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Evaluation of six indices for monitoring agricultural drought in the south-central United States

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ABSTRACT

Drought indices are widely used for drought monitoring. This study evaluates the performance of six indices (Palmer's Drought Severity Index (PDSI), Palmer's Z-index, precipitation percent normal, precipitation percentiles, Standardized Precipitation Index (SPI), and the Standardized Precipitation Evapotranspiration Index (SPEI)) to determine which are most appropriate for monitoring agricultural drought in the south-central United States. Soil moisture and crop yield data for winter wheat, corn and cotton are used to assess the performance of drought indices. The results indicate that SPEI is the most representative of soil moisture conditions. The best drought index for crop yield varies depending on crop type and growth stage. Z-index and SPEI have relatively higher correlations with all the crop yields. However, when only considering years with weather and yield conditions that are substantially above or below normal, all of the drought indices are highly correlated with crop yield. Our results demonstrate that no single drought index can capture all aspects of agricultural drought in the south-central United States. Therefore, it is important to quantitatively evaluate multiple drought indices to determine which is most appropriate for the location and crop of interest.

1. Introduction

Drought is one of the most complex natural hazards and it can have a substantial impact on agriculture. It is difficult to have a single definition of drought because of the substantial variability in water supply and demand across the world (Alley, 1985; Dai et al., 2004; Keyantash and Dracup, 2002; Wilhite, 2000). The American Meteorological Society (AMS) established formal definitions for meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought (American Meteorological Society, 1997) and these definitions have been used in many studies (Heim, 2002; Mishra and Singh, 2010; Zargar et al., 2011). In this paper, we define agricultural drought as a prolonged period of soil water deficits that has an adverse effect on crops and/or livestock. These soil water deficits may arise due to below normal precipitation and/or above normal evaporation and transpiration (Quiring, 2015).

Drought indices are widely used for quantification of moisture conditions. However, because of the complexity of drought characteristics and definitions, it is difficult to have a single index to adequately capture the intensity and severity of drought and its potential impacts (Vicente-Serrano et al., 2012). Many studies have developed drought indices to characterize drought conditions. At present, there are more than 150 drought indices that are used in the literature (Zargar et al., 2011). These indices can reflect different drought types and conditions. Some of the indices are designed to characterize meteorological drought, for example, Standardized Precipitation Index (SPI; McKee et al., 1993), Rainfall Anomaly Index (Van Rooy, 1965), Drought Severity Index (Bryant et al., 1992), and National Rainfall Index (Gommes and Petrassi, 1996). While others are most appropriate for monitoring agricultural and hydrological drought impacts, such as Crop Moisture Index (Palmer, 1968), Crop Specific Drought Index (Meyer et al., 1993) and Palmer Hydrological Drought Index (Palmer, 1965; Zargar et al., 2011).

A number of previous studies have reviewed the development of drought indices and summarized their advantages and disadvantages (Heim, 2002; Mishra and Singh, 2010). These evaluations are often specific to the application and region of interest. For example, Kempes et al. (2008) evaluated several different drought indices, including Palmer Drought Severity Index (PDSI) and Standardized Precipitation Index (SPI), to identify the indices that are most strongly related to tree-ring growth in the southwestern United States. Their results indicated that the PDSI was best indicator. Quiring (2009) compared the suitability of PDSI, Palmer's Z-Index (Z-index), SPI, Effective Drought Index (EDI), Vegetation Condition Index (VCI), precipitation percent normal

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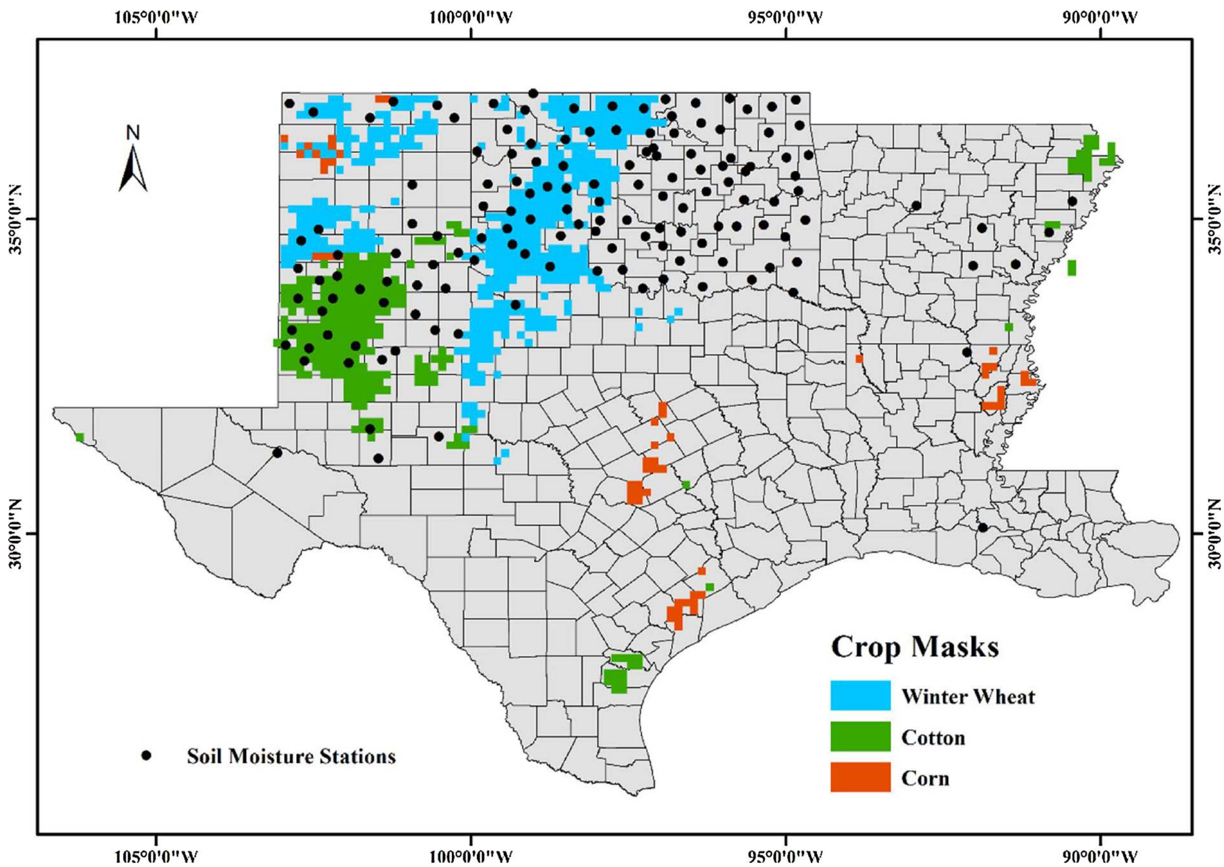

