3D FOREST STRUCTURE ANALYSIS FROM OPTICAL AND LIDAR DATA

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ABSTRACT

In Austria about half of the entire area (46 %) is covered by forests. The majority of these are highly managed and controlled in growth. But besides timber production forest ecosystems play a multifunctional role including climate control, habitat provision and, especially in Austria, protection of settlements. The interrelationships among climatic, ecological, social and economic dimensions of forests require technologies for monitoring both the state and the development of forests. This comprises forest structure, species and age composition and, forest integrity in general. Assessing forest structure for example enables forest managers and natural risk engineers to evaluate whether a forest can fulfil its protective function or not. Traditional methods for assessing forest structure like field inventories and aerial photo interpretation are intrinsically limited in providing spatially continuous information over a large area.

The Centre for Geoinformatics (Z_GIS) in collaboration with the National Park Bayerischer Wald, Germany and the Stand Montafon, Austria, has tested and applied advanced approaches of integrating multispectral optical data and airborne laser scanning (ALS) data for (1) forest stand delineation, (2) single tree detection and (3) forest structure analysis. As optical data we used RGBI line scanner data and CIR air-photos. ALS data were raw point data (10 pulses per sqm) and normalised crown models (nCM) at 0.5 m and 1 m resolution. (1) Automated stand delineation was done by (a) translating a key for manual mapping of forest development phases into a rule-based system via object-relationship modelling (ORM); and (b) by performing multi-resolution segmentation and GIS analysis. (2) Strategies for single tree detection using raw ALS data included (a) GIS modelling based on a region-growth local maxima algorithm and (b) object-based image analysis using super class information class-specific rule sets. (3) Vertical forest structure has been assessed statistically by (a) applying basic statistics (like mean, standard deviation, and variation coefficient) on the raw data using a moving window approach; and (b) by applying landscape metrics (Shannon Evenness Index, SHEI, and division index, DIVI) for different strata extracted from the nCM.

Key words: object-based image analysis, ALS data, GIS, forest monitoring, remote sensing

MOTIVATION

Forests in Austria: their economical and ecological meaning

Forests belong to the most widely spread natural resources in Central Europe, in Austria for instance about 46 % of the entire area are covered by forests. The majority of forest ecosystems in Austria (83 %) are highly managed and controlled in growth, as being a natural resource with high economic relevance. Unlike in other regions of the Earth, in most European countries including Austria clear cut harvesting is prohibited by law. (This applies for clear cuts larger than 3 ha, and even for clear cuts above 0.5 ha permission is required). Wood production and logging need to respect the principle of sustainable use, a concept dating back to European mercantilist states in the 18th century (Höltermann and Oesten, 2001). According to this code of use, the amount of harvested wood should never exceed the reproduction rate in a certain area.

Needless to say that forests being the vegetation type at the climax stage in Central Europe serve more than mere economic purposes. Man-environment interrelationships in this respect are multidimensional, meaning that forested areas play a multifunctional role. Forest functions include climate control (carbon dioxide sinks, ‘green lungs’), habitat provision (ecological niches and biodiversity pools in both living and dead woods), social welfare (recreation, education, health), and of course, timber production. Still, not only the latter has considerable economic aspects: climate control is nowadays considered an economic factor in itself (Kyoto protocol, trade of greenhouse gases), and the social aspect is a rich source for tourism (especially in near-natural regimes as in National Parks or nature reserves). Yet another function which indirectly contributes to the overall economic dimension is maybe less obvious from an international perspective. The protective function of forests which applies for 29 % of Austrian forests is a crucial one in mountainous, especially Alpine areas. Under conditions where steep slopes require settling in hazard-prone areas, the presence and maintenance of protection forests is essential for preserving settlements from avalanches, rock falls, landslides and the like. These forests are usually situated in rough terrain, and therefore hard to access. They are characterised by a comparatively large number of standing or laying dead wood (so-called biotope wood), which is usually about twice the amount as in economic forests.

