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# Estimation and analysis of gross primary production of soybean under various management practices and drought conditions

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ABSTRACT

Gross primary production (GPP) of croplands may be used to quantify crop productivity and evaluate a range of management practices. Eddy flux data from three soybean (*Glycine max* L.) fields under different management practices (no-till vs. till; rainfed vs. irrigated) and Moderate Resolution Imaging Spectroradiometer (MODIS) derived vegetation indices (VIs) were used to test the capabilities of remotely sensed VIs and soybean phenology to estimate the seasonal dynamics of carbon fluxes. The modeled GPP ($GPP_{VPM}$) using vegetation photosynthesis model (VPM) was compared with the GPP ($GPP_{EC}$) estimated from eddy covariance measurements. The VIs tracked soybean phenology well and delineated the growing season length (GSL), which was closely related to carbon uptake period (CUP, $R^2 = 0.84$), seasonal sums of net ecosystem $CO_2$ exchange (NEE, $R^2 = 0.78$), and $GPP_{EC}$ ($R^2 = 0.54$). Land surface water index (LSWI) tracked drought-impacted vegetation well, as the LSWI values were positive during non-drought periods and negative during severe droughts within the soybean growing season. On a seasonal scale, NEE of the soybean sites ranged from $-37$ to $-264\ g\ C\ m^{-2}$. The result suggests that rainfed soybean fields needed about 450–500 mm of well-distributed seasonal rainfall to maximize the net carbon sink. During non-drought conditions, VPM accurately estimated seasonal dynamics and interannual variation of GPP of soybean under different management practices. However, some large discrepancies between $GPP_{VPM}$ and $GPP_{EC}$ were observed under drought conditions as the VI did not reflect the corresponding decrease in $GPP_{EC}$. Diurnal $GPP_{EC}$ dynamics showed a bimodal distribution with a pronounced midday depression at the period of higher water vapor pressure deficit (>1.2 kPa). A modified $W_{scalar}$ based on LSWI to account for the water stress in VPM helped quantify the reduction in GPP during severe drought and the model's performance improved substantially. In conclusion, this study demonstrates the potential of integrating vegetation activity through satellite remote sensing with ground-based flux and climate data for a better understanding and upscaling of carbon fluxes of soybean croplands.



## 1. Introduction

As atmospheric $CO_2$ concentration is rising due to anthropogenic activities, there is a growing interest for a better understanding of the dynamics of $CO_2$ fluxes. Over the last decade, a large number (>600) of eddy flux tower sites are established to determine net ecosystem $CO_2$ exchange [NEE, the balance between gross primary production (GPP) and ecosystem respiration (ER)] between terrestrial ecosystems and the atmosphere (Baldocchi et al., 2001). The NEE studies are used to assess the carbon uptake potential of ecosystems and GPP is estimated from NEE data (Falge et al., 2002). The GPP is used to quantify crop productivity, determine better management practices (Baker and Griffis, 2005), and understand temporal differences in productivity (Falge et al., 2002). In addition, $CO_2$ fluxes from terrestrial ecosystems are important to monitor atmospheric $CO_2$ concentrations (Baldocchi et al., 2001). In recent years, eddy flux data are the primary source of data to support model development and satellite remote sensing (Mahadevan et al., 2008; Running et al., 1999a; Stockli et al., 2008; Williams et al., 2009). The images from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor are used to estimate

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GPP and net primary production (NPP) at 1 km spatial resolution (Running et al., 2004). These products provide valuable estimates of vegetation productivity, but it is important to validate these products with in-situ measurements. The NEE and GPP measurements from the eddy flux tower at the ecosystem-level provide opportunities for validating the MODIS NPP and GPP products (Turner et al., 2006).

While the majority of eddy flux tower sites are in natural and unmanaged ecosystems, a few eddy flux towers are established in managed agricultural ecosystems. More accurate information on GPP of croplands is of vital importance. In the U.S. North Central Region, agricultural row crops, small grain, and fallow land occupy 40% of the land area. Moreover, annual rotation of maize (*Zea mays* L.) and soybean (*Glycine max* L.) comprises 83% of the agricultural land devoted to row crops, small grain, and fallow. However, only a few short term NEE studies have been reported in soybean (Baker and Griffis, 2005; Gilmanov et al., 2014; Hollinger et al., 2005; Suyker et al., 2005). These studies have shown that soybean fields are near carbon neutral or even a small source of carbon on annual scales. There is still a lack of detailed information on carbon fluxes and the influence of major environmental factors on carbon fluxes of soybean fields under different management practices.

