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Responses of gross primary production of grasslands and croplands under drought, pluvial, and irrigation conditions during 2010–2016, Oklahoma, USA

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ABSTRACT

To accurately estimate the terrestrial carbon cycle and food production, it is essential to understand how gross primary production (GPP) of irrigated and non-irrigated grasslands and croplands respond to drought and pluvial events. This study analyzed annual GPP of irrigation-permitted and non-permitted grasslands, winter wheat (*Triticum aestivum* L.), other C3 croplands, and C4 croplands in Caddo County of western Oklahoma from 2010 through 2016, a period which consisted of extreme drought (2011) and pluvial events (2015). First, we compared GPP from the Vegetation Photosynthesis Model (GPP_{VPM}) and GPP data from the Moderate Resolution Imaging Spectroradiometer (GPP_{MOD17}) with GPP estimates from three eddy covariance towers (GPP_{EC}) in Oklahoma. GPP_{VPM} more accurately estimated mean daily GPP_{EC} at each of the three sites than GPP_{MOD17}. Second, we analyzed the seasonal and interannual dynamics of GPP_{VPM} for eight pixels, one each for the four irrigation-permitted and non-permitted land types. The interannual variation of GPP_{VPM} was due to the complexity of decision making and practice for irrigation, cropping intensity, and crop types. Finally, at the county scale, annual GPP_{VPM} from the 2011 drought and pluvial 2015 were compared with mean annual GPP_{VPM} from the other 5 years of the study period. The results show that for the 2011 drought: 1) non-permitted C4 croplands had the largest percentage decrease in GPP, but permitted C4 croplands had the smallest decrease; 2) regardless of water rights, GPP was significantly lower than the 5-year reference mean for grasslands, winter wheat, and other C3 crops; and 3) non-permitted lands were more affected by drought than irrigation-permitted lands, except for grasslands, which had similar percentage reductions in GPP. Results for the pluvial year 2015 show that: 1) GPP was significantly higher for grasslands, winter wheat, and non-permitted C3 croplands than the 5-year reference mean, but there was no significant difference in GPP for irrigation-permitted C3 croplands or non-permitted C4 croplands; and 2) GPP for C4 irrigation-permitted croplands was lower than the 5-year reference mean. Crop-specific responses to drought and pluvial events largely depend on a landowner's ability to irrigate, and caution should be used when assessing or generalizing how crops respond to climate variability, drought, and pluvial conditions in the absence of irrigation-related data.

1. Introduction

Drought can severely reduce forage, hay, crop, and livestock production, resulting in economic losses, reduced employment, and increased commodity prices that have spillover effects into other non-agricultural markets (Ziolkowska, 2016). Similarly, flooding and heavy precipitation events can cause crop damage and reduce yields (Rosenzweig et al., 2002). However, sustainable food production needs more knowledge about landscape-scale, crop-specific responses to drought and pluvial events and the role of irrigation in those responses

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to changes in climate. Recent studies have used MODIS and Landsat data products to estimate crop yield at large spatial scales (Doraiswamy et al., 2004; Xin et al., 2013), but they did not consider a water management component because it is largely unknown how crops respond to irrigation at the landscape scale (Yuan et al., 2015). More specifically, He et al. (2018) expected that more specific model calibrations for irrigated and non-irrigated crops would increase the precision of their crop yield estimates.

Although national agricultural survey and economic data can give us insight into how extreme weather events and changes in climate have affected crop-specific yields and market prices, such data does not provide wisdom on the physiological responses of vegetation to drought and pluvial events at high temporal or spatial resolution. Similarly, meteorological drought indices, such as the Palmer Drought Severity Index (PDSI) (Palmer, 1965) and the Standardized Precipitation Index (SPI) (McKee et al., 1993), are widely used as indicators of drought, but they do not measure plant productivity. Agricultural drought indices, such as the Crop Moisture Index (CMI) (Palmer, 2010), often use soil moisture to indicate drought, but they are not an explicit indicator of vegetation stress and fail to capture variances in soil moisture due to irrigation at the field scale. Satellite-based remote sensing vegetation indices (VIs), such as the greenness-related Enhanced Vegetation Index (EVI) (Huete et al., 1997; Justice et al., 1998; Huete et al., 2002), and water-related VIs such as Normalized Difference Water Index (NDWI) (Gao, 1996) and Land Surface Water Index (LSWI) (Xiao et al., 2004; Zhou et al., 2017b), have been used as proxies for several biophysical and biochemical variables such as plant response to drought (Wagle et al., 2014; Bajgain et al., 2015; Bajgain et al., 2016) and rainfall (Chandrasekar et al., 2010), leaf area index (Boegh et al., 2002), canopy chlorophyll content (Blackburn, 1998; Gitelson et al., 2005), and gross primary production (the total amount of carbon fixed by plants) (Wagle et al., 2015). However, satellite-based remote sensing techniques have not yet been developed to capture landscape-scale irrigation activities with high accuracy at interannual timescales (Masoner et al., 2003; Ozdogan et al., 2010). Thus, irrigated and non-irrigated crop-specific responses to drought and pluvial events remain unknown at large spatial scales.