Forest structure: assessment, mapping and monitoring

Forest structure can be characterized by the position of trees, the vertical layering and the tree species mixture. It is considered a key element to determine the protection capacity of mountain forests (Dorren et al. 2004). Assessing forest structure enables forest managers and natural risk engineers to evaluate whether a forest can fulfil its protective function or not. Crown closure and tree density for example, influence forest avalanche risk potential and the protective effect of a forest against rockfall. Reliable and area-extensive data on forest structure is 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 of this kind is that they cannot provide spatially continuous information over a large area.

Generalizing, the strong interrelationships among climatic, ecological, social and economic dimensions of forests are the reason why we rely on modern technologies for monitoring the state and development of forests. This comprises effective means for monitoring forest structure, species and age composition and, forest integrity in general. Considering the rich heritage of European cultural landscapes, forest monitoring also comprises observing the effects of land abandonment and land use conversion resulting in bush encroachment and spontaneous afforestation. From an economic point of view we are interested in assessing increase or decrease of biomass, quality of woods and the speed of forest renewal. Scientific monitoring on the other hand helps understand natural dynamics of forest ecosystems in terms of protection capacity or susceptibility to vermin like the bark-beetle.

All of these monitoring systems require repeatable, objective, transferable and transparent methods. Expert-based subjective assessments on site are limited even if they are complimented by visual interpretation of air-photos. The usefulness of photo interpretation is hampered by different illumination and shading effects. Limitations of on-site assessments arise from the area to be covered, from time constraints and the sample-based character of this kind of monitoring. Next to subjectivity, the lack of automation limits the effectiveness of expert-based monitoring. Forests cover large areas and in certain aspects can be treated homogenously. At the same time they show a high degree of small-scale structures which have to be considered. Maier et al. (2006), as one of the studies described in this paper, have therefore developed a generic, automated approach for assessing and quantifying forest structure using landscape metrics on height class patches of a crown model. This should lead to a more objective, transparent and repeatable result as compared to visual interpretation by a human interpreter.

VHSR optical data and ALS data supporting field inventories

Very high spatial resolution (VHSR) optical data are of increasing importance for fine-scaled ecological studies in sub-meter domain (Blaschke et al., 2005). Recent developments in optical satellite sensor technology (QuickBird, Ikonos, etc.) or air-borne digital cameras (HRSC-AX, VexCel, etc.) provide imagery that combines advantages from digital scanning (seamlessness, constant illumination, radiometric resolution, etc.), with the high degree of spatial detail of aerial photography. QuickBird for example, as operated by DigitalGlobe, provides data with an enhanced spatial resolution of 0.6 m and four spectral modes including a VNIR band. Data have high (11-bit) radiometric resolution. In comparison of aerial photographs, the entire work flow from ordering to processing is digital with no information loss due to analogue procedures and mosaicking. Still, the difference in spatial resolution between a 0.25 m aerial photograph and a 0.6 m QuickBird image can be critical when trying to identify single trees (Lang and Langanke, 2006).

Still, a flat and 2-dimensional representation of forests only reveals parts of the full picture: forest ecosystems are intrinsically 3-dimensional. While verticality can neither be visualised on nadir-looking air-photos nor fully be grasped by expert view from the ground, the third dimension today can be represented by means of air-borne laser scanning (ALS). Recorded signals of LiDAR (light detection and ranging) pulses trace the path of signal transmission from canopy to ground. By this, vertical structural aspects can be addressed, such as tree shape, species composition, age classes and strata structure. Both vertical and horizontal variability can be measured by this technology at high spatial resolutions and accuracies, dependening on the very type of the LiDAR system and its configuration (i.e. discrete return including first and last pulse or full waveform). From small footprint laser scanning data we can derive detailed digital terrain (DTM) and surface (DSM) models from the same source. Subtracting these two models of a forested area results in a normalized crown model (nCM), that is spatially continuous and not influenced by shading effects.

