



Estimation of biodiversity relevant quantities from airborne laser scanning data

Werner Mücke, Anna Hermann, Vienna

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Abstract

Assessment of biodiversity is prescribed by the European Union Fauna-Flora-Habitat directive in order to document the health of ecosystems. Remote sensing supported by terrestrial field sampling potentially provides efficient means for a regular monitoring cycle. Airborne laser scanning (ALS), also referred to as airborne LiDAR, is especially promising because of its ability to penetrate through gaps in the foliage and provide insight in the forest vegetation layer structure. Knowledge of the topography and the spatial distribution of the plant cover are considered an invaluable proxy for the estimation of biodiversity indicators. As ALS typically provides high point densities and good penetration rates, various biodiversity indicators can be estimated directly and reliably from these measurements.

In this paper it is demonstrated how data collected with ALS, especially with FWF-ALS, can be used to derive quantities relevant for biodiversity assessment. These can be terrain surface features like roughness, as well as vegetation parameters like height, predominant tree type, location of fallen trees or forest layer structure.

Keywords: full-waveform, laser scanning, biodiversity, digital terrain model, vegetation structure, classification

Kurzfassung

Die Bewertung von Biodiversität zur Dokumentation des Gesundheitszustandes von Ökosystemen wird von der Europäischen Union durch die Fauna-Flora-Habitat (FFH) Richtlinie vorgeschrieben. Moderne Fernerkundungsmethoden, welche von traditionellen terrestrischen Feldaufnahmen unterstützt werden, bieten Möglichkeiten für effiziente regelmäßige Datenerfassungszyklen. Das flugzeuggetragene Laserscanning (airborne laser scanning, ALS), welches oft auch als LiDAR (light detection and ranging) bezeichnet wird, bietet einen wesentlichen Vorteil gegenüber bildgebenden Systemen. Die Laserstrahlen können durch kleine Öffnungen in der Belaubung dringen und ermöglichen so eine Einsicht unter die Baumkronen und in die vertikale Struktur der Waldvegetation. Die Topographie im Wald sowie die räumliche Verteilung des Bewuchses werden von Biologen und Landschaftsökologen als wertvolle stellvertretende Kenngrößen für die Abschätzung der Biodiversität angesehen. Da ALS typischerweise hohe Punktdichten und gute Durchdringungsraten aufweist, können verschiedene Biodiversitätsindikatoren direkt und zuverlässig aus der Luft erfasst werden.

Im folgenden Text wird diskutiert, wie biodiversitäts-relevante Indikatoren aus den FWF-ALS Daten abgeleitet werden können. Solche Indikatoren können Eigenschaften des Geländes sein, wie zum Beispiel Krümmung oder Rauigkeit, oder aber auch Vegetationseigenschaften wie Höhe und Schichtigkeit des Waldes, vorherrschende Baumart oder die Position von umgefallenen Bäumen.

Schlüsselwörter: Full-waveform, Laserscanning, Biodiversität, digitales Geländemodell, Vegetationsstruktur, Klassifizierung

1. Introduction

The Habitat Directive, more formally known as "Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora" [1], was established by the European Union (EU) in 1992 for the conservation of wildlife and nature. The directive's main aim is the protection and conservation of habitats and species, both clearly described in the directive. One of the key terms in conservation is biological diversity, also referred to as biodiversity, which is defined as the variability among living organisms resident in all sorts of ecosystems (terrestrial and marine) [2]. This includes diversity within species, between species and of ecosystems. The Euro-

pean Commission initiated a global study named "The Economics of Ecosystems and Biodiversity (TEEB)" running from 2007 to 2010, which produced an interim report in May 2008 [3]. This report states that selected focal areas suffer from declining biodiversity as a result of human impacts like population growth, urbanisation and climate change. Subsequently, a loss of ecosystem services, such as water and air purification, climate regulation, flood and disease regulation, fisheries and timber production is imminent. It was found that some of these areas are being damaged beyond repair. As a consequence of this process, the existence of lots of species is endangered.

The awareness that natural and semi-natural ecosystems and landscapes provide benefits to human society can be dated back to the mid-1960's and early 1970's [4-6]. However, recently there has been an almost exponential growth in publications on the assessment and valuation of ecosystem services [7-13]. The SEBI 2010 (Streamlining European 2010 Biodiversity Indicators) [14] initiative launched in 2004 proposes a set of 26 appropriate biodiversity indicators, which can be used for the assessment and monitoring of ecosystem conditions. These indicators formulate the basis for the development of strategies for protection and recreation, which are paramount tasks for the conservation and management of a healthy natural environment.

