3D LANDSCAPE METRICS TO MODELLING FOREST STRUCTURE AND DIVERSITY BASED ON LASER SCANNING DATA

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ABSTRACT

This paper investigates the potential of laser scanning data to model forest 3d structure and its spatial pattern. Most of the existing methods for assessing structures in mountain forests are either inventory methods, which cannot be used for spatial assessments over large areas, or methods aimed only at assessing actual wood production. Several new landscape metrics are developed and applied to data sets from the National Park Bavarian Forest, Germany. The LiDAR data based 3d metrics are evaluated using existing geo-information such as forest maps, high resolution DEMs and ground surveys. Preliminary results give evidence that a 3d landscape metrics methodology can support forest structure discrimination, mapping and monitoring.

1. INTRODUCTION

The monitoring and reporting on the status of forest structure and biodiversity has become one of the key components of the European Union's policy on Environment and Sustainable Development (e.g., Forest Focus Regulation, Habitat Directive and monitoring obligation within the Natura 2000 framework). Multitemporal imagery from multispectral systems such as Landsat ETM+ have successfully differentiated between forest types to accuracies of better than 90%. Goodenough et al. (2003) used hyperspectral data to obtain species accuracies for some classes in excess of 90% from analysis of single images. Thus, it is possible to obtain accurate measurements of some leading forest species with hyperspectral remote sensing providing detailed information on the horizontal distribution but not the vertical distribution of vegetation in forests. Some remote sensing technologies such as light detection and ranging (LiDAR) systems are able to discern vegetation structure, in great detail, within forested ecosystems (Bergen et al., 2002). Vegetation structure is the above ground organisation of plant material. The parameterization of this three-dimensional spatial distribution of above ground biomass components is usually achieved either through regular grids or based on individual tree objects. Only relatively recently many small footprint, discrete return LiDAR systems can acquire multiple measurements from a single laser pulse but there are no methodologies as yet which guide us how to utilize the huge amount of point data for ecological applications.

This paper describes an application which combines remote sensing data and ancillary geo-information from field surveys to derive surrogate (qualitatively connected) indicators to contribute to forest monitoring. Specifically, the paper investigates the potential of laser scanning data to model forest 3d structure and its spatial pattern. LiDAR remote sensing is capable of providing both horizontal and vertical information with the horizontal and vertical sampling dependent on the type of LiDAR system used and its configuration (i.e., discrete return or full waveform LiDAR). Small footprint, multiple-return LiDAR systems should be able to detect the vertical and horizontal distribution of forest canopies. Recent work by Magnussen et al. (1999) or Naesset and Oekland (2002) clearly reveal that tree height can be recovered from LiDAR data just as accurately as from ground measurements.

For forestry applications, the ability of small footprint, discrete return sensors to capture multiple returns – to penetrate the first reflective surface of the canopy – is a critical characteristic. An investigation of this technology was conducted to determine the potential for developing information about vegetation structure and the monitoring of the structure. Most commercial LiDAR systems capture between two and five returns; referred to as multipulse or multiecho capability. Very few field projects have reported detailed statistics or analysis based on the number of returns seen in each band or examined the variance of this parameter against canopy type or environmental variables. The main premises of LiDAR data include the generation of a DEM (digital elevation model) and a DSM (digital surface model) from the same data source and volume estimations. Still, some forestry and ecological applications require an explicit consideration of discontinuities in the surface. Such discontinuities may signal abrupt changes in canopy closure, species distribution, stand age and many other parameters. Although very useful, it is important to realize that both a DEM and a DSM do not make surface properties explicit. An explicit description of surface characteristics, such as planar or higher-order surface patches, surface discontinuities and surface roughness is important for many subsequent tasks. Ecological applications rely on the knowledge of explicit surface properties. In this paper, we investigate methods to analyse forest structure through a new metrics based on laser scanning data. We concentrate on 3d point data analysis and briefly discuss alternative options of raster grid based analysis.

