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Forest canopy-structure characterization: A data-driven approach

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ABSTRACT

Forest canopy structure influences and partitions the energy fluxes between the atmosphere and vegetation. It serves as an indicator of a variety of biophysical variables and ecosystem goods and services. Airborne laser scanning (ALS) can simultaneously provide horizontal and vertical information on canopy structure. Existing approaches to assess canopy structure often focus on in situ collected structural variables and require a substantial set of prior information about stand characteristics. They also rely on predefined spatial units and are usually dependent on site-specific model calibrations. We propose a method to provide quantitative canopy-structure descriptors on different scales, retrieved from ALS data. The approach includes (i) a sensitivity assessment and a quantification of ALS-derived canopy-structure information dependent on ALS data properties, (ii) an automatic determination of the most feasible spatial unit for canopy-structure characterization, and (iii) the derivation of canopy-structure types (CSTs) using a hierarchical, multi-scale classification approach based on Bayesian robust mixture models (BRMM), satisfying structurally homogenous criteria without the use of in situ calibration information. The CSTs resulted in retrievals of canopy layering (single-, two-, and multi-layered canopies) and canopy types (deciduous or evergreen canopies). Retrievals classified seven CSTs with accuracies ranging from 52% to 82% user accuracy (canopy layering) and 89–99% user accuracy (canopy type). The method supports a data-driven approach, allowing for an efficient monitoring of canopy structure.

1. Introduction

Forests are one of the most biologically diverse terrestrial ecosystems on Earth (Pan et al., 2013). They play a pivotal role in the global biogeochemical and biophysical cycles (Ross, 2012; Bonan, 2008; Betts et al., 2001) and provide a wide range of valuable ecosystem goods and services, including food, timber, and climate moderation (Jackson et al., 2005; McKinley et al., 2011). Understanding and monitoring forest ecosystems and their underlying processes allows for the projection of biogeochemical and biophysical cycles under changing climate conditions, for example, and supports forest management, conservation biology and ecological restoration (Pan et al., 2013; Jonsson and Wardle, 2010; Sierra et al., 2009; Purves and Pacala, 2008).

The canopy structure is considered a particularly crucial constituent of forest ecosystems's functioning and processes as it, among other things, influences the energy fluxes between the atmosphere and forests (Xue et al., 2011; Shugart et al., 2010; Yang and Friedl, 2003). In view of forest management, important cost-benefit synergies can be achieved by using canopy-structure variables as indicator to determine forest's stand resistance to disturbances (Kayes and Tinker, 2012), to identify recruitment limitations (Herrera and García, 2010; Spies, 1998), and to estimate biodiversity conservation as a key objective for sustainable forest management (Gao et al., 2014; Graf et al., 2009; Lindenmayer et al., 2006; Spies, 1998).

According to Pan et al. (2013), Nadkarni et al. (2008), and Disney et al. (2006), canopy structure is considered the three-dimensional distribution of structural elements such as leaves, branches, and stems and their topology within the forest canopy. Canopy structure itself is not a measurable quantity, but properties of the canopy structure can be described by means of a wide variety of canopy-structure variables, such as tree height, tree diameter distribution, foliage density, or stand volume (McElhinny et al., 2005). Traditionally, canopy-structure variables are assessed by conventional fieldwork in relatively small sampling areas, which is time consuming and occasionally subjective (Foody, 2010; Haara and Leskinen, 2009; McElhinny et al., 2005). Advances in Earth Observation systems and analysis techniques have greatly improved the ability to determine canopy-structure variables over large areas in not only the horizontal but also the vertical dimension (Jones et al., 2012; Hall et al., 2011; Roberts et al., 2007;

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Asner et al., 2012). In particular, light detection and ranging (LiDAR) systems, particularly airborne laser scanning (ALS) systems, are suitable to provide not only horizontal information on the canopy structure but also detailed vertical information based on the physical measurement principles of active sensing and full-waveform digitization (Kane et al., 2010; Næsset, 2004).

Assessing canopy structure using ALS includes methods based on the stratification of the canopy (Ferraz et al., 2012; Lindberg et al., 2012; Morsdorf et al., 2010) and the interpretation of the horizontal patterns of strata (Nieschulze et al., 2012; Zhao et al., 2009; Maltamo et al., 2006) and of those based on individual trees and tree-crown delineations (Kaartinen et al., 2012; Ene et al., 2012; Hyyppä et al., 2008; Popescu, 2007; Morsdorf et al., 2004). As a result, a vertical canopy structure can be described on either the individual tree level (Kaartinen et al., 2012; Larsen et al., 2011; van Leeuwen and Nieuwenhuis, 2010) or on the canopy level using so-called area-based approaches (ABA: Vastaranta et al., 2012; Shugart et al., 2010; Næsset, 2004). Currently, the choice of the specific level and the definition of the related spatial unit is driven primarily by user requirements and/or the spatial unit of in situ measurements, and it is usually limited by the features present in the available data (Breidenbach et al., 2010; Treitz et al., 2012; Zimble et al., 2003). However, most canopy-structure components also have inherent spatial scales, and the choice of the respective level and the related spatial unit should be made considering the investigated structural component (Pan et al., 2013; Ishii et al., 2004; Marceau and Hay, 1999).