Remote sensing techniques, which can be partially supported by terrestrial field sampling, potentially provide efficient means for regular monitoring cycles. Airborne laser scanning (ALS) is especially promising because a number of biodiversity indicators can directly be estimated from the measurements in an accurate and reliable way, especially if efficient data acquisition over large areas is needed. According to SEBI 2010, this among others could be the indicators ecosystems coverage (No.4), invasive alien species in Europe (No.10), fragmentation of natural and semi-natural areas (No.13), growing stock estimation (No.17) and dead wood (No.18).

The aim of this study is to provide an overview on how various existing methods can be used for the derivation of quantities relevant for biodiversity assessment. Chapter 2 gives an introduction on the measurement process of ALS with focus on the technology of full-waveform systems. Chapter 3 describes how full-waveform observables can be integrated in the generation of a digital terrain model (DTM), which serves as initial product for various further modelling approaches. In chapter 4 the derivation of biodiversity relevant quantities from ALS data sets

is addressed. A conclusion and an outlook are given in chapter 5.

2. Full-waveform airborne laser scanning

Modern ALS systems combine a position and orientation system (POS), a laser ranging module and a data-recording unit. The laser generator, as part of the laser ranging module, emits short pulses of infra-red light (typically 4 – 10 ns, wavelength 1064-1550 nm), which are deflected towards the earth surface, e.g. by a rotating, oscillating or nutating mirror [15]. The emitted pulse interacts with objects on the ground and a part of it is scattered back to the ranging module, where the reflection can be detected. The travelling time from the scanner to the ground and back is directly proportional to the distance covered and can therefore be computed [16]. Usually, ALS systems are carried by a fixed wing aircraft or a helicopter and most often mounted on the fuselage or below the wings. The forward movement of the airborne vehicle, which is called the flight path, is constantly tracked by the POS, which consists of a global navigation satellite system (GNSS) receiver and an inertial measurement unit (IMU). The IMU observes the movements of the aircraft along its axes with high frequency, e.g. 100 Hz, while the GNSS provides 3D positional information. The covered distance, which is also referred to as range, together with the deflection angles of the respective laser beam and the combined GNSS and IMU data are stored and a georeferenced point cloud, representing the scanned surface, can be produced in post-processing.

The latest development for commercially available ALS systems is the so-called full-waveform (FWF) processing. Conventional systems can record the measured range and backscattered energy of one or more consecutive discrete reflections, so-called echoes. In contrast, a FWF-system is able to detect and record the whole emitted and backscattered signal [17]. These

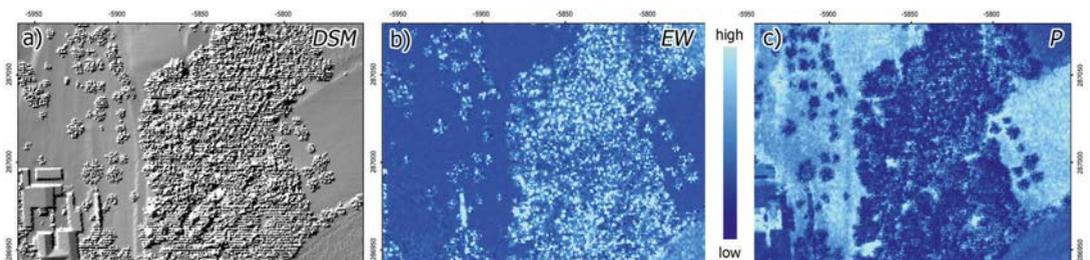


Fig. 1: (a) Digital surface model (DSM); (b) echo widths (EW), higher in vegetated (rough) areas; (c) amplitudes (P), lower in vegetated areas due to loss of backscattered energy because of multiple canopy reflections. [22]

stored signals, also referred to as waveforms, need to be analysed in post-processing. Recent papers propose different methods for ALS waveform analysis and echo extraction [18-20]. During the extraction process, the single echoes are detected and the range, as well as additional information can be derived. These additional observables are the amplitude, giving information about the reflectivity of the object hit by the laser beam, and the width of the signal, also referred to as echo width (EW), describing height distributions of small surface elements within the laser beam [16] (Fig. 1b,c). Moreover, the user-adaptable echo detection process in FWF-ALS allows for a larger number of echoes to be detected per laser shot [21] compared to discrete ALS systems, especially in vegetated areas.

