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Monitoring the effects of rapid onset of drought on non-irrigated maize with agronomic data and climate-based drought indices

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ABSTRACT

The 2003 growing season at Mead, NE began with moist and relatively cool conditions that persisted through most of June. During this moist phase of the season, soil water and parameters such as evapotranspiration (ET) and gross primary productivity (GPP) were nearly identical between a rainfed maize site (RMS) and an irrigated maize site (IMS). A drying phase began in late June, causing decline in soil water at RMS and the necessity of irrigation treatments at IMS. The drying phase turned into a "stressed" phase by early August, as only 10 mm of precipitation fell in a 40-day period between mid-July and late August. Conditions at RMS began to deteriorate even more rapidly after maize entered the critical reproductive stage, as the depletion of soil water led to (implied) reductions in stomatal conductance, which led to significant reductions in ET and GPP, compared to the well-watered IMS. Two drought indices, the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), were utilized to show the effectiveness of short-term indices at detecting flash drought versus field measurements. Results showed that both the 1-month SPI and the 1-month SPEI were quite sensitive to the onset of the flash drought and closely followed the decline in soil water and other biophysical parameters at RMS relative to IMS. Significant precipitation returned and led to some recharge prior to harvest but was far too late to be of any help to the maize at RMS, as the yield difference of 6.3 Mg/ha between RMS and IMS revealed the detrimental effects of a rapid onset of drought during the critical reproductive stage of maize.

1. Introduction

Soil water is an integral part of the hydrologic cycle and a critical parameter for plant growth and development. Dale and Shaw (1965) reported that soil water is one of the most critical factors for crop development and yield. Soil water stress at the silking stage of maize (*Zea mays* L.) can reduce grain yield by 50% (Denmead and Shaw, 1960) and an omission of a single irrigation treatment at a critical stage could reduce maize yields by up to 40% (Cakir, 2004). Meyer et al. (1993) reported that maize was most sensitive to water stress in the silking-blister dough stage and Calvino et al. (2003) showed a curvilinear response of maize yield to available water in the three weeks preceding and following silking. Earl and Davis (2003) reported maize yield reductions up to 85% during severe water stress that occurred after the sixth leaf stage in Georgia. Thus, it is well established that a lack of soil water causes stress and yield reduction in maize. But soil water is not a commonly measured variable at NOAA Cooperative (COOP) weather stations and there are but a handful of networks around the United States where soil water is a standard, quality controlled observation (Hollinger and Isard, 1994; Illston et al., 2008; Hubbard et al., 2009).

Drought is a natural, recurring phenomena that occurs everywhere at various points in time and is occurring somewhere on Earth at any given point of time. Drought is a complex topic with ecosystem impacts that vary with its intensity and duration and socio-economic impacts that often magnify problems for the most vulnerable members of society. Perhaps it is fitting that drought does not have a universal definition and is often considered in the context of four broad categories defined by Wilhite and Glantz

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Short-term drought, sometimes referred to as flash drought, is a rapid onset of drought often accompanied by high temperatures and winds that lead to rapid soil moisture depletion during a critical time in the growing season (Svoboda et al., 2002). Flash droughts can occur within a longer period of normal or above normal precipitation and bring devastating agricultural impacts. For example, although precipitation was above normal in most of Oklahoma during 1998, an intense, short-term drought during the summer decimated the state's cotton and peanut crop (Basara et al., 1998; Illston and Basara, 2003). Illston et al. (2004) described four phases of soil moisture in a flash drought case in Oklahoma: a moist plateau in the spring, transitional drying early in the summer, enhanced drying mid-summer into early autumn, and recharge during the cooler months of late autumn and winter.

The 2003 growing season at Mead, NE closely matches the description of flash drought given in Svoboda et al. (2002). It began with moist and cool conditions that persisted through much of June. However, a prolonged period of minimal precipitation with periodic spells of heat led to a rapid decline in soil water at a rainfed maize site compared to a nearby irrigated site, which led to significant reductions in biophysical parameters such as evapotranspiration (ET) and gross primary productivity (GPP). The time series of soil moisture from the growing season at the rainfed maize site closely follows the four phases introduced in Illston et al. (2004). Thus, the primary goal of this paper is to show the relationship between soil water and agroecological parameters (ET and GPP) during four phases of the growing season. A secondary goal of this paper is to show the utility of using short-term and longer-term drought indices for monitoring a flash drought that occurred during the critical reproductive stage of maize at a rainfed site. The remainder of this section describes a short history of drought indices, with a particular focus on the two normalized drought indices used in this study – the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI).

