Derivation of 3D landscape metrics from airborne laser scanning data

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Abstract

One of the key-research topics in landscape ecology is the analysis and characterization of landscape pattern and structure. A description of these two features is commonly achieved through derivation of various metrics (e.g. Contagion, Dominance or Fractal Dimension) for the assessment of landscape connectivity, fragmentation and patch shape complexity.

Up to now, only very few analyses in landscape ecology have been carried out on the basis of airborne laser scanning (ALS) data, while the majority is based on either aerial or satellite based imagery supported by conventional field survey. However, airborne and space borne images exhibit a critical drawback in comparison to laser measurements. Images can not display information from below the canopy surface, as the measurement method is not able to penetrate it. Consequently, the derivation of landscape metrics from such data is merely 2D. It can not account for the vertical structure of vegetation, a key element in forestry and the assessment of structural diversity and, as such, landscape ecology.

The laser pulses, on the other hand, are able to penetrate through little gaps in the canopy surface and can provide information on the vertical and horizontal distribution of vegetation. The aim of this study is to make use of the 3D information and penetration capability of ALS for the derivation of novel landscape metrics. The presented approach exploits the collected information about the vegetation layer structure in order to describe not only if two landscape patches are connected, but how this connection is composed in terms of vertical structure of the plants building the patches. It therefore integrates knowledge of under storey or herbaceous vegetation into the shape metrics. Additionally, 3D shape metrics that relate the surface of a patch or corridor canopy surface to its enfolded volume are introduced. In this way, information about the three-dimensional interconnection of adjacent landscape patches is obtained.

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1. Introduction

TransEcoNet, which stands for transnational ecological networks, is a project funded by the European Union regional development fund with the aim of elaborating strategies for development and management of ecological networks in Central Europe (TransEcoNet 2010). The background of this project is founded on the fact that protected areas, like national parks or conservation areas, are often isolated regions within a less or unprotected matrix, like intensively agriculturally used areas, traffic corridors or human settlements. Therefore, *TransEcoNet* aims at the analysis and assessment of landscapes regarding existing ecological processes, patterns and structures. Areas of significant ecological interest, so-called hot spots, are explored by traditional methods of landscape ecology concerning the state of the landscape functionality. Although *TransEcoNet* is a research project, its study areas comprise extended regions. Extensive manual field work, supported by remotely sensed imagery is carried out in order to map land use patterns, landscape connectivity, fragmentation, patch shape complexity and biodiversity indicators. A description of these features is commonly achieved through derivation of various metrics, such as Contagion, Dominance or Fractal Dimension. As a project partner, the Institute of Photogrammetry and Remote Sensing (TU Wien) is responsible for research on the use of airborne laser scanning (ALS) data for the derivation of biodiversity relevant quantities in order to support the ecological assessment.

Up to now, only very few analyses in landscape ecology have been carried out on the basis of ALS data, while the majority is based on either aerial or satellite based imagery supported by field survey. However, airborne and space borne images exhibit a critical drawback in comparison to laser measurements. Images cannot display information from below the canopy surface, as the measurement method is not able to penetrate it. Consequently, the derivation of metrics for quantitative and qualitative description of the landscape surface is merely 2D. It cannot account for the vertical structure of vegetation, a key element in forestry and the assessment of biological diversity, functionality and, as such, landscape ecology (Maier and Hollaus, 2008). ALS on the other hand, as it is an active measurement system, is able to penetrate through little gaps in the canopy surface. It can therefore provide information not only on the horizontal, but also on the vertical distribution of the vegetation.

Research papers have shown the need and potential of the integration of the third dimension into landscape structure indices (Jenness 2004, Höchstetter 2009). And while the usage of penetration rates of laser scanning data is common practice in forestry related studies (Naesset 2002, Korpela et al. 2009, Hollaus et al. 2008), their applications in landscape ecology are very rare. With this study we tend to make use of the 3D information and penetration capability of ALS for the derivation of novel landscape metrics. The presented approach exploits the collected information about the vegetation layer structure in order to describe not only if two landscape patches are connected, but how this connection is composed in terms of vertical structure of the plants building the patches. It therefore integrates knowledge of different vegetation layers into the shape metrics.