3. Digital terrain model generation using full-waveform data

ALS has established itself as a very suitable measurement technique in environmental studies in the recent past. In forestry related applications, which feature strong thematic intersections with biodiversity relevant applications, ALS has proven very valuable, because most often efficient data acquisition over large areas is needed [23-25]. The biggest advantage of ALS over traditional photogrammetric measurements methods, including airborne and satellite based imagery in the visible and infra-red part of the spectrum, is its ability to “see” through small gaps in the forest canopy. Parts of the laser beam penetrate the foliage and are reflected by vegetation underneath, such as understory trees, bushes, herbaceous vegetation and also the forest floor. Hence, laser scanning over vegetation usually produces more than one echo per shot due to this penetration of the canopy. In the case of ALS, the single echoes in open and the last echoes from overgrown areas are the lowest and therefore considered best candidates to represent the terrain. Using these echoes and appropriate methods for classifying them into terrain and off-terrain points, a process that is also referred to as filtering, a digital terrain model (DTM) can be calculated even in overgrown areas [26-29]. However, there are certain situations when conventional filtering methods, which are solely based on geometric criteria and topological relations, fail to eliminate off-terrain reflections, e.g. from very dense near-ground vegetation [30-31]. Reflections from such objects, if not eliminated in the filtering process, can cause the DTM to run through the vegetation and decimeters above the actual ground surface. In such

cases, the usage of the additional FWF observables (e.g. amplitude and echo width) allows for the generation of more accurate DTMs. Wagner et al. [32] stated that the width of the backscattered echo is influenced by the vertical distribution of scatterers within the footprint area of the laser beam. Vegetation, due to the penetration of the foliage, usually features larger height distributions than flat terrain and consequently larger echo widths. This information can be used in the filtering process in order to increase the DTM quality. Lin and Mills [33] developed a point labeling process, determining terrain points using a threshold for the echo width, which is then applied to complement the single 3D points. This additional surface information is integrated in a DTM generation approach employing Axelsson’s progressive densification method [27]. In Mandlbürger et al. [34], the echo width parameter is used to derive a-priori weights as input for the hierarchic robust filtering method [35]. Points featuring small echo widths are considered to stem from terrain and get high a-priori weights. On the contrary, the weight of points with larger echo width is decreased, as they are most likely to represent vegetation. Based on the approach of Mandlbürger et al. [34], Mücke [36] extended the method by assigning probabilities to the single 3D points based on the relation of their corresponding amplitude and echo width. These probabilities indicate whether an echo is likely to stem from terrain or not.

4. Retrieving biodiversity relevant quantities

4.1 Vertical structure

The quality of the derived DTM is essential for a number of secondary products relevant for the assessment of biodiversity, such as the normalized canopy model (nCM). Usually the first laser echoes per shot are used to calculate a digital canopy model (DCM), which represents the top most layer of the forest surface. The difference between the DTM and DCM (DCM minus DTM) is called nCM and it comprises the actual vegetation or tree heights. Due to the relatively small footprint size in ALS, usually about 10 – 50 cm depending on altitude, the laser beams frequently miss the tree tops. Consequently, the measured canopy heights are underestimated and the DCM is subjected to errors [37]. The influence of an incorrect DTM can therefore further decrease the quality of the nCM and products based on it. Hollaus [38] suggested that the stem volume can be estimated from the nCM. He stated that the canopy volume, which describes the volume