These derivates allow for volume estimations, but do not make surface properties fully explicit. Some forestry and ecological applications require explicit description of surface characteristics, such as planar or higher-order surface patches, surface discontinuities and surface roughness.

Recent progress in LiDAR technology and analysis methods allows for the detection of individual trees, specifically with high-density airborne laser scanner data (Holmgren and Persson, 2004). Also, variables characterizing the detected trees such as tree height, crown area, and crown base height are increasingly being measured. Lovell et al. (2003) used multiple returns from airborne laser scanning data to derive canopy structural parameters such as height, cover, and foliage profile and could reduce the bias induced by the size of the footprint of a tree canopy and the detection threshold. By additionally analysing ecologically relevant aspects of forest structure, the use of LiDAR data provides the potential for a harmonized approach to assess forest structure and partial aspects of biodiversity status and trends (Zimble et al., 2003; Morsdorf et al, 2004). The sheer amount of raw laser point data can be analysed by geostatistical or moving window techniques.

The Centre for Geoinformatics (Z_GIS) at Salzburg University in collaboration with the National Park Bavarian Forest, Germany and the Stand Montafon, Austria, has tested and applied advanced approaches of integrating multispectral optical data and LiDAR data for forest structure analysis, utilizing methods of object-based image analysis and GIS modelling. These studies are summarized and discussed in the remainder of this article.

Study sites and data sets

One study site is located in the National Park Bavarian Forest in south-eastern Germany along the border with the Czech Republic (see figure 1). It covers almost 270 ha of near natural forest stretching from the mixed mountain forest zone in the National Park to the spruce forests of the valleys zones. Different forest structures occur including spacious / closed forests, multiple tree canopy layers as well as varying tree size and species. Much of the montane spruce stands were serverely attacked by the spruce bark beetle (*Ips typographus*) in the 1990s. Due to this and the officials' decision not to intervene (according to the principles of the National Park) vast areas were destroyed. Today this is still visible by a large proportion of dead trees but also by high dynamics of natural regeneration.

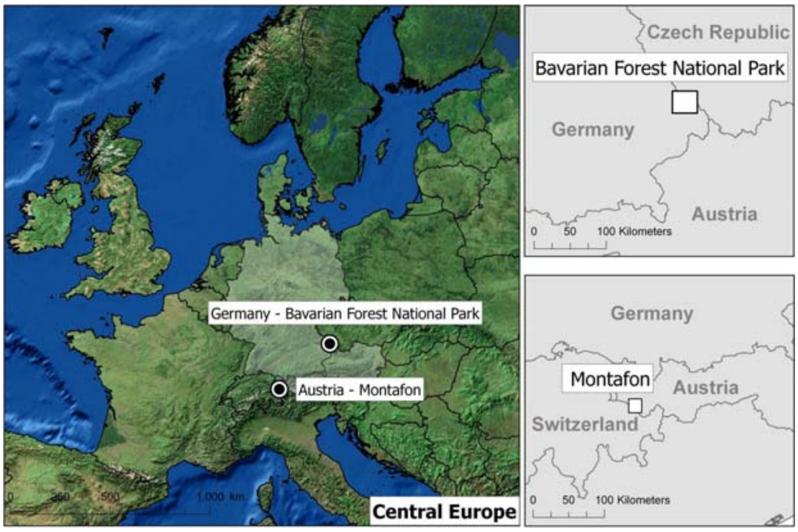

Figure 1: Overview study sites

Data from the Toposys ALS system (see Wehr and Lohr, 1999) were used. Surveying of the study area was done at three dates: leaf-off (March and May, 2002) and leaf-on (September 2002). Both first and last returns were collected during the flights and the average point density is 10pts per sqm (i.e. 15-18 returns including first and last echo). The datasets were processed and classified using TopPit (TopoSys Processing and

Imaging Tool) software. The resulting surface model (DSM) and terrain model (DTM) were subtracted to create a normalised crown model (nCM) with 0.5 m GSD. Simultaneously to the LiDAR range measurements, image data were recorded with the line scanner camera of Toposys. The camera provides four bands: B (440-490 nm), G (500-580 nm), R (580-660 nm) and NIR (770-890 nm) and a GSD of 0.5 m.