2. Study area and data set

The study area is located in the southern part of the Leithagebirge, a low mountain range on the borders of the federal states Lower Austria and Burgenland in Austria. The test site features a complex of semi natural and agricultural landscape composed of forest, vineyards and fields. Furthermore, patches of elongated as well as compact shape with different levels of vegetation height or under storey are present (figure 1a).

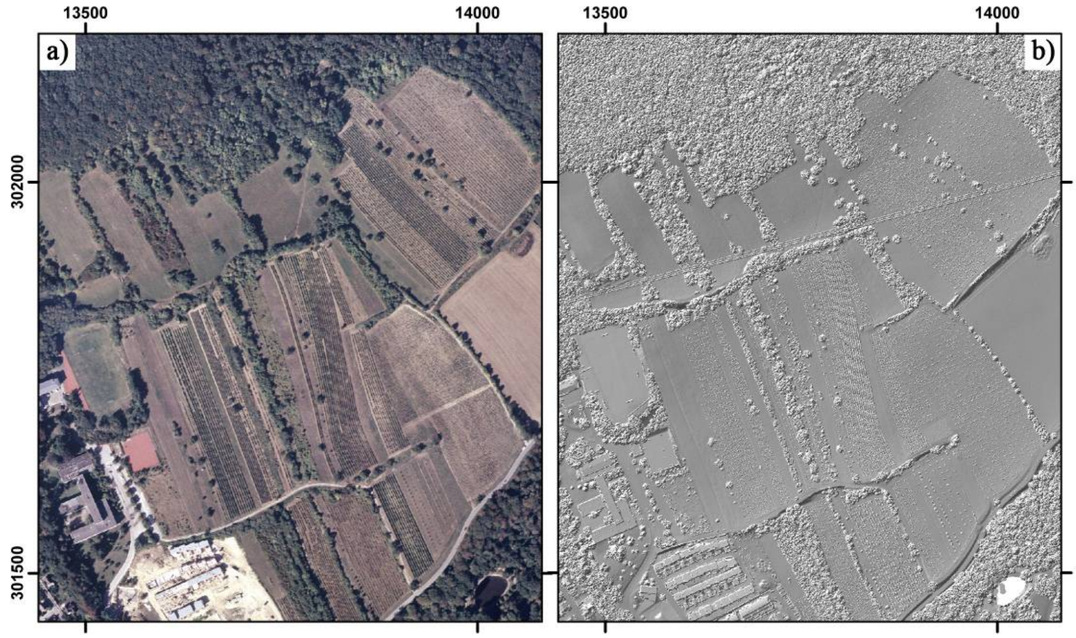

Figure 1: (a) True colour orthophoto of the study area. (b) Landscape dependent digital surface model (*DSM*).