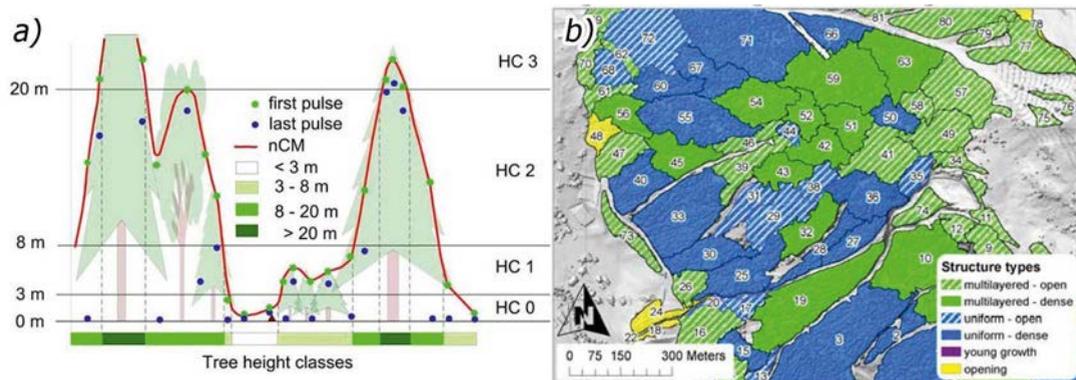


Fig. 2: (a) Classification of laser echoes into height classes according to nCM height; (b) derived structure type classification of forest sample area. [41]

between the terrain surface and the top most canopy layer, is related to the stem volume. It can therefore be defined by a linear function of the canopy volume. The nCM can also be employed to estimate the growth of the forest through comparison of ALS datasets from different acquisition times [39]. An increase or decrease in the amount of growing stock or stem volume can be a conclusive indicator for the effects of global changes, such as climate changes or natural disasters, on the condition of forested areas [40].

Alternatively, the nCM can be used for the definition of height levels above the forest floor for classifying all laser echoes according to their height above ground (Fig. 2a). In this way, information about the height distribution of scatterers and, subsequently, the forest or vegetation layer structure can be extracted (Fig. 2b) [41]. These vegetation layers are of major importance in terms of species diversity. According to Kati et al. [42], the vegetation height and structural complexity are the main environmental parameters determining species composition. For bird species diversity in forests, MacArthur and MacArthur [43] stated that the physical structure of a plant community, i.e. how the foliage is distributed vertically may be more important than the actual composition of plant species.

4.2 Horizontal structure

However, it is not solely the vertical, but also the horizontal complexity that is of importance. Robinson and Sutherland and Benton et al. [44-45] evidenced that changes at the landscape scale through the past decades have led to a decrease in spatial heterogeneity. According to Reichhoff [46], especially consolidation farming has contributed to this fact by regulation of streams, straightening of country roads and re-

moving of so far unaffected corridors, seeking to improve agricultural efficiency. An enlargement of the intensive agricultural management units implies the damage of ecologically valuable elements in between, like boundary ridges, slopes and dense thicket [47]. As a result, former natural vegetation is cleared and the complexity of the land surface decreases. As a positive correlation exists between landscape complexity and biodiversity [48-49], the mapping of spatial heterogeneity by analysis of land cover with ALS seems a promising approach for evaluating biodiversity. Nevertheless, effects of spatial heterogeneity may vary considerably between species groups. Depending on their habitat requirements and mobility, heterogeneity can lead to positive or negative effects on species diversity [50]. For example, while forest gaps increase habitat heterogeneity for butterflies [51] and birds [52], they may fragment the habitats of ground beetles, causing disruption of key biological processes, such as dispersal and resource acquisition [53].

Fragmentations in natural areas can be caused by natural, geomorphologic processes, but, in a much shorter time scale, most likely by anthropogenic structures, like road networks. This is especially critical in forests, where roads together with clear felling are the main factors causing fragmentation [54]. Major ecological impacts of road networks are the disruption of landscape processes leading to loss of biodiversity [55]. Interrupting horizontal natural processes, e.g. groundwater flow, stream flow, fire spread, foraging and dispersal, fundamentally alters the way the entire ecosystem works [56]. The habitat loss by road construction, altered water routing and downstream peak flows, soil erosion and sedimentation impacts on streams, altered species patterns as well as human access in re-