2. METHODOLOGY

2.1. Study area, data sets and data processing

The research is carried out in the Bavarian Forest National Park (NPBW) which is located in south-eastern Germany along the

borderline with the Czech Republic. Within the park three major forest types exist: above 1100 m there are sub-alpine spruce forests with Norway spruce (*Picea abies*) and some Mountain ash (*Sorbus aucuparia*); on the slopes between 600 m and 1100 m altitude, mixed mountain forests with Norway spruce, White fir (*Abies alba*), European beech (*Fagus sylvatica*) and Sycamore maple (*Acer pseudoplatanus*) can be found; in wet depressions often evidencing cold air ponds in the valley bottoms, spruce forests with Norway spruce, Mountain ash and birches (*Betula pendula, Betula pubescens*) occur. The image analysis described in this paper is performed for a test area of 270 ha stretching from the mixed mountain forest zone to the spruce forests of the valleys zone.
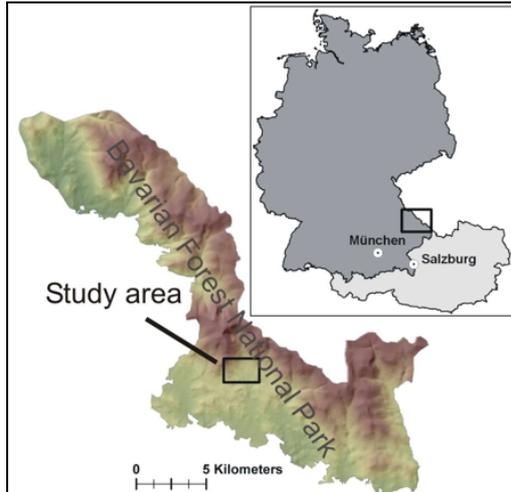
Figure 1. Study area location within the Bavarian Forest National Park

Point cloud scans were analysed from airborne LiDAR system ("Falcon") flight campaign by the German company Toposys using a push-broom technology. The test area was surveyed three times: leaf-off (March and May 2002) and leaf-on (September 2002). First and last pulse data were collected during the flights with an average pulse density of 10pts/m². Through several image processing steps original LiDAR pulses were prepared for import in a GIS software environment. Figure 2 shows first and last pulses as 3d points represented in a GIS for a subset of the study area. Various techniques were used to process the original point data and to derive information on vertical forest structure. These steps include the merging of first and last pulse data, the generation of relative heights by subtracting DEM values from LiDAR data, the correction of negative values in the resulting data set and various GIS data integration steps.
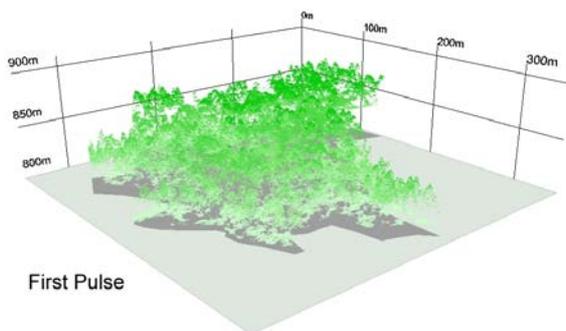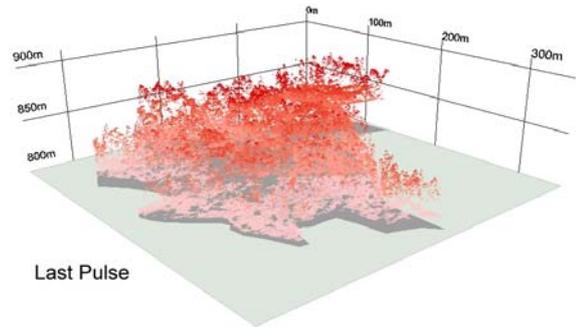
Figure 2. LIDAR point data (x,y,z-triples) imported in a GIS as seen from the side. Colour intensities represent high z-values, for both the first pulse and the last pulse signals.

2.2. 3d metrics applied to LiDAR data in a GIS

The enormous amount of point data, in our study about 10 pulses per square meter (i.e. around 17 corresponding returns per square meter in this area), can in principal be analysed geostatistically or through 3d point metrics. The LiDAR data represent quantitative measurements that vary nearly continuously across the landscape; there are no explicit boundaries. The data can be conceptualized as representing two three-dimensional surfaces or point clouds, where the measured first pulse and last pulse values at each geographic location are represented by the height values of the two surfaces, or corresponding points, respectively. We developed a new landscape metrics. Only recently, landscape metrics is criticised for being two-dimensional (McGarigal and Cushman, in press). For the NPBW, point data for subsets of different forest situations were analysed.

