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Deriving airborne laser scanning based computational canopy volume for forest biomass and allometry studies

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ABSTRACT

A computational canopy volume (CCV) based on airborne laser scanning (ALS) data is proposed to improve predictions of forest biomass and other related attributes like stem volume and basal area. An approach to derive the CCV based on computational geometry, topological connectivity and numerical optimization was tested with sparse-density, plot-level ALS data acquired from 40 field sample plots of 500–1000 m^2 located in a boreal forest in Norway. The CCV had a high correspondence with the biomass attributes considered when derived from optimized filtrations, i.e. ordered sets of simplices belonging to the triangulations based on the point data. Coefficients of determination (R^2) between the CCV and total above-ground biomass, canopy biomass, stem volume, and basal area were 0.88–0.89, 0.89, 0.83–0.97, and 0.88–0.92, respectively, depending on the applied filtration. The magnitude of the required filtration was found to increase according to an increasing basal area, which indicated a possibility to predict this magnitude by means of ALS-based height and density metrics. A simple prediction model provided CCVs which had R^2 of 0.77–0.90 with the aforementioned forest attributes. The derived CCVs always produced complementary information and were mainly able to improve the predictions of forest biomass relative to models based on the height and density metrics, yet only by 0–1.9 percentage points in terms of relative root mean squared error. Possibilities to improve the CCVs by a further analysis of topological persistence are discussed.
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1. Introduction

Carbon accounting systems and policies promoting the use of renewable energy have drawn an increasing attention toward extensive yet detailed mapping of forest biomass. Wall-to-wall estimation and mapping of forest biomass calls for various airborne and satellite remote sensing (RS) based solutions operated at local to national scales. The most recent overviews of forest biomass assessments based on RS data are provided by Koch (2010), Zolkos et al. (2013) and Popescu and Hauglin (2014).

RS of forest biomass is based on indirect relationships between remotely sensed and field measured attributes. An increasingly popular approach to provide auxiliary RS data is airborne laser scanning (ALS) that produces three-dimensional (3D) vegetation height profiles from which various forest biophysical properties such as mean height (Nilsson, 1996; Næsset, 1997a; Magnussen and Boudewyn, 1998; Magnussen et al., 1999), basal area (Means et al., 2000), stand volume (Næsset, 1997b; Means et al., 2000), and stem size distribution (Gobakken and Næsset, 2004) can be derived. Since the tree stems constitute the single most important forest above-ground biomass (AGB) component, these findings even apply to AGB predictions. However, ALS also allows assessing individual biomass components (Popescu, 2007; Næsset and Gobakken, 2008; Kotamaa et al., 2010; Hauglin et al., 2012), and may in fact produce more detailed information with respect to canopy biomass (i.e. branches and foliage) than conventional methods based on field measurement and modeling, as verified by destructive sampling (Hauglin et al., 2013; Kankare et al., 2013).

ALS-assisted large-area assessments most often rely on area-based analyses (e.g. Næsset, 2002) of the distributions of height values extracted from sparse-density data (<1 pulses per m^2; e.g. Næsset, 2007; Maltamo et al., 2011; Woods et al., 2011). Notably, such analyses employ only one of the three dimensions available in the data. Information on the horizontal distribution of forest patches may be provided by analyzing the neighborhoods of the computation units such as grid cells or segments, or their internal variation as depicted by features derived from interpolated canopy height models (Hyyppä et al., 2012; Pippuri et al., 2012; Packalén

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et al., 2013). Yet, the 3D information in the point data is usually ignored. In light of the theories on tree allometry and stem development (Shinozaki et al., 1964a,b), the method development should ideally aim at quantifying foliage mass due to its strong allometric links with other tree attributes. Optimizing the use of the existing predictor space in various machine learning frameworks has however been a more popular approach than expanding it with such an allometric reasoning.

Earlier studies carried out at the individual tree level (Vauhkonen, 2010a) propose triangulations of the 3D point data to preserve the three-dimensional properties and produce foliage mass equivalent information for various analyses. A particularly interesting approach is the concept of 3D alpha shapes (Edelsbrunner and Mücke, 1994), or α-shapes, in which a predefined parameter α is used as a size-criterion to determine the level of detail in the obtained triangulation. Volume and complexity metrics based on α-shapes were used as proxy variables for predicting the species and stem attributes of individual trees by Vauhkonen et al. (2008, 2009, 2010a,b), Reitberger et al. (2009), Rentsch et al. (2011), and Yao et al. (2012), while Vauhkonen et al. (2012) provided further insight on using these metrics to improve area-based estimations of species-specific plot volumes.

