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A satellite based crop water stress index for irrigation scheduling in sugarcane fields

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ABSTRACT

In this study, the capability of crop water stress index (CWSI) based on satellite thermal infrared data for estimating water stress and irrigation scheduling in sugarcane fields was evaluated. For this purpose, eight Landsat 8 satellite images were acquired during the sugarcane growing season (May–September 2015). Simultaneous with the satellite overpass times, in-situ measurements of canopy temperature and vegetation water content (VWC) were conducted in forty points located in eight sugarcane fields per image (in total 320 observation points in 32 fields). These fields were selected with different ages (Plant, Ratoon 1, Ratoon 2, and Ratoon 3) and irrigation schedule. Then, the CWSI was calculated in three different ways including: 1) based on the Idso method and using the handheld infrared thermometer, 2) based on the Idso method and thermal infrared data of Landsat 8 satellite imagery, 3) using a new proposed procedure for retrieving CWSI from the satellite imagery with using the hot and cold pixels. Results show a good relationship between the calculated CWSI based on field measurement and new CWSI based on satellite data with the coefficient of determination of 0.49–0.85 and the root mean square error (RMSE) of 0.12–0.29 for different images. Further, a negative relationship between VWC and CWSI, with R^2 values of 0.42–0.78, was observed. This relationship increases with developing sugarcane canopy, and decreases with an increasing plant age. Comparing recorded irrigation events in the fields, estimated CWSI and VWC shows that water stress can be classified into three critical classes including high water stress ($0.70 < VWC \leq 0.75$), medium water stress ($0.75 < VWC \leq 0.8$), and low stress ($0.8 < VWC \leq 0.85$). This classification can be used as a part of an operational procedure for appropriate irrigation scheduling. All of the aforementioned results indicate that the CWSI based on the proposed approach in this study can be used effectively for monitoring water stress and irrigation scheduling in sugarcane fields using satellite imagery without any need for ground ancillary data.

1. Introduction

Water deficit in the soil, causing vegetation water stress, is an important factor which negatively affects the crop production. Therefore estimating water stress and appropriate irrigation scheduling based on the crops response to water stress at different growth stages is very important (Geerts and Raes, 2009; Mahan et al., 2012). This activity is classically done based on the in-situ measurements of vegetation water content (VWC) or soil water content (SWC) (Baret et al., 2007). These activities are time-consuming and costly, and the point observation that are typically done have a low spatial coverage giving a poor indication of the fields' overall status (Jackson et al., 1981).Todays scientific and technological advancements like remote sensing techniques provide powerful tools for evaluating the vegetation characteristics, which can facilitate management and irrigation decisions (Yi et al., 2013). Irrigation scheduling using remotely sensed data can potentially be done based on the estimation of either canopy temperature or the VWC, as a proxy of the soil water content. Direct calculation of the VWC is difficult and has large uncertainties due to challenges in field measurements. The fact that a decreasing VWC, leads to a lower transpiration of crops and an increasing canopy temperature (Lin et al., 2012; Zhou et al., 2005) has provided signs that canopy temperature can be used as a proxy of VWC for estimating water stress and irrigation scheduling (Penuelas et al., 1993; Jackson et al., 2003). Assessing the water stress using a thermal infrared thermometer was originally suggested by (Jackson et al., 1977). This method has been largely utilized since the introduction of the Crop

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Water Stress Index (CWSI) in the early 1980s (Idso et al., 1981; Jackson et al., 1981). Since then, canopy temperature has been widely applied and studied as a proxy for water stress detection and irrigation scheduling (Idso et al., 1984; Stegman 1986; Steele et al., 1994; Irmak et al., 2000; Cohen et al., 2005; Leinonen and Jones, 2004; Moller et al., 2007; Wanjura et al., 2004; Taghvaeian et al., 2012, 2013). The most important reason for using the CWSI is the fast and easy measurement procedure (Berni et al., 2009) paying attention to the fact that CWSI can be used instead of VWC (Ben-Asher et al., 1992; Meron et al., 2010; O'Shaughnessy et al., 2011).

The main restrictions of using the CWSI, based on Idso method for monitoring water stress are the difficulties to measure canopy temperature (Tc) and air temperature (Ta) in the field and the primary calculation to determine the upper and lower limit of canopy temperature and air temperature (dT_U and dT_L). To overcome these difficulties, we propose a new procedure for calculating CWSI based on the satellite data, without the need for any ancillary data and complex calculations.