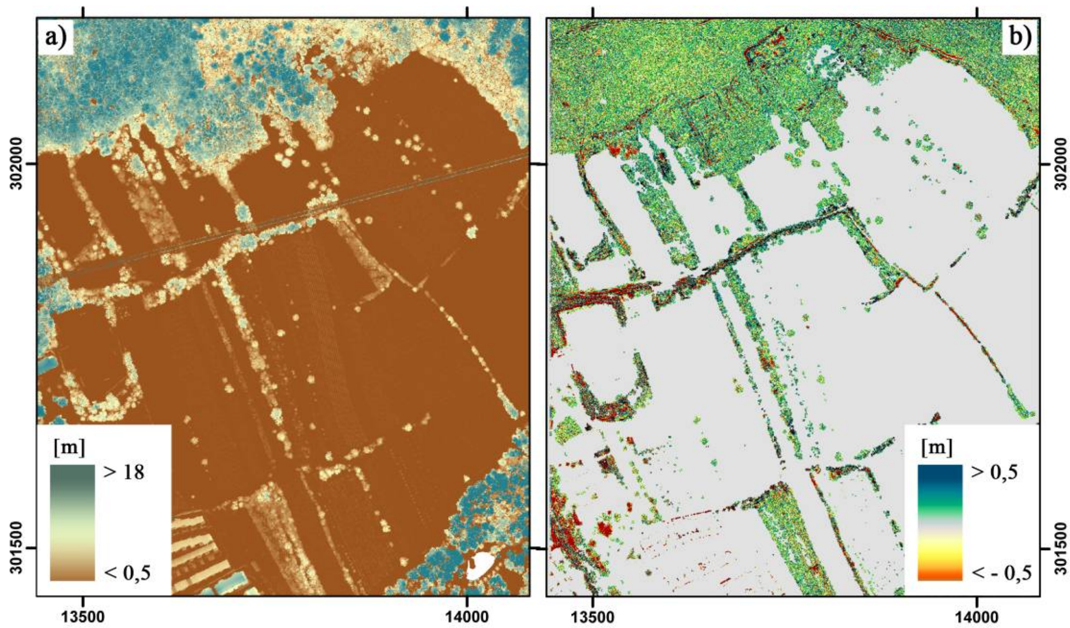

Figure 2: (a) Normalised DSM (*nDSM*), the colour coding represents the normalised heights. (d) difference model of *nDSM* and DSM_{diff}.

The utilised laser data were acquired in march 2007 under leaf-off conditions. The employed sensor was a RIEGL LMS-Q560 full-waveform laser scanner carried by a fixed wing aircraft. Due to a rather large overlap of the single ALS strips, a very high point density of 18 returns per m² on average was achieved. Based on the first and single returns a landscape dependent digital surface model (*DSM*, figure 1b) was calculated as described in Hollaus et al. (2010). The concept is based on the derivation and fusion of two different types of surface models dependent on the surface roughness. One model is calculated from the highest laser returns within a computing cell (DSM_{max}), the other by moving least squares interpolation (DSM_{mls}). The latter tends to alter the corresponding object heights due to smoothing effects, which is an undesired consequence in vegetated areas. Consequently, the heights are underestimated which can lead to differences in the range of several decimetres. Therefore, the method employs the DSM_{max} only in vegetated areas and the non-vegetated areas are represented by the DSM_{mls}. A digital terrain model (*DTM*) was calculated from the last returns in the test site by hierarchical robust filtering (Kraus and Pfeifer 1998). The normalised DSM (*nDSM*) was derived as the difference of *DSM* and *DTM* (figure 2c). Subsequently, two height models, one based on the highest and one based on the lowest point in a grid cell are computed. The difference model of the two, the so-called differential *DSM* (DSM_{diff}), is expected to depict the vertical extents of the branches, needles and leaves. Compared to using the standard *nDSM*, the deviation is up to 0.5 m in height, especially in areas with less or no under storey (figure 2d). All derived height models have a spatial resolution of 0.5 m.

3. Method

3.1. Derivation of a vegetation mask

To improve performance of the methods over large areas and to reduce computing times all of the following calculations are limited to vegetated areas only. This is achieved by the application of a vegetation mask, which is derived in a multi step approach by morphological image processing based on the *nDSM* and a measure of local transparency, the so-called echo ratio (*ER*) (Höfle et al. 2009). The first step is to discriminate between elevated and non-elevated objects within the *nDSM* by simple height thresholding. As even the lowest vegetation is interesting for our study, the height threshold is defined with 10 cm. As the result still includes artificial objects like buildings, the *ER* is employed in the second step as a distinct parameter for further separation. It basically describes whether a laser shot is able to penetrate a surface or not (figure 3a). Building areas, compared to vegetation, usually feature no penetration at all and can therefore be reliably separated with the *ER*. In the third step, the individual results are combined (figure 3b) and morphological opening with a kernel size of 3x3 pixels is applied to eliminate isolated pixels (figure 3c). The final raster layer is a binary map representing the classified vegetation pixels as 1 and everything else as 0. For further processing, the connected vegetation pixels are vectorised as shown in figure 3d.

