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Capability of crop water content for revealing variability of winter wheat grain yield and soil moisture under limited irrigation

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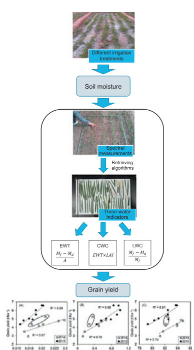
HIGHLIGHTS

- Crop water contents are sensitive to soil moisture variation before jointing stage.
- Leaf water contents are highly correlated with soil moisture at reviving stage.
- Canopy water content can interpret yield variability inducing by water stress.
- Partial least squares regression has great potential to estimate crop water content.

GRAPHICAL ABSTRACT



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ABSTRACT

Winter wheat (*Triticum aestivum* L.) is a major crop in the Guanzhong Plain, China. Understanding its water status is important for irrigation planning. A few crop water indicators, such as the leaf equivalent water thickness (EWT: g cm^{-2}), leaf water content (LWC: %) and canopy water content (CWC: kg m^{-2}), have been estimated using remote sensing techniques for a wide range of crops, yet their suitability and utility for revealing winter wheat growth and soil moisture status have not been well studied. To bridge this knowledge gap, field-scale irrigation experiments were conducted over two consecutive years (2014 and 2015) to investigate relationships of crop water content with soil moisture and grain yield, and to assess the performance of four spectral process methods for retrieving these three crop water indicators. The result revealed that the water indicators were more sensitive to soil moisture variation before the jointing stage. All three water indicators were significantly correlated with soil moisture during the reviving stage, and the correlations were stronger for leaf water indicators than that of the canopy water indicator at the jointing stage. No correlation was observed after the heading stage. All three water indicators showed good capabilities of revealing grain yield variability in jointing stage, with R^2 up to 0.89. CWC had a consistent relationship with grain yield over different growing seasons, but the performances of EWT and LWC were growing-season specific. The partial least squares regression was the most accurate method for estimating LWC ($R^2 = 0.72$; $RMSE = 3.6\%$) and comparable capability for EWT and CWC. Finally, the work highlights the usefulness of crop water indicators to assess crop growth, productivity, and soil water status and demonstrates the potential of various spectral processing methods for retrieving crop water contents from canopy reflectance spectrums.

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1. Introduction

The Guanzhong Plain (34°N, 109°E) is one of the most important grain production areas in Northwest China, and winter wheat (*Triticum aestivum* L.) is a widely cultivated crop in this region with an annual production of 4.2 billion kg of grains, accounting for about 40% of the total grain yield in Shannxi Province (Data Source: National Bureau of Statistics of China, http://www.stats.gov.cn/). During the winter wheat growing season, from mid-October to early-June of the following year, the average effective precipitation is only about 200 mm, while water demand can reach up to 450 mm (Chen et al., 2006). In particular, the ratio of water supply to demand is low during the jointing and heading stages; hence, the winter wheat is susceptible to severe water stress at these stages (Wang and Feng, 2012). Thus, irrigation is essential for winter wheat to achieve high yield in this region. However, due to scarcity of water resources, only about 40% of the total planting area receives irrigation (Data Source: Shaanxi Provincial Bureau of Statistics, http://www.shaanxitj.gov.cn/), and crops in much of the areas suffer from different degrees of water stress. Therefore, accurate and timely information on crop water status can help guide irrigation decisions.

Traditionally, the degree of crop water stress is judged by soil water status, usually represented by soil moisture content ($cm^3\ cm^{-3}$). Integrating soil moisture with soil water budget for irrigation scheduling is the most widely used practice, with a sound theoretical basis (Guo et al., 2007). However, in most regions, soil moisture measurements are only available at a limited number of monitoring sites, and are unable to capture the spatial variability of soil moisture at a larger scale. Moreover, the intensity of crop water stress varies as a function of soil texture (which modulates soil available water) and crop cultivars. Soil moisture only reveals the capacity of soil tot supply water to crop growth, but is not a direct indicator of crop water status (Zhang, J. et al., 2006). On the contrary, crop water contents have been found more relevant to crop water status (Cai et al., 2004), such as leaf water potential and stomatal morphology (Chai et al., 2015; Gago et al., 2015). More recently, non-destructive methods have been developed to estimate the crop water indicators from remote sensing data in different ecosystems such as agriculture, forest and grassland etc. (Casas et al., 2014; González-Fernández et al., 2015b; Mirzaie et al., 2014; Wang and Li, 2012; Yi et al., 2014), providing an easier way to map the spatial variability of crop water status.

