampered by different illumination and shading effects.

From small footprint airborne laser scanning (ALS), however, we can derive detailed digital terrain (DTM) and surface (DSM) models. Subtracting these two models of a forested area results in a so-called normalized crown model (nCM), that is spatially continuous and not hampered by shading effects. This facilitates assessing forest structure in 3D. Various studies show that it is possible to derive a variety of single structural attributes such as tree height, basal area, crown size and above-ground biomass from ALS-data (Hall et al. 2005, Naesset 2004, Maltamo et al. 2004, Tiede et al. 2004, Lim et al. 2003, Popescu et al. 2002). Some studies focus on tree height variance as a measure of vertical forest structure (Blaschke et al. 2004, Zimble et al. 2003). Until now, little attention has been paid to area-based structural patch metrics derived from ALS-data.

Patch and landscape metrics have been receiving considerable attention to measure landscape patterns. The use of landscape metrics within forests mainly focuses on forest fragmentation and biodiversity (Traub & Klein 1996, Venema et al. 2005, Mc Elhinny 2005) and their changes over time. In this study landscape metrics are used for the opposite purpose, namely to describe structuring of forests instead of fragmentation.

This study aims at developing a generic, automated approach for assessing and quantifying forest structure using landscape metrics on height class patches of the normalized crown model

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(nCM). It should lead to more objective, transparent and repeatable results compared to visual interpretation by a human interpreter. The results of this assessment will provide a) spatially continuous input data sets for snow avalanche and rockfall simulation models and b) a basis for deriving discrete stand structure types for practical mountain forest management.

2. METHODOLOGY AND IMPLEMENTATION

2.1 Study area

The study area covers 120 hectares of spruce-dominated protection forest on a West-facing slope near the village of Gaschurn in the Montafon region (see Fig. 1). The study area is dominated by steep rugged terrain with rock faces, gullies and torrents (see DTM in Figure 2). We mostly find old-growth forest in different structural manifestations.

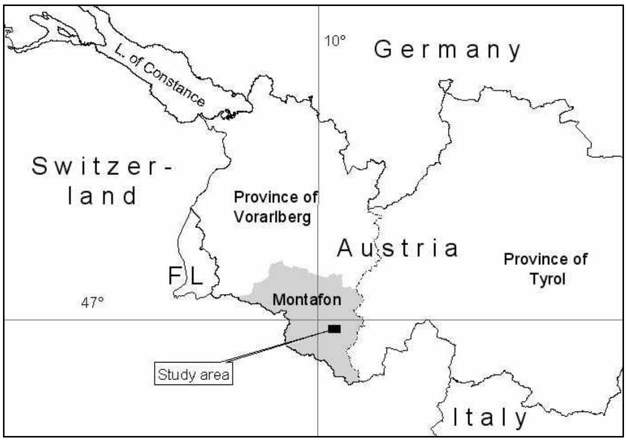

Figure 1. Study area location in the Montafon

In the lower parts of the slope, homogenous pole stands occur in areas which used to be meadows. Along the forest avalanche tracks tree regeneration and young stands can be found. In the upper part forest structure becomes more open and consists of tree clusters (tree collectives) which are typical for high altitude forests. The study area ranges form 1000m altitude in the valley floor up to 1800m at the tree line. The forest provides essential protection against natural hazards such as landslides, avalanches and rockfall. The presence of many different structure types makes this area well suited for this study.

2.2 Data

The ALS data used in this study were acquired on the 10th of December 2002 under leaf-off canopy conditions. The instrument applied was a first/last pulse Airborne Laser Terrain Mapper (ALTM 1225) made by Optech Inc. (Canada). The pulse repetition frequency of the ALTM is 25 kHz, which resulted in a point density of 0.9 points m^{-2} at an average flight height of 1000m above ground level. With a laser beam divergence of 0.3mrad, the average footprint on the ground was about 0.30m. The average ground swath width was about 725m, the maximum scanning angle 20º (Wever 2002).

