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Estimation of 3D vegetation structure from waveform and discrete return airborne laser scanning data

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ABSTRACT

This study presents and compares new methods to describe the 3D canopy structure with Airborne Laser Scanning (ALS) waveform data as well as ALS point data. The ALS waveform data were analyzed in three different ways; by summing the intensity of the waveforms in height intervals (a); by first normalizing the waveforms with an algorithm based on Beer–Lambert law to compensate for the shielding effect of higher vegetation layers on reflection from lower layers and then summing the intensity (b); and by deriving points from the waveforms (c). As a comparison, conventional, discrete return ALS point data from the laser scanning system were also analyzed (d). The study area was located in hemi-boreal, spruce dominated forest in the southwest of Sweden (Lat. 58° N, Long. 13° E). The vegetation volume profile was defined as the volume of all tree crowns and shrubs in 1 dm height intervals in a field plot and the total vegetation volume as the sum of the vegetation volume profile in the field plot. The total vegetation volume was estimated for 68 field plots with 12 m radius from the proportion between the amount of ALS reflections from the vegetation and the total amount of ALS reflections based on Beer–Lambert law. ALS profiles were derived from the distribution of the ALS data above the ground in 1 dm height intervals. The ALS profiles were rescaled using the estimated total vegetation volume to derive the amount of vegetation at different heights above the ground. The root mean square error (RMSE) for cross validated regression estimates of the total vegetation volume was 31.9% for ALS waveform data (a), 27.6% for normalized waveform data (b), 29.1% for point data derived from the ALS waveforms (c), and 36.5% for ALS point data from the laser scanning system (d). The correspondence between the estimated vegetation volume profiles was also best for the normalized waveform data and the point data derived from the ALS waveforms and worst for ALS point data from the laser scanning system as demonstrated by the Reynolds error index. The results suggest that ALS waveform data describe the volumetric aspects of vertical vegetation structure somewhat more accurately than ALS point data from the laser scanning system and that compensation for the shielding effect of higher vegetation layers is useful. The new methods for estimation of vegetation volume profiles from ALS data could be used in the future to derive 3D models of the vegetation structure in large areas.

1. Introduction

Vertical vegetation structure can be defined as the amount of vegetation material as a function of height above ground. This information is useful for habitat modeling, for example for bird species (Lefsky et al., 2002), and for mapping of tree vegetation successions. Shugart et al. (2010) also found 3D vegetation structure useful for modeling of the carbon cycle.

Airborne laser scanning (ALS) measures both the height of vegetation elements and the ground. From such data, it is possible to derive variables related to vegetation height and vegetation density as a function of height above ground. The height data can be used to describe the vegetation structure and, to a certain extent, obtain information about the height and density of different layers of vegetation such as the field layer, shrubs and canopy layers. Most commercial ALS systems deliver discrete returns or point laser data. The point data represent high intensities in the reflected light corresponding to surfaces where the light has been reflected. Due to limitations in the electronics of most ALS systems, only sufficiently spaced surfaces are distinguished as separate returns. However, with the development of sensors and electronics, waveform laser data have also become available from commercial ALS systems. ALS waveform data are values of the intensity of the reflected laser light sampled at short, regular intervals. ALS waveform data describe the whole backscattered signal and allow for more detailed processing, for example, derivation of points from the waveforms (Persson et al., 2005). The intensity of the reflected light depends on the reflectance of the reflecting object and the distance from the scanner to the reflecting object. Additionally, the gain of the laser scanner might be adjusted depending on the conditions at the moment when the light is

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received. To estimate the absolute physical properties of the reflecting object, information about sensor gain and distance to the reflecting object is necessary. However, for nearby pulses the sensor gain and the distance to the reflecting objects are similar and an approximation is to use the measured intensity as proportional to the sum of the reflectance of the reflecting object. If the reflecting objects have similar reflectance, a further approximation is to use the intensity as proportional to the area of the reflecting object.

Leaf area index (LAI) can be estimated based on ALS point data (Korhonen et al., 2011; Morsdorf et al., 2006; Solberg et al., 2009). Since parts of the laser beams penetrate through a canopy, estimation of the understory is also possible to some degree (Hill & Broughton, 2009; Martinuzzi et al., 2009). ALS data may be used to separate single-story and multi-story stand structures through the shape of the distribution of ALS point data (Maltamo et al., 2005) or by examination of the height variability of local maxima in a canopy surface model defined from the points (Zimble et al., 2003). Correlation has been reported between the vegetation cover in different height intervals and the number of points in the intervals which makes it possible to use the distribution of points to characterize forest ecological structure (Miura & Jones, 2010). A quantitative measure of the vertical vegetation structure can be derived by dividing the canopy into key layers and fitting a Weibull distribution, for example, to each layer (Coops et al., 2007; Jaskierniak et al., 2011). Su and Bork (2007) determined the height of the herbaceous layer, understory shrub and the overstory tree layer in rangeland by calculating the average height of all ALS points falling in each interval. ALS waveform data from the experimental SLICER system at NASA have been used to estimate a canopy height profile (CHP) that quantitatively represented the relative vertical distribution of canopy surface area which seems to be correlated with a CHP measured in field (Harding et al., 2001). The effects of canopy structure on the ALS waveform can be described by a 3D radiative transfer model (RTM) (Ni-Meister et al., 2001; Yang et al., 2010). To characterize the canopy structure and physical properties, RTMs have also been used to invert the waveform (Koetz et al., 2006). The range, amplitude, width, and backscatter cross-section may be estimated for each echo by modeling the waveform as a series of Gaussian pulses to provide more accurate vegetation classification (Wagner et al., 2008).