In this study, an ABA using regularly spaced grids was used because it is flexible in terms of spatial scale analysis and allows for the comparison of results across scales (Wulder et al., 2013; Vastaranta et al., 2012). ABA-based canopy-structure characterization can be derived from the ALS point cloud either directly (Ferraz et al., 2012; Morsdorf et al., 2010) or indirectly, by, for example, generating histograms using classified point cloud height distributions or based on height distribution probability functions (Leiterer et al., 2012; Wang et al., 2008; Maltamo et al., 2005). The characteristic of the echo-height distributions is affected by many factors, such as the ALS data properties (e.g., point density or scan-angle range), the specific canopy structure and the underlying size of the spatial unit (Treitz et al., 2012; Korpela et al., 2010; Wang et al., 2008; Frazer et al., 2005). Although many studies have been published on the effect of the chosen spatial unit in spatial modeling (cf. Hengl, 2006), most of them are limited to two-dimensional applications. Because canopy structure is a complex, three-dimensional feature, the definition of the spatial unit is strongly linked to the vertical canopy-structure analysis. An increase of the spatial unit will result in more mixing of the horizontal and vertical structure components within each spatial unit; we thus considered the two to not be independent of each other (Wang et al., 2008; Frazer et al., 2005).

The application of ABA for canopy-structure characterization was investigated by Næsset (2004), Wulder et al. (2013, 2012) and White et al. (2013), who found it to be robust for operational use. Variables related to the vertical stratification of the canopy, however, are rarely considered, although the relevance of canopy strata for wildlife habitat, stand productivity and forest successional stages is well-known. Moreover, existing approaches to assessing canopy structure often focus on canopy-structure variables defined by the specific application (e.g., traditional forest inventory) and thus require prior information about stand characteristics (e.g. species composition or development stage). The spatial units are often defined to coincide with the field data and the methods are dependent on the inherent characteristics of the ALS data, the site-specific model calibration (e.g., regression models in allometry) and the selected canopy-structure variables (cf. Tang et al., 2014; Whitehurst et al., 2013; Treitz et al., 2012; Ferraz et al., 2012; Zhao et al., 2011; Wang et al., 2008). Inherent spatial scales of the investigated structural components (Shugart et al., 2010; Saunders et al., 2005) are often not taken into account.

To overcome these limitations, we propose using ALS data solely for an automated and self-sustained ABA to provide objective and quantitative descriptions of canopy structure on different scales. We will use relative-frequency distributions (RFDs) of ALS echoes within a given grid cell to derive structural homogeneous areas: In the following, we will refer to them as canopy-structure types (CSTs: Leiterer et al., 2012). CSTs can be used directly as an objective, data-driven basis for forest expert interpretation or can be used indirectly as model input to calculate canopy-structure variables such as foliage distribution, canopy volume and canopy cover or to predict additional ecosystem services relevant for sustainable forest management, such as the potential for conserving biodiversity and the stand's productivity.

1.1. Aim and research objectives

The three main objectives of this study were (i) to investigate the sensitivity of ALS data properties (such as point density, scan angle, and acquisition date) on the RFD, (ii) to analyze the grid-cell size effect and to develop an automatic method to determine optimal grid-cell size, and (iii) to cluster and classify data to derive CSTs using a hierarchical, multi-scale classification approach based on Bayesian robust mixture models (BRMMs). We evaluated the application potential of CSTs for forest management with forestry experts, asking them to assess CSTs in terms of canopy layering (single-, two-, and multi-layered canopies) and canopy type (deciduous or evergreen canopies). For evaluation, we cross-compared the structure variables $canopy_{layer}$ and $canopy_{type}$ with forest inventory data.

2. Study area and data

2.1. Study site

The Laegeren site (47°28′N, 8°21′E, 200 ha) is a semi-natural mixed deciduous mountain forest that is dominated by common beech (*Fagus sylvatica* L.), European ash (*Fraxinus excelsior* L.), and sycamore maple (*Acer pseudoplatanus* L.), with scattered silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* L.) trees (Schneider et al., 2014). It is located northwest of Zurich (CH) and is part of the Swiss Jura. The site is approximately 800 ha and the elevation ranges from 515 m to 860 m above sea level, with primarily north- and south-facing slopes with inclinations between 37° to 72° (Fig. 1).

The canopy is well structured with distinct background, understory and overstory layering. The background consists of bare soil, rock, and litter, and the understory is characterized by a dense herb and shrub coverage. The canopy contains a moderate diversity of species with 12 dominant species at the top-of-canopy level. Trees are up to 165 years old, with a diameter distribution of up to 150 cm (Eugster et al., 2007). The canopy is fairly closed with overlapping tree crowns. Extensive ground-based reference data were collected for a 9 ha core study site, located on the south-facing slope of the Laegeren mountain and centered around the FLUXNET site ('Laegeren', site CH-Lae) and a long-term forest ecosystem research site (LWF) site of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). The core study site represents very well the variation generally found in the canopy structure, including areas undergoing different forest management practices (ranging from semi-natural forests to highly intensive regimes with silvicultural interventions) and a variety of forest types (ranging from beech and spruce monocultures to mixed mountain forests).