THESIS

REMOTE SENSING TO QUANTIFY IN-FIELD SOIL MOISTURE VARIABILITY IN IRRIGATED MAIZE PRODUCTION

Submitted by

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ABSTRACT

REMOTE SENSING TO QUANTIFY IN-FIELD SOIL MOISTURE VARIABILITY IN IRRIGATED MAIZE PRODUCTION

Agriculture is the largest consumer of water globally. As pressure on available water resources increases, the need to exploit technology in order to produce more food with less water becomes crucial. The technological hardware requisite for precise water delivery methods such as variable rate irrigation is commercially available. Despite that, techniques to formulate a timely, accurate prescription for those systems are inadequate. Spectral vegetation indices, especially Normalized Difference Vegetation Index, are often used to gauge crop vigor and related parameters (e.g. leaf nitrogen content and grain yield). However, research heretofore rarely addresses the influence of soil moisture on the indices. Canopy temperature measured using inexpensive infrared thermometers could also serve as an indicator of water stress, but current methods which exploit the data can be cumbersome. Therefore, the objectives of this study were to determine 1) if vegetation indices derived from multispectral satellite imagery could assist in quantifying soil moisture variability in an irrigated maize production system 2) the period of time which a single image is representative of soil moisture conditions 3) to determine the relationship between synchronous measurements of crop canopy temperature and in-field soil moisture tension, and 4) to understand the influence of discretionary crop canopy temperature stress thresholds on the relationship between soil moisture tension and crop canopy temperature. A variable rate irrigation pivot was used to form six water treatment zones. Each zone was equipped with both a set of tensiometers installed in the center of the plots at 20, 45, and 75cm depths and an infrared thermometer pointed into the crop canopy to individually monitor conditions in the water treatment zones. Water was applied for each treatment as a percentage of the estimated evapotranspiration (ET) requirement: i.e., 40, 60, 80, 100, 120, and 140 percent of the ET. Data collected from tensiometers was paired with the image pixels corresponding to the ground location of the tensiometers and with the synchronous canopy temperature data. Statistical analysis was performed separately to assess whether vegetation indices and canopy temperature are representative of soil moisture at several crop growth stages. Findings from this study indicate that Red Edge Normalized Difference Vegetation Index could quantify variability of soil moisture tension at V6 (six leaf) ($r^2 = 0.850$, $p = 0.009$) and V9 (nine leaf) ($r^2 = 0.913$, $p = 0.003$) crop growth stages. Results suggest that satellite-derived vegetation indices may be useful for creating time-sensitive characterizations of soil moisture variability at large field-scales. When integrated with a stress threshold, synchronous canopy temperature was able to quantify soil moisture tension with some success during the reproductive crop growth stages. Further study is necessary to investigate additional crop growth stages, more crops, and other sources of multispectral imagery. Future studies are also needed to evaluate field-scale yield implications of variable rate irrigation management.

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I am very thankful for the constant support of my parents Richard and Patrice, who always stressed the value of education. My sisters Whitney and Hillary, who set an impeccable example, always offered optimism and encouragement throughout my studies.

DEDICATION

For my mother and father, Patrice and Richard Siegfried.

And for my sisters Whitney and Hillary.

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CHAPTER ONE

MULTISPECTRAL SATELLITE IMAGERY TO QUANTIFY IN-FIELD SOIL MOISTURE VARIABILITY

Introduction

With a rapidly expanding population, more food, fiber, and fuel will need to be produced to maintain and improve the quality of life for humanity. Projections from the Population Division of the United Nations indicate that the world population will reach 9.6 billion by the year 2050 (UN, 2013). As more land is developed for residencies to meet housing demand for this growth, the amount of arable land is likely to decrease – even as food production requirements necessitate agricultural expansion. The Food and Agriculture Organization of the United Nations estimates that a sixty percent increase in worldwide agricultural production will be necessary to satisfy food demand by 2050 (FAO, 2013). The world's agriculturalists are tasked with producing more with fewer resources.

Irrigated agriculture is a promising domain for increasing crop yields while enhancing environmental stewardship to answer this challenge, since for many reasons irrigated land is capable of producing higher yields on smaller quantities of land. This is especially true when considering semi-arid climates where crop production is challenging. Although irrigation covers about twenty-percent of cropland worldwide, it is responsible for over forty-percent of the total food production (FAO, 2016).

Agriculture already places a heavy burden on available water resources. In the United States, irrigation systems utilize about eighty percent of the available freshwater (Lea-Cox, 2012). Heightened water demand from non-agriculture sectors is expected to increase overall water demand and pressure on water resources. When compounded with significant population growth and climate change, irrigated agriculture faces serious challenges and conflicts for national water use – especially where the majority of irrigation occurs, in the Western United States (Schaible and Aillery, 2012). More efficient irrigation systems in those western states have previously contributed to decreases in water application: although irrigated acres increased by 850,000 hectares between the years 1984 and 2008, agricultural water applications were reduced by over 120 million cubic meters (Schaible and Aillery, 2012). These efficient irrigation systems, such as center-pivots and linear-move systems, can be exploited to further reduce water usage through precision water management strategies and technology.

One possible solution, which relies on variable rate technology, is precision irrigation. Precision irrigation is site-specific water management: the amount of water applied is spatially explicit and timing is planned in order to enhance yield, economic gains, and environmental stewardship (Srinivasan, 2006). When juxtaposed with traditional irrigation – treating the entire application area equally – precision irrigation may further use variable rate technology to adjust the amount of water applied at every location within the field. These adjustments are meant to reflect the local water requirements within a field in order to optimize water usage.

Early studies of precision irrigation identified cost-feasibility as an issue, especially when considering water alone (Evans et al., 1996; Lu et al., 2005; Srinivasan, 2006). However, necessary hardware costs decrease over time and pressure on water resources continues to increase, contributing to renewed interest in the area. Watkins et al. (1999) recognize the potential of variable-rate water application for increased crop production and improved protection of the environment, but further elucidate that economic benefits must be established before farm operators will embrace the technology. Kim and Schaible (2000) demonstrated that traditional economic modelling of irrigation water is proportionally biased with deep percolation, evaporation, and runoff losses – which are not accounted for and are difficult to estimate. The authors suggest that this issue contributes to additional water usage and diminishes the attractiveness of more efficient irrigation techniques, especially when considered by farmers for purchase and implementation. Antiquated water allocation law can also diminish the attractiveness of investing in precision irrigation technology. As of 2008, the percentage of irrigators using moisture sensing technology or commercially available irrigation scheduling packages was less than ten percent in the western states (Schaible and Aillery, 2012). Increased pressure on water conservation due to drought and disagreements regarding resource allocation may revitalize interest in precision irrigation technology as monetary concerns and perceptions change (Sadler et al., 2005).

Srinivasan (2006) identifies the feasibility and value of presently prevalent irrigation systems – center pivot and lateral move setups – for use with precision irrigation: the area of application is extensive and a platform upon which sensors can be mounted is already extant. Retrofit kits for precision irrigation have since become commercially available However, the fundamental question for precision agriculture must be answered: “Can the scale of variability in space and time be quantified, an optimal scale identified, and does it present any management opportunities?” (Whelan and McBratney, 2000). Evans et al. (1996) identified defining and formulating a prescription for precision water application as the foremost problem for researchers to address. More specifically, the aforementioned authors suggested that “identification and quantification of contributing factors and their interactions that influence a real-time prescription are difficult.”

Electrical conductivity is often used as a practical surrogate measurement for quantifying in-field variability of soil physical parameters. Apparent electrical conductivity is consistently linked with certain soil characteristics, especially hydraulic properties (Hedley and Yule, 2009). Soil texture, organic matter, and bulk density are examples of field variability to be accounted for since these characteristics influence the interaction of water with soil, which is most important when considering irrigation (Whelan and McBratney, 2000). Zhu and Lin (2011) observed that terrain characteristics, such as slope and elevation, best described soil moisture variability when slope was at least eight percent. However, crop and soil parameters were the most influential when slope was less than eight percent. Landrum et al. (2015) concluded that: "a static delineation of homogeneous units for soil-water management is probably insufficient."

Continually changing conditions are likely to make decision algorithms highly temporally dependent, and techniques commonly used today to formulate water prescriptions – such as electrical conductivity – do not directly account for temporal variability. Sadler et al. (2005) concludes that the inconsistent, highly dynamic nature of actual field circumstances probably necessitates strategically placed sensors to monitor soil moisture and micrometeorological variability in real time.

Srinivasan (2006) agrees that real-time soil sensors may be necessary for precision agriculture to move forward. One such method of obtaining real-time data are wireless sensor networks. A study conducted by Hedley and Yule (2009) used a soil moisture sensor network with a singular sensor fitted in each of three electrical conductivity delineated management zones for variable rate irrigation scheduling. They concluded that an increased number of zones – and thus additional moisture sensors – would be requisite to effectively account for the variability at their study location (Hedley and Yule, 2009). Tensiometers are particularly applicable because the measurements can be related to implications of water content on plant growth independently of soil type (Brady, 1985). Advancements in sensor technology will allow these networks to be more spatially extensive and affordable in the future. While hardware enabling precision irrigation exists, current literature does not agree on how to inform the decision support and management systems which drive that hardware (Srinivasan, 2006). This is especially true when considering the highly heterogeneous nature of soil water content throughout a crop growing season, as current commercially available decision support systems rely on static measurements related to soil physical properties. Conventionally these measurements comprise a mere one-time data acquisition and the dynamic nature of a growing season is neglected.

Vegetation is characterized by a unique, strong contrast between reflectance of near-infrared light and absorption of visible red, which makes multispectral data suitable for estimating plant biophysical parameters (Campbell and Norman, 2012) at multiple time points. For decades, spectral vegetation indices have been employed to remotely monitor crops and other vegetation by means of these spectral properties. They have long been used for many endeavors, such as land cover estimation and classification; detection of crop disease, insect damage, and other strain; and assessing the effects of hail storms, flooding, and other disasters (Lillesand et al., 2008). While crop spectral properties can identify the presence of stress, they also have the potential to function as a surrogate measurement of the severity of that stress.

The red edge, a narrow portion of wavelengths (about 680 to 730 nanometers) between the red and near-infrared regions of the electromagnetic spectrum, could improve on traditional broadband sensors to enhance the quality of information derived from multispectral satellite imagery because of its greater sensitivity to stress – which manifests as an early decrease in chlorophyll content in the plant canopy (Carter and Miller, 1994). The rapid change in leaf reflectance characterized within the red edge makes it particularly useful for early stress detection. One example of a satellite platform making use of the red edge is the RapidEye™ Satellite Constellation (BlackBridge, Berlin, Germany), which captures the red edge region between 690 - 730 nanometers. This may be used as a more plant-sensitive replacement for the conventional red band in broadband vegetation index calculations, but very few agricultural studies have investigated it.

A number of studies covering many plant species have concluded that the most discernible variation in plant optical response to stress occurs within the red edge, near 700 nanometers (Carter and Knapp, 2001; Carter and Miller, 1994; Horler, et al., 1983). The majority of these studies focused on narrow wavebands, but Eitel et al. (2011) found that red edge indices derived from RapidEye™ imagery detected stress in a conifer woodland earlier than broadband indices which utilize traditional red and green bands. Based on a study with dryland wheat, Eitel et al. (2007) suggested that broadband red edge vegetation indices may also be useful for crop nitrogen management. Broadband indices could be faulted as too coarse a measurement, as they cannot discriminate very subtle changes in the spectral response of vegetation (Carter and Miller, 1994). This does not diminish the efficacy of broadband indices, but is certainly connected with their sensitivity to slight changes in plant optical response. While increased spectral resolution may contain more specific information, the additional data involved also requires more intensive processing as noise can be an issue when sensors are pushed to their sensitivity limits (Steven et al., 1990).

Advances in technology have made remote sensing data vastly more available. Until the beginning of the second millennium, aerial imagery was the prevailing source of remote sensing for agricultural interpretation (Lillesand et al., 2008). However, improvements in both spatial and temporal resolution along with rapid data availability have drastically increased the use of satellite imagery for precision agriculture. These benefits could potentially be used to monitor in-field variability of plant water stress at a large scale (e.g. an entire section equipped with sprinkler irrigation) and thus inform precision irrigation systems. Utilizing the information available from remote sensing is an important challenge for irrigated agriculture, as water resource managers rarely take advantage of numerous remote sensing opportunities (Bastiaanssen et al., 2000).

Few studies exist that have addressed the use of multispectral data for monitoring soil water content and those typically rely on shortwave infrared, microwave, thermal data, or simply estimate crop coefficients (Clarke, 1997; Engman, 1991; Li et al., 2001; Neale et al., 2005). With increasing focus on precision agriculture and the advent of precision variable rate irrigation systems, it is important to investigate whether plant water stress can be characterized at large field scales using readily available, high spatial resolution data. Therefore, the objectives of this study were to determine 1) if vegetation indices derived from multispectral satellite imagery could quantify soil moisture tension variability in an irrigated maize production system and 2) the period of time which a single satellite image is representative of the variability.

Materials and Methods

Study site

This experiment was conducted over the 2015 maize growing season at a site located north of Fort Collins in northeastern Colorado (40.666° N, 104.998° W). The 12 hectare field has been cultivated for many years under a continuous maize cropping system, conventional tillage, and furrow irrigation until 2012 when it was precision leveled and a center-pivot sprinkler system was installed. The soil series is Kim loam, which is characterized as very deep, moderately permeable, and is classified as fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents (Soil Survey Staff, 1980). Slope at this site is between one and three percent, and the climate is semi-arid with an average annual precipitation of about 40 centimeters. The field was seeded with east-west rows on May 27, 2015 with DEKALB® DKC46-20VT3 at a population of 93,900 plants per hectare (38,000 plants per acre).

