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Lidar-based mapping of leaf area index and its use for validating GLOBCARBON satellite LAI product in a temperate forest of the southern USA

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ABSTRACT

Lidar provides enhanced abilities to remotely map leaf area index (LAI) with improved accuracies. We aim to further explore the capability of discrete-return lidar for estimating LAI over a pine-dominated forest in East Texas, with a secondary goal to compare the lidar-derived LAI map and the GLOBCARBON moderate-resolution satellite LAI product. Specific problems we addressed include (1) evaluating the effects of analysts and algorithms on *in-situ* LAI estimates from hemispherical photographs (hemiphoto), (2) examining the effectiveness of various lidar metrics, including laser penetration, canopy height and foliage density metrics, to predict LAI, (3) assessing the utility of integrating Quickbird multispectral imagery with lidar for improving the LAI estimate accuracy, and (4) developing a scheme to co-register the lidar and satellite LAI maps and evaluating the consistency between them. Results show that the use of different analysts or algorithms in analyzing hemiphotos caused an average uncertainty of 0.35 in *in-situ* LAI, and that several laser penetration metrics in logarithm models were more effective than other lidar metrics, with the best one explaining 84% of the variation in the *in-situ* LAI (RMSE = 0.29 LAI). The selection of plot size and height threshold in calculating laser penetration metrics greatly affected the effectiveness of these metrics. The combined use of NDVI and lidar metrics did not significantly improve estimation over the use of lidar alone. We also found that mis-registration could induce a large artificial discrepancy into the pixelwise comparison between the coarse-resolution satellite and fine-resolution lidar-derived LAI maps. By compensating for a systematic sub-pixel shift error, the correlation between two maps increased from 0.08 to 0.85 for pines ($n = 24$ pixels). However, the absolute differences between the two LAI maps still remained large due to the inaccuracy in accounting for clumping effects. Overall, our findings imply that lidar offers a superior tool for mapping LAI at local to regional scales as compared to optical remote sensing, accuracies of lidar-estimate LAI are affected not only by the choice of models but also by the absolute accuracy of *in-situ* reference LAI used for model calibration, and lidar-derived LAI maps can serve as reliable references for validating moderate-resolution satellite LAI products over large areas.

1. Introduction

As a key canopy structural characteristic, leaf area index (LAI) serves as an important input or state variable for a variety of process-based ecological and biogeochemical models, especially those pertinent to simulating energy and mass exchanges at the atmosphere-land interface or photosynthesis and respiration of ecosystems for carbon cycling (Turner et al., 2004). LAI is typically defined as the total one-sided area of green foliage per unit ground surface (Chen & Black, 1992). Both direct and indirect techniques, such as destructive sampling and optical methods, exist for measuring LAI *in-situ*. (Gower et al., 1999; Jonckheere et al., 2004). These *in-situ* techniques, however, are impractical for measuring LAI over large areas partly due to prohibitive costs (Cohen et al., 2003). Instead, researchers often resort to remote sensing for spatially-explicit mapping of LAI at landscape or regional levels. Reliable and accurate estimation of LAI, therefore, has become a primary task in exploiting the potential of remotely-sensed data for retrieval of biophysical variables, as demonstrated by both early studies in using optical imagery for estimating LAI and more recent efforts in mapping LAI with ranging measurements from lidar (LIght Detection And Ranging) (Jensen et al., 2008; Morsdorf et al., 2006; Riano et al., 2004; Roberts et al., 2005).

Optical remote sensing of LAI relies on spectral sensitivities to changes in vegetative components. Strong relationships between LAI and some carefully selected vegetation indices are both observed from experimental data and revealed theoretically by physically-based canopy reflectance models (Chen & Cihlar, 1996; Myneni et al., 1997).

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Among others, the utility of the normalized difference vegetation index (NDVI) for estimating LAI has been proven by extensive studies across various biomes using different remote sensing datasets such as Landsat TM/ETM+, MODIS, SPOT/VEGETATION and AVHRR (Eklundh et al., 2001; Garrigues et al., 2006; Tan et al., 2005; Yao et al., 2008). It is found that LAI-NDVI relationships not only depend on vegetation types but also vary seasonally and annually (Wang et al., 2005). Many studies report that NDVI saturates with high LAI, particularly for deciduous forests (Birky, 2001). At the global scale, several time series of moderate resolution LAI products have been generated from various satellite data, which, for example, include Terra/Aqua MODIS, GLOBCARBON (http://geofront.vgt.vito.be), and CYCLOPES (http://postel.mediasfrance.org). Accuracies of these products are of major concern to the scientific community. The improvement of LAI retrieval accuracy is limited by many interplaying factors such as the uncertainty of satellite reflectance measurements, the characterization of canopy architectures in retrieval algorithms, the natural variability of surface spectra and the mixture of species (Shabanov et al., 2005). To guide the informed use, practical efforts for validation or intercomparison of these global satellite LAI products, especially GLOBCARBON and MODIS products, have been completed or are ongoing at a range of sites worldwide (Cohen et al., 2003; Garrigues et al., 2008; Wang et al., 2004). The major recognized difficulties in assessing the quality of these products include the limited number of representative validation sites and the scale discrepancies between *in-situ* and satellite measurements, although other factors, such as the mis-registration of satellite products with reference data, also will complicate the validation processes (Tan et al., 2006).

