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ScienceDirect
Agricultural and Forest Meteorology 147 (2007) 99–109
AGRICULTURAL AND FOREST METEOROLOGY
www.elsevier.com/locate/agrformet

Incorporation of a soil water modifier into MODIS predictions of temperate Douglas-fir gross primary productivity: Initial model development

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Received 13 September 2006; received in revised form 1 July 2007; accepted 6 July 2007

Abstract

The moderate resolution imaging spectroradiometer (MODIS) is being used to monitor gross primary production (GPP), both spatially and temporally, routinely from space. However, estimates of GPP at various flux stations indicate that the MODIS algorithm may (i) over-predict GPP at sites where limitation to growth by low-soil water content is not adequately captured by the reduction in stomatal conductance by vapor pressure and (ii) under-predict GPP in highly productive, evergreen, needle leaf forests, due to a reduced radiation-use-efficiency term. The objective of this paper is to determine if any systematic bias exists in the MODIS algorithm relative to eddy covariance (EC) estimates of GPP made over an evergreen, needle leaf temperate rainforest on Vancouver Island, Canada, which is routinely water-stressed in summer months. Results indicate that 8-day GPP as predicted by the standard MODIS algorithm, with appropriate parameters for evergreen needle leaf forest, was highly correlated to EC-measured GPP ($r^2 = 0.89$, $p < 0.001$, S.E. = 0.9 g C m^{-2} day^{-1}), however with significant bias, under predicting GPP by as much as 30%. Increasing the radiation-use-efficiency term ε_{max} (g C MJ^{-1}) from the MODIS lookup value to the maximum observed at the site resulted in a reduced bias in the predicted GPP, however estimates were 8% higher than EC measurements. To account for soil water stress on plant growth, we implemented a soil water modifier initially proposed by Leuning et al. [Leuning, R., Cleugh, H., Zegelin, S., Hughes, D., 2005. Carbon and water fluxes over a temperate Eucalyptus forest and a tropical wet/dry savanna in Australia: measurements and comparison with MODIS remote sensing estimates. Agric. For. Meteorol. 129, 151–173] that accounts for rainfall and potential evaporation in the antecedent 3 months, a surrogate for soil water availability. Results confirm that field observations of relative available soil water content in the 0–60 cm layer matched the proposed soil water modifier closely with the relationship between the modified MODIS algorithm GPP and the EC-measured GPP remaining highly significant ($r^2 = 0.91$, $p < 0.001$, S.E. = 1.1 g C m^{-2} day^{-1}) with no significant bias. Whilst broad scale implementation of such a soil water modifier into the MODIS algorithm is still limited due to lack of rainfall data, at least in the short-term, the modifier does provide an alternative for researchers and land mangers, interested in applying the MODIS GPP products over regional areas, but who may have, or are observing, over-estimated production estimates due to the lack of inclusion of soil water modification to growth.

Keywords: Gross primary productivity; MODIS; Eddy covariance; Soil water; Radiation use efficiency; f_{APAR}

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0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2007.07.001

1. Introduction

Satellite remote sensing estimates of gross primary production (GPP) enable evaluation of scientific questions related to environmental degradation and the impacts of pollution and climate change on the global carbon cycle (Running et al., 2004; Zhao et al., 2005). Estimates of GPP from the Terra and Aqua platforms, using the moderate resolution imaging spectroradiometer (MODIS) sensor, integrate climate and broad vegetation classifications and have demonstrated utility at regional, continental and global scales (Nemani et al., 2003; Running et al., 2004). The sensors, launched in 1999 and 2001, respectively, provide near daily coverage of the globe at 1-km resolution in 36 spectral bands (Heinsch et al., 2006) using state-of-the-art geo-location, atmospheric correction and cloud screening techniques. 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, simulates vegetation growth under a range of conditions, and allows the prediction of GPP. A key parameter in the MODIS GPP algorithm is the radiation conversion efficiency, ε_{max}, which varies with different vegetation types and is constrained by suboptimal temperatures and vapor pressure variations that limit plant photosynthesis. The MODIS algorithm however does not incorporate other factors, which expressed at local and regional scales can limit plant growth, such as nutrient availability, soil type, and soil water availability (Pan et al., 2006; Gebremichael and Barross, 2006).

Ultimately the value and utility of such datasets for environmental and carbon (C) modeling is determined by our ability to quantify and explain uncertainties in the MODIS predictions. One approach is to use data from a ground-based monitoring network of micro-meteorological tower sites (FLUXNET (Baldocchi et al., 2001) such as AmeriFLUX (Law et al., 2002) and FLUXNET Canada (Coursolle et al., 2006)), that measure exchange of carbon dioxide, water vapor and energy between the biosphere and the atmosphere. These tower based systems estimate GPP as the sum of daytime net ecosystem production (NEP) and ecosystem respiration (R) measured at night but adjusted for daytime temperature and radiation (Turner et al., 2003; Heinsch et al., 2006). Data from these networks are being used to improve our understanding of processes controlling the coupled cycles of C, water and energy in ecosystems at multiple temporal and spatial scales (Baldocchi et al., 2001; Falge et al., 2002; Law et al., 2002; Leuning et al., 2005). The success of the flux station methodology relies on measurements to provide detailed process understanding on short to medium time scales and the use of soil–vegetation–atmosphere models that are informed and parameterised by these measurements. Extrapolation to large spatial and temporal scales is possible when flux measurements and models are combined with remote sensing. Data from flux stations thus can make a valuable contribution to this task, particularly when the data are obtained from contrasting ecosystems in widely varying biogeoclimatic regimes (Leuning et al., 2005).

Comparisons to date of the MODIS 8-day, seasonal and annual GPP products with data acquired from the Fluxnet network is producing some coherent trends. Turner et al. (2005) evaluated MODIS GPP and net primary production (NPP) across six sites which varied widely in climate, land use and vegetation physiognomy, and compared these to estimates derived from a combination of ground measurements, Landsat satellite imagery and process-based models. There was no consistent over- or under-prediction of NPP across sites relative to the validation estimates derived from field measured leaf area index (LAI) and process-based models. Closest agreement occurred for the temperate deciduous forest, arctic tundra and boreal forest sites with strong overestimation for the desert grassland and 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. Results indicated that the MODIS algorithm overestimated GPP when compared to that derived from a process-based biochemical-hydrology model for the mixed forest biome and underestimated GPP for the open scrublands, due in part to the global meteorology used in the MODIS algorithm. Leuning et al. (2005) compared estimates of LAI and GPP from MODIS with field based estimates at two sites, and found that the MODIS overestimated field based estimates of LAI by a factor of two in forested sites but gave reasonable magnitudes and seasonal variation for the savanna. GPP estimates matched the annual maximum at the forested site but failed to capture seasonal variation for both the savanna and forested sites.

Pan et al. (2006) compared estimates of MODIS NPP with estimates from a forest ecosystem process model and ground-based observations for forest types of the mid-Atlantic region of the United States. The regional means were similar but MODIS underestimated NPP for less-dominant northern hardwood forests and overestimated NPP for coniferous forests. Proposed