Experimental Procedure

A Valley® variable rate irrigation pivot (Valmont Industries, Valley, NE) was utilized to form six water treatment zones. Each zone was equipped with Hortau® tensiometers (Hortau Simplified Irrigation, Lévis, QC, Canada) installed in the center at 20, 45, and 75 centimeter depths. Water was applied for each treatment as a percentage of the estimated evapotranspiration (ET) requirement: 40, 60, 80, 100, 120, and 140 percent. The depth of water applied at those rates corresponds to 20, 30, 41, 51, 61, and 71 centimeters for the entire growing season, respectively. Estimated ET requirements, or the amount needed to replenish water used by the plants and lost to evaporation, are based on weather conditions such as solar radiation, wind speed, and humidity. For information on calculating crop water requirements, refer to Allen et al. (1998). To address the possibility of surface runoff, straw wattles were fixed at susceptible locations. See Figure 1.1 for a visual representation of the experimental design.

The tensiometers were configured to upload data to server storage at 15 minute intervals throughout the growing season. Raw tension data was then downloaded from the web. On multiple occasions during the growing season, the tensiometer water reservoirs became depleted and required rehydration. This process generated data points not representative of actual soil moisture conditions. The date and time was noted for each rehydration event. The period between sensor dehydration and 24 hours after hydration was removed from the data. The return to normal sensor behavior was confirmed by viewing a plot of surrounding data points.

Orthorectified imagery from the RapidEye™ satellite constellation was processed and provided by FarmLogs (FarmLogs, Ann Arbor, MI). The radiometric resolution is 12-bit with spatial resolution of five meters and a revisit time of 5.5 days. Spectral bands are outlined in Table 1.1. The nine spectral vegetation indices examined were calculated using the formulas as defined in Table 1.2.

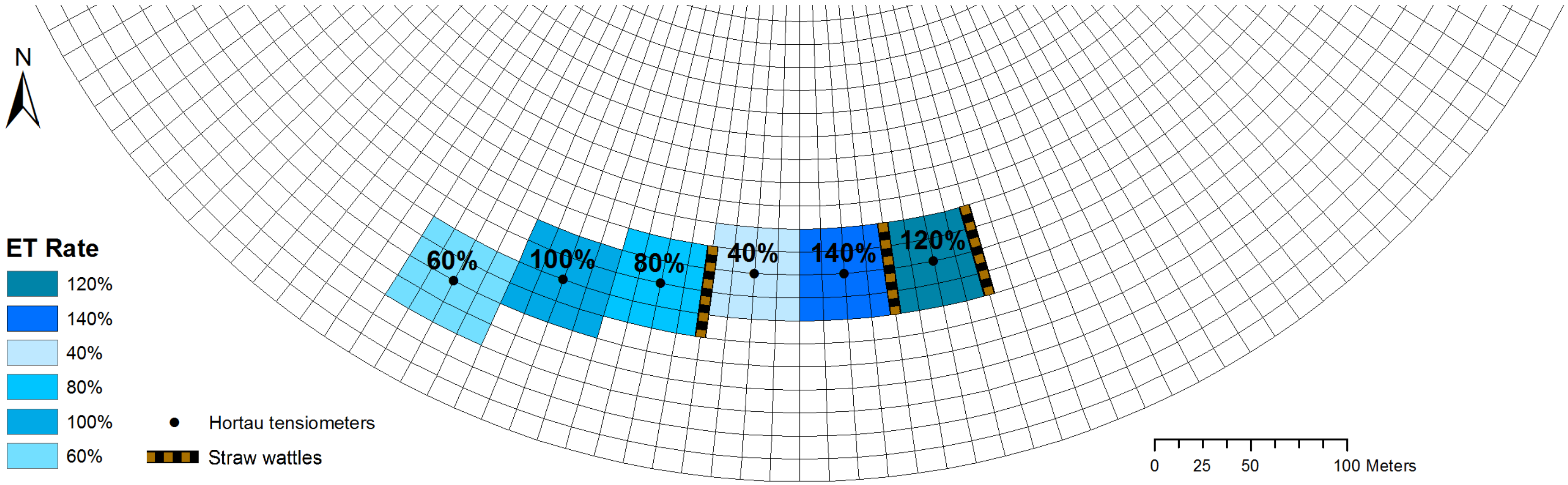

Figure 1.1. Variable rate irrigation grid used for the center pivot at Colorado State University Agricultural Research Development & Education Center. Irrigation treatments are represented as filled cells. A different color designates each zone and includes a point for the tensiometer locations, which are labeled with the percentage of estimated evapotranspiration used to calculate irrigation requirements for this study in 2015.

Table 1.1. Spectral bands for the RapidEye™ satellite constellation.

Name	Range (nanometers)
Blue	440 - 510
Green	520 - 590
Red	630 - 685
Red Edge	690 - 730
Near-infrared	760 - 850

Source: BlackBridge. Satellite Imagery Product Specifications (2015). Retrieved from http://www.blackbridge.com/rapideye/upload/RE_Product_Specifications_ENG.pdf

Table 1.2. Formulas for spectral vegetation indices.

Vegetation Index	Formula
Red Edge Normalized Difference Vegetation Index (RENDVI)	$RENDVI = \frac{NIR - Red\ Edge}{NIR + Red\ Edge}$
Red Edge Chlorophyll Index (RECI)	$RECI = \frac{NIR}{Red\ Edge} - 1$
Renormalized Difference Vegetation Index (RDVI)	$RDVI = \frac{NIR - Red}{\sqrt{NIR + Red}}$
Optimized Soil Adjusted Vegetation Index (OSAVI)	$OSAVI = \frac{1.5 * (NIR - Red)}{NIR + Red + 0.16}$
Normalized Difference Vegetation Index (NDVI)	$NDVI = \frac{NIR - Red}{NIR + Red}$
Green Ratio Vegetation Index (GRVI)	$GRVI = \frac{NIR}{Green}$
Green Normalized Difference Vegetation Index (GNDVI)	$GNDVI = \frac{NIR - Green}{NIR + Green}$
Green Atmospherically Resistant Index (GARI)	$GARI = \frac{NIR - [Green - 1.7(Blue - Red)}{NIR + [Green - 1.7(Blue - Red)}$
Enhanced Vegetation Index (EVI)	$EVI = 2.5 * \frac{NIR - Red}{NIR + 6 * Red - 7.5 * Blue + 1}$

Note: Near-infrared is abbreviated as NIR.
Source: Exelis Visual Information Systems. Broadband Greenness (2015). Retrieved from http://www.exelisvis.com/docs/BroadbandGreenness.html

Data Analysis

An average soil tension was calculated for each irrigation treatment (40-140% of estimated ET requirement) over three temporal periods prior to the satellite image acquisition dates: one day, one week, and the entire interval between planting and image acquisition. Those averages were paired with vegetation index values, which were extracted from the satellite images using georeferenced points and GIS software in order to obtain the pixel values corresponding to the actual ground location of the tensiometers. Points used for this process were acquired with a Trimble Ag114 DGPS receiver (Trimble Navigation Limited, Sunnyvale, CA) equipped with OmniSTAR® VBS correction service (OmniSTAR, Houston, TX).

Ordinary least squares regression of soil tension on vegetation indices was performed using the R software environment (R Core Team, 2015). To determine whether vegetation indices derived from multispectral satellite imagery could quantify soil moisture tension, three time intervals prior to each image acquisition were evaluated: average from the previous day, previous week, and from planting to date. This was done in order to assess the sensitivity of the satellite-derived indices to immediate, short term, and long term soil moisture variability, respectively. Results presented below are therefore grouped by these time intervals. All combinations of vegetation indices and tension averages were analyzed independently for all of the satellite images (Table 1.3). In addition to the four crop growth stages (Figure 1.2), an image acquired shortly after crop emergence (bare soil) was also analyzed. Significant results as determined with the Student's t-test are presented in Tables 1.4 – 1.6. See Appendix A for results from analysis of all vegetation indices and depths examined.

Table 1.3. Satellite image acquisition days and corresponding crop growth stages.

DOY†	Growth Stage
164	Emergence (bare soil)
178	Two leaf
192	Six leaf
204	Nine leaf
242	Milk

† Day of year is abbreviated as DOY.

Results and Discussion

The month of May was especially wet during the 2015 growing season, receiving more than double the historical average precipitation and contributing to above average annual precipitation (Western Regional Climate Center, 2015). These conditions delayed planting by several weeks. The beginning of May is conventional, but the corn was planted on May 27th for the 2015 season. The relationship between vegetation indices and in-field soil moisture tension was studied at three soil depths where soil moisture tension readings were recorded throughout the growing season. For ease of understanding, the results are presented separately for each time period of ET measurement: 24 hours, 1 week, and planting to date.

Average Soil Tension from the Previous Day (24 hours)

Regression analysis of soil tension averaged over the day previous to image acquisition on the selected indices produced several noteworthy results (see Table 1.4). Red Edge Normalized Difference Vegetation Index (RENDVI) performed best with strong negative linear relationship at both V6 and V9 crop growth stages (Ritchie and Hanway, 1989) at 20 centimeters deep. As shown in Figure 1.3, functions for both models at this depth were very similar: the slopes were almost identical – less than 2% difference – and the intercept increased almost proportionally from the V6 to V9 growth stage. This indicates that images not only capture immediate soil moisture variability at separate growth stages, but also that a single image could

Table 1.4. Significant results from regression analysis of average soil moisture tension (over the 24 hours previous to satellite image acquisition) on selected indices.

Tensiometer Depth (cm)	Index†	Growth Stage‡	r^2	p-value	RMSE (-kPa)
20	RENDVI	V6	0.850	0.009	4.291
		V9	0.913	0.003	3.779
	RECI	V6	0.850	0.009	4.280
		V9	0.796	0.017	5.792
75	RENDVI	R3	0.693	0.040	11.850
	Quadratic§	R3	0.964	0.007	4.692
	NDVI	V2	0.691	0.040	0.698
	GRVI	V2	0.830	0.012	0.517
	GNDVI	V2	0.834	0.011	0.512
	GARI	V2	0.891	0.005	0.415
	EVI	V2	0.669	0.047	0.723

† RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index
‡ V6, V9, and R3 are the six leaf, nine leaf, and milk stages of maize growth, respectively.
§ A quadratic regression is included for RENDVI due to its vast improvement over the linear model.

be relatively representative of soil moisture variability between image acquisitions – perhaps up to a couple weeks as with this study. In other words, an image could be used to help inform variable rate irrigation systems a few weeks after it was initially acquired by the satellite. This is especially important since irrigation water often isn’t immediately available and satellite revisit times may not be convenient for management. Additionally, RENDVI was moderately correlated at R3 growth stage at the 75 centimeter depth. Although the linear model produced acceptable results, the scatter plot of soil tension as a function of RENDVI clearly indicated a quadratic form (see Figure 1.4).

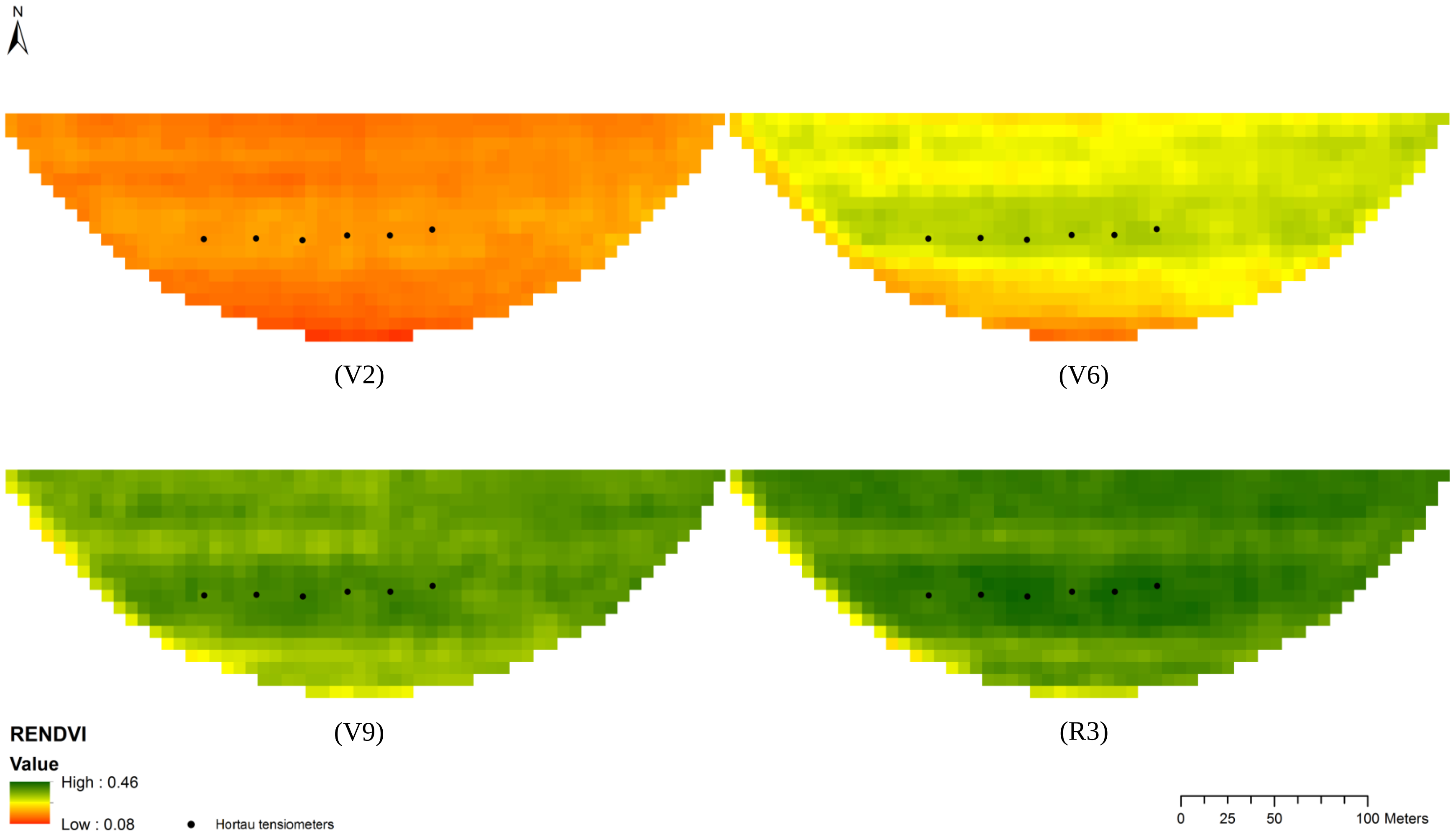

Figure 1.2. Red Edge Normalized Difference Vegetation Index (RENDVI) derived from satellite imagery is displayed over the four maize growth stages examined in this study: two leaf (V2), six leaf (V6), nine leaf (V9), and milk (R3).

