Chapter 7.2

Characterising mountain forest structure using landscape metrics on LiDAR-based canopy surface models

B. Maier[1,]*, D. Tiede[2], L. Dorren[3]

[1] Stand Montafon Forstfonds, Montafonerstr. 21, 6780 Schruns, Austria, bernhard.maier@stand-montafon.at

[2] Salzburg University, Centre for Geoinformatics, Hellbrunnerstr. 34, 5020 Salzburg, Austria, dirk.tiede@sbg.ac.at

[3] Cemagref Grenoble, 2 rue de la Papeterie, BP76, 38402 St. Martin d`Heres cedex, France, luuk.dorren@cemagref.fr

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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. LiDAR (Light Detection And Ranging) offers new ways for describing forest structure in 3D. However, mountain forest structures are complex and creative methods are therefore needed to extract reliable structural information from LiDAR. The objective of this study was to investigate if the application of landscape metrics to a normalised canopy model (nCM) allows an automatic characterisation of forest structure. We used a generic automated approach that created height class patches based on a segmented nCM. Two multi-resolution segmentations were carried

* Corresponding author

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 subsequently overlaid with level 2 stands in order to calculate the metrics 1) canopy density and vertical layering of the forest, 2) forest gap distribution and 3) canopy roughness using the Division Index (DIVI). Canopy density values of each height class allowed the classification of the vertical layering. Distinguishing between single- and multi-layered stands, 82% of all the sample plots were correctly classified. The DIVI calculated on gaps proved to be sufficient to describe the spatial arrangement of patches and distinguish between stands with many small gaps from stands with only a few but larger gaps. Canopy roughness could not satisfactorily be described using the DIVI based on the validation plots. With the approach presented, resource and natural hazard managers can assess the structure of forest stands and as such more easily 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 characterised by the horizontal distribution 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 and resilience after disturbances such as storm and snow loads (Brang 2001). Other characteristics that determine structure are crown closure and tree density. These directly influence release probability of forest avalanches and the capacity to stop falling rocks (Dorren et al. 2005). Consequently, assessing forest structure enables forest managers and natural risk engineers to evaluate if 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 and 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 im mountainous terrain is hampered by different illumination and shading effects. Small footprint airborne LiDAR, however, allows deriving detailed digital terrain (DTM) and surface (DSM) models. Subtracting these two models of a forested area results in a so-called normalised canopy model (nCM), which is spatially continuous and not hampered by shading effects - typical for optical remote sensing data. This facilitates assessing forest structure in 2.5D. 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 LiDAR data (Hyyppä et al. 2006, Hall et al. 2005, Naesset 2004, Maltamo et al. 2004, Tiede et al. 2004, Lim et al. 2003). Some studies focus on tree height variance as an indicator of vertical forest structure (Blaschke et al. 2004, Zimble et al. 2003). Until now, little attention, however, has been paid to the application of landscape metrics to LiDAR-based canopy surface models.

Landscape metrics, representing a view "from above", allow quantifying the link between landscape structure and function. Usually, they are derived for the following three levels: 1) the patch level which corresponds to individual objects, 2) the 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. 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. The use of landscape metrics within forests mainly focuses on forest fragmentation and biodiversity, and their changes over time (Traub & Klein 1996, Venema et al. 2005).

In this study, landscape metrics are used for another purpose, namely to describe fragmentation of the canopy surface height in terms of variability or structuring. Landscape metrics are expected to link forest structure with the protective capacity of a mountain forest. The general idea is that the use of landscape metrics leads to more objective, transparent and repeatable results compared to visual interpretation by a human interpreter. Our overall goal is to derive stand structure information as a basis for protection forest planning, management and monitoring. Therefore, the objective of this study was to investigate if the application of landscape metrics to a nCM allows an automatic characterisation of forest structure.

2 Study area and data

2.1 Study area

The study area covers 120 ha of spruce-dominated protection forest on a west facing slope near the Austrian village of Gaschurn in the Montafon valley (see Fig. 1). This forest provides essential protection against natural hazards such as landslides, avalanches and rockfall. The study area ranges from 1000 m altitude in the valley floor up to 1800 m at the tree line. The study area is dominated by steep rugged terrain with rock faces, gullies and torrents. Old-growth forests with different structure types dominate. The structural differences are due to various factors. Multi-layered structures with short-distance height variation in the canopy, so called fine-grained canopy patterns, grow on shallow soils that cover glacially eroded bed-rock.