The data obtained by the ALTM have been processed and interpolated by the TU Vienna using the *hierarchic robust filtering* approach (Kraus & Pfeifer 1998). As a result a digital terrain model (DTM) and a digital surface model (DSM), both with a resolution of 1m × 1m, were created. By subtracting the DTM from the DSM we obtained a "normalized crown model" (nCM), which describes an estimate of the vegetation and forest height (see Figure 2).

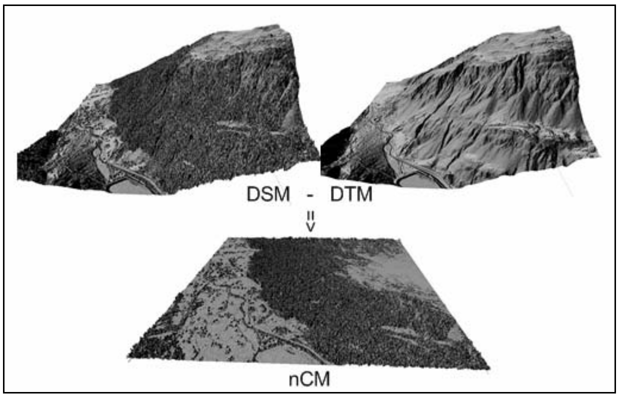

Figure 2. Generation of nCM (study area seen from southwest)

Terrestrial mapped structure types and field comparisons were used for validation purposes. As the terrestrial maps were over 10 years old, we checked the younger stands during recent field visits.

2.3 Segmentation and height classification

Our method for assessing forest structure combines object-based multi-resolution segmentation and GIS analyses. In a first step the existing forest mask from the forest management plan (Maier et al. 2005) was incorporated in eCognition in order to create a binary forest mask for all subsequent segmentations. The software eCognition normally uses a bottom-up region merging technique starting with randomly selected one-cell objects. In an iterative process smaller objects are merged into larger ones. This continues until the objects reach a maximum allowed heterogeneity which is determined by the "scale" parameter and is set by the user. While the scale parameter determines the size of the objects, the homogeneity criteria colour, smoothness and compactness influence the object's spectral homogeneity and spatial complexity (Benz et al. 2004).

Within the forest mask, two separate multi-resolution segmentations were carried out. The first segmentation aimed at delineating single tree crowns and collectives of tree crowns. The objects represented homogenous tree height patches. Attempts to incorporate different morphometric derivatives such as slope and curvature of the nCM in the segmentation process did not improve the results. Thus the nCM served as the only input for segmentation. As any single tree crown comprises different height classes, small scale factors (i.e. small segments) led to onion-like circular patterns or objects which included only parts of a crown. A big scale factor, however, levelled out the tree heights and resulted in a loss of structural complexity. In order to find the adequate segmentation parameters, the segmentation results were visually inspected. The parameter sets given in Table 1 appeared to be appropriate.

Forest stands were automatically delineated by using a second segmentation (level 2). This segmentation was created independently from level 1, to avoid strict object hierarchy between the two levels. Level 2 used the nCM, but also terrain features such as slope gradient and aspect, because they strongly influence forest growth and the development in such relief-rich environments (see Table 1). We assumed that forest stands are largely homogenous in terms of age, species and developmental stage and represented similar physiographical conditions. Objects of both levels were exported into a GIS for further processing.

Segmentation for crowns			
images layer weights		parameter settings	
nCM	1	scale parameter	10
		shape	0.5
		compactness	0.5
Segmentation for stands			
images layer weights		parameter settings	
nCM	1,0	scale parameter	110
aspect	0,1	shape	0.4
slope	0,2	compactness	0.5

Table 1. Segmentation parameters for stands and crowns

Level 2 stand objects served as a basic aggregation level for stand structure assessment. Level 1 segments were classified into four height classes which were subsequently dissolved into homogenous height class patches and overlaid with level 2 stand objects (see Figure 3). The resulting patch-structure of each stand was then described by different landscape metrics and indices.