The other study site is a 200 hectare spruce-dominated protection forest ranging from 1000m in the valley ground up to 1800m at the tree line in the Montafon region in the westernmost part of Austria (federal state of Vorarlberg). The laser data available for this study comprise an nCM with 1 m resolution originating from an Airborne Laser Terrain Mapper (ALTM 1225, Optech Inc.) with a raw data point density of 0.9 points per sqm. Additionally we used separate, but co-registered set of CIR air-photos. Terrestrial mapped structure types and field comparisons were used for validation purposes.

For all studies we used a combination of different image analysis and GIS packages including eCognition 4.0 / Definiens Developer, Erdas Imagine 8.7 and ArcGIS 9.

FOREST STAND DELINEATION AND CLASSIFICATION

Within the project "evaluation of remote sensing based methods for the identification of forest structures" mapping key for forest development phases has been translated into rule set for automated object-based image analysis techniques (Tiede et al., 2004). The aim was to automatically delineate forest stands, i.e. the key planning units for forest management in Central Europe. Multi-scale segmentation (MSS) and object relationship modelling (ORM) has been used for generating image objects and classifying stands (Burnett and Blaschke, 2003). The machine-based delineation of forest stands has been assessed by map-to-map comparison of the developmental phases derived by fieldwork. It revealed promising results (see figure 2). Limitations occurred mainly due to semantic mismatches and the problem that field data used for the accuracy assessment are also highly subjective. Results may support ground surveys by delivering objective, semi-automated and transparent analysis in terms of stable classes differentiating between coniferous/deciduous and characterizing gap distribution. To a lesser extent this approach has been proved suited for providing a ready to use map of forest development phases.