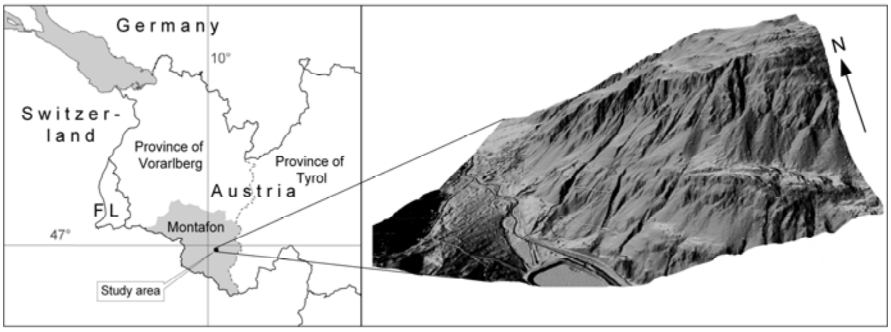


Fig. 1. Location (left) and DTM of the study area viewed from Southwest (right)

Homogenous pole stands occur in areas that used to be meadows in the lower parts of the slope. Open structures caused by windthrow are found below the rock faces in the southeastern part of the study area. Another type of open structures is found close to the tree line. These, however, consist of tree clusters (collectives), which are typical for high altitude forests. Along the avalanche tracks, tree regeneration and young stands can be found. The presence of all these 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) produced by Optech Inc. (Canada). The pulse repetition frequency of the ALTM is 25 kHz that resulted in a point density of 0.9 points m^{-2} at an average flight height of 1000 m above ground level. With a laser beam divergence of 0.3 mrad, the theoretical footprint on the ground was about 0.30 m. The average ground swath width was about 725 m, the maximum scanning angle 20º (Wagner et al. 2004).

The data obtained by the ALTM have been processed and interpolated by the TU Vienna using the *hierarchical robust filtering* approach within the SCOP++ software package (Kraus and Pfeifer 1998). As a result a DTM and a DSM, both with a resolution of 1 m × 1 m, were created. By subtracting the DTM from the DSM we obtained a nCM which describes an estimate of the forest height.

Thirty-three circular inventory plots of 314 m² served for validation. Within these plots, we recorded for each tree: diameter at breast height (1.3 m), position (azimuth and distance), height and species. In addition, we determined the vertical layering and the stand type following Maier (2007a).

3 Methodology and Implementation

3.1 Segmentation and height classification

Our method combines object-based multi-resolution segmentation and classification with GIS analyses. The rule sets for segmentation and classification are developed using CNL (Cognition Network Language), a modular programming environment available in the Definiens Developer environment. Segmentation is done using a region-based, local mutual best fitting segmentation approach. It is a pair-wise clustering process, starting with randomly selected one-cell objects. In an iterative process these objects are merged into larger ones. This segmentation process is determined by three parameters which can be set by the user. The first one is *scale* which is a stop criterion for the object growing process and thus defines the maximum segment, or object size. The other two parameters *shape (vs. colour)* and *compactness (vs. smoothness)* define the weights for the allowed heterogeneity of image values (here: height values) and shape complexity (Baatz and Schäpe 2002, Benz et al. 2004).

Segmentation was used to create two object levels which corresponded to 1) single and clustered tree crowns and to 2) forest stands. To delineate single and clustered (collectives) tree crowns the nCM was segmented into objects using a scale parameter of 5. The ancillary parameters *shape* and *compactness* were both set to 0.5. Since single tree crowns comprise different height classes, a small *scale* parameter led to onion-like concentric objects only representing parts of a tree crown. A big *scale* parameter, however, levelled out the different tree heights and resulted in a loss of structural complexity. Segmentation tests with known trees showed that a scale parameter of 5 was a good compromise. The resulting objects in this level represent homogenous tree height patches. These canopy objects were then classified according to their mean height using the height classification schema presented in Fig. 2.

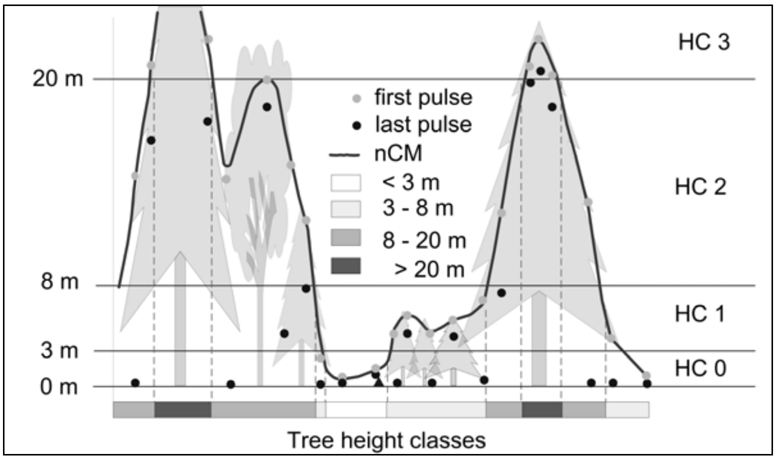


Fig. 2. Tree height classification schema

The height classification schema follows the different forest development stages that are defined in the Manual for the Aerial Photo Interpretation of the Swiss Forest Inventory (Ginzler et al. 2005). Four height classes (HC) are introduced: HC 0 comprises all segments with a mean vegetation height below 3 m. 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. HC 1 (3-8 m) corresponds to young trees and HC 2 covers the range from 8-20 m. This class contains mainly pole forests and timber forest. HC 3 consists of tree crowns higher than 20 m, which are usually thicker trees, or old growth forest. The classified objects were subsequently dissolved into homogenous height class patches and exported into a GIS readable vector format (Polygon Shape file).

