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Geometrically explicit description of forest canopy based on 3D triangulations of airborne laser scanning data

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ABSTRACT

Geometrically explicit parameterizations of the locations, orientations and properties of trees and canopy elements are useful for forest ecosystem modeling. Detailed reconstructions based on real tree geometry are, however, hard to obtain based on conventional field measurements and sampling. We describe and evaluate an alternative approach to reconstruct the forest canopy from sparse, leaf-off airborne laser scanning (ALS) data with a wall-to-wall coverage. The approach employs computational geometry and topological connectivity to generate filtrations, i.e., ordered sets of simplices belonging to the three-dimensional (3D) triangulations of the point data, and numerical optimization to select the set of simplices with a quasi-optimal relationship with field-measured forest biophysical attributes. The approach was evaluated by predicting the quantities and spatial patterns of biomass-related forest attributes according to the characteristics of the filtration. When the filtration parameters were optimized for 245 sample plots of 300 m^2 located in southern boreal forest in Finland, the coefficients of determination (R^2) between total volumes of the filtrations and basal area, stem volume, total above-ground biomass, and canopy biomass were 0.93, 0.87, 0.87, and 0.62, respectively. Considerably less accurate results ($R^2 = 0.44$–0.64) were obtained when the filtration parameters were predicted with a limited number of the calibration field plots. However, these accuracies could be obtained with modest field training data of 20–30 plots. The proposed approach is a compromise between the parameterization of the forest scene by artificial tree/crown level turbid media and realistic 3D models. The results particularly suggest that obtaining coarse wall-to-wall descriptions does not require separate data acquisitions, but may be based on data existing due to previous practical inventories.

1. Introduction

Forest structure affects the amount and distribution of light in the canopy and forest floor, and its estimation is required by many terrestrial ecosystem models. Also, studies of reflective properties of specific land cover types require parameterization of the three-dimensional (3-D) forest scene, in which locations, orientations, properties of the trees and, at the finest levels of geometric detail, branches, leaves and shoots are explicitly defined (Brunner, 1998). Obtaining these detailed parameterizations (referred to in the following text as "*geometrically explicit descriptions of forest canopy*") is complicated based on conventional field measurements and sampling. Therefore, the analyses typically reduce to the use of a dimensionless indicator such as the leaf area index (LAI), canopy cover or closure to characterize forest canopies (e.g., Smith, Anderson, & Fladeland, 2008). Even the explicit approaches (e.g., Ni-Meister, Jupp, & Dubayah, 2001; North, 1996) typically simplify the structural representation of individual tree crowns by using simple geometric primitives such as cones or ellipses to approximate the distribution of canopy elements and the actual crown shape (see also Rautiainen, Mõttus, Stenberg, & Ervasti, 2008).

Remote sensing of forest structure provides an ecologically significant advance over the conventional methods (Bergen et al., 2009; Lefsky, Cohen, Parker, & Harding, 2002; Vierling, Vierling, Gould, Martinuzzi, & Clawges, 2008). Particularly techniques based on Light Detection and Ranging (LiDAR) allow 3-D descriptions based on pulses emitted to and reflected from forest canopy. LiDAR operated from an airborne platform, i.e., airborne laser scanning (ALS), allows the collection of wall-to-wall data for vast geographical areas with high spatial resolution and positional accuracy. A variety of studies demonstrates the quantification of canopy height and the linking of extracted height metrics with field-observed forest biophysical properties (Magnussen & Boudewyn, 1998; Means et al., 2000; Næsset, 1997a,b, 2002; Nilsson, 1996) and canopy properties such as the LAI, canopy cover and canopy gap fraction (Korhonen, Korpela, Heiskanen, & Maltamo, 2011; Korhonen & Morsdorf, 2014; Lovell, Jupp, Culvenor, & Coops, 2003; Morsdorf, Kötz, Meier, Itten, & Allgöwer, 2006). ALS-based

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analyses have matured and are routinely operated in various forest inventories, of which a recent handbook of best practices (White et al., 2013) and a recent textbook focused specifically on forestry applications (Maltamo, Næsset, & Vauhkonen, 2014) are concrete examples.

ALS data collected for terrain elevation modeling at regional to national scales by the land survey authorities of several countries (e.g., Bohlin, Wallerman, & Fransson, 2012; Dalponte, Martinez, Rodeghiero, & Gianelle, 2011; Gomez-Gutierrez, Schnabel, Lavado-Contador, & Garcia-Marin, 2011; Nord-Larsen & Riis-Nielsen, 2010; Villikka, Packalén, & Maltamo, 2012) are currently the most plentiful ALS data sets for environmental mapping, monitoring and modeling. However, due to the sparse densities (<1 pulses m^{-2}), these data are mainly analyzed for their distributions of height values (White et al., 2013), while geometrically explicit modeling would, in particular, require preserving the full 3-D geometry of the point data. Although geometric modeling techniques based on ALS data exist (e.g., Koch, Kattenborn, Straub, & Vauhkonen, 2014), the use of these techniques typically demands a considerably higher data density.

Studies carried out by Vauhkonen (2010a,b), Vauhkonen, Tokola, Maltamo, and Packalén (2010, 2014); Vauhkonen, Næsset, and Gobakken (2014); Vauhkonen, Seppänen, Packalén, and Tokola (2012) and Korhonen, Vauhkonen, Virolainen, Hovi, and Korpela (2013) propose triangulations of the 3-D point data as potential structures for multiple scales and varying densities. Fig. 1 gives an example of triangulating point data, i.e., subdividing the underlying space of the points into simplices, which results in weighted simplicial complexes (e.g., Edelsbrunner, 2011) with weights quantifying the (empty) space delimited by the points. To reconstruct the canopy volume populated by biomass and to exclude that volume from canopy voids (see also Fig. 1), Vauhkonen et al. (2014) proposed a filtering approach in which the simplices were classified into either canopy biomass or voids based on numerical optimization with field-measured biomass. The main interest of the present study is to further test this filtering approach for constructing geometrically explicit, wall-to-wall descriptions of forest canopy structure, which are assumed to be highly useful for structural ecosystem modeling.