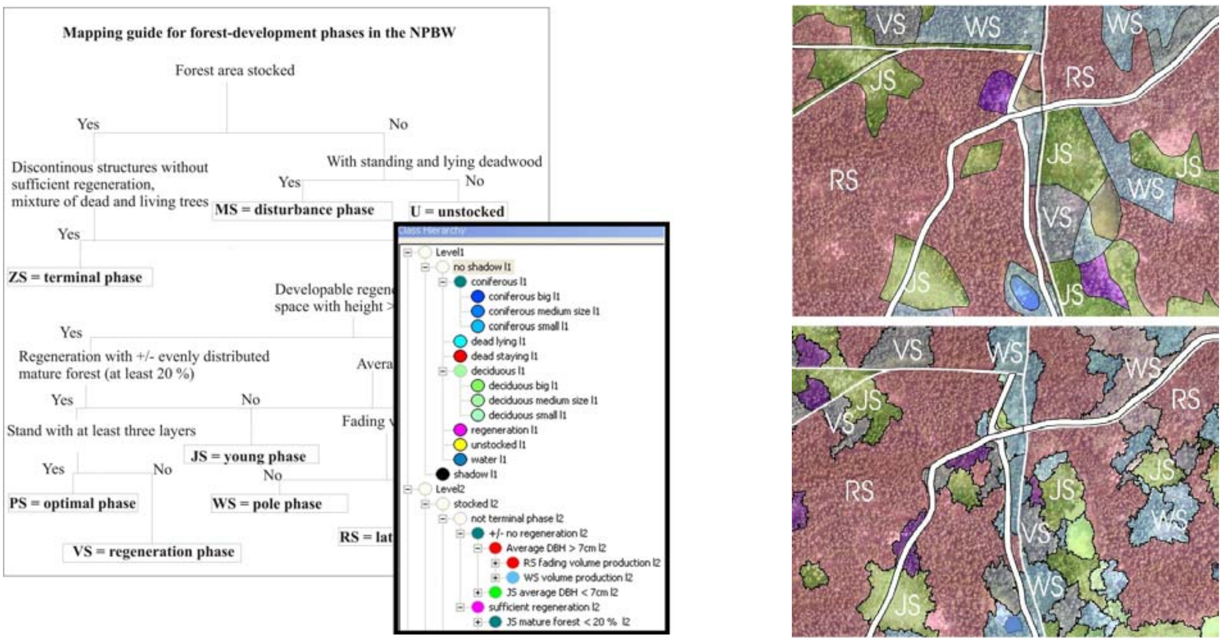

Figure 2: Left: Mapping guide for forest-development phases in the National Park Bavarian Forest.and according classification rule-base in eCognition. Right: Screenshots of the resulting maps of forest-development phases: Manually mapped by an interpreter (above) and semi-automatically constructed (below). White lines are showing forest roads and compartment borderlines. (Figures taken from Tiede et al., 2004, modified).

In the Montafon test site the method for assessing forest structure combined object-based multi-resolution segmentation, followed by GIS analyses. In a first step the existing forest mask from the forest management plan (Maier et al. 2005) was used for creating a binary forest mask for all subsequent segmentation routines. 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. 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. Objects of both levels were exported into a GIS for further processing. Level 2 stand objects served as a basic aggregation level for stand structure assessment. Level 1 segments were classified into four height classes (see figure 3).

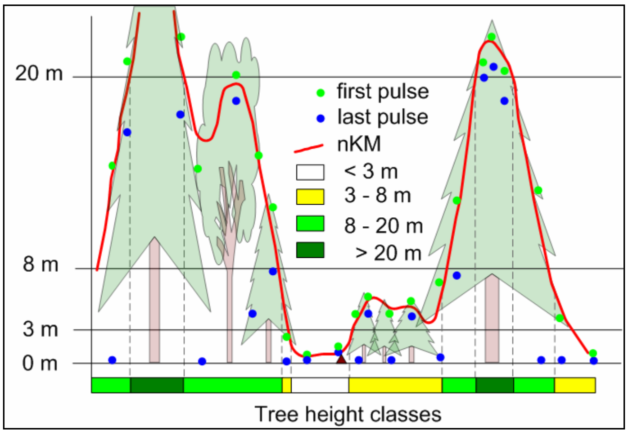

Figure 3: Tree height classification schema (from Maier et al., 2006)

STRATEGIES FOR SINGLE TREE DETECTION

The following section discusses to different strategies for single tree detection based on laser raw data, the one incorporating GIS modelling and the other object-based image analysis. The first, GIS modelling, utilized a region-growth local maxima algorithm (Tiede et al, 2005). By this we were able to differentiate between coniferous and deciduous trees, even without taking additional optical data into consideration, i.e. by analyzing first and last pulse data alone. Huge point clouds are usually converted to a raster or being pre-processed in specific software packages. Here we applied a methodology to extract and delineate single trees from small footprint, high intensity ALS point data in a GIS environment. Image data were only used for visualisation purposes and for accuracy assessment (cf. figure 4). The objective was to demonstrate the potential of a fully GIS-based workflow. First, we developed a local maxima algorithm to identify tree tops. Second, we incorporated a region growing algorithm to delineating the respective tree crowns. It utilizes the original laser point data and not a derived raster data set such as a DSM. For six plots in the Bavarian Forest, the results of extensive field surveys were available and served as reference maps. Dominant trees could be detected with an accuracy of 72.2% but the overall tree detection rate was 51%. Suboptimal scan sampling distribution hinders perfect tree crown delineation. The abovementioned objective – to establish a full GIS-based workflow – has been reached. Still, locating and counting trees in an ALS point cloud, particularly in multi-tiered deciduous plots and juvenile stands, requires assistance from field validation and subjective interpretation.