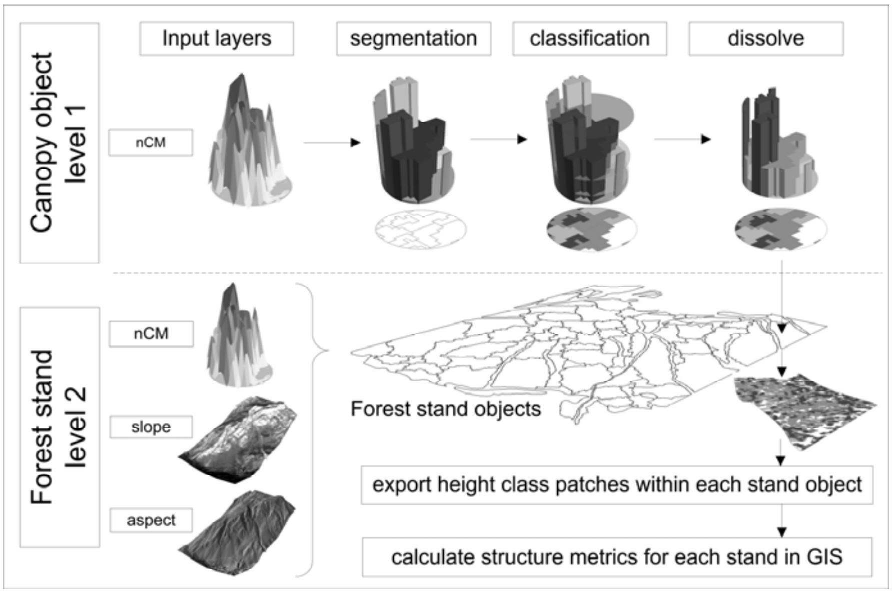


Fig. 3. Flow diagram of study methodology

To delineate forest stands, input rasters were segmented into objects using a *scale* parameter of 100, as well as a *shape* and *compactness* parameter of 0.3 and 0.4 respectively. Because terrain features strongly influence forest growth and development in relief-rich mountainous terrain, the input rasters consisted of the nCM, but also the mean slope gradient, and the aspect. We assumed that forest stands are largely homogenous in terms of age, species distribution and developmental stage and that they reflect similar physiographical conditions. The segmentation weights of the three input rasters nCM, slope and aspect were set to 1, 0.5 and 0.5 respectively. The setting of the above mentioned parameters provided the forest stand map that respected best existing stand borders observed in the field and on CIR orthophotos.

Following the segmentation and classification, a GIS was used to characterise the patch-structure (level 1) within each stand object (level 2) using landscape metrics for canopy density, vertical layering, gap distribution and canopy roughness of a forest stand. All metrics were calculated with the V-late extension for ArcGIS (Lang and Tiede 2003). Fig. 3 summarises the complete method flow of this study.

3.2 Landscape metrics calculation

The structural characteristics considered relevant for this study were: canopy density and vertical layering of the forest, forest gap distribution and canopy roughness. In the following paragraphs their calculation using landscape metrics will be explained in detail.

3.2.1 Canopy density and vertical layering of the forest

Canopy density (CD) is defined as the percentage of the area which is occupied by the horizontal projection of tree crowns. Multiple coverage in super-imposed tree layers (height classes) is not taken into account (Keller 2005). The landscape metric we used for describing CD is called CD_{total} and corresponds to the total area of all stocked height patches of HC 1, 2 and 3, in percent of the total stand area. Maier (2007b) shows that there is a good correspondence ($R^2 = 0.7$) between canopy density measured in the field by mapping crown radius and the canopy density derived from LiDAR-based canopy models.

$$CD = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100) \qquad \text{(eq. 1)}$$

P_i = proportion [%] of the stand (without gaps) occupied by height class i

a_{ij} = area [m²] of patch ij

A = stand area [m²] without gaps (HC 0)

Vertical layering or stratification can be referred to as the vertical distribution of foliage (Parker and Brown 2000). When calculating CD for the three different HC (eq. 1, see McGarigal and Marks 1995), the vertical layering of the forest can be assessed. It is important to note that superimposed tree layers cannot be detected using a 2.5D nCM. Therefore, the layering assessment is restricted to the different height levels which can be seen from above. According to the Austrian Forest Inventory (AFI), a single-layered stand has only one distinct canopy layer. Two-layered structures have in addition to the dominant canopy layer a second layer, which exhibits considerable growth potential. Here, a separate forest layer needs to have a total CD of at least 30% (Schieler and Hauk 2001). According to the Swiss National Forest Inventory, single layered stands consist of one layer that covers more than 80%. Our rules for assessing the vertical layering were principally based on these guidelines, but adapted for an nCM-based analysis (Table 1).

