ISPRS Journal of Photogrammetry and Remote Sensing 108 (2015) 151–160

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Sensitivity analysis of vegetation indices to drought over two tallgrass prairie sites

Rajen Bajgain [a], Xiangming Xiao [a,b,*], Pradeep Wagle [a], Jeffrey Basara [c,d], Yuting Zhou [a]

[a] Department of Microbiology and Plant Biology, Center for Spatial Analysis, University of Oklahoma, Norman, OK, USA
[b] Institute of Biodiversity of Sciences, Fudan University, Shanghai 200433, China
[c] School of Meteorology, University of Oklahoma, Norman, OK, USA
[d] Oklahoma Climatological Survey, Norman, OK, USA

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form 16 July 2015
Accepted 16 July 2015

Keywords:
Drought
Drought intensity
Soil moisture
Tallgrass prairie
Vegetation indices

ABSTRACT

Vegetation growth is one of the important indicators of drought events. Greenness-related vegetation indices (VIs) such as Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are often used for the assessment of agricultural drought. There is a need to evaluate the sensitivity of water-related vegetation indices such as Land Surface Water Index (LSWI) to assess drought and associated impacts. Moderate-Resolution Imaging Spectroradiometer (MODIS) derived time series NDVI, EVI and LSWI data during 2000–2013 were compared for their sensitivity to drought at two tallgrass prairie sites in the Oklahoma Mesonet (Marena and El Reno). Each site has continuous soil moisture measurements at three different depths (5, 25 and 60 cm) and precipitation data for the study period (2000–2013) at 5-min intervals. As expected, averaged values of vegetation indices consistently lower under drought conditions than normal conditions. LSWI decreased the most in drought years (2006, 2011 and 2012) when compared to its magnitudes in pluvial years (2007, 2013), followed by EVI and NDVI, respectively. Because green vegetation has positive LSWI values (>0) and dry vegetation has negative LSWI values (<0), much longer durations of LSWI < 0 were found in the summer periods of drought years rather than in pluvial years. A LSWI-based drought severity scheme (LSWI > 0.1; 0 < LSWI ⩽ 0.1; −0.1 < LSWI ⩽ 0; LSWI ⩽ −0.1) corresponded well with the drought severity categories (0; D0; D1: D2; D3 and D4) defined by the United States Drought Monitor (USDM) at these two study sites. Our results indicate that the number of days with LSWI < 0 during the summer and LSWI-based drought severity scheme can be simple, effective and complementary indicator for assessing drought in tallgrass prairie grasslands at a 500-m spatial resolution.

1. Introduction

Drought is a recurring event of Oklahoma's climate cycle (Basara et al., 2013; Christian et al., 2015) and poses significant impacts on various sectors of the economy (OWRB, 2010). Seasonal drought can occur at any time of the year and the summer drought that coincides with the growing season can cause ecological imbalances and influences surface biophysical parameters such as vegetation indices, land surface temperature, soil moisture and evapotranspiration (Ghulam et al., 2007; Reichstein et al., 2002). This ultimately impacts the productivity of the tallgrass prairie ecosystem, which can cause billions of dollars in damage to livestock's industries depending on its timing, duration and severity.

Several conceptual definitions of drought have been classified into four major categories: meteorological, agricultural, hydrological and socio-economic droughts (Wilhite and Glantz, 1985). Understanding the need to quantify drought severity, researchers have developed several methods to assess and diagnose different droughts. Meteorological drought indices (Rainfall Anomaly Index, Bhalme and Mooley Drought Index, Drought Severity Index, Standardized Precipitation Index) were solely based on meteorological data such as precipitation and temperature (Bhalme et al., 1981; McKee et al., 1993; Van Rooy, 1965). Agricultural drought indices (Crop Moisture Index, the Soil moisture Drought Index, Soil Moisture Deficit Index) considered soil

* Corresponding author at: 101 David L. Boren Blvd, Norman, OK 73019, USA. Tel.: +1 405 325 8941; fax: +1 405 325 3442.
E-mail address: xiangming.xiao@ou.edu (X. Xiao).

http://dx.doi.org/10.1016/j.isprsjprs.2015.07.004
0924-2716/

moisture and evapotranspiration deficit (Hollinger et al., 1993; Narasimhan and Srinivasan, 2005; Palmer, 1965), while hydrological drought indices (Palmer Hydrological Drought Index, Surface Water Supply Index, Reclamation Drought Index) were based on a water balance model (Shafer and Dezman, 1982; Weghorst, 1996).

