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Using LiDAR and quickbird data to model plant production and quantify uncertainties associated with wetland detection and land cover generalizations

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ABSTRACT

Spatiotemporal data from satellite remote sensing and surface meteorology networks have made it possible to continuously monitor global plant production, and to identify global trends associated with land cover/use and climate change. Gross primary production (GPP) and net primary production (NPP) are routinely derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard satellites Terra and Aqua, and estimates generally agree with independent measurements at validation sites across the globe. However, the accuracy of GPP and NPP estimates in some regions may be limited by the quality of model input variables and heterogeneity at fine spatial scales. We developed new methods for deriving model inputs (i.e., land cover, leaf area, and photosynthetically active radiation absorbed by plant canopies) from airborne laser altimetry (LiDAR) and Quickbird multispectral data at resolutions ranging from about 30 m to 1 km. In addition, LiDAR-derived biomass was used as a means for computing carbon-use efficiency. Spatial variables were used with temporal data from ground-based monitoring stations to compute a six-year GPP and NPP time series for a 3600 ha study site in the Great Lakes region of North America. Model results compared favorably with independent observations from a 400 m flux tower and a process-based ecosystem model (BIOME-BGC), but only after removing vapor pressure deficit as a constraint on photosynthesis from the MODIS global algorithm. Fine-resolution inputs captured more of the spatial variability, but estimates were similar to coarse-resolution data when integrated across the entire landscape. Failure to account for wetlands had little impact on landscape-scale estimates, because vegetation structure, composition, and conversion efficiencies were similar to upland plant communities. Plant productivity estimates were noticeably improved using LiDAR-derived variables, while uncertainties associated with land cover generalizations and wetlands in this largely forested landscape were considered less important.

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1. Introduction

Recent advances in remote sensing with light detection and ranging (LiDAR) have provided natural resource scientists and practitioners with an unprecedented opportunity to derive height, biomass and three-dimensional structural attributes of plant communities across large, heterogeneous landscapes (e.g., Nelson et al., 2004; Næsset, 2004; Lefsky et al., 2005). A powerful extension of this technology is the fusion of LiDAR and multispectral datasets to characterize the structure, composition, and functional attributes of terrestrial vegetation (e.g., Popescu et al., 2004; Coops et al., 2004). Merging structural data from LiDAR and spectral information from multispectral sensors simplifies land cover classification using schemes such as the IGBP (International Geosphere-Biosphere Programme), whose broad vegetative classes are defined by the fractional cover of trees and shrubs and percentage of evergreen and deciduous foliage (Loveland et al., 2000; Thomlinson et al., 1999). Fine spatial resolution multispectral imagery (e.g., Quickbird, IKONOS) is particularly useful for evaluating uncertainties that may exist in coarse resolution global satellite products (Morisette et al., 2003; Steinberg et al., 2006), and to verify the underlying theory and performance of algorithms that are used to derive these products (e.g., Chen et al., 2004). In addition, fine-resolution data can be used to determine the appropriate resolution of input variables that are needed to achieve accuracy at either stand- or regional-scales (e.g., Potter et al., 2007; Ahl et al., 2005).

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The Moderate Resolution Imaging Spectroradiometer (MODIS) is a moderate-resolution (≥250 m) multispectral sensor onboard NASA's earth observing satellites, Terra and Aqua. We demonstrate here how several land products derived from MODIS can be evaluated using fine-resolution LiDAR and Quickbird data. Among these derived products are land cover; leaf area index (LAI); fractional photosynthetically active radiation absorbed by vegetation (fPAR, 400 to 700 nm); gross primary production (GPP), i.e., carbon fixed by photosynthesis; and net primary production (NPP), i.e., conversion of fixed carbon to plant biomass. Land cover, LAI and fPAR are upstream products that are used to compute GPP and NPP through the use of climate-constrained light- and carbon-use efficiency models (Running et al., 2004). Several studies have demonstrated strong relationships between LiDAR data and LAI based on canopy gap fraction (Morsdorf et al., 2006; Solberg et al., 2006; Thomas et al., 2006; Riaño et al., 2004; Lovell et al., 2003), but few have demonstrated its utility for computing fPAR and modeling photosynthesis using light-use efficiency equations (Chasmer et al., 2009). Methods for quantifying canopy transmittance and daily integrated fPAR from direct measurements of canopy structure with LiDAR are lacking (e.g., Parker et al., 2001), and accuracy assessments are needed to compare LiDAR-derived fPAR and remote sensing methods that rely on land cover, multi-angle reflectance, and radiative transfer models (e.g., Shabanov et al., 2003).

The performance of light-use efficiency models and quality of GPP estimates is intimately linked to the accuracy of input variables, particularly fPAR (Zhao et al., 2005; Turner et al., 2006a). Dungan and Nemani (2006) evaluated the MODIS MOD17A2 algorithm using the Taylor series method for propagating uncertainty, and determined that the influence of fPAR on GPP was greater than the light-use efficiency parameter (ε) and incident PAR; their findings suggest that improvements in the accuracy of fPAR measurements will have the greatest impact on reducing GPP uncertainty. Most regional- and global-scale fPAR algorithms have been developed using satellite multispectral sensors and rely on radiative transfer equations or empirical relationships with vegetative indices (e.g., Huang et al., 2008; Shabanov et al., 2000; Sellers et al., 1992). The MODIS fPAR algorithm relies on the former for improved accuracy, but reduced reflectance in mixed canopies and deciduous forests limits its use in the Great Lakes region (Yang et al., 2006; Shabanov et al., 2005, 2007). The MODIS backup algorithm is used in cases where reflectance measurements are insufficient for obtaining accurate retrievals from radiative transfer equations. The backup algorithm is based on empirical relationships between NDVI and fPAR, but is considered to have greater uncertainty and lower quality (Wang et al., 2001; Yang et al., 2006). MODIS validation studies at this site and other locations with similar vegetation have demonstrated fPAR overestimation (Turner et al., 2006a; Steinberg et al., 2006; Ahl et al., 2005), and interannual variability tends to be obscured (Turner et al., 2006b).

