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Effects of water stress on water use efficiency of irrigated and rainfed wheat in the Loess Plateau, China

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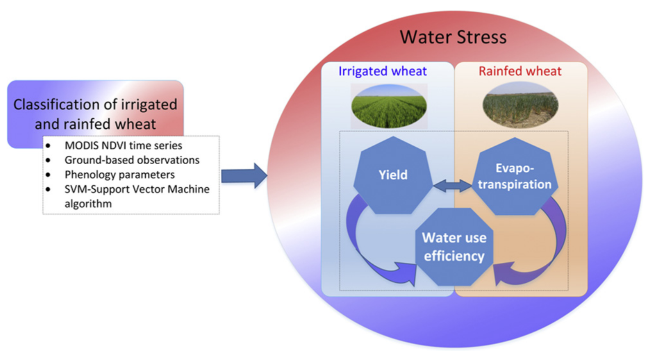
HIGHLIGHTS

- The ratio of irrigated to rainfed winter wheat in the Loess Plateau was examined.
- Maximum light use efficiency and harvest index of winter wheat were estimated.
- Higher yield and actual evapotranspiration were found in irrigated winter wheat.
- Water use efficiency decreased more rapidly in rainfed wheat under water stress.

GRAPHICAL ABSTRACT



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ABSTRACT

The Loess Plateau, the largest arid and semi-arid zone in China, has been confronted with more severe water resource pressure and a growing demand for food production under global changes. For developing sustainable agriculture in this region, it is critical to learn spatiotemporal variations in water use efficiency (WUE) of main crops (e.g. winter wheat in this region) under various water management practices. In this study, we classified irrigated and rainfed wheat areas based on MODIS data, and calculated the winter wheat yield by using an improved light use efficiency model. The actual evapotranspiration (ETa) of winter wheat and the evapotranspiration drought index (EDI) were also investigated. Then we mainly examined the synergistic relationship between crop yield, ETa, and WUE, and analyzed the variations in WUE of irrigated and rainfed wheat under water stress during the 2010–2011 growing season. The results suggested that winter wheat in the Loess Plateau was primarily dominated by rainfed wheat. The average yield of irrigated wheat was 3928.4 kg/ha, 22.2% more than that of rainfed wheat. High spatial heterogeneities of harvest index (HI) and maximum light use efficiency (ε_{max}) were found in the Loess Plateau. The ETa of irrigated wheat was 10.2% more than that of rainfed wheat. The ratio of irrigated and rainfed wheat under no water stress was 31.55% and 17.16%, respectively. With increasing water stress, the WUE of rainfed wheat decreased more quickly than that of irrigated wheat. The WUE variations in winter wheat under water stress depended strongly on the synergistic effects of two WUE components (crop yield and ETa) and their response to environmental conditions as well as water management practices (irrigated or rainfed). Our findings enhance our current understanding of the variations in WUE as affected by water stress under various water use conditions in arid and semi-arid areas.

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1. Introduction

The growing water demand due to rapid socio-economic development is not compatible with the limited water resources, and the imbalance between water supply and demand for industry, agriculture, and domestic water is becoming more severe (FAO, 2010). In Northwestern China, irrigation water accounts for over 90% of the total water use (Shen et al., 2013). The over-exploitation of ground water and low water use efficiency (WUE) are also major problems in agricultural water use (Zhang et al., 2004; Mo et al., 2005), which may compromise the capacity to cope with the growing food demand and the shortage of water resources in the future (Molden et al., 2003; Bastiaanssen and Steduto, 2017). WUE reflects the relationship between photosynthetic production of vegetation and water consumption (Mo et al., 2005; Usman et al., 2014; Xie et al., 2016). An additional 5600 km^3 of water is estimated to be lost to the atmosphere through evapotranspiration (ET) by 2050 if the crop WUE does not improve (Falkenmark and Rockström, 2004). Improving the WUE can be achieved by increasing the production per unit of water consumed, or reducing the amount of water consumed per unit yield of production.

The Loess Plateau is one of the most fragile and ecologically sensitive regions in China. During the winter wheat growing season, the water deficit is severe and precipitation generally cannot meet the water requirements for crop growth and development. Irrigation is thus needed to ensure crop yield. Over recent decades, the Loess Plateau has seen obvious increases in drought frequency, duration, and severity (Jiang et al., 2016). Plants tend to maintain a high WUE under water limited conditions to enhance their ability to absorb water and reduce the effects of water deficit (Reichstein et al., 2007; Tian et al., 2011). However, some studies suggest that, under severe water stress, the WUE may reduce significantly with increasing water stress (Reichstein et al., 2002; Dong et al., 2011). The variability of WUE under water stress is associated with considerable uncertainties due to the lack of information regarding regional water management practices (irrigated versus rainfed) and climatic factors in the Loess Plateau (Lu et al., 2016; Zhang et al., 2016; Wang et al., 2018). Therefore, it is important to analyze the influence of drought on WUE and to improve our understanding of WUE as a function of water stress in the Loess Plateau.

