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Development and evaluation of thermal infrared imaging system for high spatial and temporal resolution crop water stress monitoring of corn within a greenhouse

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ABSTRACT

Inadequate water application often decreases yield and grain quality. Existing methods using single, localized soil moisture or canopy temperature measurements do not account for crop water stress on both a high spatial and temporal resolution for precision irrigation water management decisions and scheduling. Therefore, this study was conducted to understand the feasibility of thermal cameras in order to quantify high resolution spatial canopy temperatures in relation to soil moisture. The objectives of this study were to deploy a thermal infrared imaging system (TIRIS) for high spatial and temporal monitoring of corn canopy temperature in greenhouse, test camera durability and measurement accuracy during full-season crop development, remove background temperatures with image segmentation, and sample individual plants to investigate full-season crop water stress versus soil moisture content. A TIRIS was developed using a lightweight uncooled thermal camera. Corn plants were divided into well-watered and water-stressed irrigation zones to observe stress from water deficits. Canopy temperatures were used to develop empirical canopy and air temperature deficit versus vapor pressure deficit linear regressions. Results showed that the TIRIS system maintained measurement accuracy of ±0.62 °C ($\alpha = 0.05$) while compensating for changing ambient greenhouse conditions. Canopy and air temperature deficit versus vapor pressure deficit regression equations revealed that the predicted canopy temperature was closely related to characteristic water use. Results of the 80-day study demonstrated that 82% of soil moisture variation was explained by the crop water stress index (CWSI) values between 0.6 and 1.0. Results indicated that the CWSI derived by remotely measuring canopy temperature using TIRIS can be used as an alternate irrigation scheduling method in order to quantify spatial and temporal soil moisture variability.

1. Introduction

In the United States, agriculture annually uses approximately 80% of the consumptive ground and surface water (USDA, 2014). The potential to conserve water relies heavily on decision support tools (Rodriguez et al., 2005) which can increase water use efficiency using precision irrigation technologies (Ballester et al., 2013; Cohen et al., 2005; Gontia and Tiwari, 2008). Quantity of irrigation water and application time is among critical decisions producers frequently have to make to develop site-specific irrigation plans (Alves and Pereira, 2000; Cohen et al., 2005; Wanjura et al., 1992). Precision variable rate irrigation technologies are available which can apply a desired amount of water at a controllable increment for optimum crop growth and yield (Cohen et al., 2005; Taghvaeian et al., 2013). However, large variability may exist in commercial agricultural fields due to soil type and depth, topography, climate, specific crop growth period and seed hybrid selection (Cohen et al., 2005; Evett et al., 2014). Of the many types of crop stress, water stress is the most common and restrictive factor impacting crop yield (Jackson et al., 1981; Luvall and Holbo, 1991; Scherrer et al., 2011; Zia et al., 2013) where water stress severity depends on timing and duration. Therefore, techniques and technologies are needed to accurately classify spatial and temporal crop water need, or crop water stress, to gain economic and environment advantages (Herwitz et al., 2004; Taghvaeian et al., 2013).

Several existing methods to monitor crop water stress rely on a combination of single-point soil, plant and atmospheric

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measurements (Alves and Pereira, 2000; Cohen et al., 2005). Soil moisture sensors are one of the most common tools being utilized to make irrigation decisions. Newer soil moisture probes are capable of quantifying moisture at multiple soil depths. Typically, one or two soil moisture probes are installed for a whole field due to the installation time, cost and yearly maintenance. However, soil moisture probes are subject to error from installation and location choice that do not account for spatial crop variability which may exist within the whole field (Moller et al., 2007). Alternative methods for detecting crop water stress utilize pressure chambers and leaf diffusion porometers to measure individual leaf and stem water potential and leaf stomatal conductance, respectively (Ballester et al., 2013; Berni et al., 2009a; Grant et al., 2007; Idso et al., 1977). However, these techniques are destructive, labor intensive, localized, limited by small sample size and unsuitable for automation (Ballester et al., 2013; Berni et al., 2009a; Cohen et al., 2005; Gontia and Tiwari, 2008; Jones, 1999; Leinonen and Jones, 2004). Consequently, these drawbacks make invasive plant-based crop monitoring impractical at high resolution spatial and temporal scale in large acreage production systems like corn, thereby limiting producer adoption of these technologies/methods for irrigation decision management (Ballester et al., 2013).