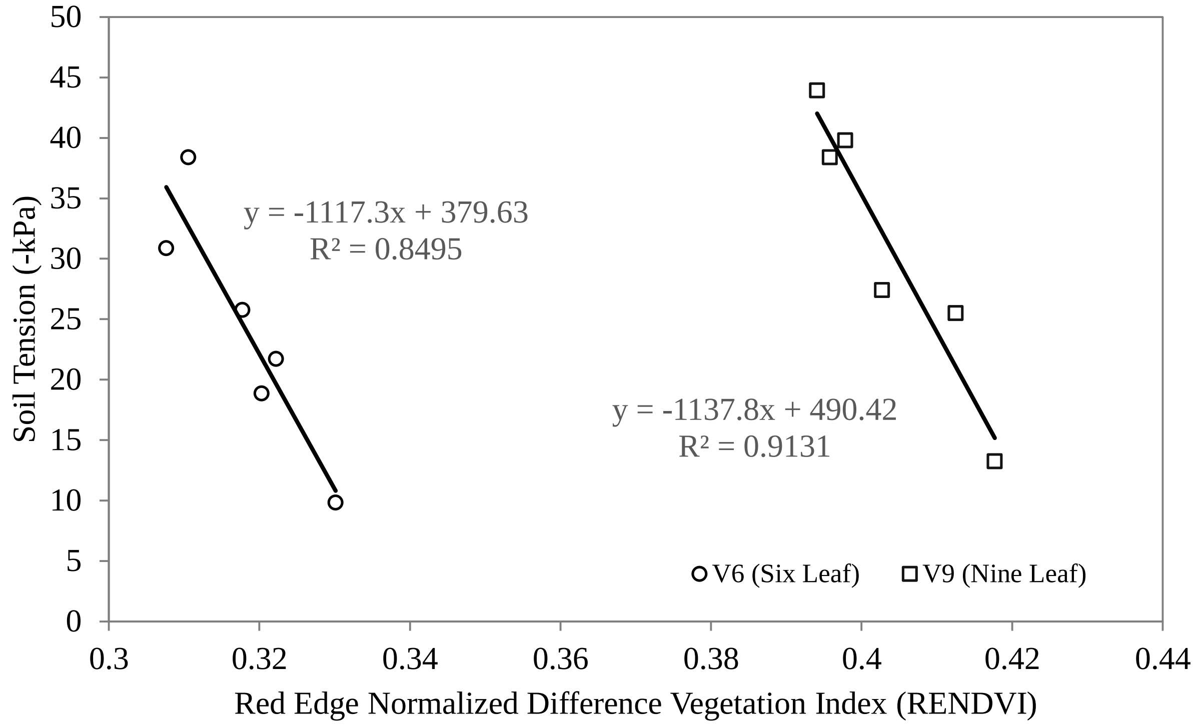

Figure 1.3. Soil tension (-kPa) as a function of RENDVI for V6 and V9 maize growth stages.

The relationship between average soil moisture tension at 75 centimeters and RENDVI at the R3 growth stage was exceptionally strong ($r^2 = 0.964$). The full spectrum of tension from very dry to nearly saturated conditions at the point of this image acquisition created the ideal scenario for analysis and thus the data took shape as expected. The quadratic curve clearly illustrates an increase in plant productivity characterized by RENDVI as soil water content increased. Concurrently, a plateau at which additional moisture abruptly ceases to improve the crop spectral response is evident at RENDVI values of about 0.445. Note that the 100% ET irrigation treatment is the point just before the trough and the three points influencing the stagnancy are the wettest on average since planting.

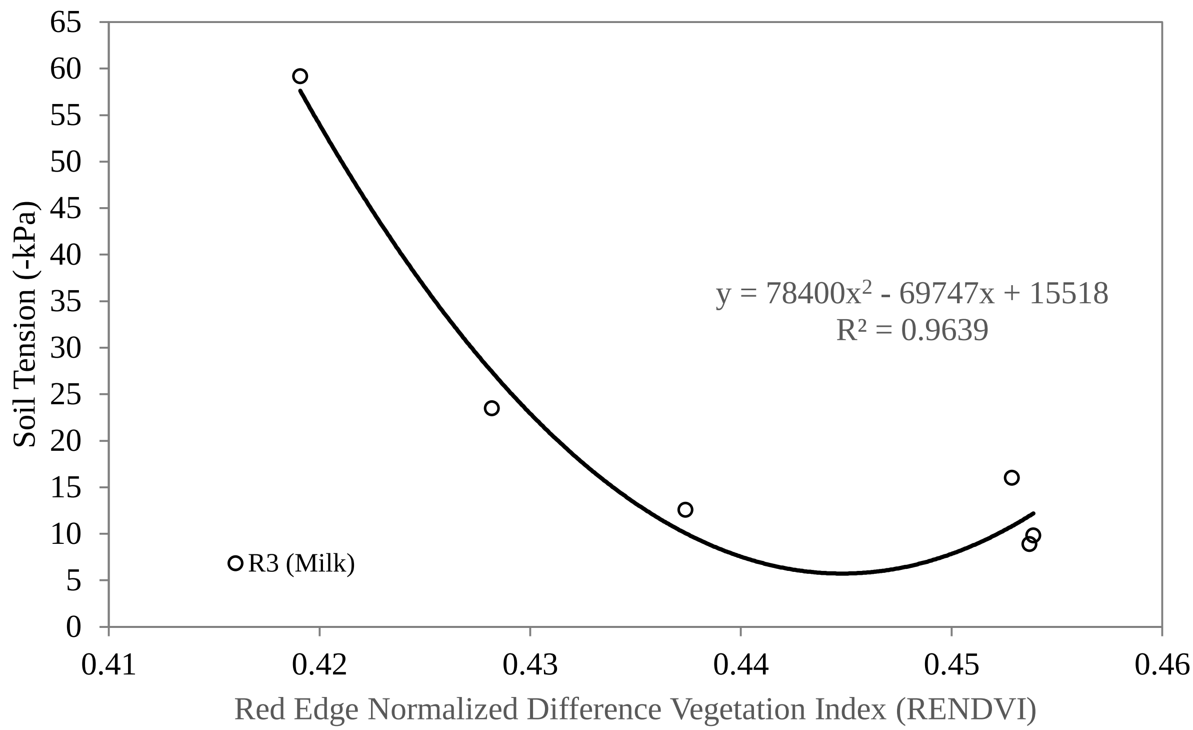

Figure 1.4. Soil tension (kPa) as a function of RENDVI at the R3 (milk) maize growth stage.

There is a very strong relationship over an extremely small range (less than 0.035) of variation in the derived RENDVI values. It is important to note that this function would be counterintuitive if extrapolated outside the range of this data.

Red Edge Chlorophyll Index (RECI) also produced significant models with good relationships for V6 and V9 crop growth stages at 20 centimeters deep. In this case, the functions between the two differed considerably and the coefficients of determination, although still very strong, indicate weaker correlations (Figure 1.5). It appears that RECI is less sensitive to changing soil water content, so the imagery did not show potential for extended post-acquisition utility as was the case with RENDVI, for which the equations over the V6 and V9 growth stages were quite similar.

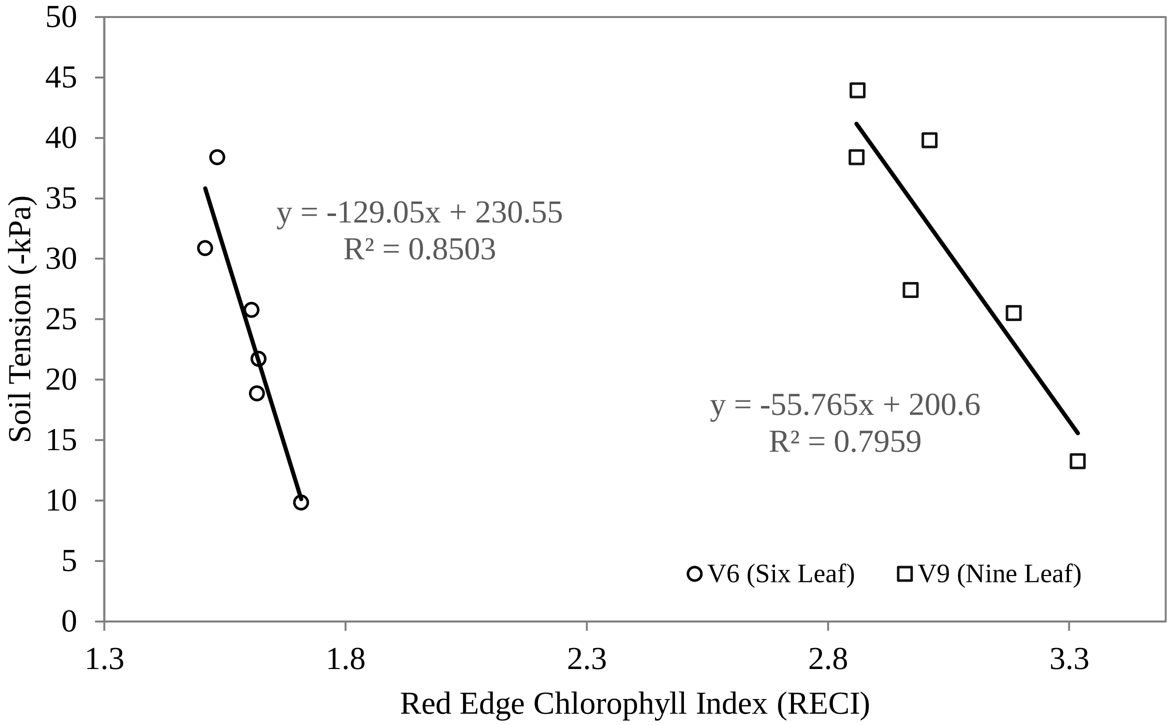

Figure 1.5. Soil tension (-kPa) as a function of RECI for V6 and V9 maize growth stages.

All of the green indices, Green Ratio Vegetation Index (GRVI); Green Normalized Difference Vegetation Index (GNDVI); and Green Atmospherically Resistant Index (GARI), were strongly correlated at the V2 stage at 75 centimeters and considerably outperformed red indices. This was expected due to the prevailing soil background during early plant growth and was only observed at V2 – the earliest growth stage examined. Our results are quite similar to those of Peterson and Baumgardner (1981), who found a strong linear relationship between soil moisture tension and green reflectance between 520 - 580 nanometers. Although their study was conducted using an indoor spectroradiometer, the wavelengths discussed are nearly the same as the green waveband of the RapidEye™ satellites used in this study.

Except for Enhanced Vegetation Index (EVI), the model for NDVI exhibited the lowest coefficient of determination of all results when considering average tension over the day previous to image acquisition. Consequently, neither NDVI nor EVI seem to be suitable for quantifying immediate variability of soil water content. Our findings agree with Carter and Knapp (2001), who found that the best regression models for chlorophyll concentration occurred within the red edge region, rationalized by the propensity of stressed leaves to exhibit a reduction in chlorophyll.

Average Soil Tension from Previous Week

Renormalized Difference Vegetation Index (RDVI) and Optimized Soil Adjusted Vegetation Index were moderately correlated with average soil tension from the week previous to image acquisition at V6 growth stage, 20 centimeters deep. Frequent precipitation may explain why RENDVI and RECI did not produce significant results as they did with both other tension intervals at 20 centimeters. Nearly an inch of rain fell that week with very little difference between irrigation treatments, which probably masked any variability detectable by means of the spectral response of the plants. Furthermore, none of the indices were found to be significant over more than one growth stage. Similar to previously discussed results, GARI and other green indices once again had higher coefficients of determination at V2 stage, 75 centimeters deep when compared to the red indices. The positive correlation between soil tension and GARI is very strong (Figure 1.6). It is notable that the image for this date is comprised mostly of bare soil, which explains the contrast with otherwise negative correlations in all the imagery with considerably more plant growth.

Table 1.5. Significant results from regression analysis of average soil moisture tension (over the week previous to satellite image acquisition) on selected indices.

Tensiometer Depth (cm)	Index†	Growth Stage‡	r^2	p-value	RMSE (-kPa)
20	RDVI	V6	0.661	0.049	5.361
75	OSAVI	V2	0.717	0.033	0.720
	NDVI	V2	0.766	0.022	0.766
	GRVI	V2	0.781	0.019	0.633
	GNDVI	V2	0.784	0.019	0.628
	GARI	V2	0.908	0.003	0.411
	EVI	V2	0.724	0.032	0.711

† RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

‡ V2 and V6 are the two leaf and six leaf growth stages of maize, respectively.