Generally, water management strategies differ for irrigated and rainfed wheat (Zwart and Leclert, 2010). For irrigated wheat, they are to improve the WUE and increase crop yield, whereas for rainfed wheat, they are to make full use of natural precipitation to achieve a stable crop yield. The actual evapotranspiration (ETa), yield, and WUE are significantly affected by water management practices. The yield of irrigated wheat can be 2.3 times higher than that of rainfed wheat during drought years in the Loess Plateau (Jin et al., 2016). In recent years, the WUE for irrigated and rainfed crops has been widely studied at a range of spatial scales (Mo et al., 2005; Liu et al., 2007; Suyker and Verma, 2010; Tian et al., 2011; Tang et al., 2014). However, differences in water availability in the Loess Plateau were less considered for estimating WUE from remote sensing data or from crop models (Bu et al., 2015; Zhang et al., 2016, 2017). This may reduce the reliability of the estimated WUE.

The development of remote sensing technology now allows us to monitor the surface-energy distribution, vegetation growth, and water conditions. This offers an opportunity to evaluate the interaction between carbon and water cycles in the context of climate change at large spatio-temporal scales. The remote-sensing-based light use efficiency (LUE) model has been widely used to estimate the net primary production (NPP), crop growth, and yield formation (Lobell et al., 2003; Gitelson and Gamon, 2015). The harvest index (HI) and maximum LUE (ε_{max}) are two important parameters in LUE models. These two parameters are generally treated as empirical constants, which cannot reflect their spatial heterogeneities and may induce uncertainties into the estimated crop yield (Lobell et al., 2003; Tao et al., 2005; Zhang et al., 2016).

The scientific objectives of this study are as follows: (1) to use the support vector machine (SVM) algorithm based on the phenological parameters extracted from MODIS normalized difference vegetation index (NDVI) to account for the different water availabilities for winter wheat in the Loess Plateau and classify irrigated and rainfed wheat in the Loess Plateau; (2) to improve the estimated wheat yield by considering the spatial variabilities of ε_{max} and HI; and (3) to evaluate the synergy between ETa, yield, and WUE, and the variation of WUE as a function of water stress under different water availabilities (irrigated or rainfed) in the Loess Plateau.

2. Material and methods

2.1. Study area and methodology

The Loess Plateau is located between 32°N-41°N and 101°E-114°E, with an area of about 648,700 km^2, accounting for 6.76% of the total land area of China. The topography of the Loess Plateau in the northwest is higher than that in the southeast, with the elevation declining from 3000 m to 500 m. The Loess Plateau is in a transition zone from a semi-humid to a semi-arid climate between the eastern and western part of China. The minimum average annual temperature is −3.1 and 15.3 °C in the northwest and southeast, respectively (Jiang et al., 2016). The precipitation is unevenly distributed spatially and temporally. In semi-humid areas of the southeastern part, precipitation exceeds 600 mm/yr; in semi-humid and drought-prone areas of the middle part, the precipitation is about 400–600 mm/yr; while in the semi-arid areas in the northwest, the precipitation is only 150–250 mm/yr. Temporally, the high interannual variability makes the Loess Plateau one of drought-prone areas in China. The precipitation in wet years can be two to five times than that in dry years. The Loess Plateau mainly contains mountains and hilly areas. Wheat and maize are the staple crops and are mostly rainfed. Agriculture in the Loess Plateau is characterized by smallholder farms and is mainly limited by water availability.

For this study, 158 counties in the Loess Plateau that planted winter wheat were selected according to the county statistics (Fig. 1). The sowing dates varied from September 18 to October 21, 2010, and the maturity dates varied from May 28 to July 18, 2011 for winter wheat. Twenty-one agrometeorological stations observe the growth of winter wheat in the Loess Plateau. The average precipitation at these stations was between 188.2 and 301.1 mm during the winter wheat growing seasons from 2005 to 2016, with the least precipitation occurring during the 2010–2011 growing season. In this study, we chose the winter wheat growing period from 2010 to 2011 in the Loess Platea as a case study to investigate the wheat WUE as a function of water stress under rainfed and irrigated conditions. This time period witnessed continuous droughts during the sowing and overwintering periods, which was a typical agrometeorological condition for winter wheat in the Loess Plateau.

The water requirement of winter wheat in the Loess Plateau is between 250.0 and 650.0 mm (Huang et al., 2004). During most growing seasons, precipitation was far from satisfying the water requirement of winter wheat for growth and development. In the Loess Plateau, the water sources for irrigation are mainly groundwater, reservoirs, and rivers. In most parts of the northwest Loess Plateau, irrigation may increase the winter wheat yield by 62% to 126% with respect to rainfed wheat (Liu et al., 2007).

The main content of this study includes two parts (Fig. 2): 1) the classification of irrigated and rainfed wheat, and 2) the evaluation of WUE as a function of water stress for irrigated and rainfed wheat. First, the irrigated and rainfed wheat are classified using the SVM algorithm based on the phenological parameters extracted from the MODIS NDVI time series. Next, the wheat yield is estimated using the LUE model, and WUE is estimated based on yield and ETa. Finally, the