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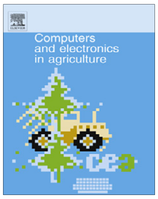

Review

# Recent advances in crop water stress detection

Samuel O. Ihuoma [*], Chandra A. Madramootoo

*McGill University, Macdonald Campus, 21,111 Lakeshore Rd, Ste Anne De Bellevue, Quebec H9X 3V9, Canada*

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ABSTRACT

In order to meet the demand for increased global food production under limited water resources, implementation of suitable irrigation scheduling technique is crucial, particularly in irrigated basins experiencing water stress. Optimizing water use in agriculture requires innovations in detection of plant water stress, at various stages of the growing season to minimize crop physiological damage, and yield loss. Remotely sensed plant stress indicators, based on the visible and near-infrared spectral regions, have the advantage of high spatial and spectral resolutions, low cost, and quick turnaround time. This paper outlines recent developments in monitoring crop water stress, for scheduling irrigation, some of the constraints experienced, and future research needs.

**Contents**

## 1. Introduction

Irrigated agriculture is essential to global food production, utilizing only 20% of cultivated land to provide 40% of the world's food supply (Garces-Restrepo et al., 2007). However, climate change, increasing worldwide shortages of water, frequent droughts, and global warming (Hirich et al., 2016) are threatening the reliability of irrigation water supplies. While the human population and demands for freshwater resources are increasing, drought and regular water scarcity can put global food security at risk (Lei et al., 2016), by severely disrupting agricultural production. The challenge is to meet rising productivity demands by improving methods of crop management (Behmann et al., 2014), and this requires a deeper understanding of plant response to abiotic stresses.

Conventional methods for monitoring crop water stress rely on in situ soil moisture measurements and meteorological variables to estimate the amount of water lost from the plant-soil system during a given period (González-Dugo et al., 2006). Regular sampling of soil to assess water depletion from the plant root zone assumes that the water holding capacity of the entire soil is uniform, so only

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[*] Corresponding author.
*E-mail address:* samuel.ihuoma@mail.mcgill.ca (S.O. Ihuoma).

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a few point measurements are used to represent water retention characteristics (Clarke, 1997). The method is time consuming, assumes uniform plant density, and the same rate of transpiration, over an entire field, which is rarely the case. Similarly, evapotranspiration models assume a freely transpiring reference crop with uniform cover and soil type within a field. These methods are time consuming and produce point information that give poor indications of the overall status of the field. Other methods of detecting plant water status involve soil water balance calculations, direct and indirect measurement of plant water status, via stomatal conductance and leaf water potential. These approaches, though reliable, are labour intensive, destructive, and unsuitable for automation, due to heterogeneity of soil and crop canopy.

In order to increase water savings and enhance agricultural sustainability, implementation of suitable irrigation scheduling methods is essential (Osroosh et al., 2015), and requires early detection of water stress in crops, before it causes irreversible damage and yield loss. Recently, studies have focused on the use of remotely sensed data as an alternative to traditional field measurements of plant stress parameters, as this provides information about the spatial and temporal variability of crops (Dangwal et al., 2015; Leroux et al., 2016; Panigada et al., 2014; Rossini et al., 2013; Suárez et al., 2010; Zarco-Tejada et al., 2013; Zhao et al., 2015). Spectral reflectance indices obtained from high resolution hyperspectral sensors, onboard small Unmanned Aircraft Systems (sUAS), can be used in precision agriculture for monitoring crop water status and scheduling irrigation (Berni et al., 2009a, 2009b; Gago et al., 2015). However, due to several confounding factors affecting the vegetation indices (VIs) at the canopy and landscape scales, and that the threshold for water stress detection is crop specific, a general agreement for their use as a pre-visual indicator of water stress is yet to be achieved. This paper reviews the recent advances in crop water stress detection that can potentially be applicable to improve irrigation scheduling of vegetable crops and aims to identify the most promising approach for large-scale application.