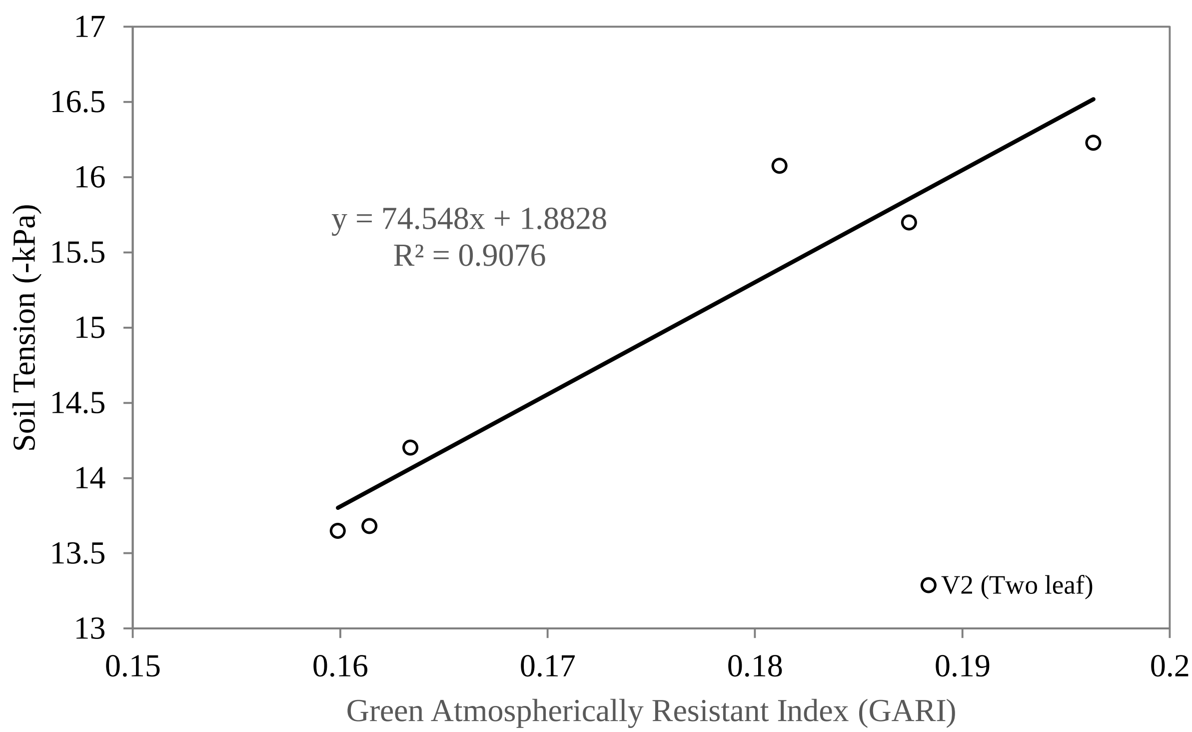

Figure 1.6. Soil tension (-kPa) as a function of GARI for the V2 (two leaf) growth stage.

Average Soil Tension from Planting to Date

The average tension from planting to image acquisition date represents the sole occasion where traditional red NDVI had the highest coefficient of determination: it was highly correlated with soil tension at 75 centimeters deep (see Figure 1.7). Unlike at other crop growth stages this is once again a positive relationship at V2, which is logical because soil color as affected by water content probably had a stronger influence on reflectance over this larger interval with frequent rainfall than the influence of sparse vegetation. The only significant correlations found at the 45 centimeter depth were at the R3 stage, probably because moisture conditions closer to the soil surface have a greater effect on immediate plant response, and measurements deeper in the profile are more representative of long-term water infiltration when consistent rainfall is prevalent. RENDVI and RECI were highly correlated at both 20 and 45 centimeter depths at the R3 stage, suggesting value for quantifying soil tension in both vegetative and reproductive crop growth stages. Although the linear models are well correlated, it is important to note that the shapes of the quadratic fits, as depicted in Figure 1.8, represent an intuitive trend. The curve in this case levels off at the wettest soil tensions. This is characteristic of excessive irrigation, at which point adding more water fails to benefit the crop and will eventually cause stress.

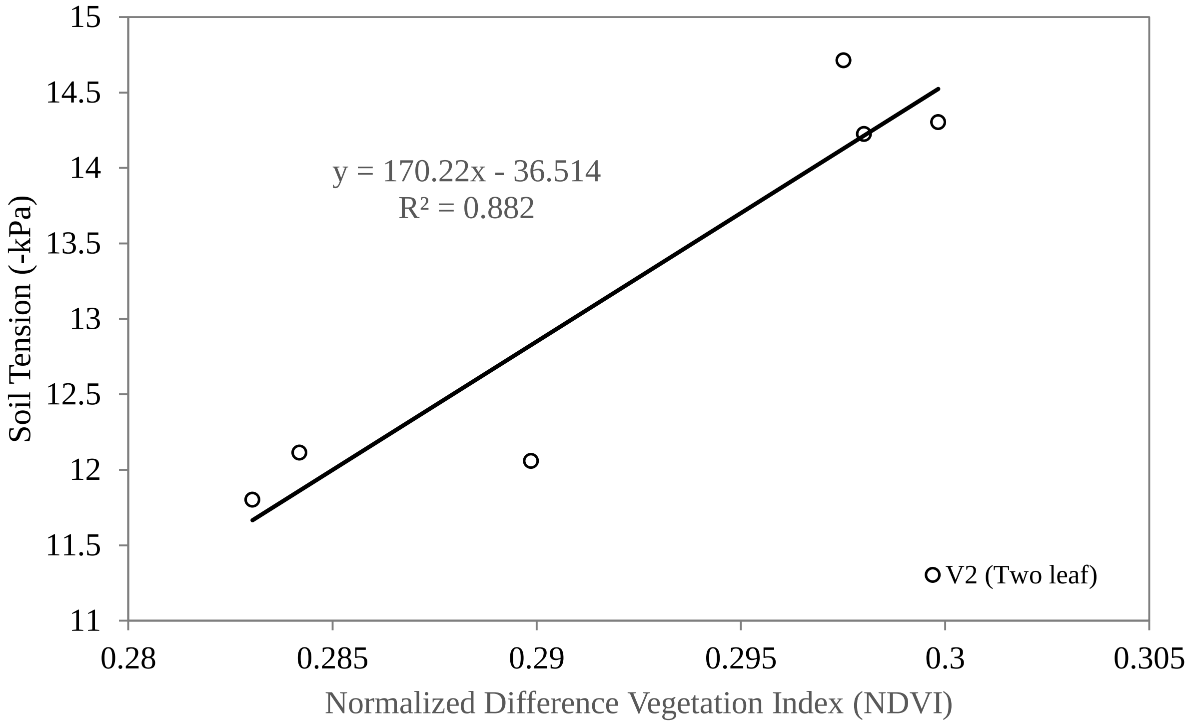

Figure 1.7. Soil tension (-kPa) as a function of NDVI for the V2 (two leaf) growth stage.

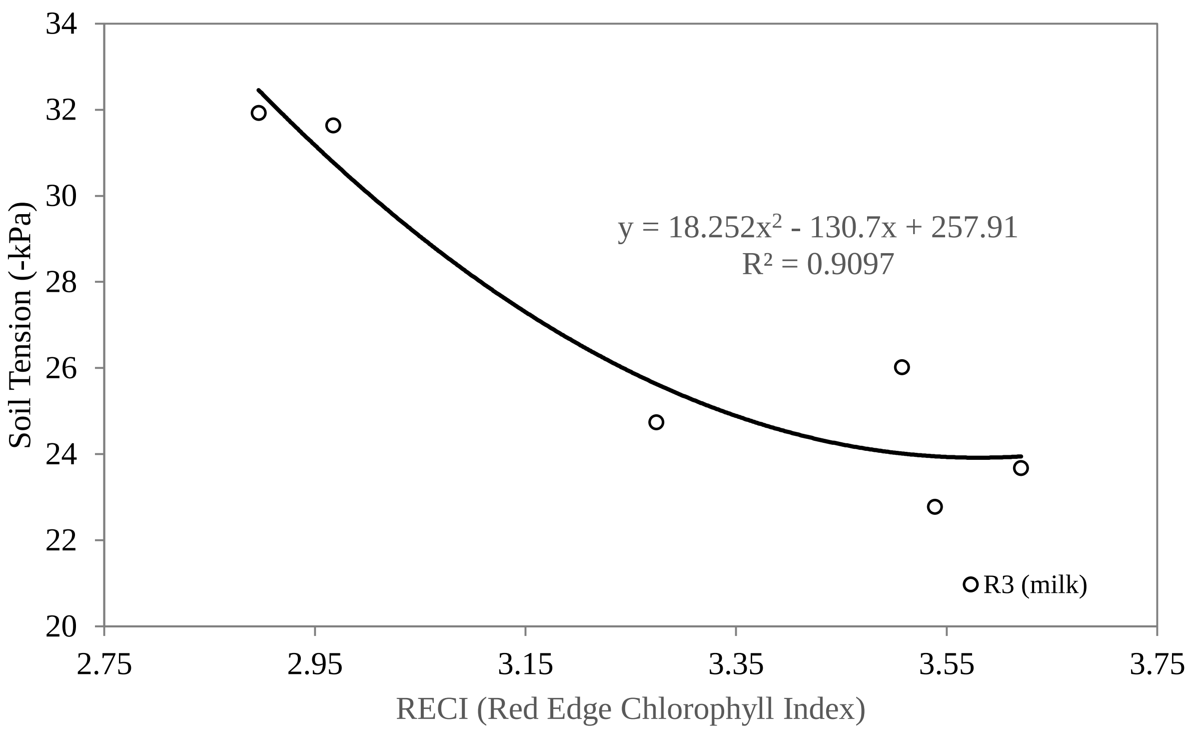

Figure 1.8. Soil tension (-kPa) as a function of RECI for the R3 (milk) growth stage.

Table 1.6. Significant results from regression analysis of average soil moisture tension (between planting to satellite image acquisition) on selected indices.

Tensiometer Depth (cm)	Index†	Growth Stage‡	r^2	p-value	RMSE (-kPa)
20	RENDVI	R3	0.772	0.021	2.143
	RECI	R3	0.861	0.008	1.672
	Quadratic§	R3	0.910	0.027	1.556
	NDVI	R3	0.699	0.038	2.461
	GRVI	V2	0.664	0.048	1.259
	GNDVI	V2	0.657	0.050	1.271
45	RENDVI	R3	0.827	0.012	4.190
	RECI	R3	0.851	0.009	3.891
	RDVI	R3	0.754	0.025	4.992
	OSAVI	R3	0.799	0.016	4.514
	NDVI	R3	0.767	0.022	4.862
75	RDVI	V2	0.736	0.029	0.771
	OSAVI	V2	0.816	0.014	0.644
	NDVI	V2	0.882	0.005	0.515
	GARI	V2	0.808	0.015	0.658
	EVI	V2	0.729	0.023	0.729

† RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

‡ V6, V9, and R3 are the six leaf, nine leaf, and milk stages of maize growth, respectively.

§ Quadratic regression is included because it is more logical than the linear model.

Bareground (Emergence) Image

Data from all three tensiometer depths examined in this study (20, 45, and 75 centimeters) indicates that soil surface albedo provides information deeper into the profile than the light can fundamentally penetrate, although the correlations tend to be slightly weaker (see Table A5 in Appendix A). For average tension between planting to the image acquisition, RENDVI and RECI produced coefficients of determination above 0.71 at both 20 and 75 centimeter depths while results at 45 centimeters were just outside the alpha = 0.05 significance level. These observations may arise from the combined influence of soil physical properties (e.g. organic matter content, texture, color) which affect its spectral response and are concurrently related to the behavior of soil when water is introduced (e.g. infiltration rate, water holding capacity).

It was demonstrated that soil reflectance as influenced by water content could be applied amongst contrasting soils if the water content were expressed as soil moisture tension instead of percent dry mass (Brady, 1985). Our results support those findings and also suggest that this can be accomplished at the field-scale. Multispectral satellite imagery could then help inform variable rate irrigation systems by accounting for temporal variability at high spatial resolution while accounting. Aerial bare soil imagery has been used at field-scale to delineate site specific management zones for variable rate nitrogen management (Khosla, 2002) but the literature does not include similar studies for variable rate irrigation. Aside from the number of studies (Bowers and Hanks, 1965; Idso et al., 1975; Skidmore et al., 1975) which provide evidence that the optical properties of soil vary with water content, our results indeed agree with the suggestion of Campbell (1988) that visible and near-infrared reflectance must also be related to soil moisture tension.

At depths greater than 20 centimeters, none of the vegetation indices were found to be well correlated with average tension over 24 hours. However, RENDVI and RECI produce moderate correlations (at alpha = 0.1) at all three depths for 1 week and planting to date tension intervals. This suggests that although immediate soil moisture conditions near the surface are strongly correlated with the spectral response of soil, conditions deeper in the soil profile are only related after a considerable lag is allowed – likely for precipitation to infiltrate to that depth.

These results support the use of bare soil multispectral imagery for characterizing heterogeneous soil moisture conditions. It is important to note that the acquisition time for the larger unmasked image is early in the morning, so the image is particularly dark.