In order to derive a continuous raster surface the point data were interpolated to produce grids with 20 and 50 cm spatial resolution. Lloyd and Atkinson (2002) demonstrated that given the high density of point data produced from LiDAR, simpler interpolators, such as the IDW interpolation technique, sufficed in producing accurate elevation models in comparison to more complicated techniques like ordinary and universal kriging. In our study, several tests of interpolation of the point data into raster grids were reported to be coupled with a loss of important structure information. Consequently, we choose the 3d point model based on single coordinate triplets of x, y, z in a GIS. Only a small portion of empirical studies deal with three dimensional point analysis methods although the algorithms behind are mature in many application fields. It is often claimed that 3d analysis and visualisation provide better understanding of the phenomena under consideration.

The first step was to define vertical structure by using tree height variance. This statistic is being tested using an analysis of variance. For representing vertical structure spatially, the percent coefficient of variation was chosen due to the more normalized nature of the metric. Various metrics were derived and tested from tree height information using field and LiDAR data. LiDAR tree heights were determined from a series of processing steps. Figure 3 illustrates the point cloud for one tree. The points in this figure were selected by the tree outline derived through image segmentation using a methodology developed by Tiede et al. (2004) and Burnett et al. (2003).
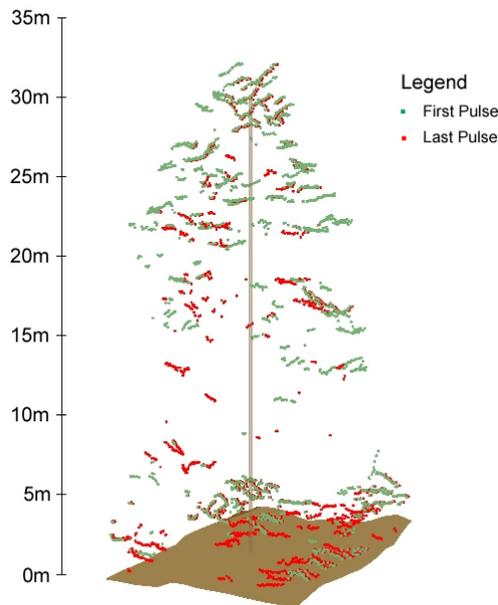
Figure 3. 3d point cloud from both, first and last pulse data falling within the outline polygon of one identified tree.

The results are reported for processing the point data in a GIS using a moving window. Similarly to the well known raster based kernels, a moving window analyses a number of points and the statistics are reported to the window centroid. We used a modified GIS extension to deriving the number of points and some statistics per window, including mean, standard deviation, variation coefficient, minimum value, maximum value and range. The size of the moving window is user defined, so it is possible to compute the statistics for different scales. Furthermore the user can choose if windows should overlap by up to half of the window size. Figure 4 illustrates the standard deviation of the merged first+last pulse point data for four different scales.
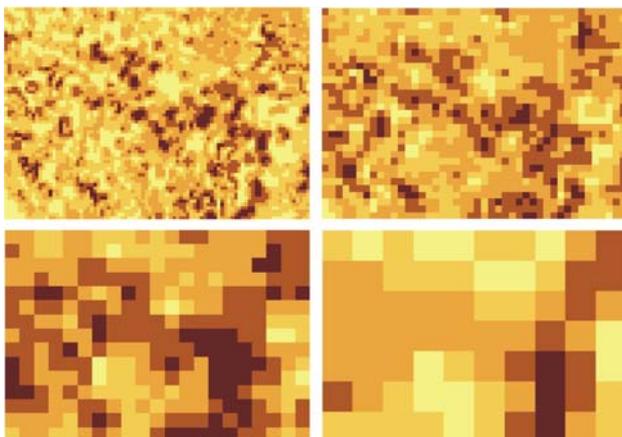
Figure 4. Resulting height standard deviation based on moving windows at four different scales. Window sizes are 5m (upper left), 10m (upper right), 20m (lower left), 40m (lower right). Dark colours indicate higher values.