Global monitoring of photosynthetic activity and primary production is important to natural resource planners and climate scientists alike, since Earth's climate and ability to sustain consumer demand is linked to plant growth and CO_2 uptake potential of the terrestrial biosphere (IPCC, 2007; Vitousek et al., 1986). MODIS algorithms for estimating plant production rely on light- and carbon-use efficiency equations that are less detailed than process-based ecosystem models (e.g., Running and Hunt, 1993), since biophysical responses to environmental drivers depend on globally-averaged lookup table parameters for broad land cover classes (Heinsch et al., 2003). On average, MODIS GPP and NPP estimates generally agree with independent measurements at validation sites across the globe (Heinsch et al., 2006; Zhao et al., 2005); however, local biases and uncertainties need to be addressed before MODIS products can be recommended for use in smaller regions (e.g., Pan et al., 2006). In mixed forested landscapes of the Great Lakes region of North America, MODIS tends to overestimate LAI and fPAR inputs, resulting in GPP and NPP overestimation (Turner et al., 2006a; Heinsch et al., 2006; Ahl et al., 2005). Estimates of NPP are highly sensitive to the total amount of foliage, because the MODIS algorithm is dependent on allometric relationships between the mass of leaves and other tissues to estimate maintenance and growth respiration. Wetlands are another source of uncertainty in productivity estimates, since wetland area is underestimated in the MODIS primary land cover product (IGBP; Pflugmacher et al., 2007) and there is no analogue to IGBP wetlands in the University of Maryland (UMD) classification scheme used by MODIS GPP and NPP algorithms (Friedl et al., 2002; Hansen et al., 2000; Heinsch et al., 2003). Also, while wetland parameters exist in MODIS lookup tables (see Appendix), it is uncertain how well these global parameters represent wetlands of the Great Lakes Region.

The purpose of this study was to 1) develop methods for improving IGBP land cover and LAI and fPAR estimates using combined airborne LiDAR data and Quickbird imagery; 2) evaluate the model logic and parameters in the MODIS GPP algorithm using independent observations from a 400 m flux tower; 3) develop biome-specific relationships for computing carbon-use efficiency and NPP from LiDAR-derived biomass; 4) determine how a wetlands class might change landscape-scale estimates of photosynthesis and production; and 5) quantify the effect of land cover generalization on GPP and NPP estimates in a heterogeneous landscape in the Great Lakes region of North America. We hypothesized that fine-resolution inputs would better capture the heterogeneity and spatially variability within landscape. We also hypothesized that the difference between fine- and coarse-resolution estimates, when integrated across entire landscapes, could be used to quantify uncertainties in regional GPP and NPP that are associated with land cover generalizations and the failure to account for wetlands and wetland processes.

2. Materials and methods

2.1. Site description

This study was conducted in a highly fragmented, forested landscape near Park Falls, Wisconsin, USA, which experiences a continental climate with warm, wet summers and cold winters. At the center of the 6×6 km study area is a 400 m broadcasting tower (45.9470 °N, 90.2732 °W) instrumented to measure local meteorology and landscape-scale fluxes of CO_2, H_2O vapor, and heat by eddy covariance (Davis et al., 2003; Berger et al., 2001). Observations from this tall tower are unique due to the large flux footprint, permitting continuous surface flux measurements over a heterogeneous landscape that typifies much of the region surrounding the Great Lakes (Desai et al., 2008). This flux tower is part of the Chequamegon Ecosystem-Atmosphere Study (ChEAS), AmeriFlux, and FLUXNET networks, and data are publicly accessible through ChEAS (http://cheas.psu.edu) and the US Department of Energy's Carbon Dioxide Information Analysis Center (http://cdiac.ornl.gov).

The landscape surrounding the flux tower also serves as one of NASA's Earth Observing System (EOS) land validation core sites (Nickeson et al., 2007; Morisette et al., 2003; http://landval.gsfc.nasa.gov), including products derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), a multispectral sensor onboard NASA's earth-observing satellites, Terra and Aqua. MODIS provides global estimates of land cover, LAI, fPAR, GPP, and NPP, and field campaigns have been conducted in the surrounding area to determine the accuracy and spatial variability of these products (e.g., Turner et al., 2006a; Ahl et al., 2004; Burrows et al., 2002). Eddy covariance data and previous MODIS validation studies at this site allowed estimates from this study to be compared and reconciled with the flux tower time series; geostatistical interpolation (Burrows et al., 2003); and a gridded, process-based ecosystem model (BIOME-BGC; Turner et al., 2005).

The study area has a mean elevation 455 m above sea level, and local relief varies by <20 m. Although subtle, this difference in elevation is partially responsible for the complex mosaic of wetland and upland ecosystems that is characteristic of the region. Early- to mid-successional upland forests dominate the landscape, but approximately one-third of the study area is composed of structurally and physiologically distinct lowland plant communities (Anderson, 2007; Ahl et al., 2004; Ewers et al., 2002; Mackay et al., 2007). Upland stands are generally characterized by