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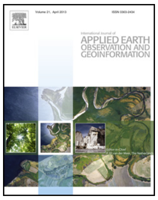

Application of 3D triangulations of airborne laser scanning data to estimate boreal forest leaf area index

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ABSTRACT

We propose 3D triangulations of airborne Laser Scanning (ALS) point clouds as a new approach to derive 3D canopy structures and to estimate forest canopy effective LAI (LAI_e). Computational geometry and topological connectivity were employed to filter the triangulations to yield a quasi-optimal relationship with the field measured LAI_e. The optimal filtering parameters were predicted based on ALS height metrics, emulating the production of maps of LAI_e and canopy volume for large areas. The LAI_e from triangulations was validated with field measured LAI_e and compared with a reference LAI_e calculated from ALS data using logarithmic model based on Beer's law. Canopy transmittance was estimated using All Echo Cover Index (ACI), and the mean projection of unit foliage area (β) was obtained using no-intercept regression with field measured LAI_e. We investigated the influence species and season on the triangulated LAI_e and demonstrated the relationship between triangulated LAI_e and canopy volume. Our data is from 115 forest plots located at the southern boreal forest area in Finland and for each plot three different ALS datasets were available to apply the triangulations. The triangulation approach was found applicable for both leaf-on and leaf-off datasets after initial calibration. Results showed the Root Mean Square Errors (RMSEs) between LAI_e from triangulations and field measured values agreed the most using the highest pulse density data (RMSE = 0.63, the coefficient of determination (R^2) = 0.53). Yet, the LAI_e calculated using ACI-index agreed better with the field measured LAI_e (RMSE = 0.53 and R^2 = 0.70). The best models to predict the optimal alpha value contained the ACI-index, which indicates that within-crown transmittance is accounted by the triangulation approach. The cover indices may be recommended for retrieving LAI_e only, but for applications which require more sophisticated information on canopy shape and volume, such as radiative transfer models, the triangulation approach may be preferred.

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1. Introduction

Green vegetation has a central role in determining the energy exchange between land surfaces and atmosphere. Areal interphase between land surfaces and atmosphere is quantified using Leaf Area Index (LAI), which is defined as the hemisurface area of the foliage per unit horizontal ground surface area (Chen and Black, 1992). LAI is also one of the Essential Climate Variables (ECVs) defined by the Global Climate Observing Systems -network (GCOS, 2012). Forest canopy LAI can be measured either directly (e.g. litter harvest) or indirectly using allometric foliage mass models or inversion of canopy light transmittance according to Beer's law (Monsi and Saeki, 1953): $LAI = -1/k \ln(T)$, where the term $1/k$ (β) is estimated using regression (k = extinction coefficient, which depends on foliage inclination angle distribution and reflectance), while T is the canopy transmittance. Optically measured (e.g. using LAI-2000 or hemispherical photography) estimate of LAI is called effective LAI (LAI_e), because it underestimates LAI due to shoot-level clumping (Stenberg, 1996) and possible tree-level clumping (Stenberg et al., 2014). Alternatively, stand-level LAI may be estimated based on foliage biomass models which take measured tree variables (e.g. diameter-at-breast-height (dbh) and tree height (h)) as an input. Allometric models estimate dry foliage mass which can be converted to area using Specific Leaf Area (SLA, m^2/kg) values and stem count. Yet, the optical measurements and allometric model estimates may result in very different LAI estimates (Majasalmi et al., 2017, 2013).

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Neither optical measurements nor allometric models are directly applicable to cover large geographical areas. Beer's law and Airborne Laser Scanning (ALS) may be used to create maps of LAI based on an estimate of canopy gap fraction in vertical direction (e.g. Solberg et al., 2009, 2006). However, application of Beer's law requires that the β is known. Optical methods are commonly applied to estimate β, because determining β based on allometric methods remains complicated. β may be obtained using field measured optical data (i.e. gap fraction readings) or from literature as e.g. a value of 2 denotes spherical leaf angle distribution (Korhonen and Morsdorf, 2014). The typical range of β in Nordic boreal forest for indices, which contain all ALS echoes ranges between two and three (Korhonen et al., 2011; Solberg, 2010; Solberg et al., 2009). LAI_e estimation using ALS data is based on cover indices, which may be calculated after ALS echoes are divided into canopy and ground echoes based on specified height threshold (e.g. 1–2 m). First echo Cover Index (FCI) and All echo Cover Index (ACI) are determined as fractions of canopy echoes so that the FCI is computed using first-of-many and single echoes, and ACI using all echoes (Korhonen and Morsdorf, 2014). ALS systems vary (e.g. maximum number of echoes, vertical separation of echoes) as do the acquisition settings (e.g. height → signal losses and footprint size → target illumination), which can influence the number of echoes and their height distribution (Korpela, 2016). The FCI may be used as a proxy for canopy cover, i.e., the proportion of the forest floor covered by the vertical projection of the tree crowns, whereas the ACI quantifies the total canopy transmittance (Korhonen and Morsdorf, 2014). Thus, ACI-based estimates of gap fraction are usually larger than FCI-based, because the fraction of ground echoes increases when the last echoes are included. The drawback of the cover index-based LAI_e estimates is that independent field data is needed for each ALS acquisition for unbiased results.

