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Evaluation of the MODIS LAI product using independent lidar-derived LAI: A case study in mixed conifer forest

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ABSTRACT

This study presents an alternative assessment of the MODIS LAI product for a 58,000 ha evergreen needleleaf forest located in the western Rocky Mountain range in northern Idaho by using lidar data to model ($R^2 = 0.86$, RMSE = 0.76) and map LAI at higher resolution across a large number of MODIS pixels in their entirety. Moderate resolution (30 m) lidar-based LAI estimates were aggregated to the resolution of the 1-km MODIS LAI product and compared to temporally-coincident MODIS retrievals. Differences in the MODIS and lidar-derived values of LAI were grouped and analyzed by several different factors, including MODIS retrieval algorithm, sun/sensor geometry, and sub-pixel heterogeneity in both vegetation and terrain characteristics. Of particular interest is the disparity in the results when MODIS LAI was analyzed according to algorithm retrieval class. We observed relatively good agreement between lidar-derived and MODIS LAI values for pixels retrieved with the main RT algorithm without saturation for LAI LAI ≤ 4. Moreover, for the entire range of LAI values, considerable overestimation of LAI (relative to lidar-derived LAI) occurred when either the main RT with saturation or back-up algorithm retrievals were used to populate the composite product regardless of sub-pixel vegetation structural complexity or sun/sensor geometry. These results are significant because algorithm retrievals based on the main radiative transfer algorithm with or without saturation are characterized as suitable for validation and subsequent ecosystem modeling, yet the magnitude of difference appears to be specific to retrieval quality class and vegetation structural characteristics.

1. Introduction

Quantifying and monitoring productivity of terrestrial landscapes relies on the ability to account for specific canopy structural characteristics such as leaf area index (LAI), the ratio of green foliage area per unit ground area. The foliage of vegetation canopies serves as the primary surface for mass and energy exchange between the atmosphere and terrestrial surface (Sellers et al., 1997), thus LAI is often utilized as a primary input or validation measure for spatially-explicit models of vegetation productivity, hydrologic forecasting, evapotranspiration, and surface energy balance (Bonan, 1993; Running & Coughlan, 1988; Turner et al., 2004).

Local and regional estimates of LAI traditionally have been determined by establishing relationships between multispectral band information from high resolution passive optical sensors and field-measured LAI obtained from destructive sampling or optical instruments (Berterretche et al., 2005; Chen & Chilar, 1996; Curran, 1983; Curran & Williamson, 1987; Fernandez et al., 2004; Jordan, 1969; White et al., 1997). Moreover, this method of localized LAI estimation has been the most frequently employed method to evaluate the performance and accuracy of coarse resolution operational LAI products. While multispectral-based methods may be appropriate for many vegetation types and biomes with relatively low LAI (e.g. LAI ≤ 3–5) (Chen & Chilar, 1996; Turner et al., 1999), LAI estimation for canopies above this LAI threshold remains a significant challenge. In light of this problem, recent studies suggest lidar as a compelling means to estimate LAI in moderate to high biomass ecosystems using either airborne (Chen et al., 2004; Jensen et al., 2008; Morsdorf et al., 2006; Riaño et al., 2004; Zhao & Popescu, 2009) or terrestrial-based (Clawges et al., 2007) lidar systems.

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Moderate Resolution Imaging Spectroradiometer (MODIS) data are currently used to derive a 1 km (actual pixel dimension of 926.625 m) LAI product at 4- and 8-day product intervals based on the observed maximum fraction of photosynthetically-active radiation (fPAR) (Knyazikhin et al., 1999). Significant efforts have been invested regarding MODIS LAI (LAI_{MODIS}) product validation; namely, but not limited to, investigations via the BigFoot project (Cohen et al., 2003; Cohen & Justice, 1999) and LAI_{MODIS} algorithm development and validation activities (e.g. Myneni et al., 2002; Tian et al., 2002; Yang et al., 2006a,b,c). A suite of published works have assessed the agreement between MODIS-derived LAI via radiative transfer inversion compared to multispectral-based empirical estimates of LAI for a variety of vegetation biome types including evergreen needleleaf forests (Chen et al., 2005; Cohen et al., 2006, 2003; De Kauwe et al., 2011; Heinsch et al., 2006; Pisek & Chen, 2007; Wang et al., 2004), broadleaf crops (Tan et al., 2005), evergreen deciduous (Aragão et al., 2005), and semi-arid landscapes (Cohen et al., 2006; Fensholt et al., 2004; Hill et al., 2006; Pisek & Chen, 2007).

Prior MODIS product assessments have identified study-specific retrieval conditions that influence LAI_{MODIS} retrieval accuracy including aerosol contamination (Yang et al., 2006b), input surface reflectance (Tan et al., 2005; Wang et al., 2001; Yi et al., 2008), sensor view zenith angle (Tan et al., 2005) and land cover classification (Cohen et al., 2003; Heinsch et al., 2006; Myneni et al., 2002). Such studies are valuable as they provide insight regarding algorithm performance and contribute information that may be used for algorithm improvement and refinement.

Part of the difficulty in determining specific causes of LAI_{MODIS} retrieval accuracy was expressed by Tan et al. (2005), who summarized that variation in retrieval method complicates any inferences made regarding the true error associated with a specific pixel because LAI_{MODIS} may vary significantly over a short period of time. The cause of such variation is largely attributed to the aforementioned upstream data products and input data quality (Yang et al., 2006a). Though these prior assessments are undoubtedly of great value, it is reasonable to consider that multispectral evaluation products may be subject to similar conditions and constraints as the LAI_{MODIS} products, and hence any inferences drawn.