Even if several previous studies have used ALS data to model the vertical vegetation structure, we have only found three studies that validate the results against detailed ground measurements. Harding et al. (2001) estimated canopy height profiles for four selected forest stands from ALS data from SLICER using measurements from a telephoto lens calibrated to measure distances as ground truth. Hilker et al. (2010) estimated canopy volume profiles for four forest stands from ALS point data and compared them with canopy volume profiles estimated from terrestrial laser scanning. Hosoi et al. (2010) estimated Leaf Area Density (LAD) in a forest plot from ALS data and compared with LAD estimated from TLS data. All three studies showed reasonably good agreement between the estimates from ALS data and ground measurements.

The aim of this study is to develop and evaluate automatic methods to detect vertical vegetation structure from ALS data to represent the shrub layer and one or several tree layers. The study compares different methods of estimating the vegetation volume profile from ALS waveform data. In one method the ALS waveform data is used directly (direct waveform (a)), in a second method care is taken to first compensate for the shielding effect of higher vegetation layers on reflections from lower layers (normalized waveform (b)), and in a third method points are derived from the ALS waveform (waveform points (c)). For comparison, the vegetation volume profile is also estimated from the vertical distribution of conventional, discrete return ALS points from the laser scanning system (system points (d)). The vegetation volume profile is defined as the volume of all tree crowns and shrubs in 1 dm height intervals in a field plot. The vegetation volume profile is used rather than biomass profiles or LAD (Morsdorf et al., 2006) since it is feasible to measure in a large number of field plots. The vertical distribution of ALS data is compared with the vegetation volume profile and the vegetation volume at different heights above the ground is estimated. The results from the different methods are evaluated with cross validation to find the methods which produce the most accurate results.

2. Field reference data

2.1. Study area

The study area is located in the southwest of Sweden (Lat. 58° N, Long. 13° E). Parts of the study area have been used in studies of remote sensing for forest management planning (Holmgren et al., 2003). The most common tree species and their fraction of the total basal area are Norway spruce (*Picea abies (L.)*) (38.5%), Scots pine (*Pinus sylvestris (L.)*) (28.0%), birch (*Betula pendula (L.) and Betula pubescens (L.)*) (18.0%), oak (*Quercus robur (L.)*) (6.0%), alder (*Alnus glutinosa (L.)*) (5.5%), maple (*Acer platanoides (L.)*) (2.0%), aspen (*Populus tremula (L.)*) (0.5%), rowan (*Sorbus aucuparia (L.)*) (0.5%), and other broadleaved trees (0.5%). Additional small trees and shrubs in the area include bird cherry (*Prunus padus (L.)*) (0.5%), hazel (*Corylus avellana (L.)*), juniper (*Juniperus communis (L.)*), rose (*Rosa spp.*), willow (*Salix spp.*), raspberry (*Rubus idaeus (L.)*), currant (*Ribes spp.*) and other shrubs.

2.2. Field data collection

The study area was stratified on crown coverage and shrub coverage. An 80 × 80 m grid of points was laid out in the study area. Forest land was identified by using an existing forest management plan. The forest management plan was based on manual photo interpretation and contained polygons with forest stands and other land use types. Points outside forest land were divided into five crown coverage strata based on manual photo interpretation. Only points with crown and/or shrub coverage > 0 were included. Points inside forest land were divided into five volume density strata. Volume density is a function of the stem volume divided by the mean tree height (Jonson, 1914). The stem volume was taken from the forest management plan and the 95th percentile of the ALS data represented the mean tree height in each point. Only points where the maximum height of the ALS data was ≥20 m were included.

The result was ten crown coverage strata: five from manual photo interpretation and five from volume density. Three hundred and twenty nine points were randomly selected; one point in each polygon in the forest management plan. During the field inventory, the selected points were visited and the shrub coverage was estimated by counting the number of trees and shrubs with height 0.3–3 m within 5 m from the point. The point was placed in a shrub coverage stratum for numbers 5–15, 16–25, 26–35, 36–45 and ≥45. If the number of already measured field plots in the stratum was less than three, the point was chosen as the center of a field plot.

Sixty-eight circular field plots with 12 m radius were allocated during July and August 2009 (Table 1, Fig. 1). The positions of the center of the field plots were measured using a Differential Global Positioning System (DGPS). The accuracy of the DGPS has been validated for 18 points in forest with crown coverage ≥50% and mean basal area weighted height 6 m in the north of Sweden. The root mean square error of the DGPS positions was 0.27 m after post processing. The positions of all trees and shrubs were measured relative to the center using an ultrasound instrument (Lämås, 2010). Within the field plots, the diameter at breast height (DBH) of all trees and shrubs with DBH ≥ 40 mm was measured using a caliper and the species was recorded. The width of the tree crown was measured in two perpendicular directions, one of which was the direction towards the field plot center. If the crown was overlapping with another crown, the whole diameter was still measured. The total number of trees and shrubs in this