General discussion

Results from regressions of soil tension on RENDVI and RECI indicate that spectral vegetation indices derived from multispectral satellite imagery are capable of characterizing high frequency soil moisture variability at single time points and at large field-scales. Simple linear models had high coefficients of determination at more than one vegetative growth stage (both V6 and V9) at the same 20 centimeter depth. For RENDVI, the slopes were also nearly identical between stages and the increase in the y-intercept for V9 growth stage was almost proportional. This consistency suggests that a single satellite image acquisition could be reasonably representative of soil moisture variability over time – at least up to a couple weeks after image acquisition – and may help mitigate issues with temporal resolution for actual irrigation management.

Considerable differences between the models at V6 and V9 growth stages suggest that RECI may indeed reflect immediate soil moisture variability, but also that conditions may not be well represented up to a couple weeks as is the case with RENDVI, which is particularly sensitive to slight change. Conversely, models for RECI do appear to be slightly more representative later in the growing season, once reproductive growth is well underway. The shape of the quadratic curves also suggests that the red edge indices are capable of characterizing the stagnant point where applying more water will not benefit the crop. Models from the R3 crop growth stage indicate that long term (planting to date) soil moisture conditions are also well represented up to 45 centimeters deep.

Conclusions

Multispectral satellite imagery, particularly with a red edge waveband, demonstrates potential for quantifying soil moisture tension variability, and hence could be used for variable rate irrigation management. RENDVI was especially sensitive to soil moisture tension and demonstrated that a single image could be representative of variability up to two weeks after acquisition. However, it is necessary to confirm repeatability of these results at more maize growth stages and other crops. Finally, an economic study to evaluate the monetary and environmental implications of such management at field scale would help transition these findings into industry adoption.

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CHAPTER TWO

INFRARED THERMOMETRY TO QUANTIFY IN-FIELD SOIL MOISTURE VARIABILITY IN IRRIGATED MAIZE PRODUCTION

Introduction

Plant canopy temperature was early identified as a potential indicator of soil moisture conditions (Tanner, 1963). Colaizzi et al. (2012) explain the relationship of canopy temperature with plant and soil water conditions in terms of evapotranspiration effects. Reductions in temperature are due to the consumption of heat energy by evapotranspiration and the resultant cooling effect of water vapor moving away from the crop canopy. When factors such as reduced available soil water content cause a decrease in evapotranspiration rate, such cooling is inhibited and the temperature increases. A few degrees Celsius can have substantial biochemical effects when considering respiration, photosynthetic, and growth rates (Gates, 1964). Hence measuring canopy temperature could serve as an indicator of plant water stress (Wanjura et al., 1995).

Early endeavors to measure plant temperature often utilized contact sensors which were cumbersome and only provided data at the leaf contact points (Ehrler, 1973; Gates, 1964; Wallace and Clum, 1938). Measurements from the plant are more directly indicative of its status than atmospheric or soil physical characteristics (Durigon and van Lier, 2013). With the advent of affordable, reliable, and convenient non-contact thermometers, acquiring plant temperature has become more practical (Hatfield et al., 2008). Because infrared thermometers provide quick measurements of average temperature within the sensor field of view, they are particularly suitable for measuring canopy temperature (Jackson et al., 1981).

Infrared radiation thermometry is a remote sensing technique used to estimate the temperature of an object's surface within the sensor's field of view. The Stefan-Boltzmann blackbody law enables a calculation which relates thermal radiation emitted from an object and the object emissivity to its temperature (Fuchs and Tanner, 1966). The relative efficiency of an object to emit radiation is termed emissivity (Mazikowski and Chrzanowski, 2003). Although emissivity corrections for accurate temperature measurement by means of infrared radiation thermometry are often discussed, the error induced by assuming emissivity of 1 for a plant canopy has been estimated to be a maximum of ± 0.2°C (Bartholic et al., 1972; Gates, 1962; Monteith and Szeicz, 1962). However, emissivity correction is more important when soil background is included in the sensor field of view, because the magnitude of the error has been observed to increase with the amount of soil contributing to the measured radiance (Heilman et al., 1981; Sánchez et al., 2008).

While using infrared thermometers for irrigation scheduling in maize (*Zea mays* L.), Clawson and Blad (1982) did not find a dependence of canopy temperature on the sensor view direction. Using infrared thermometers, Carlson et al. (1972) observed that the canopy temperature of two different varieties of soybean (*Glycine max* L.) differed significantly. Some other concerns, such as calibration, are discussed by Jackson et al. (1980). For example, the authors observed substantial temperature inaccuracies when a dust canister with 2,2-4 dichloro-difluoroethane propellant was used to clean the sensor.

Idso et al. (1978) introduced the concept of a Stress Degree Day (SDD), which was calculated as the difference between canopy and ambient temperature at 14:00 hours. However, this integrated only one time measurement per day into the SDD index. Numerous studies utilize canopy temperature data to calculate the Crop Water Stress Index originally proposed by Idso et al. (1981), which is a modification to their SDD concept that is widely accepted but requires additional climatic information such as vapor pressure deficit that can make it cumbersome to calculate. Canopy temperature has been shown to be individually correlated with physiological stress measurements (DeJonge et al., 2015) and it has been suggested by others that the fundamental differences in temperature between well-watered and stressed crops could be representative of relative irrigation requirements (Bartholic et al., 1972). Relative irrigation requirements determined by in field canopy temperature variability, independent of ancillary data, could be exploited for formulation of variable rate irrigation prescriptions to efficiently distribute water within a field.

Thermal imagery was early established as a potential tool for irrigation scheduling. Millard et al. (1978) noted that airborne thermal imagery could characterize the different irrigation treatments and variability within plots of wheat (*Triticum aestivum* L.). They suggested that thermal imagery would be useful for irrigation scheduling when ground cover is adequate. This was quickly recognized and continues to be a limiting factor, especially for early crop growth stages (Hatfield, 1983; Thomson et al., 2012). More recent studies have attempted to remove influences of soil background from the thermal imagery (Alchanatis et al., 2010; Hu et al., 2011; Leinonen and Jones, 2004).

Evans et al. (2000) mounted twenty-six infrared thermometers on a center pivot in order to measure crop canopy temperature at high resolution. They found that temporally adjusted canopy temperature explained 65 - 95% of variability across their soil mapping units. The authors also commented that the financial investment was low since the existing pivot was used as the sensor vehicle, the data was easily acquired, and that it could have many uses in irrigation management. Some of the discussed possibilities are checking for irrigation application issues, irrigation scheduling, and real time variable rate irrigation – when the thermometers are mounted in front of the sprinklers and water spray can be avoided.

Peters and Evett (2004) conducted a study using a continuous stationary reference temperature curve in order to scale up additional one time of day measurements to daily temperature dynamics. They found that their method was successful and suggested that it could be used for irrigation scheduling and to map temperature variability for variable rate irrigation. González-Dugo et al. (2006) observed that the standard deviation of canopy temperature in cotton was sensitive to moderate water stress variability but advised that it isn't suitable for severely stressed crops.

A threshold temperature indicative of water stress has been examined by several research teams and for several crops (Evett et al., 2000; Mahan et al., 2005; O'Shaughnessy and Evett, 2010; Wanjura et al., 1992). Evett et al. (1996), for example, suggested that a 28° Celsius threshold, centered within the thermal kinetic window for optimal maize growth (Burke, 1993), and a short decision interval would probably be optimal for irrigation scheduling in maize. All of these studies focused on time above the threshold for irrigation scheduling, but none comment on the possibility of using the spatial distribution of canopy temperature for variable rate irrigation. Nor did the authors consider how much warmer the temperatures were above the threshold, which could enhance the method to also gauge the severity of water stress. DeJonge et al. (2015) compared different methods for calculating stress indices with canopy temperature in maize. One method included the difference between a stress threshold temperature (28°C) and the canopy temperature, but the authors did not address the possibility of using other temperatures, such as 27°C or 29°C, for the stress threshold.

Although the Stress Degree Day and Crop Water Stress Index were designed to quantify stress for irrigation, they have considerable limitations. The Stress Degree Day is calculated using only one afternoon canopy and ambient temperature measurement, while the Crop Water Stress Index requires water stressed and non-water stressed baselines specific to the crop and local climatic conditions.

The previous research presents a logical opportunity to enhance our understanding of crop canopy temperature and its relationship with water management, particularly with respect to variable rate irrigation management. Therefore, the objectives of this study were: 1) to determine the relationship between synchronous measurements of crop canopy temperature and in-field soil moisture tension, and 2) to understand the influence of discretionary crop canopy temperature stress thresholds on the relationship between soil moisture tension and crop canopy temperature.

Materials and Methods

Study Site

This experiment was conducted over the 2015 maize growing season at a site located north of Fort Collins in northeastern Colorado (40.666° N, 104.998° W). The 12 hectare field, which has been cultivated for many years under continuous maize cropping system, conventional tillage, and furrow irrigation, was precision leveled and modified to a center-pivot sprinkler system in 2012. The soil is classified as the Kim loam series, which is characterized as very deep, moderately permeable, and is classified as fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents (Soil Survey Staff, 1980). Slope at this site is between one and three percent, and the climate is semi-arid with an average annual precipitation of about 400 millimeters. The field was seeded on May 27, 2015 with DEKALB® DKC46-20VT3 at a population of 93,900 plants per hectare (38,000 plants per acre).

Experimental Procedure

Using a Valley® variable rate irrigation pivot (Valmont Industries, Valley, NE), six water treatment zones were formed – each with Hortau® tensiometers (Hortau Simplified Irrigation, Lévis, QC, Canada) installed in the center at 20, 45, and 75 centimeter depths. Water was applied for each treatment as a percentage of the estimated evapotranspiration (ET) requirement: 40, 60, 80, 100, 120, and 140 percent. The depth of water applied at those rates corresponds to 20, 30, 41, 51, 61, and 71 centimeters for the entire growing season, respectively. Estimated ET requirements, or the amount needed to replenish water used by the plants and lost to evaporation, are based on weather conditions such as solar radiation, wind speed, and humidity. Details on deriving crop water requirements are presented in Allen et al. (1998). To mitigate the possibility of surface runoff, straw wattles were fixed between water treatment zones at susceptible locations.

Using the open-source Arduino microcontroller platform, six identical dataloggers were custom built for this study – one for each tensiometer location. Six MLX90614 digital infrared thermometers (Melexis Microelectronic Integrated Systems, Tessenderlo, Belgium) with a 35° field of view were used to measure canopy temperature. These infrared thermometers, which are particularly notable for low cost, are factory calibrated for accuracy better than ±0.5°C when sensing between 0 to 50°C (Melexis Microelectronic Integrated Systems, 2010). The high thermal stability of these units, which reduces the effect of extraneous heat sources on the sensor temperature, also makes them suitable for field usage. Since the emissivity of a plant canopy is approximately one (Jackson et al., 1981), the factory default object emissivity value of one was used. Extreme low power datalogging shields (Dead_Bug_Prototypes, Sandnes, Norway) with microSD card slots were used to write and store temperature data every 15 minutes.

The infrared thermometers were installed in the field on June 30, when the plants were at the V3 growth stage. Thermometers were mounted on the existing post which housed the tensiometer equipment. Maize rows were planted east-west and all thermometers were facing east into a single corn row at 90 degrees from the plant and vertically centered on the leaves near the top of the canopy (see Figure 2.01). They were raised during the growing season to keep the sensor field of view in the top third of the canopy. Data was downloaded from the microSD cards one month after installation and again at the end of the growing season.

Every 15 minutes throughout the growing season, the soil moisture tension data was wirelessly uploaded to server storage. Raw tension data was then downloaded from the web. The tensiometer water reservoirs became depleted and required rehydration several times during the growing season. This process generated data points unrepresentative of actual soil moisture conditions. The date and time was noted for each rehydration event. The period between sensor dehydration and 24 hours after hydration was removed from the tension data and concurrent temperature data.

Figure 2.01. Image showing infrared thermometer pointed into the maize canopy. The actual thermometer (black) is at the bottom of the weather resistant box.

Data Analysis

For the purpose of data analysis, a simple program was written in the Java language (see Appendix Figure B1 and B2) to read the data from a text file and perform calculations for statistical analysis. Its processing algorithm was designed to iterate through one day of temperature data in order to calculate the total difference between canopy temperature and a temperature threshold between 26 and 30 degrees Celsius. This iteration resulted in the canopy temperature being compared with the threshold temperature for each data point (every 15 minutes) in the entire day. Where canopy temperature was greater than the threshold temperature, the difference was added to the sum for the day. A result of 0 indicates no stress on that day. Figure 2.02 provides a graphical representation of the total temperature difference area over one day. Soil moisture tension was averaged for each day and paired with the calculated daily total temperature difference.

Linear regression analysis of total temperature difference on soil moisture tension was performed using the R statistical package (R Core Team, 2015) and linear models were evaluated with the coefficient of determination and root mean squared error. Significant results were determined using the Student's t-test. Days which produced more than one no-stress value were excluded because the distribution of canopy temperature was too limited for reasonable statistical comparison with the other days. In addition, total temperature difference was averaged monthly for both August and September to examine the effect of extending the time interval for calculations. Results for soil moisture tension at 75 centimeter depth were excluded due to a lack of significant findings.

