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Plant temperature-based indices using infrared thermography for detecting water status in sesame under greenhouse conditions

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ABSTRACT

There have been studies on the effect of water stresses on leaf stomatal conductance (g_s); however, the scientific reports on using non-contact techniques such as thermography for sesame (*Sesamum indicum* L.) are rare. The objectives of this study were hence to detect water status in sesame (genotype, "Naz-Takshakhe") under greenhouse conditions using Crop Water Stress (CWSI) and stomatal conductance (I_g) Indices. One hundred and fifty pots were randomly assigned to three equal groups which were irrigated at soil water potential of −0.1 MPa (well-watered, WW), −1.0 MPa (moderate-water stressed, MWS), and −1.5 MPa (severe-water stressed, SWS). Four formulations of CWSI and two of Ig using canopy temperature (T_C) from the WW treatment or temperature from a wet reference for the upper threshold and T_C from the SWS treatment, temperature from a dry reference or air temperature plus 3° as the lower threshold were compared. Moreover, an additional CWSI and Ig formulations were also obtained by non-water stress baseline (NWSB) information using meteorological data. Furthermore, the relative water content (RWC) and g_s were measured on the youngest and uppermost fully developed leaves of each pot. T_C of MWS and SWS plants was higher than WW plants by 1.9 and 2.6 °C, respectively. A significant and linear relationship ($P < 0.001$) between CWSI/I_g and g_s/RWC was found. Therefore, both physiological traits of g_s and RWC can be estimated by temperature-based indices of CWSI/I_g. The results also showed the developed system enables us to estimate actual time variations in canopy temperatures. This study validates the effectiveness of using CWSI/I_g for non-destructive detection of water stress and estimation of relative water content in sesame.

1. Introduction

Agricultural productivity is limited worldwide by various biotic and abiotic stresses (Kumar, 2013). Drought is of particular importance since it is the main abiotic stress factor which causes the highest yield losses (Manavalan and Nguyen, 2012). From the agricultural point of view, crop water stress occurs when the amount of the water provided through rainfall and irrigation is not sufficient to meet the needs of plant evapotranspiration. Like other crop stresses, water stress influences on a large number of physiological, biochemical, and molecular reactions of plants (Lisar et al., 2012; Manavalan and Nguyen, 2012). Precision irrigation can help to improve water use efficiency and to increase the crop productivity.

Several methods for monitoring crop water stress have been introduced which can be classified as: soil-based and plant-based measurements (Alves and Pereira, 2000; Cohen et al., 2005; Cohen et al., 2012). Among these methods, soil moisture sensors, pressure chambers and leaf diffusion porometers have been widely used for measuring soil moisture, individual leaf/stem water potential and leaf stomatal conductance, respectively (Ballester et al., 2013; Idso et al., 1977; Moller et al., 2006). However, these techniques are unsuitable for automatic monitoring of crop water stress since they are destructive, labor-intensive, and time-consuming. Therefore, the applications of these methods for spatial and temporal monitoring of crop water stress in large acreage production systems are not feasible (Ballester et al., 2013).

From plant physiology, if a plant is experiencing water stress, the stomata tends to close, leads to a reduction in transpiration and rising the leaf temperature (Ballester et al., 2013; Jones, 1999, 2004; Leinonen and Jones, 2004). Therefore, the increase in canopy

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Nomenclature

ASW	Available soil water [cm^3]
a	Crop specific intercept for NWSB [°C]
b	Crop specific slope for NWSB [°C kPa^{-1}]
CWSI	Crop water stress index [−]
DV	Digital value [−]
DW	Dry weight [g]
ΔT_1	Temperature difference of WW canopy and air [°C]
ΔT_2	Temperature difference of plant canopy and air [°C]Temperature difference of plant canopy and air [°C]
ΔT_3	Temperature difference of assumed upper limit canopy (air temperature plus 3 °C) and air [°C]
EC	Electrical conductivity [dS m^{-1}]
FOV	Field of view [Degree]
FW	Fresh weight [g]
SWS	Severe-water stressed [−]
g_s	Stomatal conductance [mmol m^{-2} s^{-1}]
MWS	Moderate-water stressed [−]
Ig	Stomatal conductance index [−]
LWIR	Long wave infrared [μm]
MAD	Maximum allowable depletion [cm^3]
NWSB	Non-water stressed baseline [−]
P	Fraction of ASW that can be depleted from the root zone [%]
pH	Potential of hydrogen [−]
RDI	Regulated deficit irrigation [−]
RH	Relative humidity [%]
RWC	Relative water content [%]
ρ_b	Bulk density the of the soil [g cm^{-3}]
T_C	Plant canopy temperature [°C]
T_{dry}	Upper bound for canopy temperature [°C]
T_{wet}	Lower bound for canopy temperature [°C]
T_{air}	Air temperature [°C]
T_{WWC}	Well-watered canopy temperature [°C]
TW	Turgid weight [g]
θ_{FC}	Gravimetric soil–water content at field capacity [%]
θ_{PWP}	Gravimetric soil–water content at permanent wilting point [%]
UAV	Unmanned aerial vehicles [−]
Virrig	Volume of irrigation [cm^3]
VPD	Vapor pressure deficit [kPa]
V_{pot}	Volume of the pot [cm^3]
WSB	Water stress baseline [−]
WW	Well-watered [−]
X	Canopy temperature measured by thermal camera [°C]
X_1	Temperatures of wet reference in thermal images [°C]
X_2	Temperatures of dry reference in thermal images [°C]
Y	Predicted canopy temperature [°C]
Y_1	Measured surface temperatures of wet reference [°C]
Y_2	Measured surface temperatures of dry reference [°C]