3.2. Segmentation of vegetated areas

The aim of the segmentation step is to extract homogenous features like shrubbs, single tree crowns or sub-tree crowns for larger distributed single tree crowns (e.g. large deciduous trees). The derived segments are subsequently used as a reference unit for the calculation of structure parameters using the original 3D point cloud. Based on the *nDSM* an edge-based segmentation procedure is applied. This segmentation approach has already been tested in densely forested areas (Höfle et al., 2008, Hollaus et al. 2009) and in densely built-up urban areas (Höfle and Hollaus 2010). The main idea of the segmentation is to delineate convex objects (i.e. tree crowns) in the *nDSM* by finding concave edges between the convex objects. The constraints for the concave edge detection are a minimum curvature in the direction perpendicular to the direction of maximum curvature and an *nDSM* threshold of again 10 cm, as we want to include also the lowest vegetation. The *nDSM* is masked with the prior computed vegetation mask and a window of 7x7 *nDSM* raster cells is employed for calculation of the curvatures. The derived potential edge areas are skeletonised to extract the final edge map, which corresponds to the segment boundaries. Finally, a connected component labelling and vectorisation of the connected region boundaries are applied to derive the segment polygons (figure 4b).

3.3. Penetration index

Diversity of structure leads to diversity of species, because different ecological niches are created (Tews et al. 2004). Not only structural diversity on the surface, but particulary in the third dimension leads to a further diversification of habitats. Especially birds and insects are species groups who benefit the most of diverse habitats (Burel F. 1992). Structural diversity usually results from any kind of disturbance (Roxburgh et al. 2004). This can either be of natural cause, like fires, windfall or damages caused by game animals, or by human activity, which is mostly agricultural or due to forest maintainance. As landscape elements are permanently changing systems, they become of high relevance for nature conservation if the changes, e.g. in structural complexity, happen to fast. In combination with a lack of stepping stones and corridors they can lead to local extinction of species.

The distribution of the laser echoes in the vegetation allows us to draw conclusions on its structural complexity. Due to the fact that the ALS data were acquired during leaf-off conditions, the penetration of the vegetation by the laser pulses is assumed to be very good. The lack of returns below the upper most branches is therefore considered to stem from the absence of under storey, rather than from occlusion by high trees. A so-called penetration index is calculated as a measure of penetrability and geometric structure. The 3D point cloud is reduced to the vegetated areas by intersection with the vegetation mask. Further, it is divided into a terrain point cloud and a vegetation point cloud using an *nDSM* height threshold of 10 cm. Subsequently, the points are assigned to height levels, which were derived as percentage of the maximum occurring point height within a grid cell of 0.5 m. The defined levels are 0 to 33% (*L1*), 34 to 66% (*L2*) and 67 to 100% (*L3*). Then the ratio of the total number of points within a grid cell and the number of points within the same grid cell and respective height level is computed. The derived segmentation of the vegetated areas is used to accumulate the raster values to the tree crown segments as spatially better represented objects. Each segment is assigned the according values from the resulting three raster maps. Mean values for each segment are derived and a decision tree based strategy is used to classify the segments, the results of which represents the penetration index map (figure 5).

3.4. Vegetation surface - volume ratio

As the majority of geometric analysis in landscape ecology is based on airborne or space borne imagery, conventional landscape shape metrics derived from these data sources are merely 2D. In chapter 1 the demand for a description of the three-dimensional interconnection of adjacent patches was argued.