The response of vegetation to drought and pluvial events are not only determined by external factors such as temperature, precipitation, and sunlight, but also by the species' photosynthetic pathways. Generally, plants with the C3 photosynthetic pathway are less drought-resistant than plants that perform C4 photosynthesis (Tilman and Downing, 1994; Nayyar and Gupta, 2006). Previous studies have shown that C4 plants (1) have a higher quantum yield (Ehleringer et al., 1997), or light use efficiency (LUE) (Haxeltine and Prentice, 1996; Xiao, 2006; Chen et al., 2011), in that they can fix more CO_2 per photon absorbed by chlorophyll than C3 plants; and (2) have a higher water use efficiency (WUE) (Hsiao and Acevedo, 1974; O'Leary, 1988), in that they can fix more CO_2 per molecule of water than C3 plants. Thus, the response of a monoculture to drought and pluvial events are expected to differ for C3 or C4 crop species (Chaves et al., 2003), and the response of grasslands depends upon the ratio of C3 to C4 species in the grassland community (Tilman and Downing, 1994).

In this study, we hypothesized that the responses of grassland, winter wheat (*Triticum aestivum* L.), other C3 cropland, and C4 cropland to drought and pluvial events are largely determined by their respective photosynthetic pathway and landowners' ability or inability to irrigate. The specific objective of this study was to analyze the response of gross primary production (GPP) for irrigated and non-irrigated grasslands, winter wheat, other C3 croplands, and C4 croplands in Caddo County, Oklahoma (Fig. 1) to the 2011 drought and pluvial 2015.

2. Materials and methods

For our analysis, we used four datasets each year from 2010 to 2016: (1) satellite-based GPP data from the Vegetation Photosynthesis Model (GPP_{VPM}) (Jin et al., 2015; Zhang et al., 2017); (2) the MODIS GPP product (GPP_{MOD17}) (Running and Zhao, 2015); (3) the Cropland Data Layer (CDL); and (4) irrigation permit data from the Oklahoma Water Resources Board (OWRB). Our analysis included three main steps: (1) we compared GPP estimates at three eddy flux towers (GPP_{EC}) placed in sites with native grassland, old world bluestem pasture (*Bothriochloa caucasica* C.E. Hubb.), and winter wheat in El Reno, Oklahoma, with GPP_{VPM} and GPP_{MOD17}; (2) we compared 8 day, intra-annual GPP_{VPM} estimates in 2011, 2013, and 2015 for eight 500 m pixels, one each for irrigation-permitted and non-permitted grasslands, winter wheat, other C3 croplands, and C4 croplands in Caddo County; and (3) we analyzed the responses of each land cover type at the county scale to the 2011 drought and pluvial 2015. For steps 2 and 3, we determined which 500 m GPP_{VPM} pixels were suitable for study in each year 2010–2016 using the workflow illustrated in Fig. 2.

2.1. Study area

The state of Oklahoma, located in the Southern Great Plains of the United States (US), has been characterized as being in a region with reoccurring periods of drought (Basara et al., 2013; Christian et al., 2015), heavy rainfall events (McCorkle et al., 2016), high variability in precipitation (Weaver et al., 2016), and increased climate variability (Flanagan et al., 2017b). For Oklahoma, a period of prolonged drought began in 2011 (Fernando et al., 2016; Flanagan et al., 2017a) and persisted for most of the state until May 2015 when it was broken by record amounts of precipitation (Oklahoma Climatological Survey, 2015). Thus, these dipolar climate events in Oklahoma provided a suitable region in which we were able to conduct our study.

We selected a Caddo County, Oklahoma as our pilot study area because it has a high concentration of both irrigation-permitted and non-permitted land (Fig. 3(a)) and the county experienced the extreme climate events of 2011 and 2015. Apart from a brief break in the drought in the spring of 2012, no less than 60% of Caddo County was in climatological drought for 4.5 years, from January 2011 to May 2015 (Fig. 4). Entering 2015, 100% of the county was in drought. However, 2015 became the wettest year on record for Caddo County with precipitation of 1285 mm as recorded by the Fort Cobb Mesonet station in Caddo County, beating the old record set in 1923 by 61 mm (Oklahoma Climatological Survey, 2017a).

The predominant geologic formation in the study area is the Permian-age Rush Springs formation, which is composed of cross-bedded, fine-grained sandstone with some dolomite and gypsum beds ranging from 57 to 91 m in thickness (Becker and Runkle, 1998). Soils in Caddo County are characterized as dark and loamy with clayey to loamy subsoils developed on Permian shales, mudstones, sandstones and/or alluvial deposits under tall grasses (Carter and Gregory, 2008).

Caddo County largely overlies the Rush Springs Aquifer, a bedrock aquifer that has provided adequate flow for irrigation in the northern portion of the county. The Rush Springs Aquifer is the second most developed aquifer in the state after the Ogallala Aquifer (Oklahoma Water Resources Board, 2012). Some irrigation wells have been reported to produce over 3785 L of water a minute, and daily crop irrigation water use (159 million liters) accounts for 77.8% of daily water withdrawals on average (Becker and Runkle, 1998). Due to the accessibility of groundwater from the Rush Springs Aquifer and the high density of irrigation-permitted lands, Caddo County ranked third in the state of Oklahoma for area of land permitted for irrigation (438 km^2) as a proportion of the county's total land area (13.1%) in 2016. There were 1062 active permits in the county for irrigation during the 2016 planting season. The total area of land in the county dedicated to active irrigation permits was 43.5% of the county's total cropland area (1006 km^2) (Oklahoma Water Resources Board, 2017).

Natural vegetation types in Caddo County are primarily tallgrass prairie dominated by little bluestem (*Schizachyrium scoparium*) and post oak-blackjack forest (Hoagland, 2000; Johnson and Luza, 2008). The