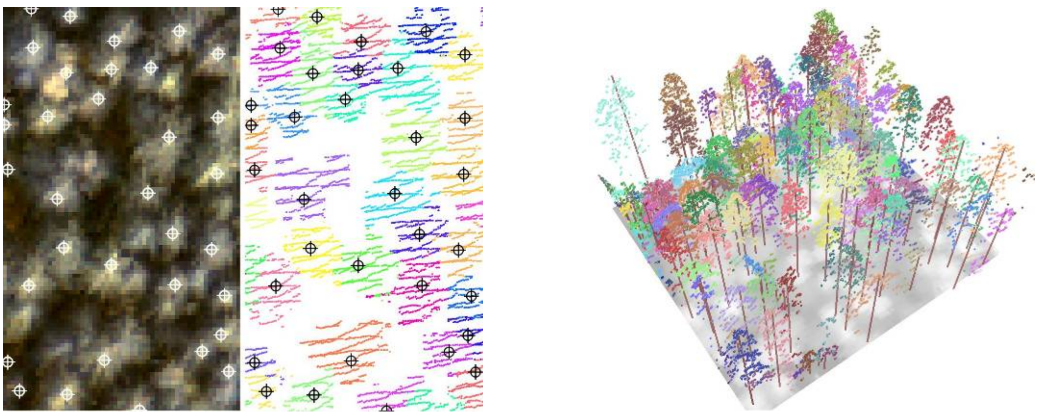

Figure 4: Delineated trees in LiDAR point data in a GIS environment (left): local maxima and assigned laser point data. 3D scene of the assigned point data with extruded local maxima illustrated graphically as tree trunks (right). (Figure taken from Tiede et al., 2005)

Similar results we could obtain by performing segmentation in an adapted way on nCM data. In this study segmentation was done controlled by super-class information, i.e. deciduous vs. coniferous forest (Tiede and Hofmann, 2006). These kind of class-specific rule sets for different forest types are further developed by Tiede et al. (2006) and applied to the whole 270 ha test site. Leading to an advanced supervised domain-specific segmentation approach this strategy includes scale-specific segmentation strategies within one single scene. Initially, broad classes are distinguished, such as closed vs. spacious, deciduous vs. coniferous, juvenile vs. mature forest. The background for the strategy of regionalized segmentation has been theoretically discussed in Lang, 2005.

STRUCTURAL ASSESSMENT – VERTICAL AND HORIZONTAL

In the Bavarian Forest study vertical forest structure has been assessed statistically by applying '3D landscape metrics' based on laser point raw data (Blaschke et al., 2004). Basic statistics (like mean, standard deviation, and variation coefficient) were calculated in a moving window approach. An increasing window size from 5 m to 40 m reflected different scales and levels of aggregation (see figure 5). This kind of upscaling was performed by differentiating between tree types, i.e. deciduous, coniferous, and dead trees.

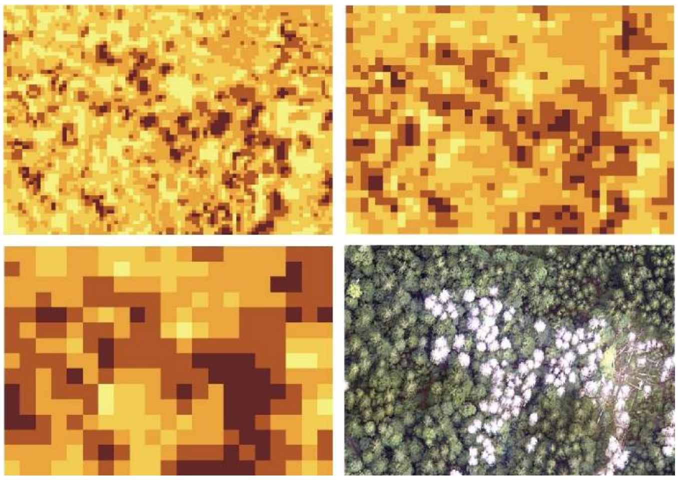

Figure 5: Resulting height standard deviation based on moving windows at three different scales on laser point raw data. Window sizes are 5m (upper left), 10m (upper right), 20m (lower left). Dark colours indicate higher values. Lower right picture represents a multispectral image of the same area. (From Blaschke et al., 2004)