temperature can be a good water stress indicator that can be measured by means of infrared thermometers or thermal cameras (Moller et al., 2006). These methods offer non-contact and non-destructive monitoring of crop water stress (Jones, 2004; Leinonen and Jones, 2004).

Infrared thermometers are more limited in use since they provide a single point average temperature value of all objects within the sensor's field of view such as shaded and unshaded parts of plant canopy and/or soil surface. The accuracy of this sensor is even worse when the plant is immature because soil covers a majority of the surface (Maes and Steppe, 2012). However, thermal imaging is a potential tool for estimating plant temperature, which can be used as an indicator of stomatal closure and water deficit stress. Recently, the emergence of thermal cameras, particularly, when combined with the automated analysis of images, makes the use of thermal images much easier. The accuracy of this method is higher than that obtained using infrared thermometer because in this imaging method, by segmentation of canopy thermal images, the influence of soil background can be minimized (Maes and Steppe, 2012). However, thermal cameras are capable of measuring relative temperature rather than actual temperature. To quantify actual surface temperature, the thermal camera has to be calibrated at environmental conditions (Mangus et al., 2016).

There are three broad categories of remote sensing platforms: ground based, airborne, and satellite. The platform used in this research is laboratory-instruments ground-based which is used almost exclusively for research. However, for monitoring water status in field crops, other remote sensing platforms should be used to cover large surfaces of crops in very short times by mounting thermal cameras on board drones, aircrafts or satellites. Low altitude aircraft/drone is good for acquiring high spatial resolution data. The most stable platform aloft is a satellite, which is space borne. Nevertheless, for satellite data, atmospheric correction may be needed to obtain accurate surface temperature estimates (Ramírez-Cuesta et al., 2017).

Several indices have been presented for quantifying and monitoring the crop water stress in which T_C (crop canopy temperature) is the main factor for evaluating the crop water status. The first indicator, which was developed for the arid climate of Arizona (where has a similar climate to the arid regions of central Iran) was known as Crop Water Stress Index (CWSI) (Jones, 1999). For calculating CWSI, T_C must be normalized with well-watered and non-transpiring crop canopy temperatures as lower and upper leaf temperature bounds, respectively (DeJonge et al., 2015).

S. indicum is an ancient warm season oilseed crop which is said to be partially resistant to some environmental constraints (Bedigian, 2010; Mortazavian and Kohpayegani, 2010). Sesame oil contains an unique antioxidants that cannot be found in other edible oils and make the sesame oil the high quality one. In addition to the oil, crop seed is used as a source of proteins, vitamins and minerals for humans as well as in animal feed (Boureima et al., 2012). Thus, the seed owes its great economic potential to the pharmaceutical and cosmetic industries, yet greater economic interest lies in its oil content, which is used in the production of high-quality edible oil. Sesame is usually cultivated in semi-arid region and like many other crops, it is sensitive to drought during its vegetation stage, therefore its production potential can be affected widely by water stress (Boureima et al., 2012).

Although there have been studies on the effects of water stresses on leaf stomatal conductance (Yousefzadeh Najafabadi and Ehsanzadeh, 2017), there are few scientific reports on using non-contact instruments such as thermometers for sesame (Hall et al., 1979). To the best of our

Table 1
Some physical and chemical properties of the experimental soil.

Soil texture	Sand (%)	Clay (%)	Silt (%)	θ_{FC} (%)	θ_{PWP} (%)	ρ_b (g cm^{-3})	pH	EC (dS m^{-1})
Sandy clay loam	55.3	26.4	18.3	18	9	1.3	7.7	2.45

θ_{FC} is the percentage of the gravimetric soil–water content at field capacity, θ_{PWP} is the percentage of the gravimetric soil–water content at permanent wilting point, and ρ_b is the bulk density.