Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 107 (2007) 385–401
Remote Sensing of Environment
www.elsevier.com/locate/rse

Comparison of MODIS, eddy covariance determined and physiologically modelled gross primary production (GPP) in a Douglas-fir forest stand

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Received 14 May 2006; received in revised form 16 September 2006; accepted 17 September 2006

Abstract

Quantification of the magnitude of net terrestrial carbon (C) uptake, and how it varies inter-annually, is an important question with future potential sequestration influenced by both increased atmospheric CO_2 and changing climate. However the assessment of differences in measured and modeled C accumulation is a challenging task due to the significant fine scale variation occurring in terrestrial productivity due to soil, climate and vegetation characteristics as well as difficulties in measuring carbon accumulation over large spatial areas. The Moderate Resolution Imaging Spectroradiometer (MODIS) offers a means of monitoring gross primary production (GPP), both spatially and temporally, routinely from space. However it is critical to compare and contrast the temporal dynamics of the C and water fluxes with those measured from ground-based networks, or estimated using physiological models. In this paper, using a number of approaches, our objective is to determine if any systematic biases exists in either the MODIS, or the modeled estimates of fluxes, relative to the measurements made over an evergreen, needleleaf temperate rainforest on Vancouver Island, Canada. Results indicate that 8-day GPP as predicted with a simple physiological model (3PGS), forced using local meteorology and canopy characteristics, matched measured fluxes very well ($r^2=0.86$, $p<0.001$) with no significant difference between eddy covariance (EC) and modeled GPP ($p<0.001$). In addition, modeled water supply closely matched measured relative available soil water content at the site. Using canopy characteristics from the MODIS fraction of photosynthetically active radiation (fPAR) algorithm, slightly reduced the correspondence of the predictions due to a large number of unsuccessful retrievals (83%) due to sun angle, snow and cloud. Predictions of GPP based on the MODIS GPP algorithm, forced using local meteorology and canopy characteristics, were also highly correlated with EC measurements ($r^2=0.89$, $p<0.001$) however these estimates were biased under predicting GPP. Estimates of GPP based on the most recent MODIS reprocessing (collection 4.5) remained highly correlated ($r^2=0.88$, $p<0.001$) yet were also the most biased with the estimates being 30% less than the EC-measured GPP. Most of the variance in GPP at the site was explained by the absorbed photosynthetically active radiation. We also compared the nighttime respiration as measured over 2 years at the site with the minimum 8-day MODIS land surface temperature and found a significant relationship ($r^2=0.57$), similar to other studies.

Keywords: Gross primary productivity; MODIS; Physiological modelling; 3PGS; fPAR

1. Introduction

The terrestrial biosphere can sequester significant amounts of atmospheric CO_2 (Wofsy et al., 1993) with future potential sequestration influenced by both increased atmospheric CO_2 and changing climate (Nemani et al., 2003, 2002). As a result, quantification of the magnitude of the net terrestrial carbon (C) uptake, and how it varies inter-annually, is an important question facing the ecological and global climate change communities (Barford et al., 2001; IPCC, 2001). As the magnitude of this uptake remains uncertain, understanding the C cycle at local, regional and global scales requires Earth surface processes to be monitored at high spatial and temporal resolutions (Zhao et al., 2005). Globally, the Moderate

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0034-4257/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2006.09.010

Resolution Imaging Spectroradiometer (MODIS), on board the TERRA and AQUA platforms, is a critical tool providing a monitoring capacity of the C cycle as part of the NASA Earth Observing System (Zhao et al., 2005). The MODIS sensors, launched in 1999 and 2001, provide a near daily coverage of the globe at 1-km resolution in 36 spectral bands (Heinsch et al., 2006) and include state of the art geo-location, atmospheric correction and cloud screening provided by MODIS science team. Using the MODIS instrument, estimates of foliage characteristics can be determined using visible and near-infrared spectral wavelengths and this, combined with global meteorology and a set of biome-specific parameters, which simulate vegetation growth under a range of conditions, allow the estimation of gross primary productivity (GPP), the photosynthetic accumulation of C by plants.

Ultimately, the value and utility of such datasets for environmental and C modeling is determined by our ability to quantify and explain uncertainties in the MODIS predictions. However the assessment of differences in measured and modeled C accumulation is a challenging task due to the large fine scale variation occurring in terrestrial productivity due to soil, climate and vegetation characteristics (Gebremichael & Barross, 2006) as well as difficulties in measuring C accumulation over large spatial areas.