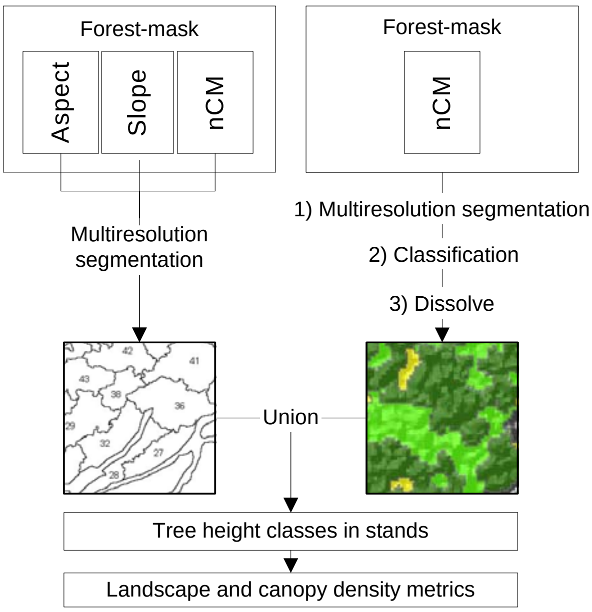

Figure 3. Flow diagram of the used method.

Figure 4 presents the height classification schema. It follows the different forest developmental stages defined in the Manual for the Aerial Photo Interpretation within the Swiss Forest Inventory (Ginzler et al., 2005). Height class 0 comprises all segments with a mean vegetation height below 3m. Those are regarded as unstocked as the differentiation accuracy of the laser allows no distinction between surface roughness (lying dead wood, rocks, stumps or low vegetation) and young trees. Height class 1 (3-8m) includes young trees. Height class 2 covers the range from 8-20m and contains mainly pole forests and timber forest. Height class 3 consists of tree crowns higher than 20m which are usually thicker trees or old growth forest.

2.4 Landscape metrics calculation

Landscape metrics act as a quantitative link between landscape structure and ecological or environmental processes. They can usually be derived for one of three levels: 1) patch level defined for individual polygons, 2) class level, i.e., characteristics of all patches of the same type and 3) landscape level which integrates all patch types or classes across the extent of the data). For some applications a fourth level, the region level, is introduced (cp Rempel 2003). This level indicates a sub-area of the landscape. If we translate the landscape metrics nomenclature into the forest structure context of this study, landscape refers to the whole forest, region refers to stand, class to tree height class and patch to tree height patch.

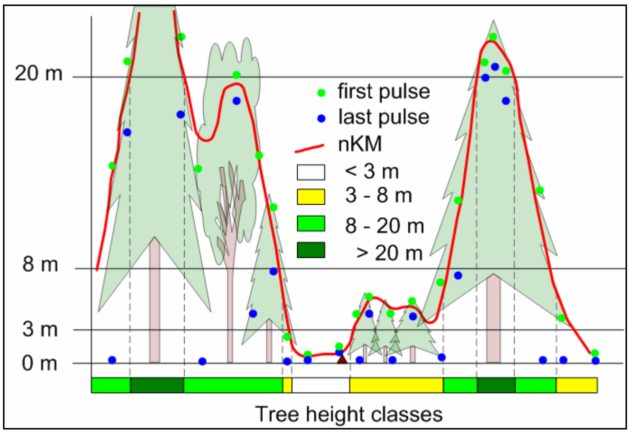

Figure 4. Tree height classification schema

There exists a plethora of different landscape metrics. Riitters et al. (1995) suggest using fewer, not more, indices, because many of them are highly correlated. Since we aimed for a simple, easily transferable and interpretable structure assessment approach, we applied only two metrics combined with canopy density values to describe structure types. The Shannon Evenness Index (SHEI), which is a diversity metric, refers to the distribution of area between the different height classes within a stand. A stand in which the height classes are fairly equally distributed is considered much more “even” than one in which a single height class dominates. In that sense evenness is the complement of dominance.