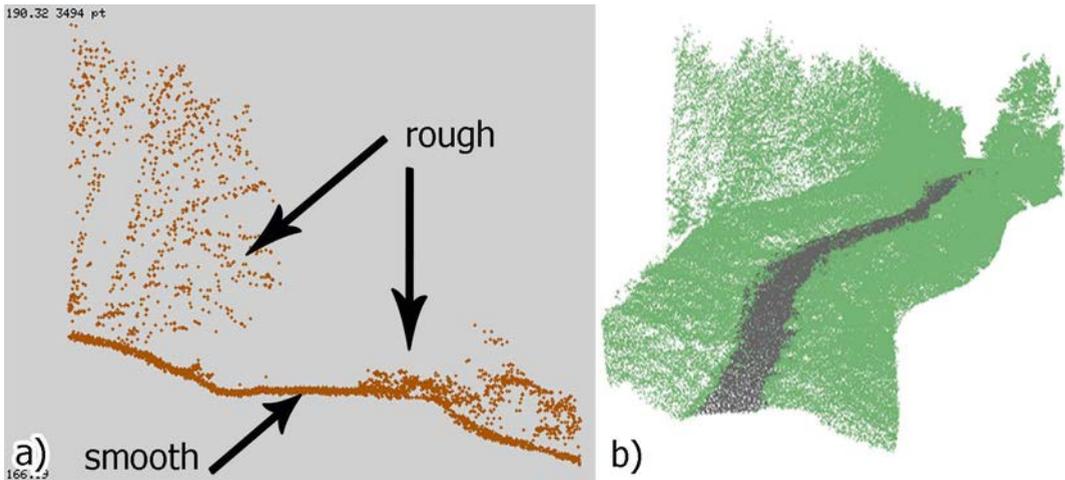


Fig. 3: (a) Profile of forest road (smooth surface) with roadside vegetation and overhanging trees (rough surface); (b) result of 3D segmentation of a forest road, black dots represent the road. [55]

more areas is seen as a major ecological effect. Therefore, road density is often used as a proxy for forest intactness [57]. Forest road networks may create distinctive spatial patterns, such as converting convoluted to rectilinear shapes, decreasing core forest area, and creating more total edge habitats than logged areas [58-59]. Thus, interior species, species with large home ranges, rare native species and species dependent on disturbance and horizontal flows are affected by those structures. General spatial-process models illustrate that forest roads have the greatest ecological impact early in the process of land transformation, by dissecting the land, leading to habitat fragmentation, shrinkage, and attrition [60-61,57]. Locating and assessing these man-made barriers is of great interest for understanding the connectivity of habitats. In densely grown forests, the roads are often overgrown and occluded, therefore not easily visible for airborne measurement systems. To retrieve them from the 3D ALS point cloud, a measure of surface roughness in terms of height variation of scatterers can be used [62]. In this context, roads tend to be planar and smooth surfaces, compared to e.g. roadside vegetation, which usually features height variations and therefore appears coarser (Fig. 3a). Based on this assumption, roads can be detected directly and automatically in the 3D point cloud by using a 3D segmentation algorithm. Segmentation-based approaches are trying to produce homogenous groups of points. In this case, the homogeneity criteria is the planarity of the surface and the local roughness, both a-priori computed for each single point. A result

of the segmentation of a small scene can be seen in Fig. 3b, where the detected forest road is represented by the black points. The fragmentation of forests due to the road networks could subsequently be estimated by computation of road kilometres per hectare.

4.3 Corridors, patches and gaps

Apart from detecting the disturbances in the landscape connectivity, also the mapping of existing corridors is of concern in landscape ecology [63]. A corridor in terms of landscape ecology is a relatively narrow landscape element that differs from its adjacent areas on either side [64]. It usually connects habitat patches, which are homogeneous areas that differ from their surroundings, and provides routes for the movement of organisms between them [65]. As Vogt et al. [63] pointed out, the assessment of biodiversity indicators is a multiple-scale concept and assessment methods that allow multi-scale analysis should be preferred. They used morphological operations for the automated mapping of corridors, patches and gaps based on Corine Land Cover [66] data, stressing the fact that they were interested in regional to continental scale. Using a similar set of morphological image operations, these landscape elements could be extracted from ALS-based raster maps (e.g. vegetation maps), while extending to a finer, local scale level and exploiting the much higher resolution of the laser data. The penetration ability of ALS can further be used for a description of not only if two landscape patches are connected, but how this connection is composed in terms of vertical distribution of the foliage [67].