## 2. Plant response to water stress

Crop water stress is a deficiency in water supply, detected as a reduction in soil water content or from the physiological responses of the plant to water deficit. Plants absorb root zone soil water to meet their evapotranspiration needs, and this depletes soil available water. Under limiting soil moisture conditions, chemical and hydraulic signals are transmitted to the plant leaf through xylem pathways (Limpus, 2009), which leads to physiological responses such as stomatal closure and reductions in photosynthesis rate. Wang et al. (2015) indicated that water stressed crops have reduced evapotranspiration, and manifest other symptoms such as leaf wilting, stunted growth, and leaf area reduction. Also, water stress adversely affects the physiological and nutritional development of crops, leading to reduced biomass, yield, and quality of crops (Aladenola and Madramootoo, 2014; Rossini et al., 2013; Zhang et al., 2017a, 2017b). Plant water status measures the response of a plant to the combined effects of soil moisture availability, evaporative demand, internal hydraulic resistance, and uptake capacity of the plant-root interface. It is a more sensitive indicator of stress than soil moisture (Jones, 2010). Plant response to water stress depends on environmental conditions and crop evapotranspiration needs, as irrigation must replenish soil moisture deficit from evapotranspiration losses. FAO-56 defines the irrigation water requirement for a well-watered crop as water loss through evapotranspiration of a disease-free crop under non-limiting soil conditions (Allen et al., 1998). Measures of plant water status are required to better understand the mechanisms of plant response and adaptation to water stress, and for the optimisation of crop production (Osakabe et al., 2014), through precision irrigation.

Similarly, evapotranspiration (ET) models are used to predict how changes in weather parameters can affect plant water status (Osroosh et al., 2016). The frequently used ET models are the Penman-Monteith (PM) (Allen et al., 1998) and Hargreaves (Hargreaves and Samani, 1985) equations. The Hargreaves model needs fewer data than the PM model and can estimate ET using air temperature as only input. Other researchers have used the CROPWAT-8, which is based on the Penman-Monteith method, to assess reference evapotranspiration (ETo), crop evapotranspiration (ETc), and irrigation water requirements (Bouraima et al., 2015; Patel et al., 2017; Surendran et al., 2017). The most common and practical approach widely used for estimating crop water requirement, and the operational monitoring of soil-plant water balance is the FAO-56 method. In the FAO-56 approach, crop evapotranspiration is estimated by the combination of $ET_o$ and crop coefficients. There are two different FAO-56 approaches: single and dual crop coefficients. The single crop coefficient approach is used to express both plant transpiration and soil evaporation combined into a single crop coefficient (Kc). The dual crop coefficient approach uses two coefficients to separate the respective contribution of plant transpiration (Kcb) and soil evaporation (Ke), each by individual values (Allen et al., 2005). Kcb is multiplied by water stress coefficient (Ks) (range 0–1) to account for the reduction of ET due to soil moisture depletion. It has been shown that Ks is related to crop water stress index (CWSI) according to Eq. (1).

$$K_s = 1 - CSWI \tag{1}$$

Several researchers have evaluated the accuracy of water stress coefficient methods for estimating crop ETc under different levels of deficit irrigation. For instance, Bausch et al. (2011) successfully used a ratio of canopy temperature (Tc) as a substitute for the soil moisture based Ks. Kullberg et al. (2017) observed that using appropriate Ks method has the potential to improve irrigation scheduling to properly manage stress and ensure optimum crop yield under limited irrigation water supply. The main methods that are used for monitoring plant water stress have been summarized in Table 1, and are discussed below.

### 2.1. Plant-based approach

Stress quantification from plant-based approaches include the direct measurement of leaf water potential with a pressure chamber (Scholander et al., 1965). Leaf water potential is assumed to represent the mean soil water potential next to the plant roots (Ameglio et al., 1999), and provides good indication of leaf water status. It is widely adopted for scheduling irrigation in various crops (Alchanatis et al., 2010; Ameglio et al., 1999; Bellvert et al., 2016; Zarco-Tejada et al., 2012). However, the approach is slow and destructive, with limited temporal and spatial resolution, and is not suitable for strongly isohydric crops, which maintain a stable leaf water status over a wide range of evaporative demand or soil water supplies (Limpus, 2009). The amount of water in plant leaves can be measured by laboratory analysis, using Relative Water Content (RWC) and Equivalent Water Thickness (EWT) (Colombo et al., 2011). The EWT is the hypothetical thickness of a single layer of water averaged over the whole leaf area and can be computed in laboratory by measuring Fresh Weights ($FW$) and Dry weights ($DW$) and the one-sided leaf Area ($A$), as shown in Eq. (2).

$$ETW = \frac{FW - DW}{A} \tag{2}$$