To meet this end, a global ground based monitoring network of micrometeorological tower sites is in place that use eddy covariance (EC) fluxes to estimate gross primary productivity (GPP) as the sum of net ecosystem production (NEP) and ecosystem respiration during daylight periods (Goulden et al., 1996; Turner et al., 2003). Towers operate in many countries, across all continents, through a network known as FLUXNET, (Baldocchi et al., 2001) and at present, over 200 tower sites are operating on a long-term and continuous basis, with data colleted on fluxes as well as vegetation, soil, hydrologic, and meteorological characteristics. In addition to MODIS satellite predictions, and ground based measurements, a third approach to the determination of site-level GPP, is to estimate C exchange through the use of ecosystem process-based models using a range of site-level measured meteorological, biophysical, and soil inputs (Friend, 1995; Garcia-Quijano & Barros, 2005; Running & Gower, 1991). Such models incorporate an understanding of physiological processes and predict the growth and respiration of plant tissue. With adequate data, model estimations can be scaled both spatially and temporally, allowing for comparisons of the spatial pattern, and seasonal to inter-annual variability, of vegetation activity to be assessed (Heinsch et al., 2006; Schimel, 1995).

Validation and verification of the MODIS GPP product is underway. Turner et al. (2003) compared 2001 MODIS GPP with GPP estimates based on model-scaled ground observations at temperate hardwood and boreal conifer forested sites. The ground-based GPP scaling approach relied on a C cycle process model, BIOME-BGC, run in a spatially distributed mode (Turner et al., 2003). At the hardwood forest site, the MODIS GPP phenology started earlier than the scaled modeled GPP, and the summertime MODIS GPP was generally lower than the scaled modeled GPP values. The timing of the MODIS fall-off in production at the end of the growing season was similar to the validation data. At the boreal forest site, the MODIS and scaled model GPP phenologies generally agreed as both responded to the strong signal associated with minimum temperature. The boreal midsummer MODIS GPP was generally higher than the scaled model GPP values. The differences between the MODIS and the scaled model GPPs were driven by seasonal changes in the fraction of photosynthetically active radiation (fPAR) and the magnitude of the light use efficiency (ε) as well as by differences in other inputs to the MODIS GPP algorithm such as radiation, minimum temperature, and vapor pressure deficit (VPD). As a follow on to this work Turner et al. (2005) evaluated MODIS production estimates across six sites with varying climate, land use, and vegetation physiognomy, and compared them to estimates derived from a combination of ground measurements, Landsat imagery and process modelling (BIOME-BGC). There was not a consistent over- or under-prediction of production across sites relative to the validation estimates. Closest agreement occurred at the temperate deciduous forest, arctic tundra, and boreal forest sites with overestimation at the desert grassland and at the dry coniferous forest sites. Gebremichael and Barross (2006) evaluated the MODIS GPP estimates in two tropical ecosystems: a mixed forest site in the humid tropics and an open shrubland site in a semi-arid region using a process-based biochemical-hydrology model (LEHM, Land EcoHydrology Model) driven by flux tower meteorological observations. Results indicated there was a positive bias in predictions for the mixed forest biome and a negative bias for the open scrublands due in part to the global meteorology used by the MODIS algorithm. Heinsch et al. (2006) has undertaken a comprehensive evaluation of the MODIS GPP product using estimates derived from measured net ecosystem exchange (NEE) at a number of flux towers across North America. In this comparison, 4 years of MODIS GPP data were compared at 15 sites covering a range of biome types. The results indicted that, relative to the tower-based estimates, MODIS overestimated GPP by an average 20–30% at most of the sites with intra-annual variability varying by time-scale and biome. The results also indicated however MODIS substantially underestimated GPP between 19% and 40% at the most productive site (the Duke Forest site, North Carolina consisting of evergreen needleleaf forest). These results indicate that the combined underestimation of VPD from inadequate global meteorological data and the lack of accounting for soil moisture within the MODIS GPP algorithm leads to errors in estimating GPP and to difficulties in capturing seasonal dynamics, particularly for water-limited sites across the U.S.A. (Baldocchi et al., 2001; Heinsch et al., 2006; Turner et al., 2003). In the case of the higher productivity sites the maximum radiation conversion use efficiency, ε, was likely underestimated and conversely reductions imposed by the minimum temperature and VPD overestimated.

In this paper, we utilize a combination of EC-measured, physiological model, and satellite model (MODIS) derived estimates of GPP and compare the temporal dynamics of the C fluxes at 8-day, seasonal and annual intervals. By using a combination of ground-based and satellite observations, our