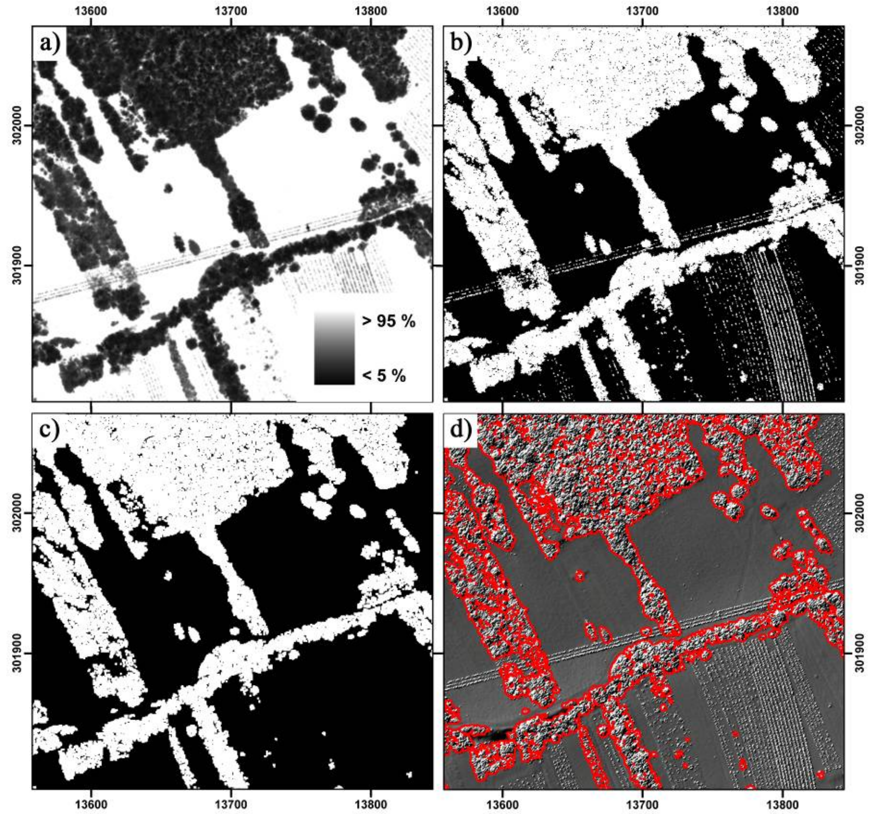

Figure 3: (a) Echo ratio (*ER*) in percent; darker areas indicate penetrable surfaces. (b) Binary map where $nDSM > 0.10$ m combined with $ER > 85\%$; white areas represent potential vegetation regions. (c) Vegetation regions after morphological opening with 3x3 kernel. (d) Final vectorised vegetation mask. The resolution of the raster images is 0.5 m.

The main concept of the described approach is the relation of a patch's surface, defined as the area of its enveloping canopy, to the volume enclosed by it. So if a vegetation object is shaped like a sphere, meaning it is very compact, it will show a very small surface compared to its enclosed volume. This will be the case e.g. for dense hedgerows or forested areas with a sufficient presence of under storey. On the contrary, if a vegetation object is more branched, its surface will get larger compared to the volume it encloses. This results from large trees with high crown height variability and only few or even no under storey.

The surface is computed as the sum of all visible lateral faces and the top face of a cell column in the raster domain. The workflow is implemented in GRASS GIS (GRASS GIS 2010). First, the DSM_{diff} is filtered by four different 3x3 kernels, each calculating the height difference between the center pixel and each of the four neighbouring pixels by subtraction of the neighbouring from the center pixel. Secondly, the values of the four difference raster layers are added if the difference is positive, indicating that it is a cell on the ascending part of the surface. Multiplying the respective sum of the differences with the raster resolution the area of all lateral faces of the cell columns is obtained, which is subsequently added to twice the cell area to generate the final surface. The computation of the volume is achieved by multiplication of the respective value of the DSM_{diff} and the cell size. Finally, the ratio of the surface and the volume are computed for each raster cell and assigned to the vegetation segments in the same manner as described in section 3.3.

4. Results and discussion

4.1. Vegetation mask

Reducing the area of actual computation to only the vegetated areas increased performance of the applied methods significantly and therefore efficient analysis of the reduced original point cloud was possible. As the vegetation mask was derived from raster layers of 0.5 m, it is very accurate, as can be seen in figure 3d.

However, in the case of very dense plant cover the *ER* becomes very similar for vegetation and artificial (impenetrable) objects. Under these circumstances discrimination could not be achieved, which lead to undesired holes in the vegetation mask that could only be corrected manually.

But from experience from previous studies (Höfle et al. 2008, Höfle et al. 2009, Höfle and Hollaus 2010) it can be stated that this does not occur very frequently. Still, if the results appear to be insufficiently because of this matter, of course the integration of additional information (e.g. building outlines from the cadastre) might be useful.