Earlier, Nord-Larsen and Schumacher (2012) and Villikka et al. (2012) verified the suitability of the data acquired for ground elevation modeling also for forest inventories, while Maltamo et al. (2010) and Vauhkonen et al. (2012, 2014) have developed triangulation-based approaches for sparse point densities. Particularly, our study is a continuation of Vauhkonen et al. (2014), who introduced the concepts of triangulation and filtration for modeling volumetric canopy surfaces from sparse ALS data and assessed canopy volumes derived from 40 sample plots. Our study extends the setup of Vauhkonen et al. (2014) in two particular ways: We focused the evaluation on (*i*) the geometrically explicit models produced and (*ii*) the potential to produce these as a part of a practical forest inventory based on a limited set of field plots for model fitting/calibration. Regarding (*i*), we assessed the correspondence of the spatial arrangement of the obtained filtrations and the trees mapped in the field (Packalen et al., 2013). Regarding (*ii*), we fitted the models based on leaf-off ALS data acquired for ground elevation modeling and simpler forest variables measured in typical forest inventories rather than total or canopy biomasses (Vauhkonen et al., 2014). Finally, the data of 245 plots altogether allowed the separation of training and testing data, an evaluation of whether the workflow was operationally feasible, and a more robust validation of the previous results (Vauhkonen et al., 2014).

The purpose of this study is thus to evaluate the workflow for the 3-D reconstruction of forest canopy from the leaf-off, sparse

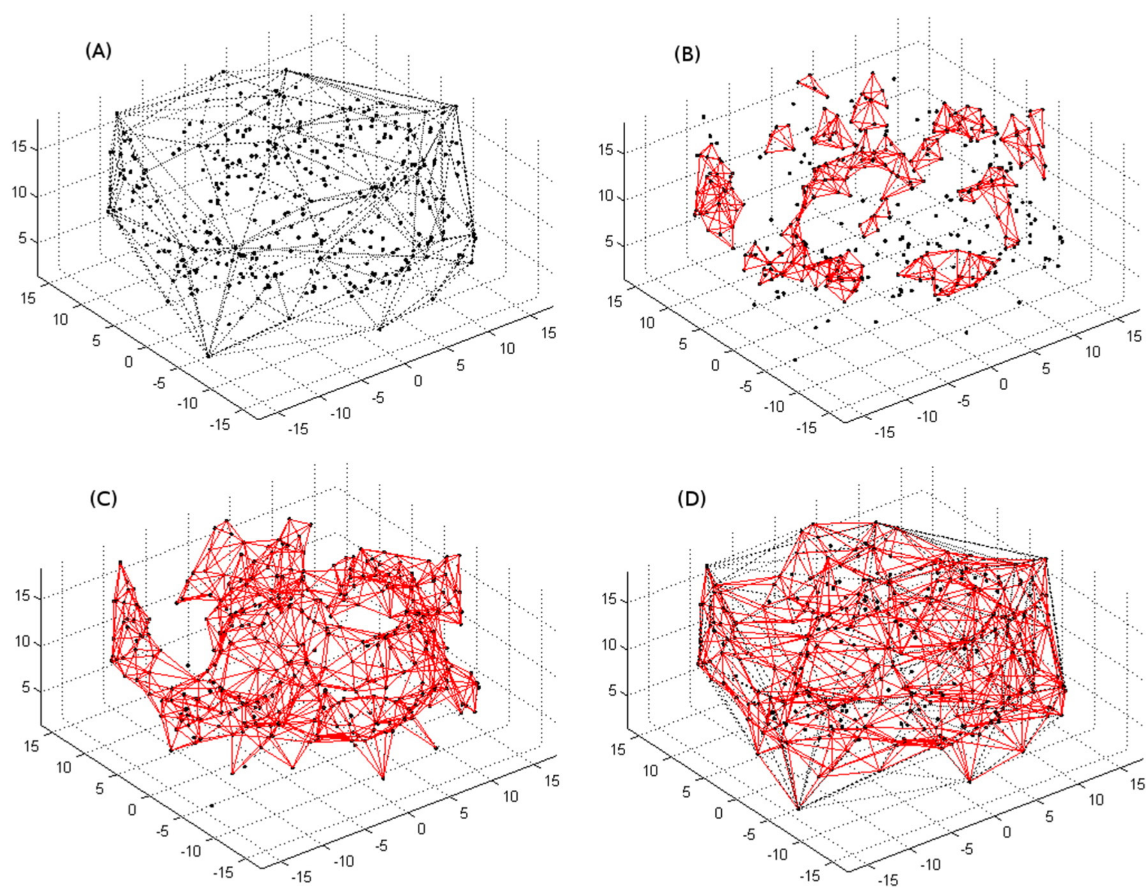

Fig. 1. Triangulation and filtration of an example set of 3D points. Subplot (A) shows the extreme values of the filtration: the initial set of points and the convex hull of the point data denoted by dashed lines. The red lines in subplots B, C, and D show three example simplicial complexes belonging to a filtration in which the subcomplexes were ordered according to parameter α increasing between B and D.