Sugarcane fields and its by-products are the major agricultural activities in the southwest of Iran and the biggest agricultural industry in Iran, covering an area of more than 100,000 ha. Water stress – among other factors such as a shallow water table and soil salinity is one of the main factors affecting sugarcane crop yield in this area (Hamzeh et al., 2013, 2016). The water requirement of this crop is high and full or supplementary irrigation water is essential for its appropriate growth and production (Inman-Bamber and McGlinchey, 2003). As a results, sugarcane fields have become one of the largest sources of water consumption in the region. Therefore, accurate estimation of crop water stress, appropriate irrigation scheduling and new irrigation strategies are essential to improve irrigation management of this area thus allowing an appropriate response to the growing water demands and preserve sustainability in the future. But, crossing sugarcane fields that have a full canopy is hard and the measurement of soil and plant characteristics for irrigation management is difficult, thus detection of water status for sugarcane fields using remote sensing tools is extremely essential.

Reviewing the literature shows that using the calculated CWSI based on remotely sensed data could be the best operational method for monitoring and assessment of water stress and irrigation scheduling of sugarcane fields located in this area. The lack of studies on sugarcane water stress using thermal infrared remote sensing data, such as the Landsat 8 TIR bands, and their validation of the satellite measurements with in-situ measurements for appropriate irrigation scheduling led to the present study. We provide a step toward the optimization of irrigation scheduling in the sugarcane fields extended in the southwest of Iran, with the following objectives: (I) to evaluate the capability of satellite and ground-based thermal infrared data for estimating water stress in sugarcane fields, (II) developing a new procedure for calculating CWSI based on satellite data, without the need for any ancillary ground data, (III) exploring the relationship between CWSI, as a proxy for water stress, vegetation water content (VWC) and number of passed days since irrigation events, and (IV) present an appropriate remote sensing based approach for irrigation scheduling and water management of sugarcane fields.

2. Materials and methods

2.1. Study area

The experiment was conducted in the Salman Farsi Agro Industry sugarcane fields, one of the seven farming and agro industry units of sugarcane located in the southwest of Iran between latitudes 31° 00′ 30″–32° 30′ 00"N and longitudes 48° 15′ 00″ E-48° 40′40″ E (Fig. 1). This area has an arid and semi-arid climate with an average annual precipitation of 266 mm and annual evaporation from open pans of 2788.3 mm yr^{-1}. The study area was uniformly divided into rectangular fields with an area of 25 ha (1000 m × 250 m). All fields are irrigated using a surface furrow irrigation system with a low pressure hydro-flume with an outlet for each furrow and each field has a subsurface drainage system on an average depth of 1.8 m. Irrigation starts in May and continues until early November when cool temperature impedes further growth. In addition, the applied irrigation water for normal growth is 3000 mm with peak water use of 10–13 mm/day. Irrigation time consumption for each field varies from three to five days.

Planting, harvesting and other operations are similar in all fields (Hamzeh et al., 2013). The irrigation scheduling is based on the classical method of measuring the vegetation water content in one representative field for 5 fields, which is very difficult and time-consuming.

2.2. Field measurements

Field measurements were done in 32 selected sugarcane fields with different ages (Plant, Ratoon 1, Ratoon 2, and Ratoon 3). All the selected fields have a comparable soil texture and irrigation and drainage system.

In order to evaluate the capability of Landsat 8 satellite imagery for estimating crop water stress, in-situ measurements including canopy temperature and vegetation water content were made between 10:30 until 11:30 am, during the acquisition of Landsat 8 images over the study area on 24 May, 9 June, 25 June, 11 July, 27 July, 12 August, 28 August and 13 September 2015. Field data were gathered on 40 locations in eight fields (five locations per field) with different irrigation days, and the position of each point was registered with GPS. All measurements were done at a distance of 60 m from the edge of the fields. In total 320 sets of ground observation data in 32 fields with different plant age were collected in period of research. Fig. 2 shows the location of the experimental fields in the study area with their plant age, the meteorological station and laboratory site of Salman Farsi agro-industry unit. The weather station is in one of the fields near the laboratory that logs the hourly air temperature, air humidity, wind velocity, wind direction, atmospheric pressure, precipitation amount and evaporation using evaporation pan class "A". Also the scheme of the sugarcane fields and the locations of the measurement points in each field are shown in Fig. 3.

2.2.1. Plant sampling and vegetation water content

To measure VWC, three average-looking plants at each location were cut without root, placed and sealed in plastic bags, then placed in a cool dark container to avoid water loss during transfer to the laboratory. The fresh weight (FW) of the gathered samples was recorded using an analytical balance in the laboratory immediately after arrival, and then samples were put into an oven to dry at 65 °C for 48 h until a constant dry weight (DW). The vegetation water content (VWC) was calculated for each sample using Eq. (1).

$$VWC = \frac{FW - DW}{DW} \times 100 \quad (1)$$

The statistical summary of the measured VWC data is given in Table 1. For the laboratory analytical balance measurement accuracy, yield readability to two decimal places to the right of the decimal point (up to 0.01 g).

Sheath water content has been found a good indicator for irrigation scheduling (Sund and Clements, 1974). The maintenance of the Moisture Index (MI) of the leaf sheath at 75% may assist in achieving optimum growth of the plant (Bakker, 1999). Consequently, VWC