Agricultural and Forest Meteorology 226–227 (2016) 132–147

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Canopy and climate controls of gross primary production of Mediterranean-type deciduous and evergreen oak savannas

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ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form 26 May 2016
Accepted 30 May 2016

Keywords:
Vegetation Photosynthesis Model (VPM)
Vegetation index (VI)
Climate change
Drought
NDVI

ABSTRACT

Understanding the interactions of climate, vegetation growth, and gross primary production (GPP) is critical for accurate estimation of GPP over years. The eco-physiological response of two functional savannas (deciduous and evergreen) to temporal variations in biophysical factors under similar Mediterranean climate is still unclear. In this study, we compared dynamics of major climatic variables, eddy covariance (EC) tower-based GPP (GPP_{EC}), and vegetation indices (VIs: normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), and land surface water index (LSWI)) over the last decade in a deciduous savanna (Tonzi Ranch in California, USA) and an evergreen savanna (Las Majadas del Tietar in Caceres, Spain) under the Mediterranean climate. We also examined the relationships among VIs, GPP_{EC}, and major climatic variables in dry, normal, and wet hydrological years. Seasonal dynamics of climatic variables and GPP_{EC} were similar, but seasonal dynamics of VIs differed at two savanna sites. Both savannas' VIs and GPP_{EC} had similar responses to air temperature. The evergreen savanna showed larger variations in VIs and GPP_{EC} with respect to changes in annual precipitation than did the deciduous savanna. We simulated GPP of these two savanna sites using a light-use efficiency based Vegetation Photosynthesis Model (VPM). The modeled GPP (GPP_{vpm}) at both savanna sites agreed well with the seasonal and interannual dynamics of GPP_{EC} over the study period (slopes of 0.83–1.15 and R^2 values of 0.91–0.97). The LSWI-based water scalar parameter in VPM helped to accurately estimate GPP under dry, normal, and wet years. The results of this study help better understanding the eco-physiological response of evergreen and deciduous savannas, and also suggest the potential of VPM to simulate the interannual variations of GPP in different Mediterranean-type savannas through the integration of vegetation indices and climate data.

1. Introduction

Mediterranean-type savannas provide many ecological services with rich species and unique natural and human landscapes (Baldocchi et al., 2010; Correia et al., 2014). These savannas are composed of sparse trees and continuous understory herbaceous cover, shaped by both human activities and ecological factors (Bugalho et al., 2011; Kobayashi et al., 2013; Marañón et al., 2009). These savannas experience large interannual variations in temperature, rainfall, and soil moisture (Joffre et al., 1999; Ma et al., 2007). In addition, climate models have projected large changes in the Mediterranean climate in this century, including increased mean air temperature, significantly reduced precipitation, more concentrated rainfall events, and longer drought periods (Gao and Giorgi, 2008; Hertig and Jacobeit, 2008). These factors are likely to result in even more complicated interannual variations in gross primary production (GPP) of Mediterranean-type savanna ecosystems than that of sub-tropical, temperate, and boreal ecosystems (Ma et al., 2007). An accurate estimation of GPP for Mediterranean-type savannas is, therefore, critical to better understand the feedbacks of these savannas to climate change.

In past decades, production efficiency models (PEMs) based on the light use efficiency (LUE) concept (Monteith, 1972) have been widely used to estimate GPP of terrestrial ecosystems (Goetz et al., 1999; Running et al., 2004; Turner et al., 2006; Veroustraete et al., 2002; Xiao et al., 2004a; Yuan et al., 2007). These PEMs estimate GPP

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http://dx.doi.org/10.1016/j.agrformet.2016.05.020
0168-1923/

as the product of photosynthetically active radiation (PAR), the fraction of absorbed PAR (FPAR), and LUE (Monteith, 1972; Potter et al., 1993). The tree-grass mixed and open canopies of Mediterranean-type savannas present a challenge to accurate estimation of leaf area index and FPAR (Hilker et al., 2008; Ruimy et al., 1999; Ryu et al., 2010; Widlowski, 2010), which may in turn present a challenge for LUE-based GPP models to capture large interannual GPP variations due to year to year changes in temperature, rainfall, and soil moisture.

The LUE-based Vegetation Photosynthesis Model (VPM), which estimates GPP at temporal scales ranging from daily to 8-day, has successfully simulated GPP across a variety of terrestrial ecosystems including tropical savannas (Jin et al., 2013), croplands (Kalfas et al., 2011; Wagle et al., 2015b), grasslands (Wagle et al., 2014), and forests (Xiao et al., 2005a,b). VPM uses temperature (Tscalar) and water (Wscalar) down-regulation scalars to characterize the effects of these factors on LUE. Satellite-based land surface water index (LSWI) that can track drought-impacted vegetation (Bajgain et al., 2015; Wagle et al., 2014, 2015b) is used in VPM to compute Wscalar. For these reasons, several GPP model comparison studies have shown VPM's performance to be better than several other commonly used GPP models in capturing the impacts of drought on GPP in grasslands (Dong et al., 2015; Wu et al., 2010). In this study, we evaluate the performance of VPM in estimating seasonal dynamics and interannual variability of GPP in two oak savannas sites (one deciduous savanna in the United States and one evergreen savanna in Spain). These two sites have comparable Mediterranean climates and have in-situ climate and carbon flux data over a decade (Casals et al., 2009; Gilabert et al., 2015; Ma et al., 2007).