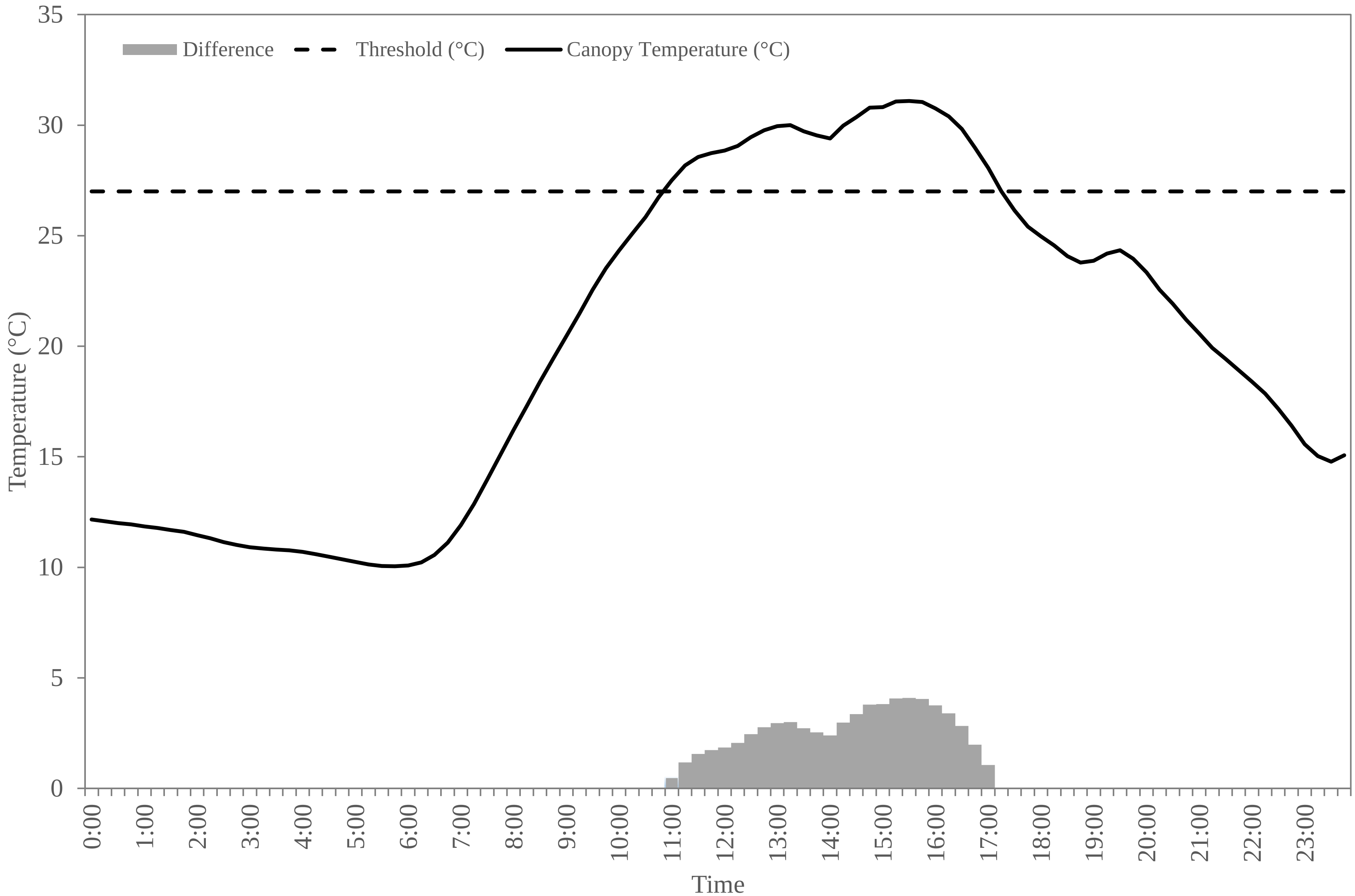

Figure 2.02. Representation of the daily total temperature difference, which is calculated by subtracting the canopy temperature (solid line) from the threshold temperature (dashed line) when it is exceeded. The resultant difference area is designated by the gray bars. For a more clear visual, the canopy temperature curve was formed using a five point triangular smoothing process for August 5th data.

Results and Discussion

The relationship between synchronous measurements of crop canopy temperature and in-field soil moisture tension was studied at three soil depths where soil moisture tension readings were recorded throughout the growing season. For ease of understanding, the results are presented separately for soil moisture measurements at 20 and 45 centimeter depths. Figure 2.03 provides a graphical representation of crop growth by calendar date. Results for soil moisture tension measurements at 75 centimeters depth are excluded due to a lack of significant findings.

Average Daily Soil Moisture Tension at 20 Centimeters

In the month of July, total temperature difference regressed on soil moisture tension did not produce significant linear models. At the beginning of August, after the plants began tasseling, the temperature thresholds began to produce significant models (Appendix Table B1). The standard deviation of soil moisture tension increased substantially from about 15 kPa to 25 kPa around this time (Figure 2.05). Relationships between synchronous measurements of crop canopy temperature and in-field soil moisture tension at 20 centimeters were positive and linear: the stress thresholds produced larger temperature differences while soil moisture tension increased as illustrated in Figure 2.04. Over August and September, a majority of the days examined were related at $\alpha = 0.05$ level of significance. If the results within $\alpha = 0.1$ level were included, over three-quarters of the days examined in those two months, when reproductive growth was prevalent, would exhibit significant positive correlations with soil moisture tension measured at 20 centimeters depth. Although the lowest temperature thresholds produced significant relationships across a larger number of days, the root mean squared error decreased as the threshold temperature was raised (Figure 2.06). The coefficient of determination was also inclined to increase with the threshold temperature (Figure 2.07), denoting that a higher threshold temperature is more precisely indicative of actual soil moisture tension. These observations suggest that canopy temperature is most suited for agronomic operations where moderate to high water stress occurs regularly, which would result in larger more quantifiable canopy temperature increases relative to low water stress conditions.

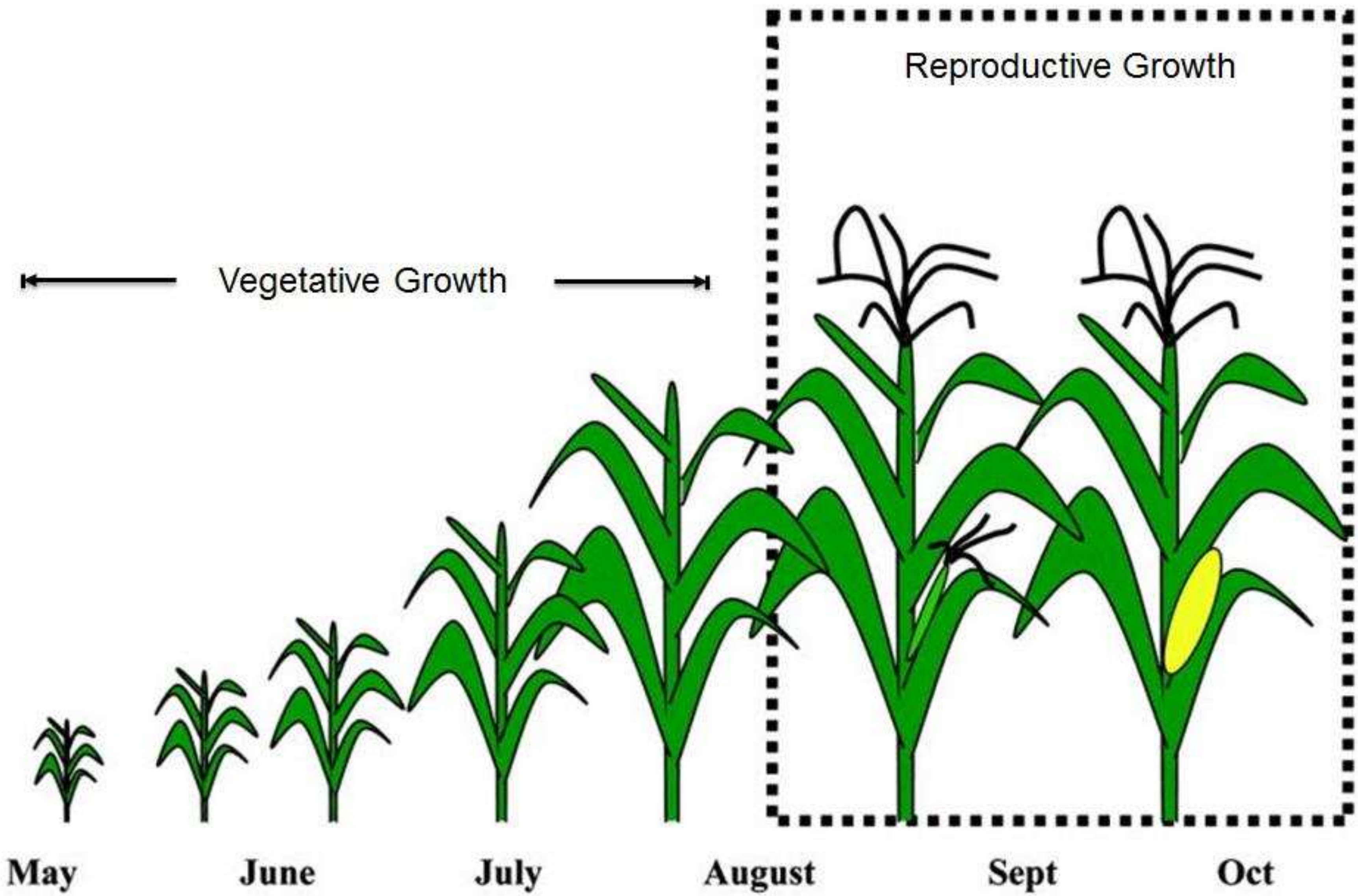

Figure 2.03. Maize growth stages organized by calendar date, with the majority of vegetative growth occurring in June and July and reproductive growth in August and September. Adapted from Lee and Tollenaar (2007).

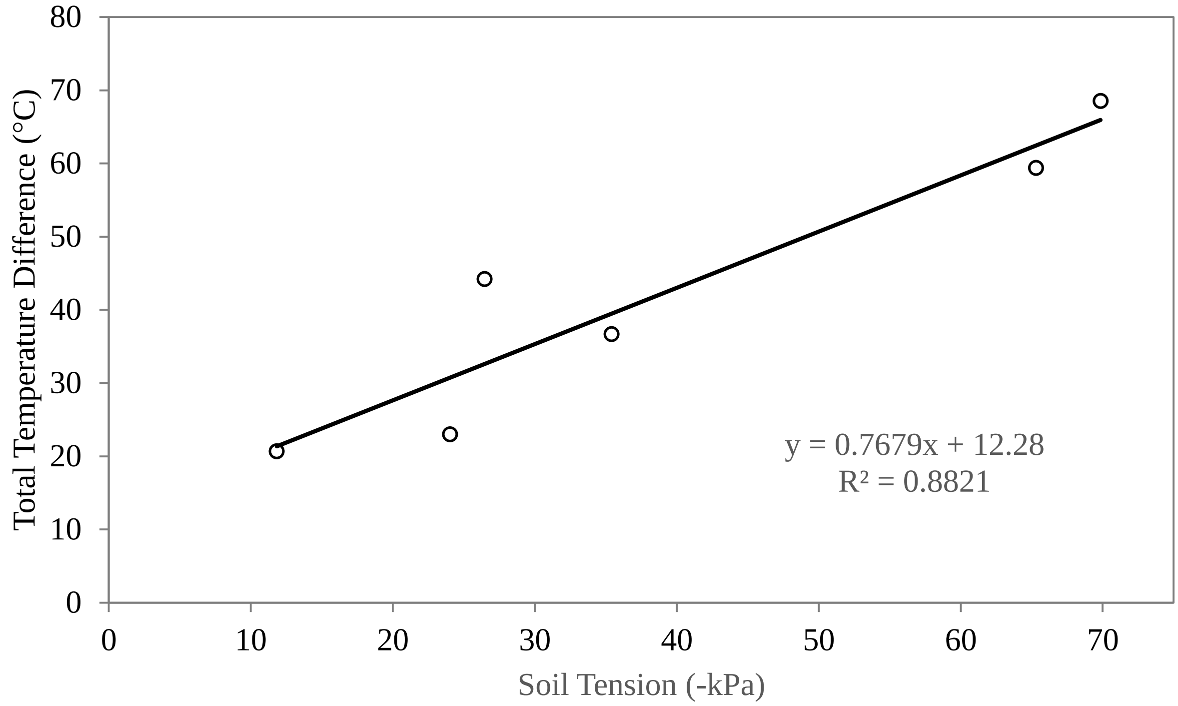

Figure 2.04. Total Temperature Difference, which is calculated over one day by subtracting the canopy temperature from the threshold temperature when it is exceeded, as a function of soil moisture tension measured at 20 cm depth on August 5 (tasseling crop growth stage).