In the Montafon study we analyzed vertical structure as represented in different strata, which were extracted from the nCM by reclassification (Maier et al., 2006; Lang and Blaschke, in press). The transformation of the surface information into 2D planar patches allows for the application of spatial applications, like mean patch size or diversity. By this we could investigate the specific spatial arrangement of relevant strata levels and vertical structure in general. The aim of this was to evaluate protection capability and advanced forest inventory.

Building upon the results from stand delineation and classification into height classes (see above, figure 3), the level 1 objects were dissolved into homogenous height class patches and overlaid with level 2 stand objects. The resulting patch-structure of each stand was then described by different landscape metrics and indices. 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), a diversity metric, refers to the distribution of area between the different height classes within a 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). Additionally, we calculated canopy density metrics for each height class per stand and tried to express six discrete structure types defined by Bebi (1999) using the above mentioned metrics and canopy density values (see figure 6).

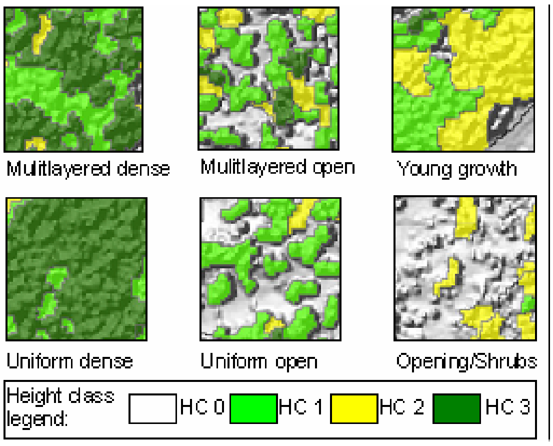

Figure 6: Discrete structure types examples (from Maier et al., 2006)

Expert-based validation with terrestrially mapped structure types revealed that 69 of 78 stands were correctly classified. This corresponds to 85% of the area. Although the SHEI proved useful for pointing out homogenous stands, its capability to differentiate between multilayered and uniform stands was limited. 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 (Lang and Blaschke, in press).

CONCLUSIONS

The article has shown that a combined use of novel analysis approaches and recent technological advances may help to significantly step ahead in the direction of an automated assessment of forest structures. On the other hand, the approaches being discussed in this paper will and should not replace detailed field investigations, but will help to assess stand-related information and forest structure in an area-extensive and efficient manner: The goal of providing a transferable, yet cost-effective, transparent and objective approach for spatially continuous, updated information over large areas has been accomplished.

With approaches like the ones described, 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. Automated structure assessment can be used in the course of protection forest planning, management and monitoring. It 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. Future research will focus on the development of more elaborate structure types, as for instance different static and dynamic height classification schema should be tested and forest stability features evaluated. Moreover, 3D surface explicit measures shall be established. In general, optimizing both the performance and the stability of the automated extraction/classification routines need further effort.

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REFERENCES

BEBI, P. *Strukturen im Gebirgswald als Beurteilungsgrundlage ausgewählter Waldwirkungen*. Dissertation ETH-Zürich, 125 pp, 1999.

BLASCHKE, T., et al. 3D landscape metrics to modelling forest structure and diversity based on laser scanning data. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XXXVI-8/W2, Freiburg, pp. 129-132, 2004.

BLASCHKE T. et al. Object-based analysis of remote sensing data for landscape monitoring: Recent developments. *Anais XII Simpósio Brasileiro de Sensoriamento Remoto*. Goiania, 2879-2885, 2005.

BURNETT, C.; BLASCHKE, T.. A multi-scale segmentation/object relation-ship modeling methodology for landscape analysis. *Ecological Modeling*, 168: 233-249, 2003.

