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Important LiDAR metrics for discriminating forest tree species in Central Europe

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ABSTRACT

Numerous airborne LiDAR-derived metrics have been proposed for classifying tree species. Yet an in-depth ecological and biological understanding of the significance of these metrics for tree species mapping remains largely unexplored. In this paper, we evaluated the performance of 37 frequently used LiDAR metrics derived under leaf-on and leaf-off conditions, respectively, for discriminating six different tree species in a natural forest in Germany. We firstly assessed the correlation between these metrics. Then we applied a Random Forest algorithm to classify the tree species and evaluated the importance of the LiDAR metrics. Finally, we identified the most important LiDAR metrics and tested their robustness and transferability. Our results indicated that about 60% of LiDAR metrics were highly correlated to each other ($|r| > 0.7$). There was no statistically significant difference in tree species mapping accuracy between the use of leaf-on and leaf-off LiDAR metrics. However, combining leaf-on and leaf-off LiDAR metrics significantly increased the overall accuracy from 58.2% (leaf-on) and 62.0% (leaf-off) to 66.5% as well as the kappa coefficient from 0.47 (leaf-on) and 0.51 (leaf-off) to 0.58. Radiometric features, especially intensity related metrics, provided more consistent and significant contributions than geometric features for tree species discrimination. Specifically, the mean intensity of first-or-single returns as well as the mean value of echo width were identified as the most robust LiDAR metrics for tree species discrimination. These results indicate that metrics derived from airborne LiDAR data, especially radiometric metrics, can aid in discriminating tree species in a mixed temperate forest, and represent candidate metrics for tree species classification and monitoring in Central Europe.

1. Introduction

Discrimination of tree species is a major task undertaken in a wide range of environmental applications, such as biodiversity monitoring (Shang and Chazette, 2014; Suratman, 2012), ecosystem services assessment (Jones et al., 2010; Skidmore et al., 2015), invasive species detection and control (Boschetti et al., 2007), as well as sustainable forest management (Pcorona et al., 2006). Remote sensing can provide a valuable information source towards our understanding of ecosystem structure and function over large spatial scales (Baldeck et al., 2015). The identification and mapping of tree species is usually conducted through visual interpretation of aerial photographs by human experts coupled with forest inventory (*in situ*) plots, which is labour-intensive, time consuming and costly. More importantly, this method is not practical or applicable to large forested areas (Kim et al., 2009). Optical remote sensing such as airborne or spaceborne multispectral and hyperspectral images have been used to map tree species over the last few decades (e.g. Aspinall, 2002; Boschetti et al., 2007; Feret and Asner, 2013; Immitzer et al., 2012; Jones et al., 2010; Leckie et al., 2003, 2005; Somers and Asner, 2014). However, during the process of developing these remote sensing solutions, it has also been realized that multi- and hyper-spectral images have their own limitations (Heinzel and Koch, 2012). For instance, the same tree species can have different spectral signatures in different parts of forest (Immitzer et al., 2012). Also, different tree species may possess similar spectra as well, particularly in a mixed pixel (Ghiyamat and Shafri, 2010). Furthermore, multi- and hyper-spectral images are generally restricted to the horizontal plane,

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providing limited insight pertaining to the vertical profile of tree structure (Jones et al., 2010).

Recent developments in active remote sensing, particularly the light detection and ranging (LiDAR) technique, have shown great potential for tree species mapping due to its capability of capturing three-dimensional (3D) information of objects of interest (Brandtberg, 2007; Clark et al., 2004; Coops et al., 2007; Holmgren and Persson, 2004; Hyyppä et al., 2001; Lindberg et al., 2014; Næsset, 2002). Unlike multi- and hyper-spectral images, it is possible to retrieve structural properties of trees from LiDAR, based on the discrete points or full-waveform data (Alonzo et al., 2014; Asner et al., 2008; Coops et al., 2007; Dalponte et al., 2014; Onojeghuo and Blackburn, 2011; Shang and Chazette, 2014). From a morphological point of view, tree species differ in their foliage distributions and branching patterns under different canopy conditions, resulting in diverge architectures which can be captured by LiDAR. For instance, the foliage of Norway spruce (*Picea abies*) (Fig. 1a) is clustered near the stem with pyramidal crown shape, while the foliage of European beech (*Fagus sylvatica*) (Fig. 1b) is more evenly distributed along the stem and has an oval crown shape. Histograms of laser pulse return frequency within varying height bins illustrate reflection allocation throughout the canopy (Fig. 1). A larger number of returns are reflected within the upper layer of spruce compared to beech. Under leaf-off condition, more returns were allocated towards the bottom of the canopy yet the top of the canopy was still well-represented by the LiDAR point cloud distribution (Fig. 1b). Thus, tree morphology characterized by LiDAR metrics may increase the ability to accurately discriminate tree species.