Palmer (1965) developed the Palmer Drought Severity Index (PDSI) with an objective of "developing a general methodology for evaluating drought in terms of an index that permits time and space comparisons of drought severity." The PDSI is calculated from a simple water balance model that uses factors such as precipitation, temperature and latitude for the calculation of potential evapotranspiration (Thornthwaite, 1948), recharge, runoff, and soil moisture loss to determine whether recent precipitation was sufficient to maintain a normal water balance. The PDSI is divided into 11 categories ranging from extreme drought to extreme wet spell (Heim, 2002).

McKee et al. (1993) developed the Standardized Precipitation Index (SPI) in response to demand from Colorado decision makers for an index that expressed current conditions in terms of water supply, deficit, and probability. The SPI has the advantage of being spatially invariant and an indicator of drought on multiple time scales (Guttman, 1999), though caution has been advised when comparing the SPI between sites with very different periods of record and at short time scales during distinct dry seasons (Wu et al., 2005).

The SPI has been widely used for operational and research purposes. Hayes et al. (1999) showed that the SPI detected drought conditions a full month ahead of the PDSI during the U.S. southern Plains drought of 1996. Livida and Assemakopoulos (2007) used the SPI to show that mild and moderate drought were more common on the 3- and 6-month time scale across northern Greece while severe drought was more frequent across southern Greece. Brown et al. (2008) integrated the SPI with satellite derived vegetation metrics and biophysical data to produce 1-km maps of the Vegetation Drought Response Index (VegDRI). McRoberts and Nielsen-Gammon (2012) used daily precipitation from the Advanced Hydrologic Prediction Service multisensor precipitation estimates (MPE) and COOP station data to obtain a high resolution SPI to be used as guidance for the U.S. Drought Monitor (Svoboda et al., 2002). Thus, it was recommended by the World Meteorological Organization to be the primary drought index for national meteorological and hydrological agencies in monitoring meteorological drought across the globe (Hayes et al., 2011).

One criticism of a precipitation-only index like the SPI is that it does not account for temperature effects on drought. For example, Hu and Willson (2000) showed that the temperature and precipitation dependent PDSI was affected by both large anomalies of temperature and precipitation in the central United States. Vicente-Serrano et al. (2010) addressed this issue with the development of the SPEI. The SPEI is based on the monthly (or weekly) difference between precipitation and potential evapotranspiration (ET_p), using the ET_p method from Thornthwaite (1948). The Thornthwaite method of ET_p was chosen over more robust methods, such as the Penman–Monteith (Monteith, 1964), due to the simplicity of its calculation and its reasonable performance when calculating a drought index, such as the PDSI (Mavromatis, 2007).

The development of drought indices allows for useful comparisons of conditions between locations and over long periods of time. However, caution should still be applied when applying an index to long time-series of climate data. Inhomogeneities in data from station relocations, instrumentation changes, and growth of vegetation and urban boundaries do exist and analyses can be erroneous if these items are not accounted for (Peterson et al., 1998). Nevertheless, climate-based drought indices are useful at identifying the severity and duration of drought and continued research will only make existing indices more accurate and robust.

2. Materials and methods

2.1. Study site

The CSP is located at the University of Nebraska-Lincoln (UNL) Agricultural Research and Development Center near the town of Mead, NE. The CSP commenced in the spring of 2001 and consists of three sites. The first agroecosystem is an irrigated, continuous maize (ICM) site centered at 41°09′54.2″ N, 96°28′35.9″ W with an irrigated area of 48.7 ha. The second agroecosystem is an irrigated, rotated maize-soybean (IMS) site centered at 41°09′53.5″ N, 96°28′12.3″ W with an irrigated area of 52.4 ha. Both ICM and IMS were irrigated rotations of maize and soybeans under no-till in the 10 years prior to the initialization of the CSP. The third agroecosystem is a rain-fed, rotated maize-soybean (RMS) site centered at 41°10′46.8″ N, 96° 26′22.7″ W with an area of 65.4 ha. Prior to the CSP, RMS had 2–4 ha plots of maize, soybeans, wheat, and oats with tillage (Verma et al., 2005). ICM was not considered in this analysis as its management practice (i.e., continuous maize) made it less comparable to RMS than IMS.

Each CSP site consists of six, 20 m × 20 m intensive management zones, hereafter referred to as IMZ's, where detailed process-level studies of soil water, soil carbon dynamics, canopy and soil gas exchange, crop growth and biomass partitioning are established. Prior to the onset of the CSP in 2001, all three sites were uniformly tilled by disking the top 10 cm to incorporate Phosphorous (P) and Potassium (K) fertilizers and to homogenize the soil layer (Suyker and Verma, 2009). Nitrogen (N) fertilizer applications were applied to IMS and RMS prior to planting in 2003; subsequent N applications were applied in June at IMS through the center-pivot system in a process known as fertigation.

The IMZ locations were selected using *k*-means clustering applied to six layers of 4 m × 4 m cells based broadly on soil type,