An important step in the analyses based on α-shapes is the selection of α, for which the selected value should enable separation of void spaces from those populated by canopy biomass. Vauhkonen et al. (2008, 2009, 2010a,b, 2012) evaluated a range of α's, but rather than selecting one particular value, they used metrics quantifying the difference of the shape obtained with the range of α's to the convex hull of the point data, which corresponds to α-shapes with $\alpha \rightarrow \infty$. The other studies mentioned in the previous paragraph do not explain the selection of α. Korhonen et al. (2013), attempting to model individual tree crown volume, selected a quasi-optimal α so that the resulting α-shape enclosed the point data within a single connected component. However, they found the volume based on the convex hull to have a closer correspondence with the field-measured reference crown volume, which also included void space due to the applied measurement principle.

Most interestingly, Vauhkonen (2010b) proposed iterating over a sequence of α's and by that vertically delineating individual tree crowns, which was further tested in an area-based application by Maltamo et al. (2010). This approach has a formal basis in topological connectivity and is particularly related to *filtration of simplicial complexes* (e.g. Delfinado and Edelsbrunner, 1995). Triangulating ALS point data corresponds to 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. We hypothesize that filtering these complexes according to the weights could provide a means to reconstruct the volume populated by biomass and separate that volume from the canopy voids (Fig. 1).

Thus, the purpose of this study was to develop a filtering and optimization procedure for deriving a "biomass-optimal" computational canopy volume (CCV) from the triangulations of plot-level ALS point clouds. Two criteria were employed to filter the triangulations of the point data, and the resulting filtration parameters and CCVs were evaluated on field data with respect to the total and canopy biomass, stem volume and basal area as target biophysical properties.

2. Methods

2.1. Study area and data

The study area is located in the municipality of Aurskog-Høland, in southeast Norway (59°50′N, 11°34′E, 120–390 m a.s.l.). The dominant tree species are Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). Younger stands have a larger portion of deciduous species than mature stands. Birch (*Betula pubescens* Ehrh.) is the dominant deciduous species. For further details, see Magnussen et al. (2010), who studied the same area.

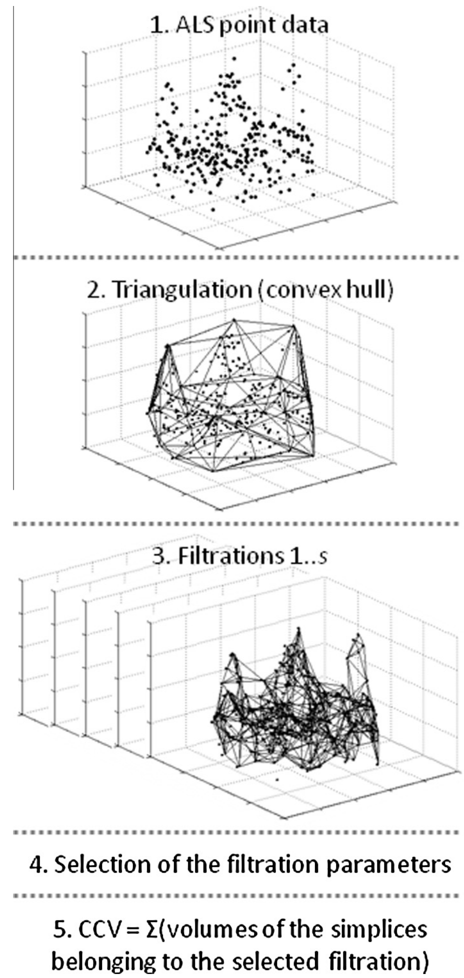

Fig. 1. Derivation of the CCV from the ALS point data of an example plot (schematic). Each step constitutes the input of the next consecutive step.

2.1.1. Field plots

Altogether 40 circular field plots (36 of 1000 m^2 and 4 of 500 m^2) were measured during the fall of 2007 and winter of 2008. These plots were located along five systematically spaced lines, but the exact plot locations within the lines were determined subjectively to obtain a sample of 20 spruce dominated and 20 pine dominated stands. Furthermore, 5 and 15 plots covered young and old growth for each of the two species, respectively. Each plot center was geographically referenced with a survey grade Global Positioning System and Global Navigation Satellite System receiver (Topcon LegacyE) applying differential post-processing by the Pinnacle software package version 1.00 (Anon, 1999). Based on the positional standard errors reported by Pinnacle, the estimated accuracy of the planimetric plot coordinates ranged from 0.1 to 0.35 m, with an average of 0.12 m.

All trees with a diameter at breast height (DBH) >5 cm were measured for the DBH and species. For the dominant tree species, the height of two trees in each of five diameter classes – covering the entire range of diameters – was measured using a Vertex hypsometer. Up to five trees of each minor species, selected with a probability proportional to stem basal area, were measured for

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