$$SHEI = \frac{-\sum_{i=1}^{m} (P_i * \ln P_i)}{\ln m} \tag{1}$$

where P_i = proportion of the stand occupied by height class i
m = number of height classes present in the stand

In order to assess the spatial distribution of height class patches, we calculated the Division Index (DIVI). The DIVI is defined as the probability that two randomly selected locations do not occur within the same patch in the forest (Jaeger 2000). Although this index is ecologically motivated by the likeliness that two organisms will meet within the same patch, it can also refer to the gappiness of a forest stand. To strengthen its focus on the aspect of gappiness, DIVI was only calculated for height class 0 (unstocked).

$$Division = 1 - \sum_{i=1}^{n} \left(\frac{a_i}{A} \right)^2 \tag{2}$$

where a_i = area (m²) of patch i
A = here: total area of height class 0 in one stand

Basically, mountain forest structure can be described by a combination of canopy density in different height classes and crown closure. Canopy density is defined as the percentage of the area which is covered by tree crowns. Expressed in terms of patches and classes it corresponds to the total patch area of each height class in percent of the whole stand. Canopy closure, however, describes the way tree crowns touch each other (dense, closed, light or open). Bebi (1999) defined six structure types which he tried to automatically delineate by means of aerial photographs. We calculated canopy density metrics for each height class per stand and tried to express these discrete structure types using the above mentioned metrics and canopy density values.

3. RESULTS

3.1 Landscape metrics

The results of the Shannon Evenness Index (SHEI) are given in Figure 5. SHEI differentiates between evenly distributed height classes (dark blue) and those dominated by only one or two height classes (light blue to green). The majority of the stands show rather evenly distributed height structures. SHEI does not differentiate between the open or dense crown closure. For example, the open stand #57 at the tree line and the dense homogenous stand #27 (young growth) and #30 (near the valley floor) show similar index values. The broadleaved and mixed forests in the northwestern part of the study area also appear uniform in height. This is due to the fact that the area was scanned during leaf-off season reflecting predominantly the terrain and not tree crowns.

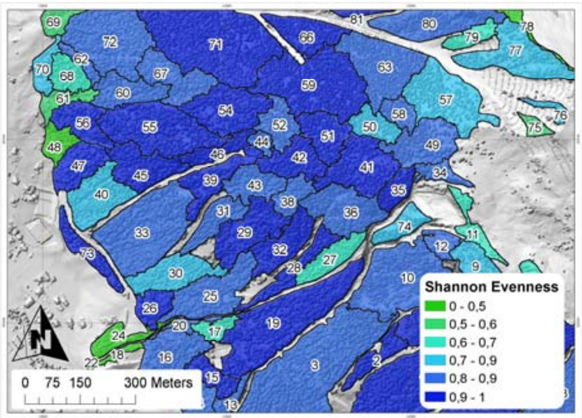

Figure 5. Distribution of Shannon Evenness Index

The division index calculated on height class 0 (unstocked) very well identifies the stands with prevailing open or light crown closure (values below 0.25). As shown in Figure 6, open structures dominate in the uppermost parts close to the tree line as well as near the valley floor (stands in light blue and green). The latter represent the mixed and broadleaved stands which appear open due to the lack of crown reflection in the leaf-off season. The forests in the central part of the study area exhibit light and open structures due to the numerous rock fall channels just below the massive rock faces in that area. The open structures indicated in the upper parts correspond to the gappy mosaic typical for high altitude forests.

3.2 Discrete structure types

Figure 7 illustrates the six structure types defined by Bebi (1999) with examples taken from the height class map of the study area. Bebi (1999) used an elaborate binary classification schema based on canopy density, crown closure and other structural variables, such as percentage of trees in clusters or long-crowned trees. Applying his classification rules solely based on canopy density values to our data, allowed us to only classify 27% of all the stands in the study area. Uniform stands were particularly difficult to identify by these rules.

