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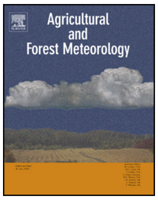

Characterising forest gap fraction with terrestrial lidar and photography: An examination of relative limitations

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Previous studies have shown that terrestrial lidar is capable of characterising forest canopies but suggest that lidar underestimates gap fraction compared to hemispherical camera photography. This paper performs a detailed comparison of lidar to camera-derived gap fractions over a range of forest structures (in snow affected areas) and reasons for any disagreements are analysed.

A terrestrial laser scanner (Leica C10 first return system) was taken to Abisko in Northern Sweden (sparse birch forests) and Sodankylä in Finland (spruce and pine forests) where five plots of varying density were scanned at each (though one Abisko plot was rejected due to geolocation issues). Traditional hemispherical photographs were taken and gap fraction estimates compared.

It is concluded that, for the sites tested, the reported underestimates in gap fraction can be removed by taking partial hits into account using the return intensity. The scan density used (5–8 scans per 20 m by 20 m plot) was sufficient to ensure that occlusion of the laser beam was not significant. The choice of sampling density of the lidar data is important, but over a certain sampling density the gap fraction estimates become insensitive to further change. The lidar gap fractions altered by around 3–8% when all subjective parameters were adjusted over their complete range.

The choice of manual threshold for the hemispherical photographs is found to have a large effect (up to 17% range in gap fraction between three operators). Therefore we propose that, as long as a site has been covered by sufficient scan positions and the data sampled at high enough resolution, the lidar gap fraction estimates are more stable than those derived from a camera and avoid issues with variable illumination. In addition the lidar allows the determination of gap fraction at every point within a plot rather than just where hemispherical photographs were taken, giving a much fuller picture of the canopy. The relative difference between TLS (taking intensity into account) and camera derived gap fraction was 0.7% for Abisko and −2.8% for Sodankylä with relative root mean square errors (RMSEs) of 6.9% and 9.8% respectively, less than the variation within TLS and camera estimates and so bias has been removed.

1. Introduction

The work presented here is part of a larger project which aims to improve numerical models used for weather and climate (Reid et al., 2013). Land surface models (LSMs) are used in general circulation models to make predictions of climate and water availability (Clark et al., 2011). Snow has a dramatic effect upon climate, but snow processes are a known weakness of LSMs, particularly in forests (Rutter et al., 2009). Part of this weakness comes from predicting snow melt over different land cover types that affect radiation balance and heat fluxes in different ways.

Radiative transfer (RT) schemes, which form a part of LSMs, model how forests interact with radiation (both long and shortwave) and how much reaches the snow, contributing to melt energy (Musselman et al., 2013). RT models with a range of complexities exist, but all struggle with validation. Complex models require vast amounts of data whilst simpler models subsume processes into effective parameters which are not directly measurable. In both

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cases it is difficult to determine whether the correct result is being reached for the right reasons (Widlowski et al., 2005) and so how transferable a model is.

A terrestrial laser scanner (hereafter referred to as lidar or TLS) is capable of measuring the full structure of a forest canopy in far more detail than any other practical method (Omasa et al., 2003; Jupp et al., 2009; Seidel et al., 2012). This allows the development of a complex radiative transfer (RT) model which can be used to test more efficient models for use in LSMs.

In this study we are primarily interested in capturing the effect of vegetation on light rather than in measuring the vegetation itself (although that is relevant to other applications) and so no attempt was made to derive biophysical parameters such as plant area index (PAI). The most readily available method for validation is by comparison of gap fraction estimates against hemispherical photos (Bréda, 2003; Danson et al., 2007). Validation against directly measured canopy area is possible over small areas (Hosoi and Omasa, 2007) but is very time consuming.

1.1. Background

A number of previous studies have used terrestrial lidar to characterise forest structure. Tree trunks are not too different from buildings and other solid surfaces that TLS has been developed to measure and there have been a number of papers reporting success in determining diameter at breast height (DBH) and biomass (Watt and Donoghue, 2005; Tansey et al., 2009). The radiation regime beneath a forest is controlled by the canopy and this is a different problem, requiring the characterisation of many small elements clumped into larger structures (Chen and Cihlar, 1995; Widlowski et al., 2005). The canopy must be characterised to determine the forest's effect on snowmelt.

Danson et al. (2007) used the proportion of a single hemispherical lidar scan's beams recording hits to the total number to determine PAI, in the same way as a hemispherical photograph (Jonckheere et al., 2005). They found that the lidar tends to underestimate gap fraction compared to a camera and suggest that this may be due to the laser beam width; a hit would be recorded for any gap smaller than the beam width. They conclude that a better understanding of the interaction of lidar and a forest canopy is needed before it can be relied upon.