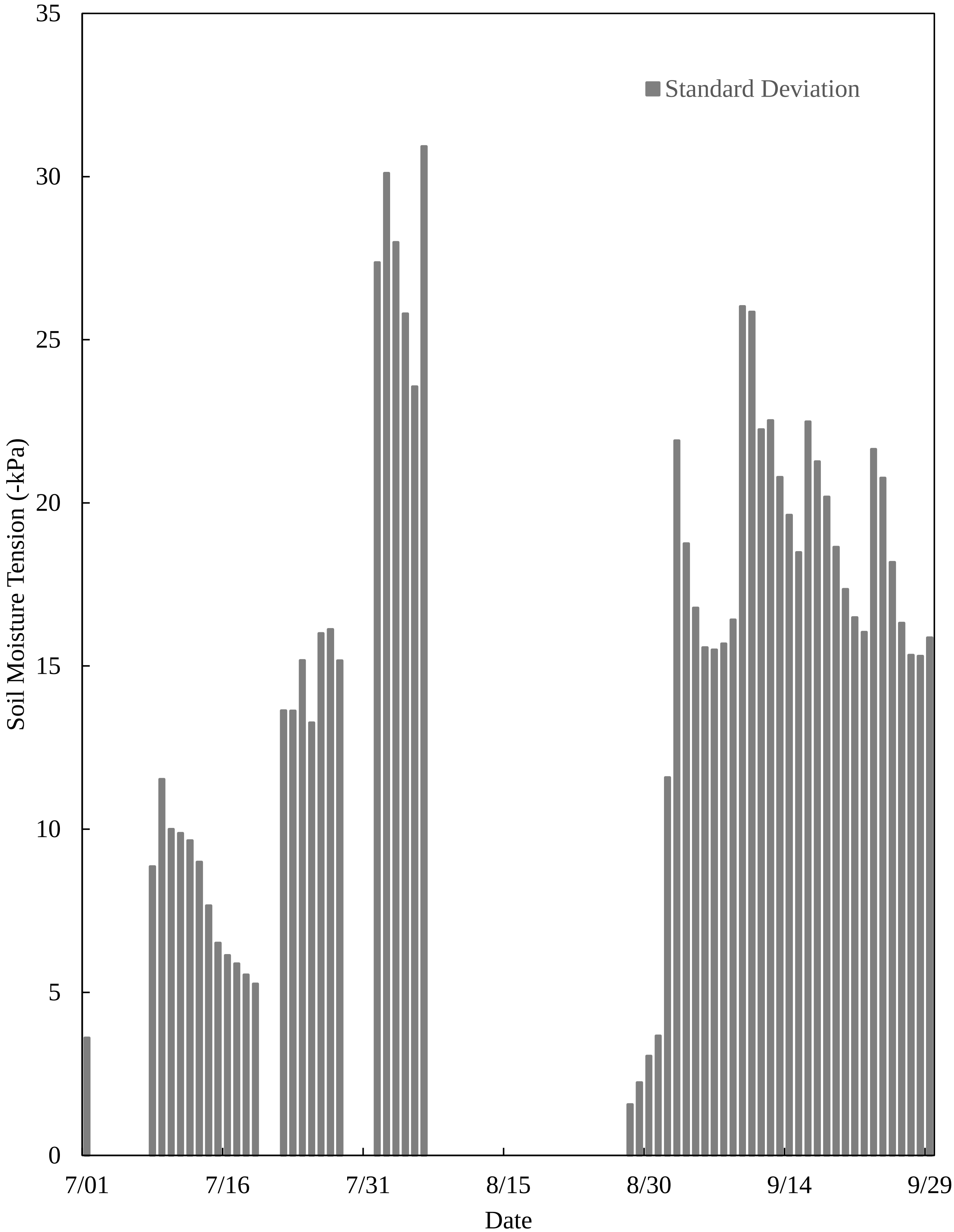

Figure 2.05. Standard deviation of soil moisture tension measured at 20 cm depth as a function of time. The gaps indicate time periods where data was removed during the data cleaning process.

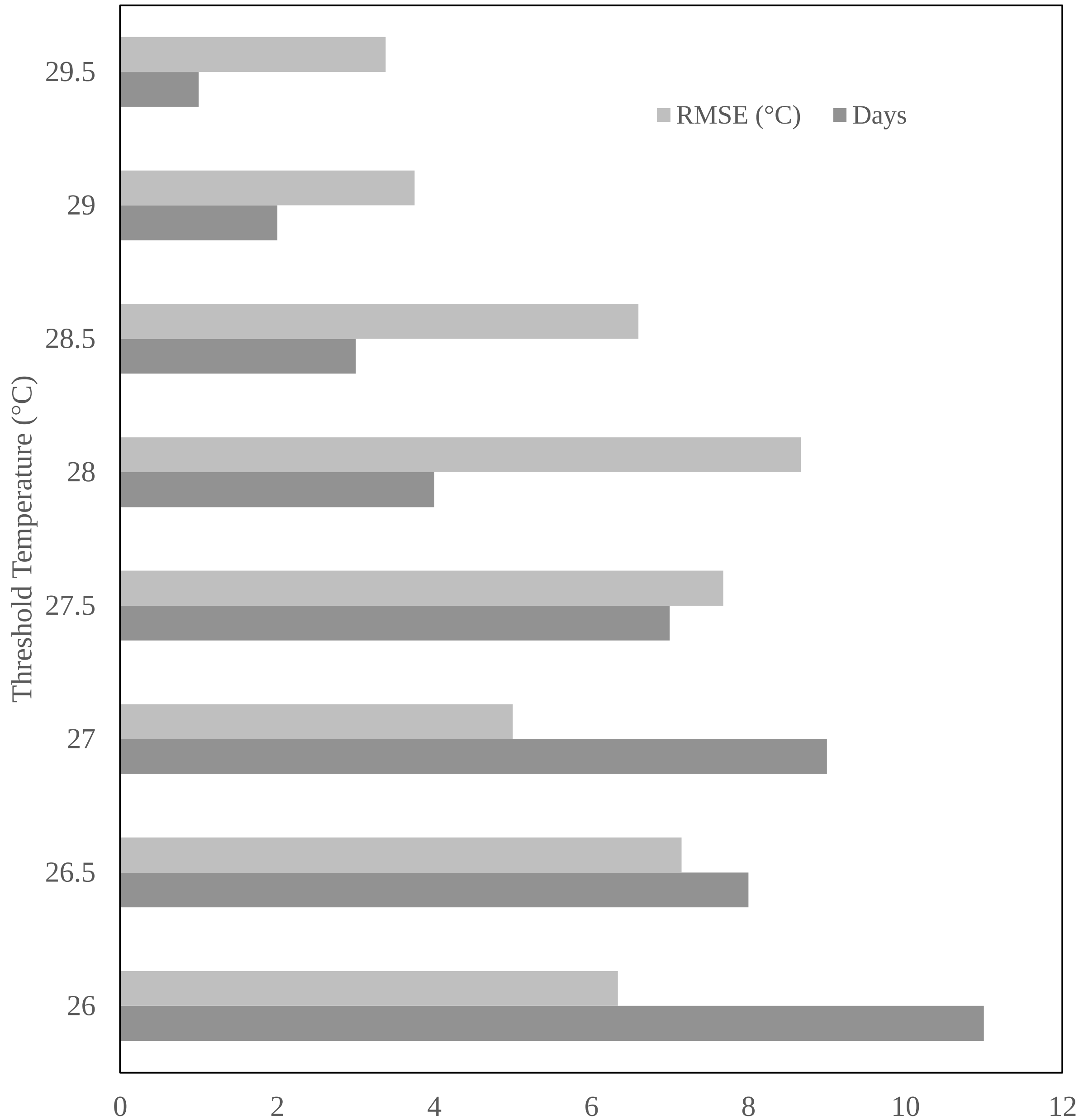

Figure 2.06. Number of statistically significant days and average root mean squared error (RMSE) for linear models using each of the temperature thresholds examined in this study for soil moisture tension measured at 20 cm depth.

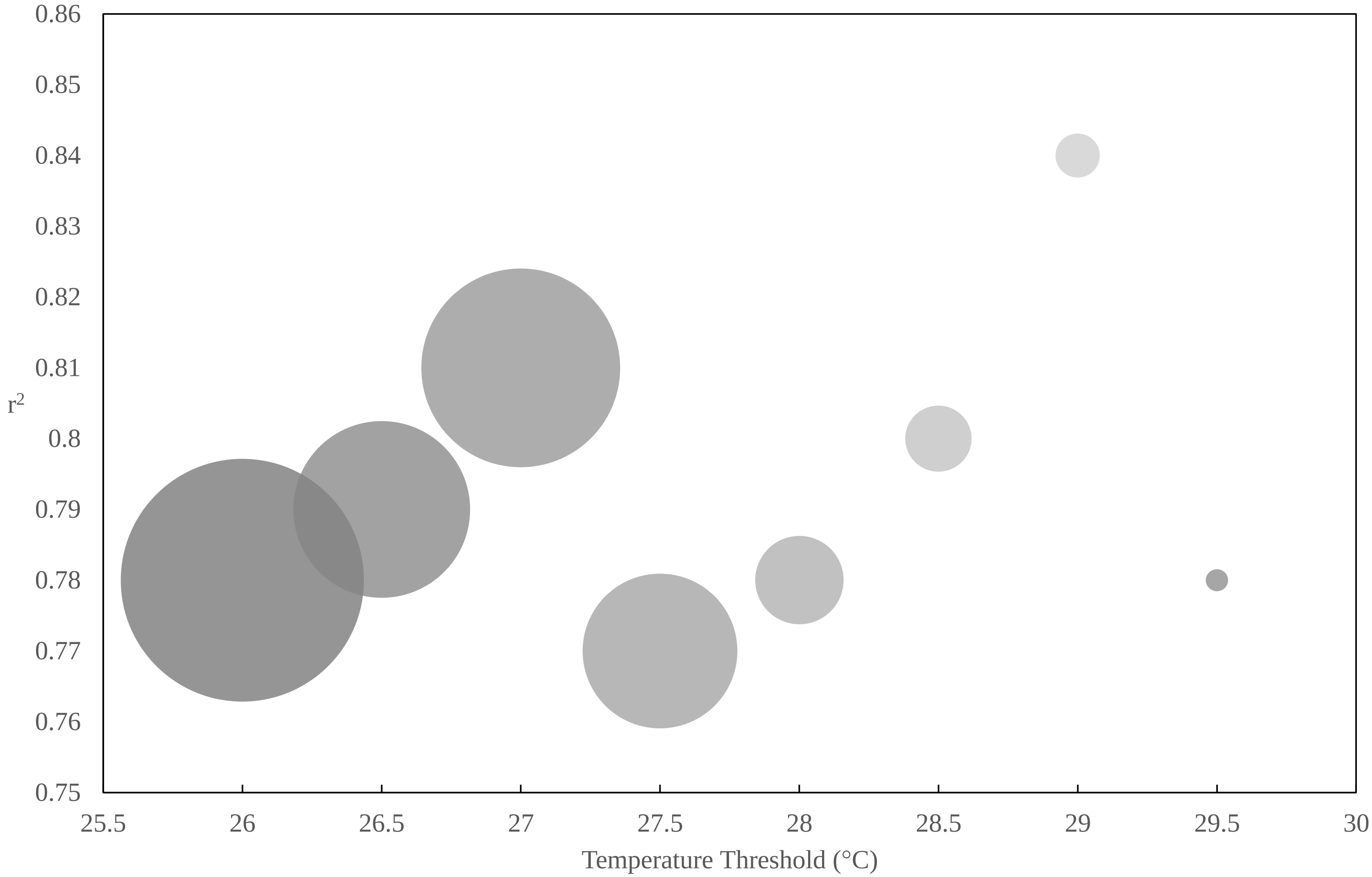

Figure 2.07. Average coefficient of determination (r^2) for linear models using each temperature threshold examined in this study with soil moisture tension measured at 20 cm depth. The number of days statistically significant using the threshold is indicated by the size of each circle.

Average Daily Soil Moisture Tension at 45 Centimeters

Deeper in the soil profile, the temperature stress thresholds produced results similar to those at 20 centimeters: significant positive linear relationships between synchronous measurements of crop canopy temperature and in-field soil moisture tension at 45 centimeters were found early in August through September. Those months correspond to the beginning and majority of reproductive crop growth. There are more significant results later in the season compared to the findings observed for soil moisture tension measurements at 20 centimeters. This could be attributed to the expanding crop root system as it matures because a root system distributed more deeply in the profile is more affected by soil moisture tension at those depths. See Figure 2.08 below for a visual representation of maize root growth at several growth stages.

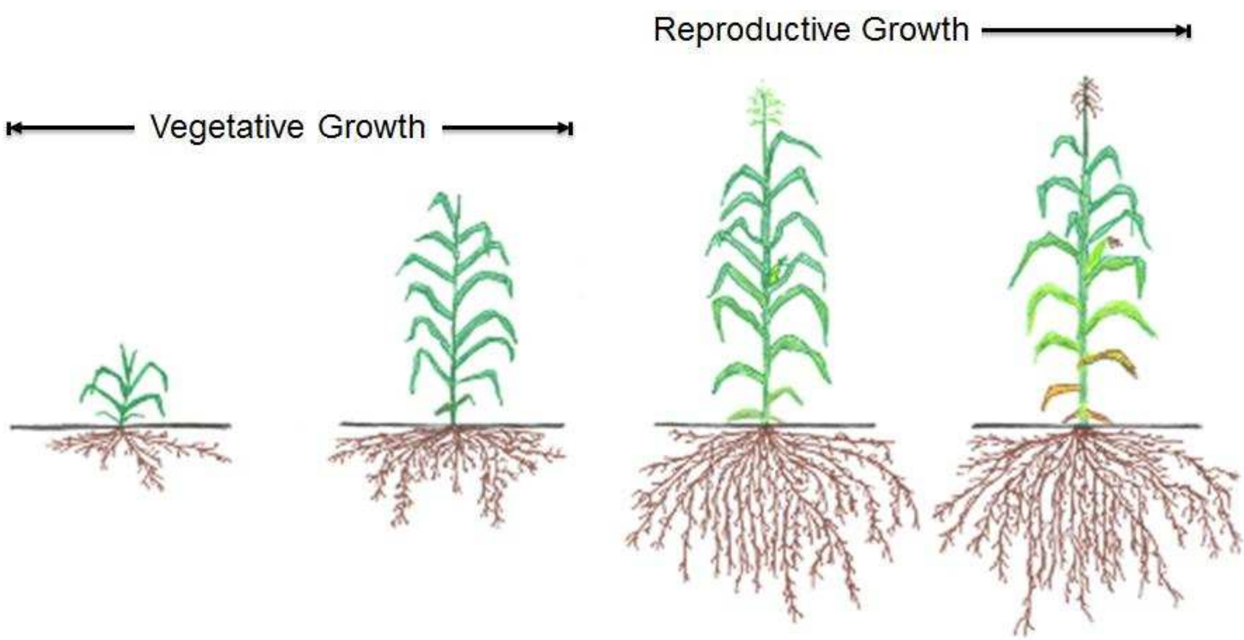

Figure 2.08. Maize rooting depth by growth stage. Roots shown in brown color are much deeper as the plant matures, especially during reproductive growth. Adapted from UC Davis (2015).