Crop water indicators can be assessed at either the leaf level or the canopy level. At the leaf level, the equivalent water thickness (EWT) is described as the thickness of a water layer in leaf, equaling to the weight of water per unit leaf area. It is not commonly used in crop physiology but is used as a parameter to model light interaction with the leaf, such as in the PROSPECT model (Jacquemoud and Baret, 1990). The fuel moisture content (FMC) is another leaf water indicator, representing the water content as a percentage of leaf dry or fresh weight. For wildfire risk assessment, FMC is usually computed on the dry weight basis (Danson and Bowyer, 2004; Yebra et al., 2008). We used the leaf water content (LWC), which is the FMC expressed on the fresh weight basis (Garnier and Laurent, 1994; Turner, 1981). At the canopy level, the most common water indicator is the canopy water content (CWC), defined as the amount of crop water per unit ground area. The variable reveals canopy level crop response to water stress (Ustin et al., 2012), and can be used to help with surface soil moisture estimation from microwave remote sensing (Pierdicca et al., 2010).

Methods for retrieving crop water indicators from remote sensing data include 1) empirical models based on the red edge indices or parameters (Liu et al., 2004; Zhang and Zhou, 2015), vegetation index (VI) (Casas et al., 2014; Wang et al., 2013), or other spectrum analytical methods (González-Fernández et al., 2015a; Köksal, 2011; Mirzaie et al., 2014); 2) physical model inversion (Colombo et al., 2008; Trombetti et al., 2008; Zarco-Tejada et al., 2003). During the last few decades, machine learning techniques (e.g., neural network, support vector machine, and decision tree) have been developed and widely used for terrestrial vegetation indicators retrieval (e.g. chlorophyll, LAI and biomass), due to their adaptiveness and robustness, and capability of achieving satisfactory accuracy (Durbha et al., 2007; Li, X. et al., 2014; Verrelst et al., 2012; Zheng et al., 2015). However, fewer studies have used the machine learning technique to retrieve crop water indicators and to evaluate the retrieval accuracy.

Many studies have been devoted to the estimation of crop water indicators from spectral measurements; however, limited study has focused on assessing the capability of these indicators for revealing crop growth and soil moisture variability. Thus, the objectives of this study were: 1) to investigate the effect of different water stress conditions on the variation of crop water indicators across a growing season; 2) to evaluate the capability of the water indicators in revealing soil water status and grain yield at different growth stages; and 3) to evaluate the methods for estimating crop water indicators from spectral measurements using various spectral processing techniques.

2. Materials and methods

2.1. Study area

The experiment was conducted at a water-saving irrigation station in an irritated agricultural region in the Guanzhong Plain, Northwest China (34°17′N, 108°04′E, 506 m a.s.l). It was operated by the Laboratory of Agricultural Soil and Water Engineering, Northwest Agriculture and Forest University, China. The experiment was conducted over two consecutive winter wheat growing seasons (2014 and 2015). The climate is characterized by a typical semiarid warm temperature and continental monsoon, with annual average temperature, precipitation and potential evapotranspiration of 12.9 °C, 635.1 mm and 1500 mm, respectively. Inside the experimental fields, the soil is classified as loamy texture with soil moisture at field capacity of 0.31 $m^3\ m^{-3}$, wilting point of 0.12 $m^3\ m^{-3}$ in the top 1-m soil layer and an average dry bulk density of 1.31 $g\ cm^{-3}$. The available Carbon, Nitrogen and pH in the 0–20 cm surface layer is 8.20 $g\ kg^{-1}$, 0.62 $g\ kg^{-1}$ and 8.14, respectively. The meteorological data (air temperature, relative humidity, and sunshine hours, etc.) during winter wheat growing seasons were automatically collected from Yangling National Meteorological Station 200 m away from the study site (http://data.cma.cn).

2.2. Experimental design

Plot experiments were conducted to explore the response of winter wheat to various water stress scenarios during the 2013–2014 and 2014–2015 growing seasons. Two factors, irrigation periods and depth, were considered in the experimental design. Generally, the full growth cycle of the crop can be divided into four phenological stages after emergence, namely, tillering, jointing (stem elongation), heading, and ripening (grain development). Since the tillering stage of winter wheat can last >3 months and two irrigations could be applied in practice, the tillering stage was further divided into a dormancy stage in the winter and a reviving stage in the spring. This leads to five growth (and irrigation) stages defined approximately by the day of year (DOY): winter dormancy (from emergence in previous year to DOY 49 in current year), reviving (DOY 50–85), jointing (DOY 86–112), heading (DOY 113–127) and filling (DOY 128 to harvest). The two irrigation levels were determined as sufficient (80 mm) or deficit (40 mm) according to seasonal water demands of the crop in this region (Chen et al., 2006; Wang and Feng, 2012). The following irrigation treatments were designed: 1) one control treatment with 80 mm irrigation depth at each growth stage (I_{80}); 2) four treatments with no irrigation at each two-consecutive stages (D_{12}, D_{23}, D_{34}, D_{45}), but with a fixed irrigation depth at either 40 mm (I_{40}) or 80 mm (I_{80}) of water at all the other growth stages, for an annual total of 120 mm and 240 mm respectively. Hence, there are 9 treatments in total. The control treatment had two replicates, whereas the other treatments had three replicates. The