Table 1. Rule set for vertical layering according to canopy density (CD) per height class (HC)

single-layered	one HC with CD > 60%, no other HC > 35%
two-layered	two HC with CD > 30% or one HC > 50% and one HC >20%
multi-layered	three HC with CD > 20%

For validation, we compared the vertical layering classification with the vertical structures recorded in the 33 field plots.

3.2.2 Forest gap distribution

Gaps are unstocked patches in a forest matrix. They can be formed by harvesting trees (silvicultural intervention), by natural succession or disturbances. When trees die, they create gaps that allow the sunlight reaching the ground, which could initiate forest regeneration. Windthrow, snow break and subsequent bark beetle infestations belong to the natural gap-making processes and disturbances. Small gaps are distinct and common features of mountain forests, and do not pose problems to the protective function of the forest against natural hazards. Large openings in the forest cover, however, do. They are potential avalanche release areas or can accelerate rockfall.

Therefore, the size and spatial distribution of gaps influence the protective capacity of a forest. The bigger and longer a gap is in the slope direction, the more likely forest avalanche release or falling rocks acceleration is. Gap length can be calculated by defining the longest flow path in slope direction. These values can then be compared with existing protection forest management guidelines (e.g. Frehner et al. 2005) in order to assess the need for silvicultural intervention or tending.

$$DIVI_{HC0} = 1 - \sum_{i=1}^{n} \left(\frac{a_i}{A} \right)^2 \qquad \text{(eq. 2)}$$

where a_i = area [m²] of gap patch i
A = here: total area [m²] of gaps in one stand (HC 0)

In order to assess the spatial distribution of gaps, we calculated the Division Index (DIVI, see eq. 2). 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 originates from ecology where it refers to the likeliness that two organisms will meet within the same patch, it can also refer to the degree of gap fragmentation, or "gappiness" of a forest stand. In other words, it expresses if gaps occur as single big unstocked areas or highly fragmented small gaps throughout the stand.

3.2.3 Canopy roughness

Finally, we tried to quantify the graininess or roughness of the forest canopy by measuring the overall fragmentation of all height classes and interpret it as a degree of structuring. This is done by calculating the Division Index on all height classes on a stand level (eq. 3). This measure of fragmentation describes if the canopy is vertically homogenous or heterogeneously structured, following McGarigal and Marks (1995), who used this index to differentiate between coarse- and fine-grained landscape structures. Within the conventional repertoire of forest inventory parameters, the parameter *StandType* (Schieler and Hauk 2001) which defines uniform, irregular and single tree structures (see Table 2) appeared the only one to represent canopy roughness (CR) as a structural parameter.

$$DIVI = 1 - \sum_{i=1}^{n} \left(\frac{a_i}{A} \right)^2 \qquad \text{(eq. 3)}$$

where a_i = area [m²] of patch i
A = here: total area [m²] of stand

Table 2. Definition of stand type according to the Austrian Forest Inventory (Schieler and Hauk 2001)

Uniform	Homogenous, more or less closed canopy with uniformly distributed trees or tree groups
Irregluar	Stands consisting of tree groups of similar height with a distinct green mantle forming inner forest edges
Single trees	Dissolved stand structure with single trees and a canopy density below 30%; trees loosely distributed over the whole area

4 Results

4.1 Canopy density and vertical layering

Canopy density results are given in Fig. 4. The stands with prevailing open or light canopy density dominate in the uppermost parts close to the tree line as well as near the valley floor (stands with CD_{total} < 60%).