Over the past decade, a large number of airborne LiDAR-derived metrics have been proposed for tree species classification (Brandtberg, 2007; Brandtberg et al., 2003; Cao et al., 2016; Holmgren and Persson, 2004; Hovi et al., 2016; Kim et al., 2011, 2009; Li et al., 2013; Lin and Herold, 2016; Moffiet et al., 2005; Ørka et al., 2009; Reitberger et al., 2008). Generally, these LiDAR metrics can be categorized into two groups, namely geometric and radiometric metrics. The geometric metrics describe the geometric structure of trees (e.g. crown shape, tree height and crown volume) while the radiometric metrics refer to specific echo parameters that are extracted from the received waveform (e.g. the backscatter cross-section, the energy of laser points, and the distance between two waveform echoes) (Koenig and Höfle, 2016; Wagner, 2010). Particularly, intensity of the backscattered signal is additionally related to foliage type, leaf size, leaf orientation, leaf clumping and foliage density (Kim et al., 2009; Korpela et al., 2010; Suratno et al., 2009). The echo width is dependent on the amount, distribution and orientation of scattering elements along the laser beam direction. These properties can all vary within and between tree species and thus may be useful for differentiating materials and ultimately tree species. Previous studies have demonstrated that LiDAR metrics can be used to improve the mapping accuracy of tree species. However, most of these studies focused on data-driven or algorithm-driven approaches and pursued an optimization of classification accuracy (Fassnacht et al., 2016). Consequently, an in-depth ecological and biological understanding of the linkage between tree species morphology and LiDAR derived metrics has not been performed. Identifying essential LiDAR metrics for tree species classification can not only reduce the "redundant" or "overfitting" caused by highly correlated metrics, but also help us build links between the inherent architectural differences of tree species and how they manifest in LiDAR metrics.

The phenological development of tree species is characterized by distinct seasonal phases of bud burst, leaf flushing, flowering, senescence and dormancy (Calle et al., 2010). The physical changes in canopy structure are particularly prominent for deciduous tree species. The integration of LiDAR data acquired under leaf-on and leaf-off conditions has been proven useful for tree species classification in previous studies (Kim et al., 2009; Ørka et al., 2010; Reitberger et al., 2008; Yao et al., 2012). Although some of these studies suggested several important LiDAR metrics for tree species classification, the majority of them focused on the effects of different canopy conditions on tree properties or only considered a few LiDAR metrics. The role of LiDAR metrics derived from both discrete point and full-waveform data under leaf-on and leaf-off conditions for individual tree species classification has not been explored. Moreover, Sumnall et al. (2016) concluded that the greatest complimentary information about a forest canopy profile can be derived from both leaf-on and leaf-off data rather than discrete return or full-waveform LiDAR data. Nonetheless, due to the incompatibility of LiDAR collections, data availability as well as

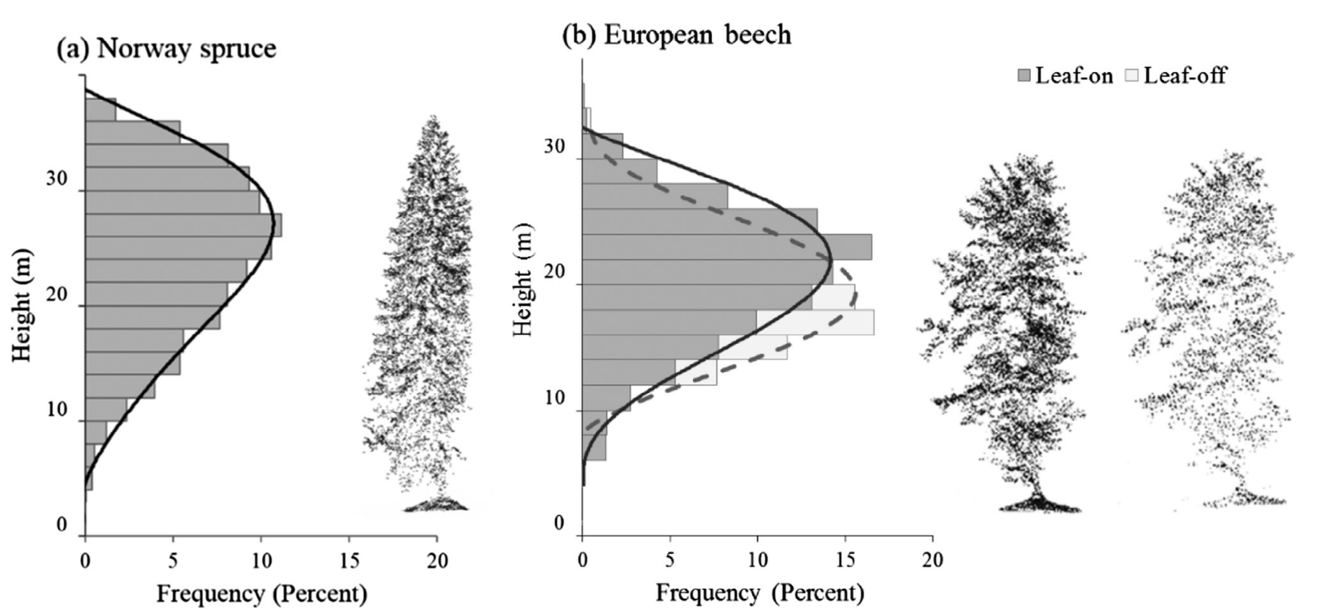

Fig. 1. Example of distributions of canopy laser pulse returns within (a) Norway spruce, and (b) European beech under leaf-on and leaf-off conditions using airborne LiDAR data.