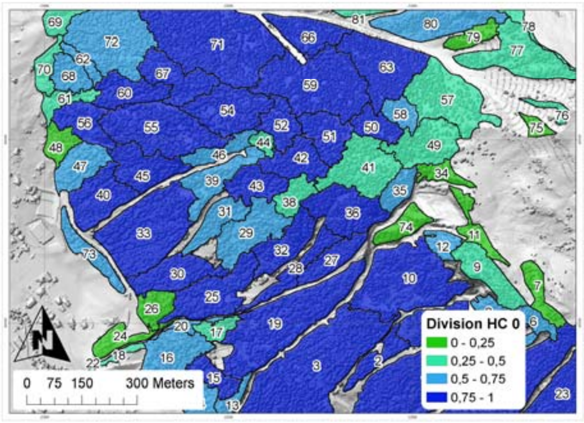

Figure 6. Distribution of Division Index

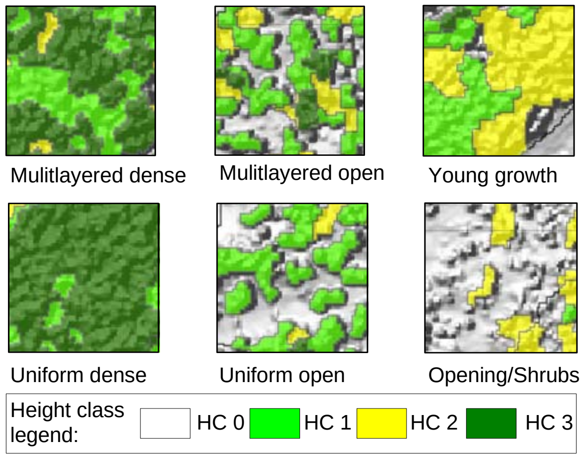

Figure 7. Discrete structure types examples

Rule set	Structure type	No. of Stands	Area in %
HC1 > 50%	Young growth	0	0
Division Index >= 0.75; HC2 or HC3 > 50% or two HC with > 30%	uniform dense	18	36
Division Index <= 0.75; HC2 or HC3 > 50% or two HC with > 30%	uniform open	11	9
Division Index >= 0.75; no HC > 50% and not two other HC with > 30% and CD > 20%	multilayered dense	14	27
Division Index <= 0.75; no HC > 50% and not two other HC with > 30% and CD > 20%	multilayered open	29	26
CD < 20%	opening	6	2
Total		**78**	**100**

Table 2. Modified classification rules and resulting structure types (HCx = canopy density of height class x; CD = overall canopy density)

We modified the classification rules and deployed canopy density values in each height class as a measure for the layering of the forest and used the DIVI as a measure of crown closure. A DIVI threshold value of 0.75 distinguished between open and dense. Uniform stands had either one height class with more than 50% canopy density or two classes with more than 30% each. Openings were defined by an overall canopy density below 20% which only occurred in the mixed and broadleaved stands due to the misleading leaf-off effect. Only stand #27 could be regarded as young growth, but it was not classified as such because its canopy density is just below the threshold of 50%. The complete classification rules and results are given in Table 2.

According to Figure 8 and Table 2, 53% of the study area is covered by multilayered stands which predominate the upper part of the study area. An expert-based validation with terrestrially mapped structure types revealed that 69 of 78 stands were correctly classified. This corresponds to 85% of the area.