In terms of lidar-based MODIS product evaluation, Chasmer et al. (2008) examined the agreement between lidar-modeled and MODIS-retrieved fPAR and found that lidar-based canopy fPAR estimates were within 10% of MODIS retrievals. To our knowledge, a lidar-based LAI_{MODIS} product evaluation has not been addressed. Given that lidar data are not prone to the same saturation issues as passive multispectral sensors, lidar data can be used to discriminate higher values of LAI, which makes it valuable for comparison with coarse-resolution LAI products in moderate-to-high biomass ecosystems or for vegetated landscapes where modeling of canopy LAI is influenced by understory vegetation reflectance.

Importantly, active lidar sensors respond more directly to the structural characteristics of the canopy than passive optical sensors, and LAI is fundamentally a structural characteristic. Further, previous studies of LAI in northern Idaho conifer forests have reported LAI ranging from 0 to 13, with the majority of observations exceeding LAI = 4 (Duursma et al., 2003; Jensen et al., 2008; Pocewicz et al., 2004). As a result, LAI estimates based on lidar data should be more accurate and consistent across variable atmospheric and solar illumination conditions than LAI estimates based on multispectral remote sensing data (e.g. Landsat or SPOT) for the purpose of MODIS-retrieved LAI product comparisons, and thus may reveal insights to improving or characterizing conditions that influence LAI retrieval accuracy or quality. As such, our primary research objectives were to: 1) evaluate the agreement between lidar-derived (LAI_{LIDAR}) and MODIS-retrieved LAI (LAI_{MODIS}) by specific MODIS algorithm retrieval class, and 2) evaluate the conditions over which LAI_{MODIS} retrievals may be influenced by sun/sensor view angles or sub-pixel structural characteristics.

2. Materials and methods

2.1. Study area

The St. Joe Woodlands (SJW) study area is located along the western edge of the Rocky Mountains in northern Idaho, USA. (N47°07–N47°17′ and W115°58′–W116°22′) The area totals approximately 58,000 ha. The SJW is an evergreen needleleaf forest landscape dominated by *Thuja plicata* (THPL; western red cedar) and *Abies grandis* (ABGR; grand fir), though other important conifer species including *Pseudotsuga menziesii* (PSME, Douglas fir), *Larix occidentalis* (LAOC; western larch), *Tsuga heterophylla* (TSHE, western hemlock), *Abies lasiocarpa* (ABLA; subalpine fir), *Picea engelmannii* (PIEN; Engelmann spruce), *Pinus contorta* (PICO; lodgepole pine), *Pinus ponderosa* (PIPO; ponderosa pine), and *Pinus monticola* (PIMO; western white pine) occur in mixed stands throughout the study area (Hudak et al., 2006). Understory vegetation is comprised of perennial herbs, shrubs and ferns including snowberry (*Symphoricarpos* spp), huckleberry (*Vaccinium globulare* Rydb), thimbleberry (*Rubus parviflorus* Nutt), twinflower (*Linnaea* spp), Kunth bride's bonnet (*Clintonia unifora*), American trailplant (*Adenocaulon bicolor* Hook), common ladyfern (*Anthyrium filix-femina*) and alder (*Alnus* spp).

Elevation ranges from 658 to 2000 m with most of the study area exhibiting complex terrain (e.g. slopes range from 0 to 51°; $\mu = 17°$). Mean annual temperature and total annual precipitation are 8.5 °C and 124.4 cm, respectively. The area is managed for commercial timber production where primary harvest activities include selective thinning and clear-cut operations. As such, rotations of large tracts of forest land are common, the result being a matrix of evergreen needleleaf forest in various seral stages.

2.2. LAI field data collection and processing

Field data were acquired for forty-six 0.07 ha (15 m radius) forest inventory plots during the summer and early Fall of 2006 (Julian Dates (JD) 264–266; 287) and 2007 (JD 200–204; 255–258; 249). In 2003, Hudak et al. (2006) established and inventoried forest plots in the SJW for a lidar-multispectral integration study to estimate conifer basal area and stem density. Of the 81 original plots established by Hudak et al. (2006), a subset of plots (n = 46) was selected for LAI measurements relevant to this study. During the plot selection process for this study we excluded very young regeneration stands since such stands tend to be dominated by shrubs and would exhibit higher growth rates than mid-to-late seral and mature stands. We also excluded plots that had been disturbed by forest management activities during the intervening three years. Selection of the final 46 plots was based on a stratified random approach that best represented the diversity of species, size, and stem density in proportion to their occurrence. Such plot selection restrictions were implemented to mitigate temporal differences in field observations and lidar acquisitions discussed in the next section.

Field observations of effective LAI were acquired using two LAI-2000 Plant Canopy Analyzers. The LAI-2000 implements a fisheye optical sensor comprised of five concentric silicon detector rings for a 148° field of view to simultaneously measure attenuation of diffuse solar radiation transmitted through a vegetation canopy (Welles & Norman, 1991). The first sensor was mounted and leveled on a tripod in a nearby clearing and programmed to automatically log readings of sky condition at 15 s intervals, while the second sensor was used to rove within forest plots for manual collection of temporally-coincident below-canopy readings. Both sensors were affixed with 45-degree view restrictors to mitigate limitations imposed by lack of substantial clearings (for above-canopy readings) and to minimize slope effects. Three below-canopy measurements were obtained 1 m on either side of six LAI sample stations at a height of 1.37 m resulting in a total of 36 canopy vegetation observations for each plot (Fig. 1).