Agricultural Water Management 189 (2017) 98–110

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Research paper

Thermal imaging and passive reflectance sensing to estimate the water status and grain yield of wheat under different irrigation regimes

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ARTICLE INFO

Article history:
Received 2 October 2016
Received in revised form 5 May 2017
Accepted 6 May 2017

Keywords:
High-throughput
Infrared thermal image
NRCT
Phenotyping
Spectral reflectance
Water stress

ABSTRACT

The water demand for agricultural purposes is steadily increasing. The use of contactless sensing techniques, such as passive reflectance sensors and thermal imaging cameras, is therefore becoming imperative and will be one of the major adaptation strategies to control the irrigation schedule under arid and semi-arid conditions. In this study, the performance of hyperspectral passive reflectance sensing and infrared thermal imaging was tested to assess their relationship with the water status and grain yield (GY) of wheat cultivars via simple linear regression and partial least square regression (PLSR) analyses. The models included data of the (i) normalized relative canopy temperature (NRCT); (ii) PLSR based on selected spectral indices; (iii) data fusion model of PLSR based on selected spectral indices and the NRCT; and (iv) data fusion model of PLSR based on selected spectral indices, NRCT, relative water content (RWC), and canopy water content (CWC). The experimental treatments involved two wheat cultivars (Gmiza 11 and Sods 1) and three water regimes (irrigated with 100%, 75%, and 50% of estimated crop evapotranspiration). The results show that the NRCT was closely and significantly associated with RWC, CWC, and GY, with $R^2 = 0.84$, 0.87 and 0.81, respectively. The data fusion model of PLSR based on selected spectral indices, NRCT, RWC, and CWC improved the yield prediction under three irrigation regimes ($R^2 = 0.97$, slope = 0.99, root-mean-square error = 26.48 g/m^2). In conclusion, improvements can be made in the yield prediction when traits that are physiologically related in different ways to the yield are combined with non-destructive data.

1. Introduction

The water shortage in arid and semi-arid regions worsens due to abrupt climatic changes and excessive water consumption in the agricultural sector using the available water supply (El-Hendawy et al., 2015). Therefore, the use of contactless sensing techniques, such as passive reflectance sensors and thermal imaging cameras, is becoming imperative and will be one of the major adaptation strategies to control the irrigation schedule under arid and semi-arid conditions. Traditional methods, such as pressure chambers or oven-drying, for the assessment of the water stress of plants by estimating their water status are time-consuming.

In the field, frequent changes of environmental conditions might further influence the measurements; thus, fast measurements are needed (Peñuelas et al., 1997; Elsayed et al., 2011; Winterhalter et al., 2011). Therefore, it is very important to develop high-throughput sensing methods for the assessment of water stress in crops, which should be reliable, fast, simple, practical, and economic. The early detection of water stress factors, such as the canopy water content (CWC) and relative water content (RWC), which were measured in this study with remote sensing methods, is crucial because it could help to identify the water stress status

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http://dx.doi.org/10.1016/j.agwat.2017.05.001
0378-3774/

on larger temporal and spatial scales before any damage is clearly visible.

Thermal imaging is an important technique to detect the water stress based on the plant temperature. With the ability to point and shoot high-quality thermal images (Jerbi et al., 2015), it is possible to measure the temperature of plants in large-scale water regimes. Thermography allows the simultaneous monitoring of large groups of leaves, providing an overview of stomatal conductance variation and dynamics (Zia et al., 2011). It measures infrared radiation and uses it for the calculation of the spatial distribution of the temperature of the plant canopy. The use of plant temperature to assess the water stress depends on stomatal closure during plant water deficits, which leads to a decrease of the energy dissipation and an increase in plant temperature (Idso et al., 1981; Patel et al., 2001). The plant temperature reflects the combined effects of the soil moisture content and atmospheric conditions on the crop water status, which ultimately affects the grain yield (GY) of cultivars. Idso et al. (1981) developed a crop water stress index (CWSI) based on thermal measurements that ranges between zero (full transpiration) and one (minimum stomatal conductance). The CWSI is the most commonly used index to quantify the water stress based on the canopy temperature. In addition to the CWSI, it is also important the I_g (the conductance index or the Jones Index (Jones, 1999)). It is a helpful tool to quantify the water stress and can be used for irrigation scheduling. The newly developed normalized relative canopy temperature (NRCT) index similar to the CWSI, which has been developed by Elsayed et al. (2015b), was tested in this study. The NRCT was calculated depending on the actual infrared temperature measured in the canopy, the lowest temperature measured in the whole field trial (lower baseline), and the highest temperature in the whole field trial (T_{max}, upper baseline). The advantage of this index is that no additional measurements other than that of infrared temperatures are necessary compared with the CWS Jackson et al. (1981) used a wet bulb temperature as the lower baseline and a dry bulb temperature as the upper baseline to calculate the CWSI based on the air temperature and air vapor pressure deficit, whereas canopy measurements were used in this experiment. The NRCT allows the interpretation of the temperature measurements as reductions in the stomatal conductance and the comparison of water stress levels in different field trials under different environmental conditions. The NRCT has only been used by Elsayed et al. (2015b) as an indicator for drought-stressed barley cultivars and the ability of the spectral reflectance to assess the NRCT of drought-stressed barley cultivars. In this study, the NRCT was used to assess and predict the water status and GY of wheat cultivars in different irrigation regimes.