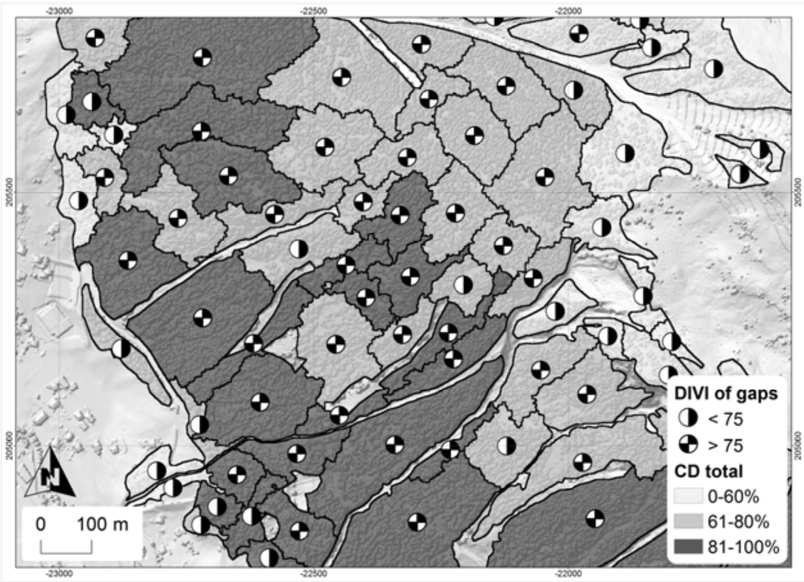


Fig. 4. Canopy density (CD_{total}) and division index (DIVI) of gaps

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 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 a mosaic with gaps typical for high altitude forests.

Results of the layering assessment show that the homogenous pole stands in the lower part of the study area are classified as single and two-layered forests. Multi-layered structures, however, can be found in sporadic stands mainly along and in between the avalanche tracks. A comparison of the automatic layering-classification with the assessment carried out in the field results in 73% correct detections. This number increases to 82% if two- and multi-layered structures are put together into one category. Most mismatches can be found in the high-altitude forests with tree clusters. Whilst they appear multi-layered in the field, their vertical variation falls within one height class during automatic classification. Half of the false detected sample plots are characterised by low CD values. Fig. 6 shows six examples of validation plots with layering assessments and different CD_{total}.

4.2 Gap distribution

The Division Index (DIVI) calculated on gaps (HC 0) quantifies the distribution of gaps within a stand. In order to get an idea of the total size of the unstocked area, it is necessary to combine the DIVI with the total canopy density (CD_{total}). As shown in Fig. 4 this combination very well distinguishes stands with many small gaps from others with a few large openings. In the central part of the study area a stand with a large windthrow opening is characterised by a low CD_{total} and a DIVI below 75, indicating low fragmentation. The forest stands in the northwestern part exhibit DIVI-values above 75 describing a high degree of fragmentation meaning that the unstocked area is divided into numerous small gaps.

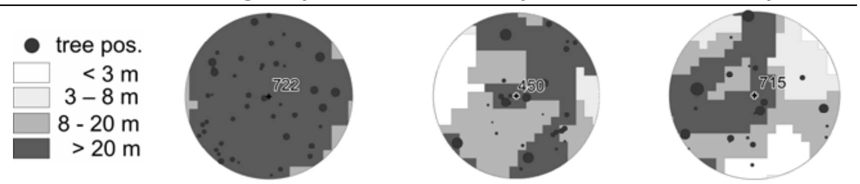
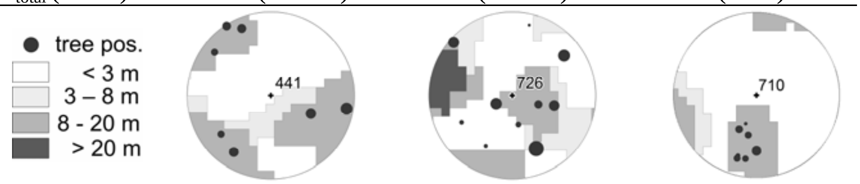
CD	Single-layered	Two-layered	Multi-layered
			
CD_{total} (valid.)	100% (correct)	87% (correct)	87% (false)
			
CD_{total} (valid.)	48% (false)	49% (false)	27% (false)

Fig. 5 Selected field validation plots (radius = 10 m) with layering and CD_{total}

The DIVI-threshold of 75 is deduced from a series of gap fragmentation patterns shown in Fig. 6. These DIVI-values are calculated on a basic gap share of 30% with increasing fragmentation.

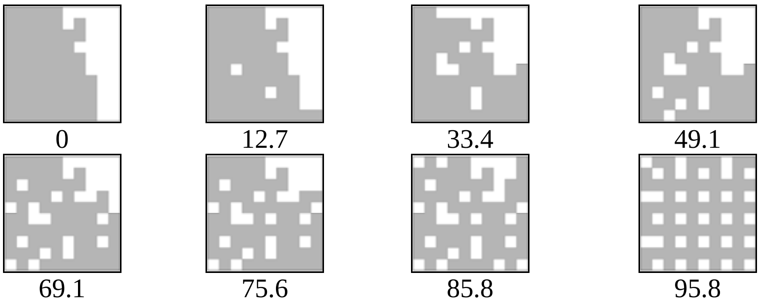


Fig. 6 Series of gap fragmentation patterns indicating the range of the Division Index (DIVI)

4.3 Canopy roughness

We regard the overall fragmentation of the height class patch mosaic as a measure for structural variability, including both the vertical as well as the horizontal structural view. Fig. 7 presents the distribution of DIVI values among the *StandType* attributes. According to a mean comparison Scheffé test (Bahrenberg et al. 1992) categories “uniform” and “irregular” are significantly different from each other (p=0.05). The category “single trees” does not significantly differ from the other two categories which may be due to the low number of samples in that class (see Fig. 7).