Recent advances in airborne laser scanners (commonly known as airborne lidar) bring a breakthrough in canopy remote sensing, with an enhanced capability of direct characterization of canopy vertical structures (Lim et al., 2003; Næsset, 2002; Popescu et al., 2004). Portions of lidar pulses penetrate into canopies and even strike on the ground, thus allowing for better characterization of all canopy layers, including understories (Nelson et al., 1988), and at the same time alleviating the saturation problem of optical remote sensing for forests of high LAI or biomass (Lefsky et al., 2002). The body of lidar literature on ecological and environmental studies is growing in such aspects as mapping terrain topography and estimating biophysical parameters such as biomass, canopy density, LAI and fuel parameters at various analysis units (e.g., individual tree, plot, stand, and woodland) (Brandtberg et al., 2003; Chen et al., 2006; Holmgren et al., 2003; Hopkinson & Chasmer, 2009; Mutlu et al., 2008; Næsset et al., 2005; Popescu & Wynne, 2004; Zhao et al., 2008a). A key factor concerning lidar-based estimation of forest attributes at scales above individual trees is the selection of appropriate lidar metrics as predictors and effective equations as model forms, preferably with certain physical meaning (Næsset, 2002; Zhao et al., 2009). Lidar metrics that have been previously investigated for LAI mainly include mean height, maximum height, percentile height, height of median energy, and canopy density metrics (e.g., ratio metrics), among others (Farid et al., 2008; Griffin et al., 2008; Hanssen & Solberg, 2007; Jensen et al., 2008; Lovell et al., 2003; Morsdorf et al., 2006). In particular, ratio metrics such as laser penetration index and laser interception index prove useful for estimating LAI (Barilotti et al., 2006). Kusakabe et al. (2005) also suggested the use of “mean free path” (penetration length into canopy) as a proxy for LAI.

Like optical remote sensing of LAI (Garrigues et al., 2006; Tian et al., 2002), estimating LAI from lidar data is also subject to scale issues, which include but are not limited to the selection of an “optimal” resolution at which to develop regression models as well as the scaling-up/down problems due to the scale-dependence of the regressed models (Patenaude et al., 2004; Zhao & Popescu, 2007). Though not indicated explicitly, almost all the lidar LAI models investigated previously are more or less scale-dependent, which is exemplified by the fact that the estimated LAI of a region by using a single metric extracted for the region does not equal the aggregated value of estimates over the sub-regions that partition the region (Zhao et al., 2009).

The primary goal of this study is to further explore the capability of discrete-return lidar for spatially-explicit mapping of LAI, with a secondary goal to examine the consistency between the lidar-derived LAI map and GLOBCARBON satellite LAI products over an eastern Texas forest. We addressed the following specific sub-problems: (1) to evaluate the effects of analysts and algorithms on uncertainties of *in-situ* LAI estimates derived from hemispherical photos (i.e., hemiphotos), (2) to investigate the effectiveness of a number of lidar metrics, including several newly proposed ones, for estimating LAI, (3) to assess the utility of integrating lidar with multispectral imagery (i.e., Quickbird-derived NDVI) for accuracy improvement of LAI estimates, and (4) to determine the extent to which misregistration could affect the comparison between the lidar fine-scale and satellite moderate-resolution LAI maps as well as to develop a practical co-registration scheme for reducing the bias induced by registration errors in comparing the two LAI maps.

2. Materials

2.1. Study area

The study area is a 48-km^2 forested region in East Texas of the southern U. S. (30° 42′ N, 95° 23′ W) (Fig. 1). It mainly comprises pine plantations in various developmental stages, old growth pine stands in the Sam Houston National Forest with many of them having a natural pine stand structure, and upland and bottomland hardwoods. The major species include Loblolly pines (*Pinus taeda* L.) and deciduous trees such as water oak (*Quercus nigra* L.), red oak (*Quercus falcata* Michx), sweetgum (*Liquidambar styraciflua* L.), and post oak (*Quercus stellata* Wangenh.). Much of the southern U.S. is covered by forest types similar to those of our study area, including similar species, productivity and patterns of land use and land cover. The area is characterized by a gentle topography and has an elevation varying from 62 m to 105 m with an average of 85 m.

2.2. Field measurements (hemiphoto)

Field work was undertaken from May to July in 2004. Hemispherical photographs (hemiphoto) were taken on 53 circular plots established across the study area, with plot centers geo-referenced by a differential GPS (Trimble Pathfinder). Of the 53 plots, 14 are mixed/hardwood plots, and the remaining 39 are pine plots with 18 of them established in young pine plantations that have little variations of height and crown width and 21 in mature pine stands. These hemiphotos have a resolution of 3264×2448 pixels and were captured at 1.5 m above the ground using a horizontally-leveled CoolPix 8700 digital camera (Nikon) equipped with an FC-E9 fisheye lens converter (Nikon). Other ground inventory data, such as tree height, crown width and crown class, were also tallied (Popescu, 2007) but not directly used in this study.

2.3. Lidar dataset

The airborne laser scanner data were acquired during the leaf-off season in March 2004 with a Leica-Geosystems ALS40 flying at an average altitude of 1000 m by M7 Visual Intelligence of Houston, Texas. The lidar system was operated to record two returns per pulse, i.e., first and last, with a reported horizontal and vertical accuracy of 20–30 cm and 15 cm, respectively. The system was configured to scan +/−10° from nadir, resulting in a swath of about 350 m wide on the ground. The acquired dataset features a full coverage of the study area from either of two perpendicular directions, i.e., with 19 flight lines in the north–south direction and 28 in the east–west direction, resulting in an average of 2.6 laser hits per m^2 (Fig. 1). From the raw