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Assessment of droughts and wheat yield loss on the North China Plain with an aggregate drought index (ADI) approach

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ABSTRACT

Frequent drought events are threatening regional/global food security. However, current models for predicting crop yield loss suffered from drought threat is still limited. In this study, seven drought indices were employed to develop an aggregate drought index (ADI) to quantify the drought effect on crop yield in the North China Plain (NCP). Based on time-series and panel regression models, relationships between climatic yield anomalies of winter wheat (ΔY) and ADI values before sowing of winter wheat and during its growth were investigated. Results showed that ADI assembled the advantages of drought indices and reasonably described the range, severity and duration of drought events. During the study period, trends of annual ADI displayed remarkable spatial heterogeneity in the growth stages. Increasing trends of ADI over 0.005/year were found in most areas of NCP at STAGE 1 (from July to September in last year). At STAGE 4 (from grain-filling to maturation), increasing and decreasing trends were observed in northern and southern NCP, respectively. Based on panel model, ADI in the four stages could predict about 20% variations of ΔY in areas with high irrigation supplies. Meanwhile, more than 40% variations of ΔY may be predicted in eastern NCP with low irrigation supplies. The study highlights the importance of integrating drought information and irrigation for assessment of winter wheat yield variations.

1. Introduction

Drought is one of the natural disasters for terrestrial ecosystems with the characteristics of wide coverage, high frequency and severe influence. It indirectly results in significant economic losses at the global and regional scales (Keyantash and Dracup, 2002; Logar and van den Bergh, 2013; Wilhite, 2000). In the context of climate change, global warming leads to an increase in surface heating. It also potentially amplifies the drought situations, especially over dry land (Dai, 2011; Trenberth et al., 2014). Increasing scarcity of fresh water supplies caused by drought will constraint the food production and put food security at risk globally under climate change (Mu et al., 2013). Thus, monitoring droughts and quantifying their impacts on crop production are essential for mitigating drought disasters and assisting water management.

Drought indices are widely used for drought assessment and monitoring at the global and regional scales to depict the duration, severity and extent of a drought (Edossa et al., 2016; Paulo et al., 2016; Vangelis et al., 2013; Wu et al., 2013; Zhao and Dai, 2015). However, it is difficult to utilize a single drought index to monitor a drought due to the complexity of a drought occurrence in space and time (Karamouz et al., 2009; Keyantash and Dracup, 2002; Mu et al., 2013; Svoboda et al., 2002). Most single drought indices were designed for specific applications, thus these drought indices are challenged. For example, three most popular climatic drought indices, i.e. Standardized Precipitation Index (SPI) (Mckee et al., 1993), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), Palmer Drought Severity Index (PDSI) (Palmer, 1965) are usually calculated by one or more hydrologic and climatic variables, such as precipitation (PPT), temperature and soil moisture (SM). They assess the drought mainly from the variations of water supply point of view rather than the variations of vegetation. By contrast, remotely sensed drought indices, such as Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974), put vegetation dynamics as the primary consideration and take less climatic variations into account when analyzing the drought threats.

So far, aggregate Drought Indices are developed to overcome the limitations of singe drought index, as Brown et al. (2008) assembled

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SPI, scPDSI and another two NDVI-based indices to establish a vegetation drought response index, and indicated that the new index had improved large-area drought monitoring in near-real time in the north-central United States. By assimilating PDSI, SPI, percent of normal precipitation, NDVI, land soil moisture, streamflow and many other indicators, Svoboda et al. (2002) developed the United States Drought Monitor (USDM) which could integrate a remotely sensed vegetation index to reflect the vegetation responses to drought. However, this index lacked consideration of evapotranspiration (ET) data, thus a new drought severity index which considered both ET and NDVI was established (Mu et al., 2013). ADIs have already applied to monitoring the drought threat to crop yield. Some studies mainly focused on the applicability of PDSI in the provincial or regional scale. For example, the capability of PDSI for assessing the drought impacts on winter wheat yield were studied in North China and revealed that PDSI got better performance in rainfed - than irrigation - dominated regions at the provincial level (Zhang et al., 2016). However, previous studies highlighted that drought had larger spatial heterogeneity (Chen et al., 2017a; Herrera-Estrada et al., 2017). Thus the difference of counties within the province should not be neglected. In this study, we will develop a comprehensive ADI at the county level, which will cover self-calibrating PDSI (scPDSI), SPI, SPEI, ET, potential ET (PET), gross primary production (GPP), NDVI and SM.

The Northern China Plain (NCP) is a primary production base of winter wheat. Therefore, clarifying the quantitative relationship between agricultural drought and winter wheat yield is significant for regional agricultural developments and food security (Tao and Zhang, 2013). The objectives of this study are: (1) to develop an ADI which is suitable for monitoring the agricultural droughts in NCP, and to analyze its spatiotemporal variations; (2) to establish the quantitative relationship between ADI and winter wheat climatic yield anomalies at county-level by optimizing the parameters of time-series model and panel model.