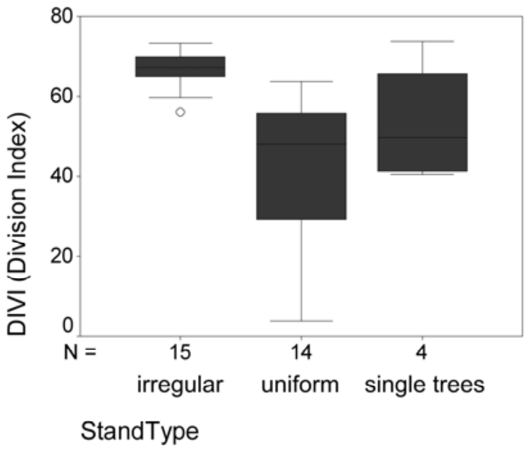


Fig. 7. Distribution of DIVI values among *StandType* categories

According to Fig. 7 we define the threshold between uniform and irregular stands at a DIVI value of 65. Using this threshold, only the open structured stands close to the tree line and the stands near the valley floor can be classified as uniform. All together only 1.5% of all stands can be classified uniform, the rest is irregularly structured.

5 Discussion

The objective of this study was to investigate if the use of landscape metrics on height class patches of the nCM allows an automatic characterisation of forest structure. For that purpose we segmented and classified the nCM and transformed it from a continuous raster surface into a polygon mosaic of vegetation height patches. This segmentation was done at the level of tree crowns and tree groups (level 1) and proved to be a straightforward way to simplify the complex canopy surface. 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 that segmentation.

The segmentation of forest stands (level 2) turned out to be more difficult. It was difficult to balance the three segmentation parameters in a way that the size and shape of the resulting stand objects correlated to natural stand borders which might have appeared obvious to an expert when visually inspecting the nCM. Many stand borders looked fissured or indented, but as soon as the compactness factor was increased, narrow elongated stands (e.g. regeneration along the avalanche tracks) were dissected. Due to the iterative process the eventual parameter setting of stand segmentation must be regarded as a specific adaptation for the study area. Therefore this segmentation setting cannot be transferred to other areas.

The study showed that the automatic detection of the vertical layering corresponded fairly well with assessments in the field. If distinguishing between single- and multi-layered stands only, 82% of all the sample plots were correctly classified. Zimble et al. (2003) reached 97% correspondence between field- and LiDAR-based classification. This might be due to the fact, that they used a method based on tree-height variability and applied it to forests with canopy closures less than 60%.

As we worked with an already interpolated canopy surface model (2.5D), it was not possible to detect a forest layer which is completely covered by an dominant crown level. But because of the distinct structural characteristics of mountain forests, this restriction did not really hamper vertical layering assessment. Usually, mountain forests exhibit a relatively open canopy and have almost no regeneration below dense layers (Ott et al. 1997). Furthermore, mountain forests are layered in tree groups, e.g. a mixture of groups with large trees and gaps filled by smaller trees. These characteristics of subalpine forersts together with the high resolution of the nCM allowed the use of already interpolated surfaces to quantify the vertical layering.

Since the perception of layering strongly depends on the scale of consideration (Parker and Brown 2000), we used forest stands as the level for detecting the vertical layering. This study showed that assessing the layering on plots with 10 m radius is possible but becomes problematic as soon as CD is very low. It turned out that the layering typology used in field inventories cannot directly be adopted to a LiDAR-nCM. The high resolution nCM we used made all the small gaps visible, which generally could not be distinguished so clearly in the field. This is why we used lower CD thresholds in our rule set for the vertical layering than suggested for field inventories.

Layering assessment very much depends on the height classification schema applied. We applied a discrete schema following the Manual for the Aerial Photo Interpretation within the Swiss Forest Inventory because it is suitable for remote-sensing based datasets and is related to practical forest management. The basic threshold of 3 m e.g. corresponds to a tree height, above which trees are regarded more stable against natural hazards and ungulate browsing. As an alternative, a height classification schema based on relative height limits for the lower, middle and upper storeys could be used. In such a schema each of the three height storeys referred to one third of the top height of a stand. By applying such a classification schema we would be able to accomodate different site and growth conditions, but at the same time it would make comparisons between stands much more complex and difficult to interpret.