Spectral reflectance measurements with passive sensors have been used to assess the canopy water status, aerial biomass, dry biomass, nitrogen status, and GY. Passive sensor systems depend on sunlight as a source of light. Several studies suggested that the water status and GY could be estimated using the vegetation spectral reflectance during different growth stages (Schmidhalter et al., 2001; El-Shikha et al., 2007; Gutierrez et al., 2010; Yang et al., 2016); for example, the normalized water stress indices 1 [NWI-1; $(R_{970}-R_{900})/(R_{970}+R_{900})$], 2 [NWI-2; $(R_{970}-R_{850})/(R_{970}+R_{850})$], 3 [NWI-3; $(R_{970}-R_{920})/(R_{970}+R_{920})$], and 4 [NWI-4; $(R_{970}-R_{880})/(R_{970}+R_{880})$] from passive reflectance sensor measurements demonstrated a great potential in differentiating high- and low-yielding genotypes in advanced lines of spring wheat under well-irrigated, water-stressed, and high-temperature conditions in diverse trials (Gutierrez et al., 2010). Lobos et al. (2014) found that the normalized NWI-3 and the normalized difference vegetation index [NDVI; $(R_{830}-R_{660})/(R_{830}+R_{660})$] were most closely related to the GY and the water status of wheat genotypes subjected to drought stress. El-Shikha et al. (2007) reported that the water index (WI) can explain variations in the plant water content of broccoli plants in different water regimes.

Few studies developed sophisticated statistical approaches to link data gathered from sensors with agronomic or physiological traits. Thus, yield-model approaches are typically based on single spectral indices (Gutierrez-Rodriguez et al., 2004). Both linear and multiple linear regression models can also be derived from spectral indices. Royo et al. (2003) found that 17.3% to 65.2% of durum wheat yield could be accounted for using multiple linear regression models based on varying spectral indices.

An alternative approach is to use partial least square regression (PLSR), which was used in this study. Orthogonal components are unaffected by collinearity in PLSR and are derived from all variables. Rischbeck et al. (2016) reported that the combination of several spectral reflectance indices that were based on the differential reflectance of the canopy in the spectral range of 350–1000 nm with CWSI data and plant height of barley cultivars in PLSR models improved the prediction of the GY. The PLSR models of the hyperspectral reflectance have been used in maize (*Zea mays* L.) at anthesis and during the milk-grain stage by Weber et al. (2012). The models successfully explained between 49% and 69% of the variation in the GY in the calibration model and 23% to 40% after model validation. The use of hyperspectral data has also been employed in yield models of PLSRs (Sharabian et al., 2014).

The data that can be obtained from passive reflectance sensors is limited to the interactions of light with plants or soil material. The transpiration is not directly related to the spectral reflectance but related to the canopy temperature (Rischbeck et al., 2016). Therefore, sensors using other physical principles might add information to spectral assessments. Therefore, statistical data fusion of sensor measurements (thermal image camera and passive reflectance sensor) in PLSR models was used and tested in this study to improve yield models in different irrigation regimes at the flowering growth stage in two years. The use of the information from passive sensors, the thermal image camera, and information about the water status might also increase the flexibility of the yield prediction in different irrigation regimes. Thus, the statistical data fusion of sensor measurements, CWC, and RWC in PLSR models was used and tested to improve yield models.

The purpose of this work was: (i) to compare the performance of the thermal image camera by using the NRCT index and selected spectral reflectance indices for the assessment of the water status and GY of wheat cultivars in three irrigation regimes, (ii) to evaluate two models (NRCT and PLSR models based on five spectral indices) to predict the water status and GY, and (iii) to assess the improvement of the yield prediction using the data fusion model of PLSR based on the NRCT and five spectral indices and to assess the improvement of the yield prediction using the data fusion model of PLSR based on the NRCT, five spectral indices, CWC, and RWC.

2. Materials and methods

2.1. Field experiments and design

Field experiments were carried out at the Research Station of the University of Sadat City in Egypt during 2014–2015 and 2015–2016. The research station of the University of Sadat City (Latitude: N30°2′ 41.185″, Longitude: E31°14′ 8.1625″) is characterized by a semi-arid climate with moderate cold winters and warm summers. The experimental treatments consisted of two wheat cultivars (Gmiza 11 and Sods 1) and three water regimes [T1, irrigated with 100% of the estimated crop evapotranspiration (ETc); T2, irrigated with 75% ETc; and T3, irrigated with 50% of ETc]. The field experiments were designed as a randomized complete block split plot design with six replicates. The three water regimes were assigned to the main