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Phenology and gross primary production of two dominant savanna woodland ecosystems in Southern Africa

Cui Jin [a], Xiangming Xiao [a,*], Lutz Merbold [b], Almut Arneth [c], Elmar Veenendaal [d], Werner L. Kutsch [e]

[a] Department of Microbiology and Plant Biology, Center for Spatial Analysis, University of Oklahoma, Norman, OK 73019, USA
[b] Department of Environmental Systems Science, Institute for Agricultural Sciences (IAS), Grassland Sciences Group, ETH Zurich, 8092 Zurich, Switzerland
[c] Karlsruhe Institute of Technology, Institute of Meteorology and Climate research/Atmospheric Environmental Research, Kreuzeckbahn Str., 19, 82467 Garmisch–Partenkirchen, Germany
[d] Nature Conservation and Plant Ecology Group, Wageningen University, Droevendaalsesteeg 3a, 6700 PB Wageningen, The Netherlands
[e] Institute for Climate-Smart Agriculture, Thünen-Institute, Bundesallee 50, 38116, Braunschweig, Germany

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ABSTRACT

Accurate estimation of gross primary production (GPP) of savanna woodlands is needed for evaluating the terrestrial carbon cycle at various spatial and temporal scales. The eddy covariance (EC) technique provides continuous measurements of net CO_2 exchange (NEE) between terrestrial ecosystems and the atmosphere. Only a few flux tower sites were run in Africa and very limited observational data of savanna woodlands in Africa are available. Although several publications have reported on the seasonal dynamics and interannual variation of GPP of savanna vegetation through partitioning the measured NEE data, current knowledge about GPP and phenology of savanna ecosystems is still limited. This study focused on two savanna woodland flux tower sites in Botswana and Zambia, representing two dominant savanna woodlands (mopane and miombo) and climate patterns (semi-arid and semi-humid) in Southern Africa. Phenology of these savanna woodlands was delineated from three vegetation indices derived from Moderate Resolution Imaging Spectroradiometer (MODIS) and GPP estimated from eddy covariance measurements at flux tower sites (GPP_{EC}). The Vegetation Photosynthesis Model (VPM), which is driven by satellite images and meteorological data, was also evaluated, and the results showed that the VPM-based GPP estimates (GPP_{VPM}) were able to track the seasonal dynamics of GPP_{EC}. The total GPP_{VPM} and GPP_{EC} within the plant growing season defined by a water-related vegetation index differed within the range of ±6%. This study suggests that the VPM is a valuable tool for estimating GPP of semi-arid and semi-humid savanna woodland ecosystems in Southern Africa.

1. Introduction

Savannas are one of the most widely distributed vegetation types, covering one-fifth of the earth land surface (Scholes & Hall, 1996). A recent modeling study estimated an annual sum of about 30 Pg C gross primary production (GPP) from tropical savannas and grasslands, accounting for 25.7% of the global terrestrial GPP (Beer et al., 2010). Africa, which is dominated by the largest area of savanna ecosystems in the world, is considered a main source of uncertainty in the global terrestrial carbon cycles (Weber et al., 2009; Williams et al., 2007). Current knowledge of Africa's carbon fluxes and storage is still limited due to the spatial extent, fire disturbance, and high interannual variability in climate and productivity (Ciais et al., 2011; Williams et al., 2007; Woollen et al., 2012).

Mopane and miombo woodlands in South and Central Africa covering 3.6 million km^2 of land are the single largest dry woodlands in the world. Over the past decade, continuous fluxes of carbon, water, and energy between the land surface and the atmosphere, as measured with the eddy covariance technique, have been used to study the temporal dynamics and spatial pattern of the carbon cycle of savanna woodlands in Southern Africa (Archibald et al., 2009; Kutsch et al., 2008; Merbold et al., 2009, 2011; Scanlon & Albertson, 2004; Veenendaal et al., 2004; Williams et al., 2009). However, such measurements have been made at only a few sites and often over short time periods (Veenendaal et al., 2004).