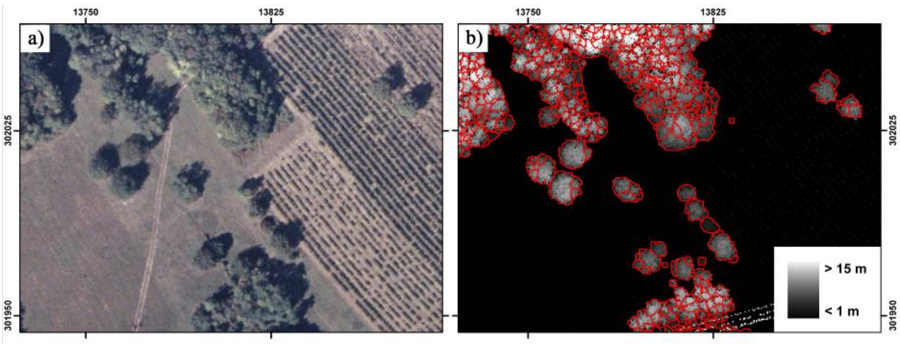

Figure 4: (a) True colour orthophoto. (b) *nDSM* overlaid with the result of the vegetation segmentation.

4.2. Segmentation of vegetated areas

The delineation of single trees or tree crowns in dense deciduous forests is generally difficult. As the applied segmentation algorithm detects convex objects separated by concave areas, it works very well for single trees with clearly distinct crowns, as can be seen in figure 4b. But especially older or larger deciduous trees often develop large crowns with multiple maxima which results in multiple convex areas and are therefore represented by more than one segment. A further limitation occurs in very dense young deciduous forest, characterised by a smooth canopy surface. Because of the less distinct crown shapes, the resulting segments often include multiple trees.

4.3. Penetration index

The resulting penetration index map for the study area can be seen in figure 5. For evaluation purposes, three profiles of the 3D point cloud, which are ment to display the structural diversity of a particular area, were created. In the chosen study area four dominant types of vegetation structure as described in section 3.3 could be identified: *L1 + L3* > 80% (red), *L2 + L3* > 80% (light green), *L3* > 80% (dark green) and equally distributed structure (yellow). Below the profiles the corresponding lines from the penetration index map are given. They demonstrate that the classification result corresponds very well with the actual structure of the forest. Deviations could be observed in areas with high local variations. Due to the comparably small cell size of 0.5 m these local variations are in general very well represented in the raster layer. However, this leads to a rather noisy impression in these areas and therefore the assignment to the segments was carried out. Hence, an averaging takes place which can no longer represent these inner segment variations.

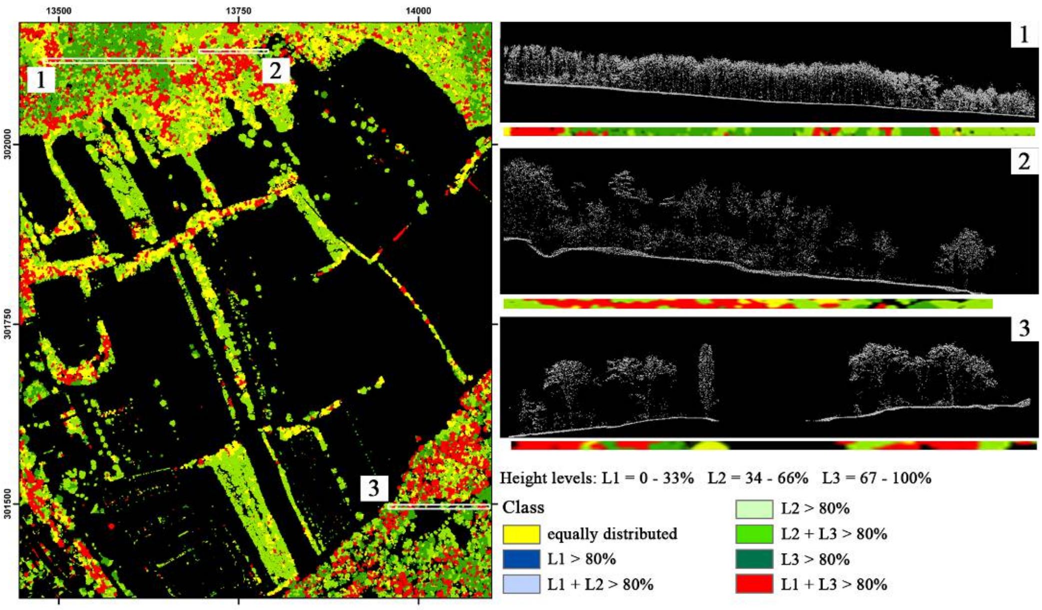

Figure 5: left: Penetration index map. Right: Profile views of the ALS point cloud. The location of the profiles can be found in the left image. Below the profiles the corresponding lines from the penetration index map are given.