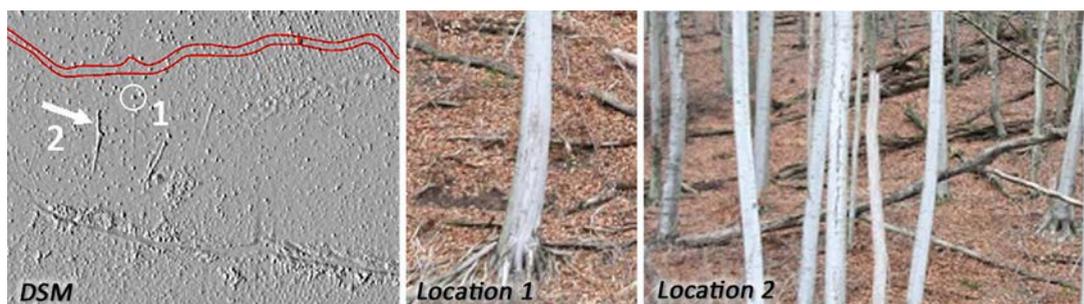


Fig. 4: DSM produced from full-waveform ALS point cloud cut of at 2 m height difference to DTM. Individual and fallen trees are clearly visible. The two images on the right were taken on-site and geo-referenced with GPS. [55]

4.4 Fallen trees and tree species

The high point densities, especially in FWF-ALS, allow for the detection of features that could not be accounted for in lower resolutions. A denser point cloud increases the probability of reflections from stems of single and fallen trees. By selecting points below a certain level of normalized height, e.g. 2 m, and computing a digital surface model (DSM) from the remaining point cloud, individual and fallen trees can clearly be seen in the model (Fig. 4). The presence of understorey or herbaceous vegetation would of course influence the result. Nevertheless, this could be controlled by adapting the height threshold with respect to the scrub layer.

Another way of locating fallen trees is by computing the relation of the number of points below 0.2 m and in the range of 0.2 to 2 m, which is a penetration rate for the near-ground zone (Fig. 5c). Hollaus [68] confirmed by visual examination that the linear structures in the resulting model correspond to broken-down trees. Dying and dead trees, either standing or fallen, provide habitats for a large number of rare and sometimes threatened species [47] and therefore have an important role in conserving forest biodi-

versity. They also influence the canopy, creating gaps when they fall. This allows for more sunlight to reach to forest ground, which can be used by different tree seedlings to grow faster [69]. Plant community composition depends upon both, the frequency of gap creation and the mode of gap-phase regeneration [70]. For example, gap-phase regeneration in tropical forests is dominated by lianas and stalled in a low-canopy state for many years, favouring the growth of a distinct suite of mature species and ultimately result in contrasting species composition [71].

The penetration rate can also be utilized for the recognition of different tree species. The method proposed by Hollaus et al. [72] is based on the assumption that the penetration differs between tree types and season. A deciduous tree loses its leaves during winter time, whereas coniferous trees usually keep their needles. Consequently, this is represented by the height distribution of the tree-wise laser echoes, which can be described by statistical measures and used for discrimination of tree types. For coniferous species like larch, which also drops its needles in winter, other discriminators provided by FWF-ALS can be used. Hollaus et al. [72] stated that the sig-

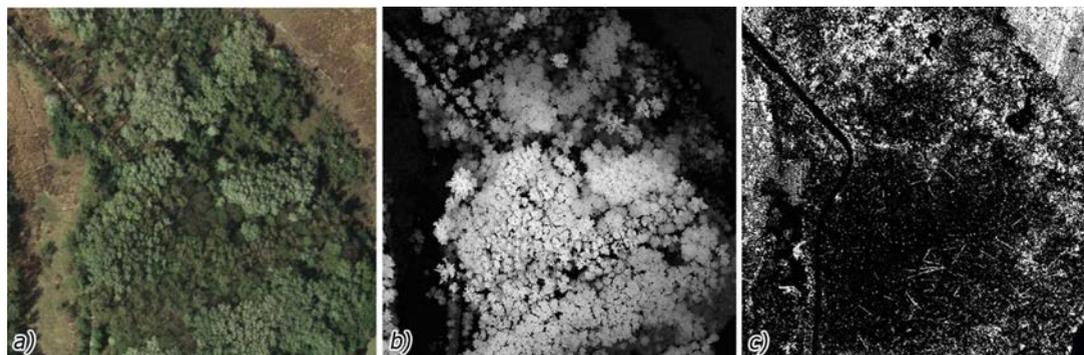


Fig. 5: (a) Orthophoto; (b) nCM (white = high); (c) ratio of points below 0.2 m and in between 0.2 and 2 m (black = only points below 0.2 m), linear structures correspond to fallen trees. [60]