Satellite remote sensing at moderate spatial resolutions provides daily observations of land surface properties at the spatial scale compatible with the footprint sizes of the eddy covariance observation sites. It has become a more and more important data source for the study of vegetation phenology (Alcantara et al., 2012; Brown et al., 2012; Jones et al., 2012; Kim et al., 2012; Kross et al., 2011; White et al., 2009) and GPP estimates (Gitelson et al., 2012; Kalfas et al., 2011; Peng et al., 2011; Sakamoto et al., 2011; Sjöström et al., 2009; Wang et al., 2010b; Wu, 2012; Wu & Chen, 2012; Zhang et al., 2012).

* Corresponding author at: Department of Microbiology and Plant Biology, University of Oklahoma, 101 David L. Boren Blvd., Norman, OK 73019, USA. Tel.: +1 405 325 8941.
E-mail address: xiangming.xiao@ou.edu (X. Xiao).

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Vegetation phenology is a fundamental determinant affecting the ecosystem processes of carbon, water, and energy exchange (Larcher, 2003). It determines the timing and duration of a photosynthetically active canopy and influences the magnitude of carbon and water fluxes throughout the plant growing season (Jolly & Running, 2004). The vegetation indices calculated from the reflectance of spectral bands have been proved to effectively monitor the vegetation phenology (Bradley et al., 2007; Moody & Johnson, 2001; Sakamoto et al., 2005; Xiao, 2006; Zhang et al., 2006). Earlier studies of phenology have focused on vegetation indices derived from visible and near infrared bands, for example, the Normalized Difference Vegetation Index (NDVI), which is calculated as a normalized ratio between near infrared and red spectral bands (Tucker, 1979), and the Enhanced Vegetation Index (EVI), which is calculated from blue, red, and near infrared bands (Huete et al., 2002). Both NDVI and EVI have been shown to effectively track the seasonality and spatial patterns of savanna phenology (Archibald & Scholes, 2007; Chidumayo, 2001; Higgins et al., 2011; Huttich et al., 2011). It is well known that the shortwave infrared band (SWIR) is sensitive to water in vegetation and soil. One SWIR-based vegetation index is the Land Surface Water Index (LSWI), which is calculated from near infrared (NIR) and SWIR (Xiao et al., 2004a, 2004b). It has been successfully applied to vegetation phenology study and phenology-based land cover mapping (Cai et al., 2011; Chandrasekar et al., 2010; Park & Miura, 2011; Xiao et al., 2004a, 2006). A prior study has already indicated that LSWI was sensitive to the wet and dry conditions in Africa (Tian et al., 2012). Therefore, whether the time-series LSWI data can effectively extract the phenological dynamics of savanna woodlands in Southern Africa across precipitation gradient and woodland species types is the first question addressed in this study. Water availability at the regional scale, an important seasonal driver for savanna vegetation growth, is the primary limit for predicting savanna phenology patterns (Archibald & Scholes, 2007).

A number of the satellite-based Production Efficiency Models (PEMs) have been developed to estimate GPP of vegetation as the product of the absorbed photosynthetically active radiation (APAR) and the light use efficiency (Coops, 1999; Monteith, 1972; Potter et al., 1993; Prince et al., 1995; Ruimy et al., 1996). In one group of PEMs, the greenness-related vegetation indices are used to estimate APAR by the canopy. NDVI is most commonly used in the earlier PEMs (Potter et al., 1993; Prince & Goward, 1995; Ruimy et al., 1994; Running et al., 2000; Veroustraete et al., 2004; Yuan et al., 2007). In the other group of PEMs, chlorophyll-related vegetation indices such as EVI and chlorophyll index are used to estimate APAR by chlorophyll (Gitelson et al., 2006; Potter et al., 2012; Sims et al., 2006; Xiao et al., 2004a, 2004b).

The Vegetation Photosynthesis Model (VPM) is the satellite-based PEMs that used the concept of chlorophyll and light absorption by chlorophyll (Xiao et al., 2004a, 2004b). The VPM has been extensively verified for temperate, boreal and moist tropical evergreen forests (Xiao et al., 2004a, 2004b, 2005a, 2005b, 2006), temperate and plateau grassland (Li et al., 2007; Wu et al., 2008) as well as agricultural ecosystems (Kalfas et al., 2011; Wang et al., 2010b). However, its performance in simulating GPP of savanna woodland ecosystems is still unknown.