Seidel et al. (2012) used a similar approach to Danson et al. (2007) but with the extra capability of predicting the gap fraction for any point within a canopy rather than just from the lidar origin. This introduces the extra complication of laser beam occlusion; beams will be blocked as they strike canopy elements, leading to fewer samples as distance from scan centres increases. The effect of this can be reduced by using multiple scans; Seidel et al. (2012) used between six and thirteen scans per forest plot, roughly 20 m by 20 m. They further corrected for occlusion by placing 3 cm cubes at each recorded return in the radiative transfer model. They report a similar issue to Danson et al. (2007) of much lower lidar than camera-derived gap fractions (a factor of 0.57 different), though they did not determine whether this was due to laser beam width or the choice of 3 cm cubes.

Rather than treating each lidar return as a solid hit that blocks all light, which can introduce errors when merging multiple scans as elements may move between scans due to wind and geolocation issues, increasing the apparent canopy cover, Hosoi and Omasa (2006) proposed splitting the scene into voxels (volumetric pixels) and using the ratio of beams recording hits to the total number of occlusion beams passing through each voxel, as the PAI. The initial study used multiple scans of individual small trees (1.6 m tall and 70 cm crown diameter) and compared PAI estimates to direct destructive sampling (Hosoi and Omasa, 2006). This gave very good agreement but there would be little occlusion over such a small crown and the laser beam width would be very small at the close ranges used, giving little indication how this method would perform over larger forests stands. The same group applied this method to a natural forest (Hosoi and Omasa, 2007), using six separate, very high resolution scans (three from the forest floor and three from 10 m above the ground) to cover an 8 m by 4 m section of canopy. The method has also been applied to woody material (Hosoi et al., 2013). Again their results were good, with only slight underestimates in PAI at the top of the canopy (total error of 9.5%), although with 38% errors in fine branch volume, but it is not practical to cover larger areas at this level of detail. Huang and Pretzsch (2010) used a similar voxel method with two separate scans of a single pine tree crown and reported lidar gap fraction underestimates compared to a camera similar to Danson et al. (2007).

Côte et al. (2009) proposed a method for extracting very detailed explicit forest models from lidar scans. This uses a semi-supervised approach and a library of expected tree shapes to grow a model tree to fit the lidar data. This has been successfully used in forests (Côté et al., 2012) but it is not yet practical for characterising larger areas, especially in dense stands with overlapping crowns.

In recent years two groups have started building lidars optimised for forest measurements (Douglas et al., 2012; Gaulton et al., 2013), the SALCA (Salford Advanced Laser Canopy Analyser) and DWEL (Dual Wavelength Echidna® Lidar) instruments; which overcome a number of issues by using full waveform and two wavelengths. SALCA and DWEL are still in development but DWEL's single wavelength predecessor, Echidna (Jupp et al., 2009), has been tested in the field. Echidna results so far have either lacked coincident PAI or gap fraction measurements for validation (Strahler et al., 2008) or else agreed poorly with camera-derived estimates (r^2 of 0.23–0.41; Zhao et al., 2011).

2. Methods

Whilst previous studies have shown that lidar can accurately measure leaf area in a relatively small, intensively scanned area (Hosoi and Omasa, 2007), these did not test radiative transfer aspects. Previous studies which have tested lidar's ability to capture radiative transfer within a forest suggest that lidar underestimates the gap fraction (Danson et al., 2007; Huang and Pretzsch, 2010; Seidel et al., 2012), which would lead to an underestimate of light reaching the ground. This paper determines gap fraction from TLS point clouds anywhere within a canopy, implementing new methods to overcome the previously reported errors. These were compared to hemispherical photography-derived estimates (which cannot themselves be considered entirely accurate; Jonckheere et al., 2005) and the reasons for disagreement determined.

2.1. Field sites

Field data were collected during two winter campaigns at Arctic sites representative of high latitude forests (Reid and Essery, 2013). The first, in March 2011, was to Abisko in Sweden (69.325° N, 18.832° E), an area of patchy, polycormic birch forest between 2 m and 4 m tall. Leaves were off during the field measurements, giving very sparse canopies.

The second, in March 2012, was to Sodankylä in Finland (67.365° N, 26.635° E). This is an area of pine and spruce forest between 2 m and 20 m tall and as these are evergreen, canopies were much denser than at Abisko.

At each site, five plots were chosen to cover a range of canopy structures, from young, very sparse canopies through medium aged, dense and homogeneous canopies to older, denser more heterogeneous canopies. Plot characteristics are given in Table 1. Each plot was a 20 m by 20 m square with one axis aligned north.