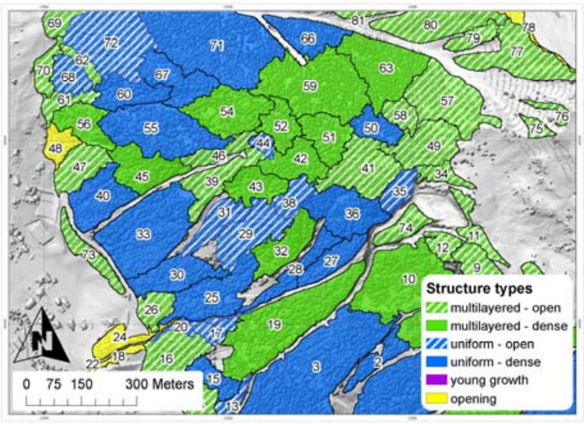

Figure 8. Distribution of discrete structure types

4. DISCUSSION AND CONCLUSIONS

4.1 Landscape metrics and structure typology

Our object-based image analysis approach for assessing mountain forest structure has highlighted a number of valuable aspects as to how a discrete typology can be expressed by landscape metrics and the degree to which they are able to quantify forest structure. Although the SHEI proved useful for pointing out homogenous stands, its capability to differentiate between multilayered and uniform stands was limited. This might be due to the narrow range of index values of most stands. It was not possible to find an adequate threshold between a SHEI of 0.7 - 0.9 that reflected the structural differences seen in the visual validation comparison. Further analysis showed that canopy density values of each height class could be used instead to separate multilayered from uniform forest stands. Canopy density of different tree heights allowed us to quantify the vertical diversity or layering of a stand. The DIVI calculated on height class 0 proved to be sufficient to describe the spatial arrangement of patches. It was highly correlated with the gappiness of a forest and could distinguish between closed/dense and light/open structures. The advantage of structure assessment using DIVI and canopy density values is that it can be carried out with only two automatically derived variables in a transparent and easily repeatable way.

This study also shows that the structure typology based on photo-interpretation, developed by Bebi (1999), cannot directly be adopted for ALS data. One reason is that Bebi used a different height classification schema which is based on relative height limits of the lower, middle and upper storeys. Each of the three height storeys refers to one third of the top height of a stand. Applying this classification schema would reduce the error of misclassification according to Bebi´s typology. At the same time it would make comparisons between stands much more complex and difficult to interpret. With stereoscopic photo interpretation the interpreter can see understorey layers even when they are covered by higher trees. This is not the case with already interpolated ALS surfaces as used in this study. This type of height classification allows only one class at a given point which is an abstraction of the conditions in a real forest. In order to overcome that, one would have to work with ALS-raw data.

4.2 Scale and bias

If the goal of the analysis is to relate the structure of a forest to its ability to provide viable protection against natural hazards, one needs to know at what scale the analysis should be performed. Selection of scale still remains one of the key requirements for spatial analyses of forest heterogeneity, because the spatial variation to be detected depends on the scale of observation. For implementing a strict single tree level, the 1m × 1m resolution of the data available seems to be too low. In the context of natural hazards and protection forests tree groups better reflect the spatial arrangement with regard to stand stability. The scale parameter setting in the course of the segmentation determines the size of the objects. In order to assess scale dependency of the SHEI, we compared the index calculations carried out on two different segmentations, one with scale factor 5 and one with scale factor 10. Results reveal only minor changes. Only 15.3% of the study area shows a change in SHEI values. In 14 of 78 stands the SHEI indicated an increase of evenness and in 3 of 78 stands SHEI indicated a decrease of evenness. This suggests that the SHEI is not strongly affected by object size. Such scale dependency tests need to be conducted for the other metrics as well.

4.3 Practical applicability and future research

Generally, such an automatic approach works particularly well in spruce-dominated mountain forests, as conifers possess well-shaped crowns and the forests are usually open and the top layer of trees is not closed. The advantage of an automatic object-based approach is that it supports delineation of boundaries using underlying data such as DTM derivatives. Conventional methods do not offer this facility. Automated structure assessment can be used in the course of protection forest planning, management and monitoring. Such an approach will and should not replace detailed field investigations, but it will help to assess structure in an area-extensive and efficient manner.

Future research will have focus on the development of more elaborate structure types. Different static and dynamic height classification schema should also be tested. Furthermore, it might be helpful to include local maxima detection to explicitly consider tree clusters as structure types and as stability features. In order to quantitatively assess the performance of such an approach, comparisons with existing structure typologies on a larger scale should be conducted.

With the approach, resource and natural hazard managers can easily assess the structure of different forests or the same forest at different times or under different management alternatives. In the light of increasing pressure to consider the protective effect of forests in natural hazard management, this forest structure assessment approach can be considered a highly valuable contribution.

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