4.4. Surface - Volume ratio

The vegetation surface and volume ratio can be seen as a proxy for the compactness of a particular landscape element. Changing compactness along a geometric element implies a change in structure and consequently permeability. This permeability is of significance for certain species, e.g. highly adapted birds, whose requirements do not allow structural changes within their habitats. In figure 6b the computed vegetation surface to volume ratio is shown. A high voltage powerline runs right through the study area crossing several vegetation corridors. It is clearly visible in the ratio image that the character of the vegetation structure is changing significantly below the powerline. For evaluation of the results, visual examination of the 3D point cloud had to be used, because of the lack of an adequate ground truth measurement method for the proposed surface to volume ratio. A profile view is given in figure 6c and it can be seen that the changing of the corridor vegetation character, as indicated by the ratio, is supported by the 3D point cloud. In this case the power line acts as a natural barrier, which is a disturbance in this particular habitat or corridor and can lead to a decrease of migration and, subsequently, inbreed and extinction.

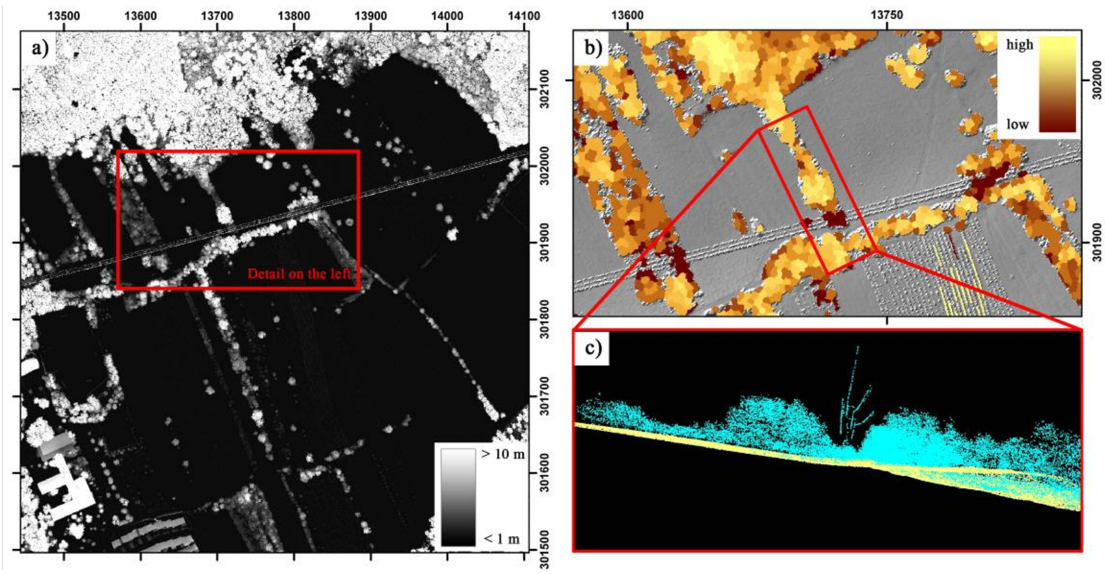

Figure 6: (a) color coded *nDSM* (b) surface to volume ratio (c) profile of point cloud showing the differing character of vegetation in particular area.

As an alternative method for the calculation of canopy surface from digital height models Jenness (2004) gave a recommendation based on triangulation. He stated that, compared to simple raster based area calculations, his method was more accurate. However, the resolution of the employed raster models was 90 m, so by far less than what is achievable with modern small footprint ALS systems, as it was used in this study. We do not expect the difference between raster and triangulation based surface calculation to be significant with a grid cell size of 0.5 m.

5. Conclusions

The penetration of the canopy surface by the laser pulses provides knowledge which is of great significance. It could be shown that 3D shape metrics derived from data acquired with ALS are a suitable indicator for the evaluation of structural diversity in vegetated areas. The hereby produced maps highlight vegetated areas with less interconnection and can help with the identification of natural barriers and can be a valuable addition to the textural information of orthophotos in traditional field work.

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