With the advancement of Earth observations from satellite-based sensors, numerous recent studies have used remote sensing data for assessing drought impacts (Ghulam et al., 2007; Peters et al., 2002; Tadesse et al., 2005; Wan et al., 2004). Over the period of more than 20 years, a number of remote sensing based vegetation indices (VIs) have been developed from various spectral band combinations to monitor vegetation (Table 1). While greenness-related VIs retrieved from remote sensing land surface reflectance such as Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetative Index (EVI) have often been used for vegetation condition monitoring (Diodato and Bellocchi, 2008; Herrmann et al., 2005; Song and Ma, 2011), NDVI derived indices such as Anomaly Vegetation Index (Weiying et al., 1994) and the Vegetation Condition Index (VCI) (Kogan, 1995) were used to relate vegetation dynamics to drought patterns. Similarly, several water related satellite-based vegetation indices that estimate vegetation water content have been used for drought detection (Chen et al., 2005; Fensholt and Sandholt, 2003; Gao, 1996; Kimes et al., 1981). Shortwave infrared reflectance (SWIR) and leaf water content are negatively related due to the large absorption (Hunt and Rock, 1989; Tucker, 1980) and is contrasted with near infrared (NIR) band to normalize the effects of other leaf parameters such as internal leaf structure for proper estimation of vegetation water content (Ceccato et al., 2001; Gao, 1996). Based on the analysis of reflectance spectra, combination of SWIR and NIR bands have been reported by numerous studies under different names: Normalized Difference of Landsat TM bands 4 and 5, ND45 (Kimes et al., 1981); Normalized Difference Infrared Index, NDII (Hardisky et al., 1983); Shortwave Water Stress Index, SWIS (Fensholt and Sandholt, 2003); Normalized Difference Water Index, NDWI (Jackson et al., 2004; Maki et al., 2004) and Land Surface Water Index, LSWI (Qin et al., 2015; Xiao et al., 2002; Zhang et al., 2015). These indices have proven to be effective in monitoring the water content of vegetation. However, NDVI has been the most popular and extensively used satellite-based index for drought monitoring over the past decades. Numerous studies have analyzed the relationships between NDVI and rainfall across geographical areas and vegetation types (Bhalme et al., 1981; Boschetti et al., 2013; McKee et al., 1993; Van Rooy, 1965). In the central and northern Great Plains grasslands, growing season rainfall, growing degree days and potential evapotranspiration exerted strong control over grassland productivity (Yang et al., 1998). There was a stronger relationship between NDVI and rainfall than between NDVI and temperature for the grassland located in the central and northern Great Plains of the US (Wang et al., 2001). Like other drought monitoring algorithms (Ji and Peters, 2003; Liu and Kogan, 1996; Nemani and Running, 1989; Pettorelli et al., 2005), the Vegetation Drought Response Index (VegDRI) introduced by the United States Drought Monitor (USDM) also used NDVI in monitoring droughts (Brown et al., 2008). A few recent publications have reported that water-related vegetation indices such as LSWI are relatively more sensitive to drought than greenness related VIs and presented as a potential drought monitoring tool (Chandrasekar et al., 2010; Gu et al., 2008; Wagle et al., 2015, 2014; Zhang et al., 2013). Long term analysis of LSWI over pluvial, dry and normal years can provide better insight into vegetation response to climate variations and complement current drought monitoring tools to incorporate water related vegetation index into their models and algorithms.

In this pilot and site-level study, we chose two tallgrass prairie sites in Oklahoma, which are the part of the Oklahoma Mesonet (McPherson et al., 2007). The objectives of this study were to: (a) explore the relationship between seasonal and inter-annual rainfall variability and dynamics of grassland vegetation growth, and (b) ascertain the sensitivity of VIs (NDVI, EVI and LSWI) to rainfall variations. This study further investigates additional drought information rendered by LSWI, based on episodic drought events over time series (2000–2013). Using the drought information generated from LSWI, a new approach (the number of days with LSWI < 0 during the plant growing season and LSWI-based drought severity classification) for an assessment of the drought impacts over grasslands is proposed in this study. This LSWI-based approach can potentially provide more insights into drought monitoring over tallgrass prairie grasslands.

Table 1
Drought indicators derived from several spectral indices, thermal products and precipitation.

Name of vegetation indices	Full name	Formula	References
1. Photosynthetic Indices (PIs)			
NDVI	Normalized difference vegetation index	$(\rho 858 - \rho 650)/(\rho 858 + \rho 650)$	Tucker (1979), Kogan (1991, 1995)
EVI	Enhanced vegetation index	$2.5 * (\rho 858 - \rho 650)/(\rho 858 + 6 * \rho 650 - 7 * \rho 469 + 1)$	Huete et al. (2002), Saleska et al. (2007)
VCI	Vegetation condition index	$(NDVI - NDVI_{MIN})/(NDVI_{MAX} - NDVI_{MIN})$	Kogan (1995)
2. NIR and SWIR based indices			
$NDWI_{1240}$	Normalized Difference Water Index	$(\rho 858 - \rho 1240)/(\rho 858 + \rho 1240)$	Gao (1996)
LSWI	Land Surface Water Index	$(\rho 858 - \rho 1640)/(\rho 858 + \rho 1640)$	Xiao et al. (2002)
SWISI	Shortwave Infrared Water Stress Index	$(\rho 1640 - \rho 850)/(\rho 1640 + \rho 850)$ or $(\rho 1240 - \rho 850)/(\rho 1240 + \rho 850)$	Fensholt and Sandholt (2003)
$NDWI_{2130}$	Normalized Difference Water Index	$(\rho 858 - \rho 2130)/(\rho 858 + \rho 2130)$	Chen et al. (2005)
NMDI	Normalized Multiband Drought Index	$(\rho 860 - (\rho 1640 - \rho 2130))/(\rho 860 + (\rho 1640 - \rho 2130))$	Wang and Qu (2007)
3. Combined indices (PIs, LST and precipitation)			
VTCI	Vegetation Temperature Condition Index	NDVI, Land Surface Temperature (LST)	Moran et al. (1994), Wan et al. (2004)
TVDI	Temperature Vegetation Dryness Index	NDVI, LST	Sanholt et al. (2002)
SDCI	Scaled Drought Condition Index	LST, NDVI, Precipitation	Rhee et al. (2010)
VCI	Vegetation Condition Index	$(NDVI - NDVI_{MIN})/(NDVI_{MAX} - NDVI_{MIN})$	Kogan (1995)
NDDI	Normalized Difference Drought Index	$(NDVI - NDWI)/(NDVI + NDWI)$	Gu et al. (2007)