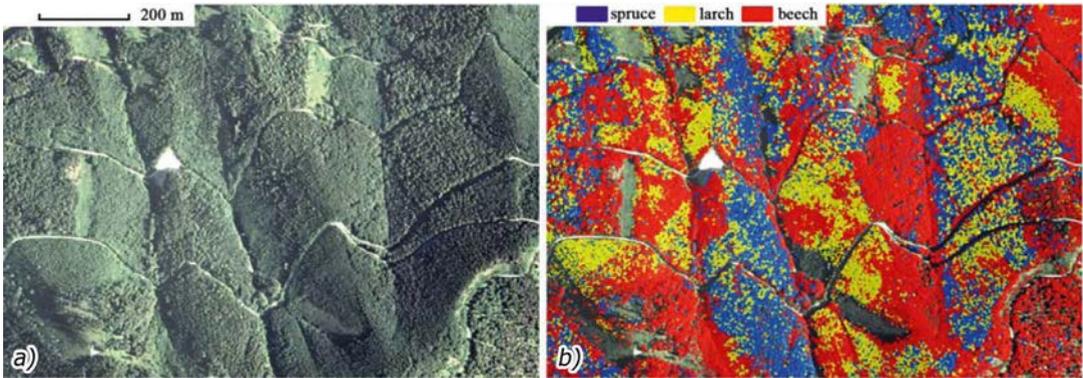


Fig. 6: (a) Orthophoto of forested area; (b) identified tree species spruce (blue), larch (yellow) and beech (red). [64]

natures of the FWF observables echo width and the derived backscatter cross section [18] show significant differences between species, which they used in a decision-tree-based classification method (Fig. 6). The naturalness of the tree species composition is a suitable indicator for the assessment of human impact on the forest by forest management practice [47].

4.5 Proglacial habitats

But it is not only ALS over forested or agricultural areas that can provide significant indicators for biodiversity assessment. In the past decade, ALS data were increasingly used for the mapping of glaciers [73-77]. Only few adapted species are able to live year-round and survive under the rather inhospitable conditions glaciers usually provide. However, within this living space they can exist and flourish because they are not endangered by competing species or predators. Glacier foreland, defined as the region between the current leading edge of the glacier and the moraines marking the latest maximum, are highly dynamic habitats, which are slowly populated by different plants and animals. Due to the melting of the glacier ice, these areas are extended and the few highly specialized species are displaced by others. Identifying areas where such processes take place is of importance for the estimation of the state of mountain ecosystems. Using the 3D point cloud and return intensities provided by ALS, maps of the spatial extent of glaciers including a classification into different surface types (e.g. crevasses, snow, firn, ice) can be created. Many glacial areas were covered by multiple scanning campaigns, so multitemporal analysis is possible. In this way, the data collected by ALS can be used for the monitoring of glaciers and provide efficient means for the

detection of natural processes and changes, like glacial retreat, melting of dead ice bodies (ice that is no longer connected to the active glacier) and development of proglacial habitats [78].

5. Summary and Outlook

This paper gives an introduction and overview on how ALS, and especially the additional observables from FWF-ALS, can be used in order to support biodiversity assessment. So far unequalled point densities offer unique possibilities for detection and modelling of features that could not be accounted for in conventional discrete ALS. As for the biodiversity indicators mentioned in the SEBI 2010 initiative, some can be directly derived with existing algorithms, like the forest stem volume or the forest layer structure (see section 4.1), fragmentation (see section 4.2 and 4.3) and dead wood (see section 4.4). While others can be estimated more indirectly, e.g. the occurrence of alien species, which could be found as the inverse of derived native species from tree species identification. For other indicators mentioned in the initiative, like the fragmentation of river systems, methods for derivation with the application of FWF-ALS are conceivable.

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Contact

Werner Mücke, Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Gußhausstraße 27 – 29, 1040 Vienna, Austria.
E-Mail: wm@ipf.tuwien.ac.at

Anna Hermann, Department of Conservation Biology, Vegetation - and Landscape Ecology, Faculty of Life Sciences, University of Vienna, Rennweg 14, 1030 Vienna, Austria.
E-Mail: anna.hermann@univie.ac.at