2. Data and methods

2.1. Study area

NCP is located in the eastern part of China, extending from latitude 32°00′N to 40°24′N and longitude 112°48′E to 122°45′E (Fig. 1) with an average elevation of 50 m above sea level. It is one of the granaries in China. The region has a typical temperate and monsoonal climate with annual mean air temperature of 8–15 °C. The annual precipitation distributes non-evenly among seasons ranging from 500 to 1000 mm. Winter wheat is one of the major food crops there, however, droughts occurred frequently in winter wheat growing season due to insufficient PPT and its uneven distribution. Under the background of global warming, increasing trend of drought was found during spring season which has intensified the water shortage and caused environmental problems in the NCP.

2.2. Data and processing

(1) Meteorological and remote sensing data

Meteorological data from 92 meteorological stations in and around NCP for the periods of 1982–2012 was derived from the China Meteorological Data Sharing Service (http://cdc.cma.gov.cn/home.do). Then the thin-plate smoothing spline method was used for spatial interpolation, in combination with a digital elevation model (DEM) (Hutchinson and Xu, 2013).

The GIMMS3 g NDVI dataset with the spatial resolution of 1/12° and temporal resolution of 15 day was obtained from the NASA Earth Exchange (NEX) (https://nex.nasa.gov/). The data were derived from Advanced Very High Resolution Radiometer (AVHRR) sensors on board several NOAA satellites (Liu et al., 2017a,b; Pinzon and Tucker, 2014; Wang et al., 2017). Corrections were made to account for the different sensors and physical conditions, including the effects of calibration loss and latitudinal variations in the solar zenith angles due to orbital drift and volcanic eruptions (Pinzon and Tucker, 2014). The improved versionof Savitzky - Golay filter was used here for further correction (Chen et al., 2004).

Daily ECV SM dataset with spatial resolution of 0.25° was derived from the combination of two active (AMI: Active Microwave Instrument; ASCAT) and four passive microwave radiometer sensors (SMMR: the Nimbus 7 Scanning Multi-channel Microwave Radiometer; SSM/I: the Special Sensor Microwave Imagers; TMI: the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager; AMSR-E). More details, including the algorithm and theoretical baseline of data processing, may refer to the previous references (Liu et al., 2012; Liu et al., 2011; Wang et al., 2016). Monthly SM data were retrieved from the daily SM data in each month.

Potential evapotranspiration (PET) were calculated according to the Penman - Monteith Formula. Actual ET was simulated by the VIP model (Mo et al., 2014). The land use type data at scale 1:100000 were obtained from Data Centre for Resources and Environmental Sciences of

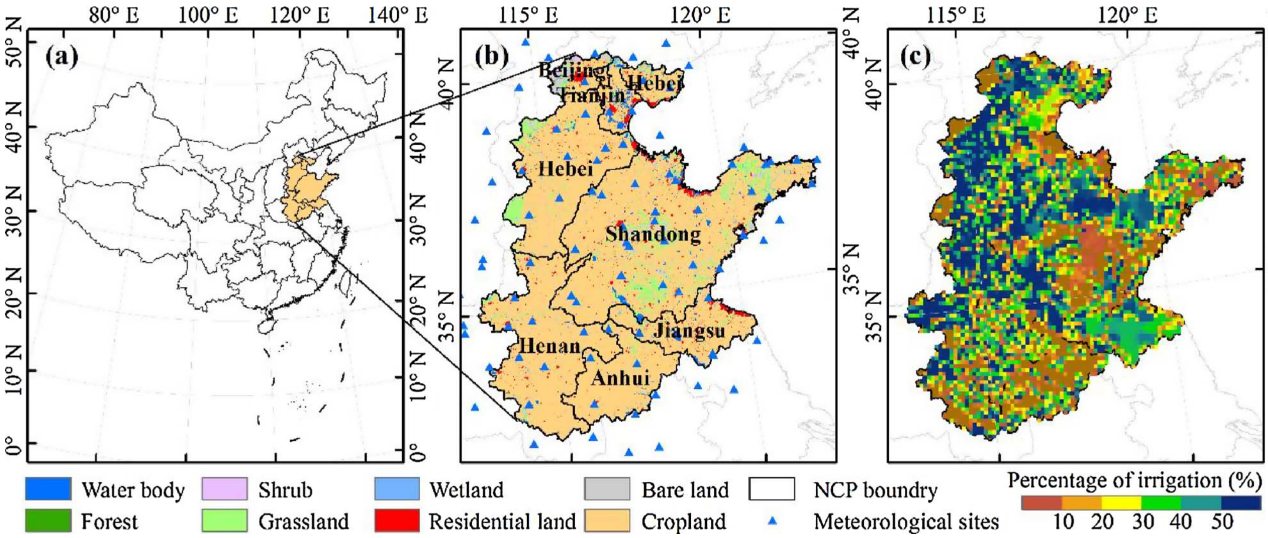

Fig. 1. (a) Location of North China Plain. (b) Land use map of the North China Plain with the locations of the meteorological sites. (c) Percentage of irrigation in North China Plain. Black solid line is the provincial boundary.