The results of the study showed that forest gaps could easily be detected by means of a segmented nCM. The DIVI calculated on patches with HC 0 proved to be sufficient to describe the spatial arrangement of gaps. It was highly correlated with the distribution of gaps and helped to distinguish between stands with many small gaps and stands with only a few but larger gaps. Gap structure and distribution changes during the transition from mature to old-growth stands (Lertzmann et al. 1996). Old-growth forests are usually dominated by many small gaps and mature forests by fewer larger gaps. Generally, this developmental gap-sequence also occurs in mountain forests but is enforced by natural disturbances and the altitudinal gradient. Windthrow is the main gap-forming disturbance in mature and old-growth forests. Snowbreak mainly occurs in young pole stands. Generally, windthrow forms larger openings and snowbreak smaller gaps Gaps from both disturbances were correctly detected in the study area. Whereas in low-altitude forests gaps occur as holes in a matrix of forest, this phenomenon reverses in high-altitude forests, where forest patches become islands in a matrix of gaps. This was also reflected in our results given in Fig. 4.

Enhancing structural diversity in mountain forests is widely recognised as a general objective of silvicultural interventions aiming at higher resistance and resilience to natural disturbances (Ott et al. 1997). In order to quantify this structural diversity or canopy roughness we used the overall DIVI on all height classes to describe if the canopy is vertically homogenous or heterogeneously structured. Whereas the concept of forest fragmentation usually implies the breakup of contiguous forest habitats by the development of settlements, roads and clearings, we were interested in the fragmentation of the nCM in terms of height variability or structuring. Within the validation plots the DIVI yielded statistically significant distinctions between uniform and irregular canopy structures. But using this threshold to distinguish between uniform and irregular types on the stand level led to almost exclusively irregular stands which did not reflect the structural reality. This might be due to the fact that the validation plots are too small to derive a suitable DIVI-threshold for stands that are on average 50 times larger than the validation plots. One would need much larger validation plots to overcome this problem.

6 Conclusions

Our object-based image analysis approach for assessing mountain forest structure confirmed the capacity of landscape metrics applied on a nCM to quantify forest structure. The selected metrics offered useful assessments of the canopy density and vertical layering as well as gap distribution and isolation. Canopy roughness could not satisfactorily be described using the DIVI based on the validation plots.

The advantage of structure assessment using landscape metrics is that it can be carried out in a transparent and easily repeatable way. But the metrics need to be calibrated with field assessments in order to link their values with local situations. Generally, this 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. 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 to focus on testing different static and dynamic height classification schema. Furthermore, it might be helpful to include local maxima detection to explicitly consider tree clusters as structure types and stability features. In order to quantitatively assess the performance of such an approach, further calibration with existing structure assessments on a larger scale should be conducted. To assess scale dependency of the various metrics, corresponding sensitivity tests should be conducted prior to further application.

With this 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 pay attention to the protective effect of forests in natural hazard management, this forest structure assessment approach can be considered a highly valuable contribution.

References

Baatz M and Schäpe A (2000) Multiresolution segmentation—an optimization approach for high quality multi-scale image segmentation. In: Strobl J, Blaschke T, Griesebner, G. (Eds) Angewandte Geographische Informationsverarbeitung XII. Beiträge zum AGIT-Symposium Salzburg 2000, Herbert Wichmann Verlag, Kahrlsruhe, pp. 12–23.

Bahrenberg G, Giese E, Nipper J (1992) Statistische Methoden in der Geographie. Band 2 Multivariate Statistik. B.G. Teubner Stuttgart.

Bebi P (1999) Strukturen im Gebirgswald als Beurteilungsgrundlage ausgewählter Waldwirkungen. Dissertation ETH-Zürich, 125 pp.

Benz UC, Hofmann P, Willhauk G, Lingenfelder I, Heynen M (2004) Multiresolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. ISPRS Journal of Photogrammetry & Remote Sensing 58, pp. 239-258.

Blaschke T, Tiede, D and Heurich M (2004) 3D landscape metrics to modelling forest structue and diversity based on laser scanning data. In: The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XXXVI-8/W2, Freiburg, pp. 129-132.

Brang P (2001) Resistance and elasticity: the management of protection forests, Forest Ecology and Management 145, pp. 107–117.

Dorren LKA, Berger F, Imeson A, Maier B and Rey F (2004) Integrity, stability and management of protection forests in the European Alps. Forest Ecology and Management 195, pp. 165-176.

Dorren LKA, Berger F, Le Hir C, Mermin E, Tardif P (2005) Mechanisms, effects and management implications of rockfall in forests. Forest Ecology and Management. 215, 1–3, pp 183–195.

Frehner M, Wasser B and Schwitter R (2005) Nachhaltigkeit und Erfolgskontrolle im Schutzwald - Wegleitung für Pflegemassnahmen in Wäldern mit Schutzfunktion. BUWAL, Bundesamt für Umwelt, Wald und Landschaft, Bern.