DORREN, L.K.A. et al. Integrity, stability and management of protection forests in the European Alps. *Forest Ecology and Management* 195, pp. 165-176, 2004.

HEROLD, A.; ULMER, U. Stand stability in the Swiss National Forest Inventory: assessment technique, reproducibility and relevance. *Forest Ecology and Management* 145, pp. 29-42, 2001.

HOLMGREN, J.; PERSSON, A. Identifying species of individual trees using airborne laser scanner. *Remote Sensing of the Environment*, 90(4), pp. 415-423, 2004.

HÖLTERMANN, A. and OESTEN, G.. Ein forstwissenschaftliches Konzept als Vorbild für die Strategie der nachhaltigen Entwicklung?, In: Landeszentrale für politische Bildung (Hrsg.): Der deutsche Wald – Der Bürger im Staat, 51. Jahrgang, Heft 1, 2001 [online]; http://www.lpb.bwue.de/aktuell/bis/1_01/wald06.htm. Last date accessed: 17 aug., 2004.

JAEGER, J. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. *Landscape Ecology* 15, pp. 115-130, 2000.

LANG, S.; BLASCHKE, T. *Landschaftsanalyse mit GIS*. UTB-Reihe, Ulmer Verlag, Stuttgart, in press.

LANG, S.; LANGANKE, T. Object-based mapping and object-relationship modeling for land use classes and habitats. P*FG - Photogrammetrie, Fernerkundung, Geoinformatik* , 1/2006, 5-18, 2006.

LANG, S. A utilização do conceito de totalidade (holismo) na geração de planos de segmentação regionalizados em conjuntos de imagens de altíssima resolução. In: Blaschke, T. ; Kux, H. (eds.), *Sensoriamento remoto e SIG avançados – novos sistemas sensors metodos inovadores, oficina de textos*, Sao Paulo, p 33-40, 2005.

LOVELL, J.L. et al. Using airborne and ground-based ranging lidar to measure canopy structure in Australian forests. *Canadian Journal of Remote Sensing*, 29(5), pp. 607-622, 2003.

MAIER, B. et al. Assessing mountain forest structure using airborne laser scanning and landscape metrics. *Bridging Remote Sensing and GIS – 1st International Conference on Object-based Image Analysis*, Salzburg, 2006.

MAIER, B. et al. Multifunktionale Waldinventur. *Österreichische Forstzeitung* 11, pp. 16-17, 2005.

MORSDORF et al. LIDAR-based geometric reconstruction of boreal type forest stands at single tree level for forest and wildland fire management. *Remote Sensing of Environment*, 3(92), pp. 353-362, 2004.

TIEDE, D.; HOFFMANN, Ch. Process oriented object-based algorithms for single tree detection using laser scanning data. EARSeL-Proceedings of the Workshop on 3D Remote Sensing in Forestry, 14th-15th Feb 2006, Vienna, 151-156, 2006.

TIEDE, D. et al. A full GIS-based workflow for tree identification and delineation using laser scanning. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. XXXVI, Part 3/W24, Vienna, pp. 9 – 14, 2005

TIEDE, D. et al. Object-based semi automatic mapping of forest stands with Laser scanner and Multi-spectral data. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XXXVI-8W2, Freiburg, pp. 328-333, 2004.

TIEDE, D. et al. Supervised and forest type-specific multi-scale segmentation for a one-level-representation of single trees. *Bridging Remote Sensing and GIS – 1st International Conference on Object-based Image Analysis*, Salzburg, 2006.

WEHR, A.; LOHR, U. Airborne Laser scanning - an introduction and overview. *ISPRS Journal of Photogrammtry and Remote Sensing*, 54, pp. 68-82, 1999

ZIMBLE, D.A. et al . Characterizing vertical forest structure using small-footprint airborne LiDAR. *Remote Sensing of the Environment*. 87, pp. 171–182, 2003.