To simulate radiative transfer in the forest canopy, the locations, orientations, and properties of the trees need to be modeled as 3D objects to be used in canopy radiation models such as DART (Gastellu-Etchegorry et al., 2012). As measuring tree crown dimensions in the field remains problematic (e.g. Korhonen et al., 2013; Rautiainen et al., 2008), the common approach is to model them using geometric primitives, such as ellipsoids or cones. However, the use of geometric primitives derived from Individual Tree Detection (ITD) in ALS has been found insufficient for tree canopy description (Schneider et al., 2014). Assuming that the crowns to have a certain shape (cuboid, spheroid or cone) also led to considerable errors in the retrieved crown parameters (Calders et al., 2013). Korhonen et al. (2013) noted that ALS-based canopy volume (CV) estimates were more in line with the field measured estimates compared to CV estimates produced using general ellipsoidal crown models. Canopy radiation modelling approaches such as the DART model do not necessarily need fixed canopy elements but can be based on flexible 3D forms. Although there are different approaches to approximate 3D canopy structures using ALS data, only a few are applicable for low pulse density ALS data (Vauhkonen et al., 2016).

We propose analyzing computational geometry and topological connectivity of the ALS points clouds (e.g. Vauhkonen et al., 2016, 2014) as an alternative approach for modeling the 3D canopy structures, which is in agreement with independently estimated LAI_e e.g. from field measurements. Three-dimensional triangulation and a subsequent filtering of the ALS point clouds separates the CVs from the voids, provided a correct level of filtering (see Section 2.3.2). The optimal filtering can be determined by numerically optimizing the relationship between selected forest variable(s) and the triangulated CV. The novelty of the approach is that after the initial optimization the degree of filtering can be predicted based on ALS canopy metrics such as percentiles (the fraction of points below a certain height-threshold) to obtain wall-to-wall estimates based on the ALS data. The triangulation approach by Vauhkonen et al. (2016, 2014) differs from other 3D triangulation approaches, as it was developed for low pulse density (<1 pulses/m^2) ALS data collected by National Land Survey (NLS) authorities for terrain elevation modeling, and thus vast amounts of data are available for free, at least in Nordic countries.

Earlier, the triangulation approach was used for the retrieval of above ground biomass, stem volume and basal area (Vauhkonen et al., 2014). The applicability of the triangulation approach to estimate canopy biomass was studied using allometric biomass models from Sweden (Marklund, 1988) and from Finland (Repola, 2009, 2008). Results showed that allometric canopy biomass (i.e. contain branches and foliage) calculated using Marklund's models (1988) agreed well with the CV predicted using triangulations ($R^2 = 0.77$) (Vauhkonen et al., 2014). Yet, the foliage biomasses calculated using the models by Repola (2008, 2009), which are also used in National Forest Inventory (NFI) in Finland, were notably less linear ($R^2 = 0.45$) with the predicted CVs, although this somewhat depended on the optimization scheme applied by Vauhkonen et al. (2016). Yet, the drawback of allometric foliage biomass models is that they cannot be used to describe changes in vegetation health (e.g. defoliation), and are (often) both climate and site-specific, which limits the spatial area where the models may be used. Calibration of the triangulations approach with optical LAI_e data might thus increase the geographical area where the triangulation approach is applicable. There is a need to research if calibration of the triangulations model with optically-based LAI_e could result in more accurate LAI_e estimates compared to allometric foliage biomass models.

From forest inventory perspective the length of the leaf-off -period without snow is short which means that ALS data may be collected under both leaf-on and leaf-off conditions. Several studies have shown that leaf-off data is better suited for separating coniferous and deciduous tree species (e.g. Ørka et al., 2010) and for estimating mean height, basal area and timber volume using area-based approach (Næsset, 2005; Villikka et al., 2012) than leaf-on data. Recently, White et al. (2015) presented pooled models for leaf-off and leaf-on ALS data for predicting top height, mean height, Lorey's mean height, basal area, quadratic mean diameter, merchantable volume, total volume and total above ground biomass. However, so far there are no pooled models for canopy LAI, and thus in this study an attempt to develop such a model is presented. We adapt the triangulation approach, which was earlier optimized for predicting biomass-related forest attributes (Vauhkonen et al., 2014, 2016), to estimate LAI_e and CV from area-based ALS data. An optimization approach is used to determine a quasi-optimal relationship between the triangulation and Leaf Area Density (LAD, m^2/m^3), instead of using a constant value (e.g. Ma et al., 2014), and this degree of filtering is predicted for the plots based on common ALS metrics. The approach thus provides a description of the canopy as 3D volume, which is in an agreement with LAD, and eventually, LAI_e. We base the evaluation of the model on a comparison with field measured optical LAI_e and with reference LAI_e obtained using Beer's law and cover index. The novelty of our approach is to use field based optical estimates of LAI_e to approximate the shape of the LAD-function. The use of the optical instead of allometric LAI_e to calibrate the model allows accounting for between and within crown transmittances, which are needed to quantify vegetation structure and radiation transfer of canopies. In addition, the robustness of the triangulation approach was tested against data from different season, pulse density and tree species, which has not been studied with such detail before.

The aim of this study was to: 1) present a new application of 3D triangulations in ALS data to estimate forest canopy LAI_e, 2) compare LAI_e from triangulations with LAI_e calculated using a cover index, 3) investigate the influence of tree species and season of

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