To be able to evaluate the results we selected three different types of trees (deciduous, coniferous and dead trees) and calculated the same statistics again. The results in table 1 exhibit (in spite of resemblances of *mean* and *range*) strong differences for the *standard deviation* and the *variation*

coefficient (%). The latter can be interpreted as an indicator for the penetration rate on the individual tree level, but also as an indicator of forest structure at a coarser scale. Currently, this GIS extension is being extended with specifically designed forest structure calculations (e.g. percentage of LiDAR points at different height levels) and an automatic comparison of first pulse, last pulse and merged data statistics.

trees	no. of points	std. dev.	mean	range	var. coeff.
coniferous	3987	8.8	32.01	47.18	27.49
dead	3163	12	27.68	41.59	43.40
deciduous	6587	4.4	27.62	37.03	19.73

Table 1. Statistical results for a subset of three different tree types.

In our study, we observed three problems or limiting factors for an operational approach for large areas. First, in most cases the correspondence of a particular pair of first and last pulse data cannot be identified. Second, the amount of points is extremely high. For the data sets used approximately over 17 returns per square meter are measured. For the single tree in figure 3 more than 1000 3d points are computed. Third, for narrow standing trees, branches significantly overlap each other. Since we did not focus on single trees in our research we can neglect the latter problem but have to deal with the first two issues.

3. DISCUSSION

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, in press). The indicators are grouped in descriptors for forest composition (forest types, land cover spatial configuration) and forest structure (vertical structure / 3d-structure, connectivity / fragmentation / isolation, edge / interior forest etc.). Most of the existing methods for assessing structures in mountain forests are either inventory methods, which cannot be used for spatial assessments over large areas, or methods aimed only at assessing actual wood production. The LiDAR based 3d metrics are evaluated using existing geo-information such as forest maps, high resolution DEMs and ground surveys. Although the results are preliminary, several application specialists are interested in using this methodology to improve forest structure discrimination and, consequently, monitoring of forest structure.

It is generally believed that some metrics correlate with landscape processes or their resulting pattern, respectively (Forman, 1995) and, more specifically, that shape regularity and complexity correspond well with the degree of human influence on the landscape. Still, there are no generally applicable rules for such expected correlations between

processes and landscape pattern and statistical correlations might confirm pseudo-correlations. 'Classic' landscape metrics are mainly used to investigate patch characteristics, shape and edge density of discrete mapping units. LiDAR based 3d metrics offer insights into "within-patch diversity" (Blaschke, 1995). This information is currently being explored to further assess vegetation patterns in terms of potential forest vulnerability to destructive insect pests to assist Park managers in the development of preventive management plans. A literature study revealed that the number of ecological applications based on airborne LiDAR data is limited. One example is the modelling of reproductive performance in Great Tits (*Parus major*) based on a woodland canopy height model derived from LiDAR data (Hill et al., 2003). It is strongly believed that such quantifications of habitat quality could greatly enhance our ability to predict impacts of changing environmental pressures on biodiversity.

Ongoing research analyses the spatial dependencies (or autocorrelation) in the measured characteristics geostatistically. A variety of techniques exist for measuring the intensity and scale of this spatial autocorrelation (Legendre and Legendre, 1998). Techniques also exist that permit the interpolation of these spatial patterns. These surface pattern techniques were developed to quantify spatial patterns from sampled data. When the data is exhaustive (i.e., the whole population) over the study landscape, as is the case with remotely sensed data, other techniques (e.g., two-dimensional spectral analysis or two-dimensional wavelet analysis) are more appropriate. Most surface pattern techniques share a goal of describing the intensity and scale of patterns in the quantitative variable of interest. In all cases, while the location of the data points (or quadrates) is known and of interest, it is the values of the measurement taken at each point that are of primary concern, in our case the height differences and their spatial distribution.

In this paper, we merged first and last pulse data but also experimented with analysing the two data sets independently. First pulse data more likely reflect on leaves or braches of trees while the laser pulses of last pulse data sometimes reflect on the ground below the trees or in between surface and ground. This study needs to be expanded to understand the effects of the different 3d metrics completely and to statistically prove the preliminary results. Additionally, methods to extract critical information from large input spaces with redundant features are under further development. Filtering and classification of the three-dimensional point cloud produced by discrete return scanning LiDAR systems is a challenge and is a focus of current research (Baltsavias, 1999). Finally, these results are for one application – examination of forests in the Bavarian Forest National Park, Germany. A broader range of land covers needs to be addressed (including agriculture, dry lands, etc.) to generate an analysis that is adequately representative to support the development of a 3d landscape metrics.

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