The goals of this study were to (1) examine the seasonal dynamics and interannual variations of climate and vegetation growth of the Mediterranean-type savannas based on flux observations and remote sensing data; and (2) estimate the potential of the LUE-based VPM to simulate GPP of the Mediterranean-type savannas under different hydrological conditions. Three specific objectives of this study were to (1) understand the seasonal dynamics of major climatic variables (temperature, precipitation, and radiation), vegetation indices (VIs), and carbon flux of two dominant functional (evergreen and deciduous) savannas under the Mediterranean climate; (2) examine the relationships among temperature, precipitation, VIs, and GPP dynamics; and (3) simulate seasonal dynamics and interannual variations of GPP over dry, normal, and wet hydrological years, using VPM.

2. Material and methods

2.1. Study sites

2.1.1. Tonzi Ranch (US-Ton) site

The Tonzi Ranch site is located in California, USA (38.4316°N, 120.9660°W, Fig. 1a). Dominant species are deciduous blue oaks (*Quercus douglasii*) and understory C_3 grasses, with tree canopy cover of about 40%. This site has a Mediterranean climate with dry and hot summers (little summer precipitation), and wet and mild winters. The mean annual air temperature is 16.5 °C and the mean annual precipitation is 562 mm. The landscape features and relevant information of this site are shown in Fig. 1b and Table 1. Detailed information on the site can be found in an earlier publication (Ma et al., 2007).

2.1.2. Las Majadas del Tietar (ES-LMa) site

The Las Majadas del Tietar site is located at Caceres, Spain (39.9415°N, 5.7734°W Fig. 1a). Dominant species are evergreen holm oak trees (*Quercus ilex* ssp. *ballota Lam.*) and annual C_3 grasses, with tree canopy cover of about 20%. This site experiences a Mediterranean climate and has a mean annual air temperature of 16.7 °C and mean annual precipitation of 528 mm with summer precipitation comprising less than 6%. The landscape features and relevant information of this site are shown in Fig. 1c and Table 1. Detailed information on the site can be found in an earlier publication (Casals et al., 2009).

2.2. Data

2.2.1. CO_2 flux and meteorological data

The climate and carbon flux data used in this study were downloaded from the AmeriFlux website (http://ameriflux.ornl.gov/) for the US-Ton site and European Fluxes Database Cluster (http://www.europe-fluxdata.eu/) for the ES-LMa site. We acquired the gap-filled half-hourly level 2 data over twelve years (2002–2013) for the US-Ton site. For the ES-LMa site, we acquired level 4 weekly data over 8 years (2004–2011) and half-hourly level 2 data for 2012. We aggregated half hourly eddy covariance tower-based GPP (GPP_{EC}) and meteorological data into 8-day intervals to match the temporal resolution of MODIS-derived VIs.

2.2.2. MODIS surface reflectance, vegetation indices, and GPP product

This study used the MODIS 8-day land surface reflectance product (MOD09A1) at 500 m spatial resolution. It includes seven spectral bands: red (620–670 nm), blue (459–479 nm), green (545–565 nm), NIR1 (841–876 nm), NIR2 (1230–1250 nm), SWIR1 (1628–1652 nm), and SWIR2 (2105–2155 nm). Three vegetation indices: NDVI (Tucker, 1979), EVI (Huete et al., 2002, 1997), and land surface water index (LSWI) (Xiao et al., 2004a,b) were calculated using the blue, red, NIR1, and SWIR1 spectral bands as shown in Eqs. (1)–(3). The MOD09A1 data were downloaded from the Earth Observation and Modeling Facility (EOMF) data portal at the University of Oklahoma (http://eomf.ou.edu/visualization/).

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}} \quad (1)$$

$$EVI = 2.5 \times \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + 6 \times \rho_{Red} - 7.5 \times \rho_{Blue} + 1} \quad (2)$$

$$LSWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}} \quad (3)$$

The MODIS land science team provides the global standard MODIS GPP (GPP_{mod}) product (MOD17A2) at 1 km spatial resolution and 8-day temporal resolution (Running et al., 2004; Zhao and Running, 2010; Zhao et al., 2005). MOD17A2 data (version-55 of 2002–2012, version-5 of 2013) were downloaded from NASA LAADS website (https://ladsweb.nascom.nasa.gov/data/search.html) for the model comparison.

2.3. Analysis of climate, vegetation indices, and carbon flux data

We examined the seasonal and interannual dynamics of PAR, mean air temperature (T_{air}), mean precipitation (Precip), soil water content (SWC), VIs, and GPP_{EC}. We computed annual precipitation (AP_{hyd}), mean annual precipitation (MAP_{hyd}), and standard deviation of annual precipitation (SD_{hyd}) over each hydrological (hyd) year (hydrological year begins in September and ends in August of the following year) across the study period. There is not a universal physical variable to quantitatively describe the types of the hydrological years (dry, normal, and wet years) at the annual scale. Precipitation is a main variable determining the humidity and dryness (Chang and Kleopa, 1991; Heim, 2002). In addition, drought indices are usually used to monitor different types of hydrological systems (McKee et al., 1993; Palmer, 1965; Vicente-Serrano et al., 2010). The Standardized Precipitation Evapotranspiration