To address these concerns, thermal sensing approaches have been investigated because they are non-contact and less labor intensive, and offer non-destructive monitoring to assess crop stress from leaf canopy temperatures (Grant et al., 2006; Leinonen and Jones, 2004). Since the 1970s, crop canopy temperature has been accepted as an indicator of crop water stress because plants close their leaf stomata when they experience water stress in order to retain water, thereby lowering stomatal conductance, reducing transpiration, and increasing leaf temperatures (Ballester et al., 2013; Grant et al., 2006; Idso et al., 1977; Jones, 1999; Leinonen and Jones, 2004; Rodriguez et al., 2005). On the other hand, when leaf stomata are open, water in the leaf evaporates through transpiration which cools the leaf (Maes and Steppe, 2012). During transpiration, energy from within and surrounding the leaf is used to convert water from liquid to a gas that under goes latent heat loss which in turn cools the leaf. Current crop growth studies have primarily used ground-based thermometry to take canopy temperature measurements and develop thermal indices that account for canopy characteristics, soil temperature, and atmospheric conditions for site-specific irrigation management and breeding programs (Idso et al., 1981; Jackson et al., 1981; O'Toole and Real, 1986). According to Zia et al. (2013), crop growth stage does not significantly impact canopy leaf temperature, thereby supporting the use of leaf temperature as a viable indicator of full-season crop health characteristic. Highly integrated thermometric systems use an array of infrared thermometers (IRTs) mounted in fixed field locations and on dynamic center pivot irrigation systems to measure crop canopy temperatures and provide a means of irrigation scheduling (O'Shaughnessy et al., 2012).

IRTs provide a single point (comprising of one pixel) average temperature value of all objects within the sensor's field of view (FOV) which could include shaded and unshaded plant material; and/or soil background. IRT inaccuracy from background temperatures limit their use until the crop reaches a particular maturity stage because when plants are small, soil covers a majority of the measurable surface, thereby dominating the temperature measurement. Additionally, IRTs cannot measure spatial temperature difference between shaded and sunlit leaves where temperature differences can drastically differ. Therefore, crop temperature must be segmented from the measured temperature value to reduce the influence of soil background and shaded lower leaves (Ayeneh et al., 2002; Luquet et al., 2003; Maes and Steppe, 2012). IRTs are typically mounted to fixed locations within the field or on dynamic pivot systems which may limit the spatial coverage area. When mounted to pivot systems, useful data may only be collected during a few hours in the day while the pivots moves 24/7. Additionally, IRTs can only operate at the temporal resolution of irrigation events (often every 3–7 days) and thus lack the high spatial and temporal measurement resolution necessary to quantify crop water stress variability critical for making weekly irrigation decisions (Colaizzi et al., 2012).

An alternate to IRTs are low cost and lightweight uncooled thermal infrared (TIR) cameras. TIR cameras can spatially map temperatures via a thermal image to measure subtle, heterogeneous characteristics of leaf dynamics (Liu et al., 2011). Each image is comprised of pixel arrays representative of pixel resolution of the TIR camera. Crop canopy temperature monitoring with thermography could allow producers to use thermal sensing for crop canopy temperature mapping (Alves and Pereira, 2000; Ayeneh et al., 2002; Berni et al., 2009b; Taghvaeian et al., 2013; Wang et al., 2010), individual crop temperature profiling (Leinonen and Jones, 2004), and manage variable rate irrigation scheduling (Cohen et al., 2005; Colaizzi et al., 2012; Fitzgerald et al., 2007). The crop water stress index (CWSI), investigated by Idso et al. (1981), has been successfully developed and implemented using IRTs that measure canopy temperatures in order to determine variable rate irrigation needs (Taghvaeian et al., 2013). Thermography has been recently utilized to further develop thermal indices and crop sensing techniques originally developed with IRTs. Temperature-based indices have shown significant correlations among crop canopy temperature, stomatal conductance, and leaf water potential as correlations become more significant as stress intensity increased (Hackl et al., 2012). Thermal imagery also requires systems and subsequent data processing techniques to capture, analyze, and interpret large amount of images. However, available knowledge regarding thermal sensing systems using TIR cameras is limited, and producers are skeptical of technology that has demonstrated potential for measuring crop temperature profiles for water management in orchards, vineyards, and other specialty crops in areas outside of the United States (Sepulcre-Canto et al., 2011).

Limited studies have been conducted using TIR camera systems in the U.S. to measure all-season crop temperature with high spatial (i.e., sub-centimeter) and temporal (i.e., minute-to-minute) resolutions while testing the thermal cameras' durability during prolonged operation time in varying environmental conditions. Therefore this study was conducted to understand the necessary hardware required to capture thermal imagery, segment crop canopy from background and establish standard operating procedures to generate absolute temperature measurement from relative pixel intensities of lightweight uncooled cameras. The specific objectives of this study were to (1) develop and deploy a thermal imaging system for monitoring corn canopy at high spatial and temporal resolutions in a greenhouse; (2) evaluate the accuracy of the thermal imaging system in measuring crop canopy temperatures during a full growing, and; (3) investigate full-season air-to-canopy temperature deficit versus VPD transfer functions for direct relationships between crop water stress index (CWSI) values and soil moisture by automatically evaluating canopy temperature images.

2. Methods and materials

The irrigation experiment was conducted within the Throckmorton Greenhouses of the Agronomy Department at Kansas State University, Manhattan, Kansas. On 10 May 2014, corn (*Zea mays*) seeds were planted in 20 cm diameter pot containers with 30 replications. For a full-season study (80 days), the plants were