Maize/soybean rotations in the U.S. are either rainfed or irrigated agricultural ecosystems. Both conventional till and no-till management practices are common. It is known that carbon fluxes are subject to change with different management practices (Angers et al., 1997; Winjum et al., 1992). Accurate estimation of spatial patterns and temporal dynamics of GPP of soybean fields at larger spatial scales under different management practices is essential to improve our understanding of carbon dynamics of this globally important ecosystem. Thus, it is necessary to upscale site-specific flux observations beyond spatial limits of flux tower footprints. One upscaling approach is to use satellite remote sensing observations and climate data (Turner et al., 2003). Repetitive and systematic satellite remote sensing observations of vegetation dynamics and ecosystems allow us to characterize vegetation structure, and estimate GPP and NPP (Potter et al., 1993; Ruimy et al., 1994). A satellite-derived vegetation photosynthesis model (VPM) estimates GPP at daily to 8-day temporal scales and has been evaluated over several flux tower sites (Xiao et al., 2004a). Previous work has examined the simulated dynamics of GPP for the maize growing seasons from two of three study sites selected in this study (Kalfas et al., 2011). The GPP simulation of soybean systems under a range of hydrometeorological conditions is a focus of this study. Eddy covariance flux data and MODIS-derived vegetation indices (VIs) from three soybean fields were used to: (a) test the capabilities of remotely sensed VIs and soybean phenology to estimate seasonal carbon dynamics, and (b) explore the underlying mechanisms of environmental controls of $CO_2$ fluxes in soybean systems. In addition, we also compared the modeled GPP ($GPP_{VPM}$) using VPM and the MODIS GPP ($GPP_{MOD17A2}$) with GPP ($GPP_{EC}$) estimated from eddy covariance measurements.

## 2. Materials and methods

### 2.1. The study sites

#### 2.1.1. The Rosemount site (US-Ro1)

This site (44.7143°N, 93.0898°W) is located at the University of Minnesota's Rosemount Research and Outreach Center, near St. Paul, Minnesota. Soil type is Waukegan silt loam (fine, mixed, mesic typic Hapludoll) with a surface layer of high organic carbon content (2.6% average) and variable thickness (0.3–2.0 m) underlain by coarse outwash sand and gravel. Prior to cultivation, the site was an upland dry prairie consisting mainly of $C_4$ and $C_3$ grasses. The harvesting of wheat (*Triticum aestivum* L.) began in 1879. Maize was consistently planted annually between 1998 and 2001. From 2002, it was changed to conventional-till management maize-soybean annual rotation field. This is a rainfed agricultural system. Further information on site characteristics can be found in Griffis et al. (2007) and at the AmeriFlux website (http://ameriflux.ornl.gov/fullsiteinfo.php?sid=63).

#### 2.1.2. The Mead irrigated rotation site (US-Ne2)

This site (41.1649°N, 96.4701°W) is located at the University of Nebraska Agricultural Research and Development Center, near Mead, Nebraska. The site is irrigated with a center-pivot system. This site had a 10-year history of maize-soybean rotation under no-till practice. A tillage operation (disking) was done just prior to the 2001 planting to homogenize the top 0.1 m of soil and to incorporate *P* and *K* fertilizers, as well as previously accumulated surface residues. Since this tillage operation, the site has been under no-till management. This site has deep, silty-clay loam soils. Details about this site can be found in Suyker et al. (2005) and at the AmeriFlux website (http://ameriflux.ornl.gov/fullsiteinfo.php?sid=73).

#### 2.1.3. The Bondville site (US-Bo1)

This site (40.0062°N, 88.2904°W) is located in the Midwestern part of the United States, near Champaign, Illinois. The site has been in continuous no-till (since 1986) with alternating years of soybean and maize from 1996 to the present (maize in the odd years and soybean in the even years). This is a rain-fed agricultural system. Soil type is silt loam consisting three soil series (Dana, Flanagan, and Drummer). Detailed site descriptions and measurements can be found in Meyers and Hollinger (2004) and at the AmeriFlux website (http://ameriflux.ornl.gov/fullsiteinfo.php?sid=44).

### 2.2. $CO_2$ flux measurements

Flux densities of $CO_2$, sensible heat, latent heat, and momentum were measured using the eddy covariance technique. Site-specific climate data [air temperature, precipitation, photosynthetically active radiation (PAR), and soil water content] and Level-4 $CO_2$ flux data were acquired from the AmeriFlux website (http://ameriflux.ornl.gov/). The Level-4 data consists of $CO_2$ fluxes at half-hourly, daily, 8-day, and monthly time steps. The Marginal Distribution Sampling (MDS) method was used to fill gaps in data (Reichstein et al., 2005). Measured NEE data were partitioned to GPP and ER. Two years of data (2004 and 2006) for the Rosemount site (US-Ro1), two years of data (2002 and 2004) for the Mead irrigated rotation site (US-Ne2), and three years of data (2002, 2004, and 2006) for the Bondville site (US-Bo1) were used in this study. We determined the carbon uptake period (CUP) as the number of days when the ecosystem was a net sink of carbon (negative NEE). The CUP starts when vegetation is large enough to photosynthesize at higher rate than the rate of ER. The CUP ends after the senescence of vegetation when ER is higher than GPP. We summed NEE and GPP for the period of soybean growing season (May–October) to get seasonal sums.

### 2.3. Satellite-derived VIs data

The 8-day composite Land Surface Reflectance (MOD09A1) data from one MODIS pixel where the flux tower is geo-located were downloaded from the MODIS data portal at the Earth Observation and Modeling Facility (EOMF), University of Oklahoma (http://eomf.ou.edu/visualization/gmap/). Blue, green, red, near infrared (NIR), and shortwave infrared (SWIR) bands were used to derive VIs [enhanced vegetation index (EVI, Huete et al., 2002),