The objectives of this study are twofold: (1) to evaluate the potential of remote sensing vegetation indices (NDVI, EVI, and LSWI) in identifying land surface phenology of savanna woodlands and determining the growing season length; and (2) to examine the potential of the VPM to simulate GPP of two dominant savanna woodland sites differing in annual precipitation and vegetation composition in Southern Africa. The leaf-on and leaf-off phenological phases need to be identified and then used to evaluate the performance of satellite-based PEMs that estimate GPP of savanna woodland ecosystems. Although a vast area in Southern Africa is covered with mopane and miombo woodlands, there are only two sites with continuous measurements of CO_2 net exchange between the woodlands and the atmosphere by eddy covariance technique; and in this study we used data from the two sites, located in Botswana and Zambia.

2. Materials and methods

2.1. Study sites

These two eddy covariance flux sites of savanna woodlands are within the Kalahari Transect (KT) in Southern Africa, one of the International Geosphere–Biosphere Program (IGBP) Transects for quantifying biogeochemistry and primary production, water and energy balance, ecosystem structure and function at the continental scale (Scholes & Parsons, 1997). Both sites are located along a precipitation gradient in the semi-arid and sub-humid regions of Southern Africa. The geo-locations and landscape features of these two sites are shown in Fig. 1 and Table 1. Detailed descriptions of the two sites can be obtained via FLUXNET — a global network of micrometeorological tower sites (http://www.fluxnet.ornl.gov/fluxnet/sitesearch.cfm) and site specific publications (Arneth et al., 2006; Merbold et al., 2011; Veenendaal et al., 2004, 2008).

The Botswana site (Maun, 19.9165°S, 23.5603°E) is dominated by broadleaf deciduous woodland (*Colophospermum mopane*) with a sparse understory of grasses, a typical mopane woodland. The climate is characterized as semi-arid, with a distinct dry season (May–September) and wet season (December–March) and a mean annual precipitation (MAP) of 464 mm (Veenendaal et al., 2004, 2008). The vegetation is relatively homogenous over a large area around the site (at 2.5 km in all directions) (Fig. 1). Maximum leaf area index (LAI) is around 1.0 during the wet season (Tian et al., 2002). For decades, this area was disturbed by various human activities, e.g. cattle grazing. This disturbance has been largely eliminated since the site was set up.

The Zambian site is situated at the Kataba Forest Reserve, 20 km south of Mongu in Western Zambia (Mongu, 15.4388°S, 23.2525°E). The site has a semi-humid climate with distinct wet and dry seasons. The mean annual precipitation is 945 mm, occurring from mid-October to April of the following year. The maximum monthly temperature ranges from 23 °C to 32 °C. The vegetation is broadleaf deciduous miombo woodland, dominated by *Brachystegia spiciformis* (24.7%), *bakerana* (29.8%), *Guibourtia coleosperma* (16.8%), and *Ochna pulchra* (24.5%). The canopy cover is about 70%, and LAI has strong seasonal dynamics ranging from 0.8 to 1.68. The ground-based fraction of absorbed photosynthetically active radiation (FPAR) was measured once a month during 2000–2002, and showed strong seasonal dynamics with the range of 0.2 in September to 0.6 in January (Huemmrich et al., 2005). Some land use activities were permitted in this area, including livestock grazing and firewood collection. Low intensity ground fires happened frequently. However, serious land cover changes caused by intense charcoal production and the conversion from woodlands to agricultural land happened in the surrounding areas during recent years (Kutsch et al., 2011; Merbold et al., 2011).

2.2. Site-specific meteorological data and CO_2 flux data

All meteorological and CO_2 flux data used in this study were downloaded from CarboAfrica data portal (http://gaia.agraria.unitus.it/newtcdc2/CarboAfrica_home.aspx). It provides the meteorological and CO_2 flux datasets at half hourly, daily, 8-day, and monthly intervals. Meteorological data and CO_2 fluxes of the two sites were available for the periods of 1999–2001 and 2007–2009 (Figs. 2 and 3). The precipitation data in 2008/2009 at the Mongu site was incomplete due to a sensor malfunction. We used precipitation data from the Zambian Meteorological Department (20 km away) to replace the missing data. At the Maun site, precipitation started in late-November and lasted until May of the next year. Annual rainfall was 197 mm in 2000/2001 and 431 mm in 1999/2000, respectively. The wet season at the Mongu site was concentrated from mid-October to the end of