Ginzler C, Bärtschi H, Bedolla A, Brassel P, Hägeli Hauser M, Kamphues H, Laranjeiro L, Mathys L, Uebersax D, Weber E, Wicki P, Zulliger D (2005) Luftbildinterpretation LFI3 – Interpretationsanleitung zum dritten Landesforestinventar. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL. Birmensdorf. 87 pp.

Hall SA, Burke IC, Box DO, Kaufmann MR and Stoker JM (2005) Estimating stand structure using discrete-return lidar: an example from low density, fire prone ponderosa pine forests. Forest Ecology and Management 208, pp. 189-209.

Herold A and Ulmer U (2001) Stand stability in the Swiss National Forest Inventory: assessment technique, reproducibility and relevance. Forest Ecology and Management 145, pp. 29-42.

Hyyppä J, Yu X, Hyyppä H and Maltamo M (2006) Methods of Airborne Laser Scanning for Forest Information Extraction. In: Koukal T and Schneider W (Eds.) Proceedings of International Workshop on 3D Remote Sensing in Forestry. Vienna, pp. 63-78.

Jaeger JAG (2000) Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landscape Ecology 15, pp. 115-130.

Keller M (Red) 2005 Schweizerisches Landesforstinventar. Anleitung für die Feldaufnahmen der Erhebung 2004-2007. Birmensdorf, Eidgenössische Forschungsanstalt WSL. 393 p.

Kraus K and Pfeifer N (1998) Determination of terrain models in wooded areas with airborne laser scanner data. ISPRS Journal of Photogrammetry & Remote Sensing 53, pp. 193-203.

Lang S and Tiede D (2003) vLATE Extension für ArcGIS – vektorbasiertes Tool zur quantitativen Landschaftsstrukturanalyse, ESRI Anwenderkonferenz 2003 Innsbruck. CDROM

Lertzmann KP, Sutherland GD, Inselberg, A, Saunders, SC (1996) Canopy gaps and the landscape mosaic in a coasteal temperate rain forest. Ecology 77(4) pp. 1254–1270.

Lim K, Treitz P, Wulder M, St-Onge B and Flood M (2003) LiDAR remote sensing of forest structure. Progress in Physical Geography 27, pp. 88-106.

Maier B (2007a) Zählen Messen Schätzen – Waldinventur im Standeswald. In: Malin H, Maier B, Dönz-Breuss M. (Ed.) Montafoner Standeswald – Beiträge zur Geschichte und Gegenwart eines kommunalen Forstbetriebes. Montafoner Schriftenreihe 18 pp. 43-66.

Maier B (2007b) Characterising Mountain Forest structure using Airborne Laser Scanning. Thesis. Department for Geography and Geology. Salzburg University

Maltamo H, Eerikäinen K, Pitkänen J, Hyyppä J and Vehmas M (2004) Estimation of timber volume and stem density based on scanning laser altimetry and expected tree size distribution functions. Remote Sensing of Environment 90, pp. 319-330.

McGarigal K and Marks BJ (1995) FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. USDA For. Serv. Gen. Tech. Rep. PNW-351.

Naesset E (2004) Practical Large-scale Forest Stand Inventory Using a Small-footprint Airborne Scanning Laser. Scandinavian Journal of Forest Research 19:164-179.

Ott E, Frehner M, Frey H-U, Lüscher P (1997) Gebirgsnadelwälder – Ein praxisorientierter Leitfaden für eine standortgerechte Waldbehandlung. Paul Haupt Bern.

Parker GG and Brown MJ (2000) Forest Canopy Stratification - is it Useful? The American Naturalist 155, pp. 473–484

Schieler K and Hauk E (2001) Instruktion für die Feldarbeit – Österreichische Waldinventur 2000/2002. Forstliche Bundesversuchsanstalt FBVA. Wien.

Schönenberger W (2001) Structure of mountain forests: Assessment, impacts, management, modelling. Forest Ecology and Management 145, pp. 1-2.

Tiede D, Heurich M and Blaschke T (2004) Object-based semi automatic mapping of forest stands with Laser scanner and Multi-spectral data. In: The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XXXVI-8W2, Freiburg, pp. 328-333.

Traub B, Klein Ch (1996) Quantitative Charakterisierung von Waldlfächenformen. Allg. Forst- u. J.-Ztg. 168(2), pp. 30-40.

Venema HD, Calamai PH, Fieguth P (2005) Forest structure optimization using evolutionalry programming and landscape ecology metrics. European Journal of Operational Research 164, pp. 423-439.

Wagner W, Eberhöfer C, Hollaus M, Summer G (2004) Robust Filtering of Airborne Laser Scanner Data for Vegetation Analysis, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. XXXVI (Part 8/W2), pp. 56-61.

Zimble DA, Evans DL, Carlson GC, Parker RC, Grado SC, Gerard PD (2003) Characterizing vertical forest structure using small-footprint airborne LiDAR. Remote Sensing of Environment 87, pp. 171-182.