Fig. 1. Soil moisture stations and crop production regions in the south-central United States. Black circles indicate stations where soil moisture is measured. Shaded regions indicate the locations where winter wheat (blue), cotton (green) and corn (orange) were grown frequently during 2008–2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and percentiles for monitoring meteorological drought in the United States using six different characteristics of an ideal drought index. He found that SPI and percentiles are most suitable for monitoring meteorological drought.

Lorenzo-Lacruz et al. (2010) compared the performance of the Standardized Precipitation Evapotranspiration Index (SPEI) and SPI to identify which index is most appropriate for monitoring the impacts of droughts and water management on various hydrological systems in central Spain. They found that SPEI is better able to reflect the temporal variability of river discharge and reservoir storage. Vicente-Serrano et al. (2012) compared PDSI, SPI and SPEI for agricultural, hydrological, and ecological drought monitoring at global scale. Their results demonstrated that SPEI is the best drought index for capturing the impacts of drought on agricultural, hydrological, and ecological variables.

Drobyshev et al. (2012) compared the performance of six drought indices to identify which was the most suitable for fire frequency analysis in Sweden. They found that the calibrated PDSI is a better proxy of fire activity for the southern region, while, the drought index calculated as a ratio between actual and equilibrium evapotranspiration is better for the northern region.

For agricultural drought monitoring, Quiring and Papakryiakou (2003) evaluated PDSI, Z-index, SPI and the NOAA drought index by comparing the yield predictions. Their results indicated that the Z-index is the most appropriate index for agricultural drought monitoring in Canadian prairies. Wang et al. (2015) compared PDSI, Self-calibrated PDSI (scPDSI), Z-index, SPEI and SPI based on the correlations with soil moisture in China. They found that SPEI has a higher correlation with soil moisture than SPI, PDSI, and Z-index. They also found that the Z-index has a higher correlation with soil moisture in the top 5 cm of soil column than PDSI, while the PDSI has a higher correlation with soil moisture at 90–100 cm depth. These findings are corroborated by Vicente-Serrano et al. (2012) who evaluated these relationships in many countries.

Vicente-Serrano et al. (2012) compared the PDSI, Z-index, SPI and SPEI to wheat yield at global and national scales. Their analysis was based on using de-trended wheat yields since there are yield trends that are due to non-climatic factors such the adoption of new varieties and better management (Potopová et al., 2015). Potopová et al. (2015) also investigated the impact of agricultural drought on crop yield for winter wheat, maize, sugar beet, and sunflower. They de-trended yield and only evaluated the performance of the drought indices during low-yielding years. Other methods can also be used to compare drought indices and determine which are most appropriate for monitoring agricultural drought. For example, Krysanova et al. (2008) compared three drought indices using a trend analysis of drought indices. Paulo et al. (2012) compared four drought indices based on comparison of drought characteristics such as drought occurrence and severity. Tadić et al. (2015) evaluated five drought indices according to the directly comparison of the values of drought indices and the drought characteristics such as drought severity, intensity and duration.

Even though many studies have compared drought indices, the results are not consistent. Previous studies demonstrate that the performance of drought indices varies based on the application and region of interest. This is because the physical environment (i.e., climate, soil and vegetation) varies from region to region and each crop responds to drought conditions differently. Therefore, this study will compare the performance of six commonly used drought indices (PDSI, Z-index, SPEI, SPI, precipitation percent normal and precipitation percentiles) to determine which are most appropriate for monitoring agricultural