Lower temperature thresholds, such as 26°C and 27°C, tend to result in significant relationships over more days (Figure 2.09) while the root mean squared error is higher. The quality of the relationships based on the coefficient of determination tends to increase with the temperature threshold (Figure 2.10). However, the slopes for the linear relationships, such as those for 27 and 28°C, are very similar (Figure 2.11). This observation suggests that the spatial distribution of canopy temperature is well predicted by the models without selecting a highly specific threshold temperature – as long as the temperature is near the center of the thermal kinetic window. Although none of the linear regression models for July were significant, good relationships between total temperature difference and soil moisture tension measured at 45 centimeters were frequent during the reproductive growth stages, which are consequently most important for irrigation management because crop yield is most highly affected by stress during that time period.

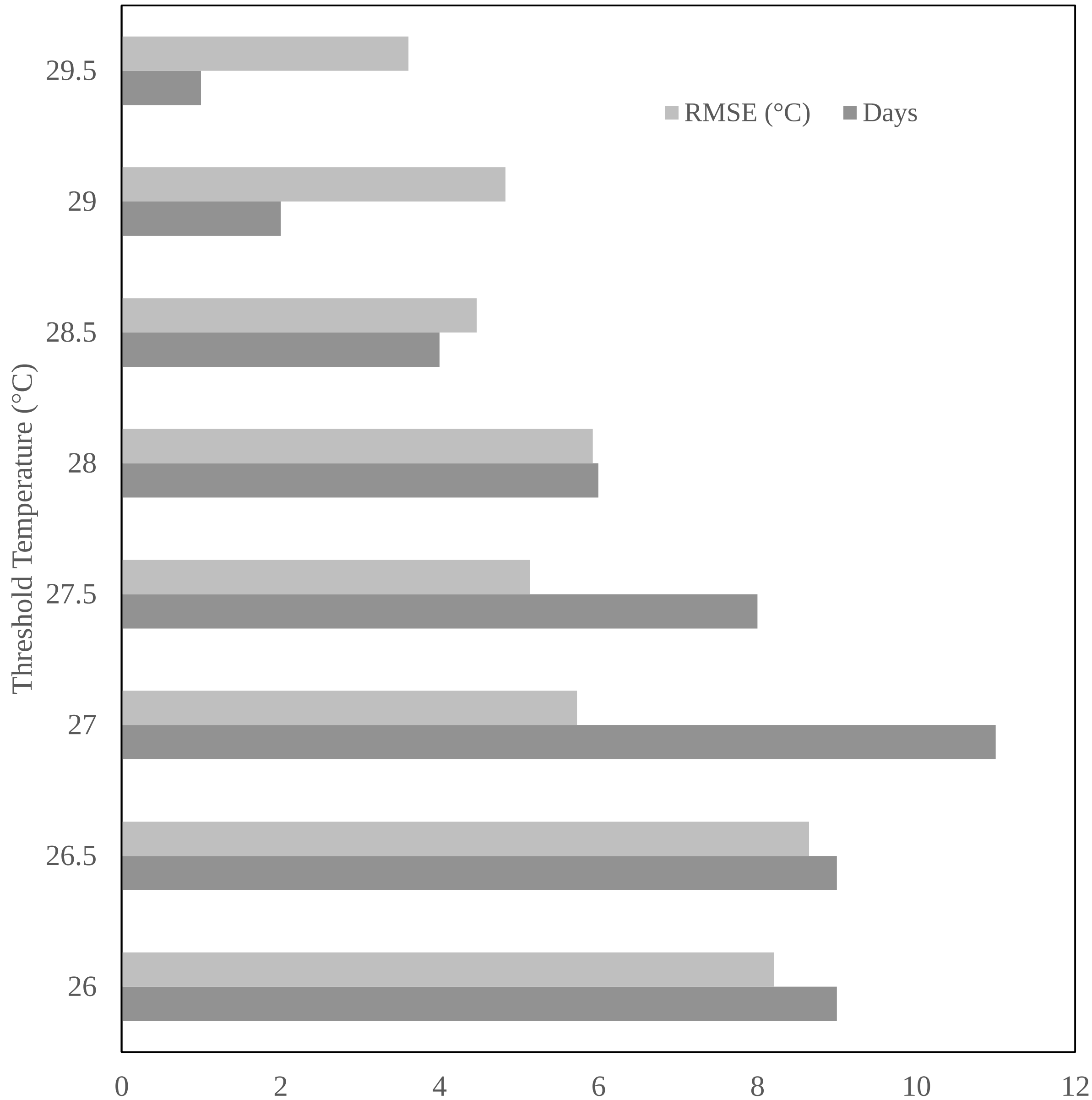

Figure 2.09. Number of statistically significant days and average root mean squared error (RMSE) for linear models using each of the temperature thresholds examined in this study for soil moisture tension measured at 45 cm depth.

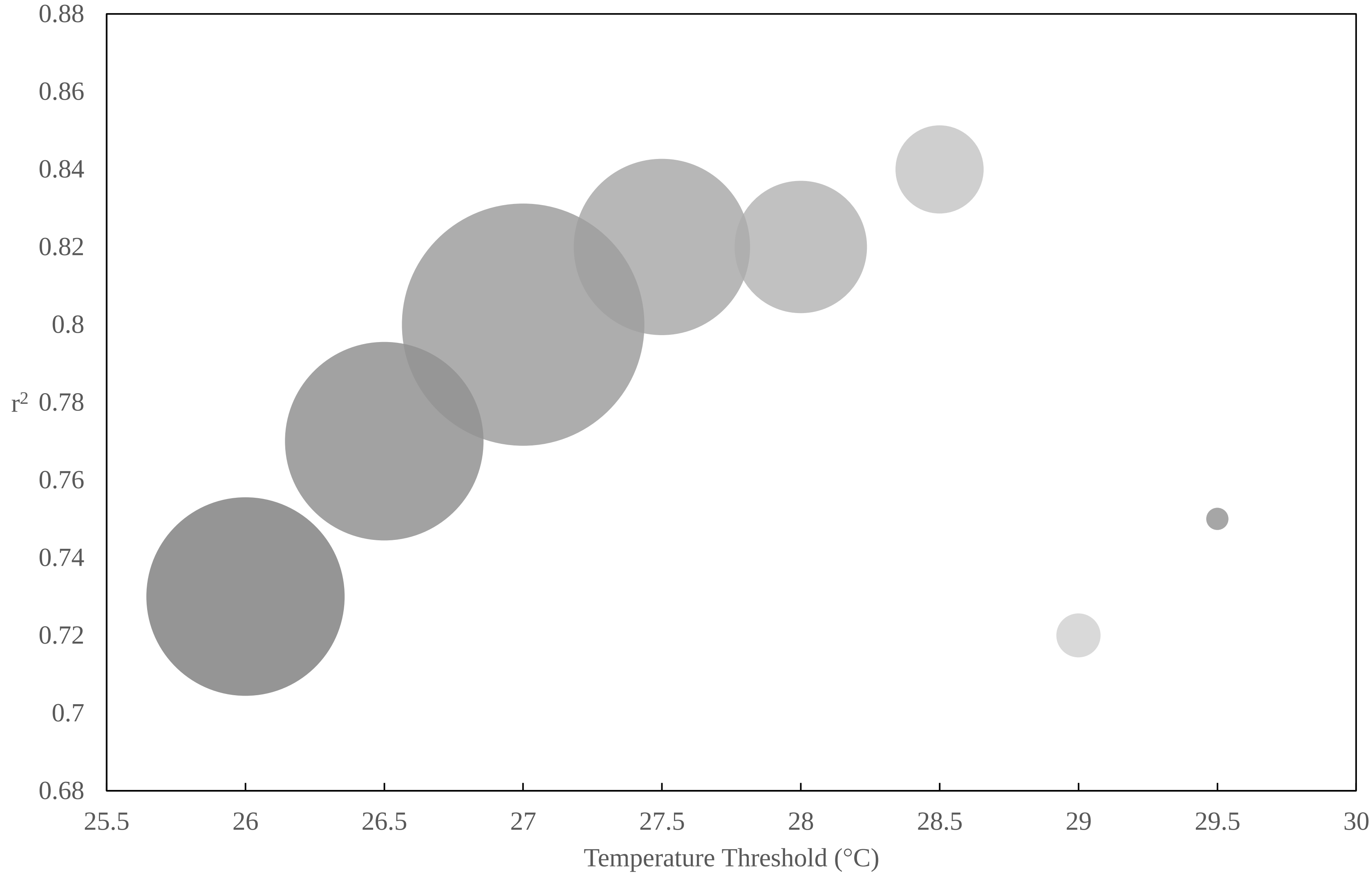

Figure 2.10. Average coefficient of determination (r^2) for linear models using each temperature threshold examined in this study with soil moisture tension measured at 45 cm depth. The number of days statistically significant using the threshold is indicated by the size of each circle.

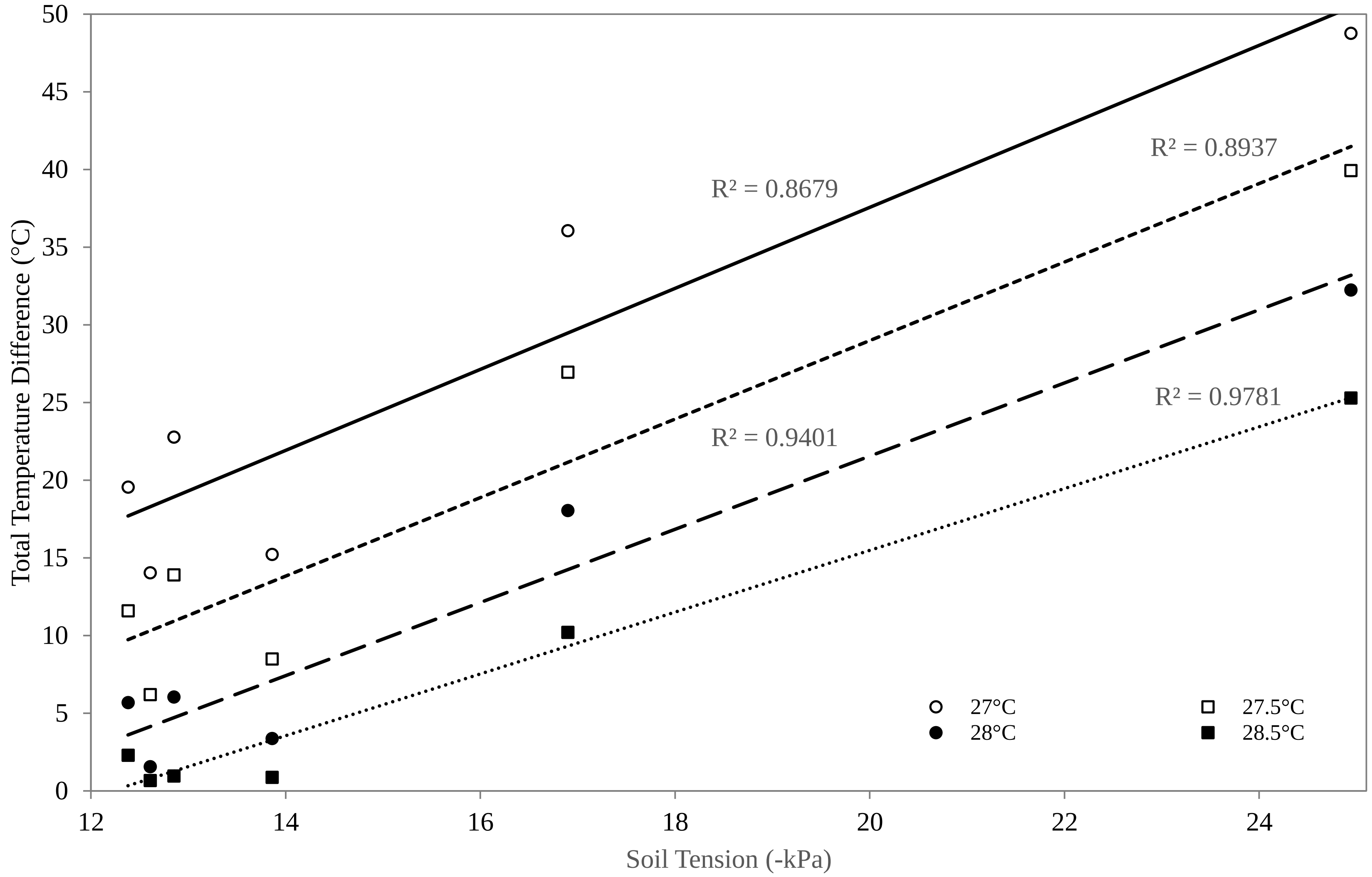

Figure 2.11. Total Temperature Difference, which is calculated over one day by subtracting the canopy temperature from the threshold temperature when it is exceeded, as a function of soil moisture tension on August 30. Four different temperature stress thresholds (27 – 28.5°C) are included to demonstrate the tendency of the coefficient of determination to increase up until zero stress values are produced.

Average Monthly Soil Moisture Tension

Total temperature difference was averaged separately for the months of August and September to evaluate the effect of extending the time period for its calculation on the strength of its relationship with soil moisture tension measured at both 20 and 45 centimeters depth. Because a significant linear relationship was not found between total temperature difference for July and synchronous soil moisture tension at 20 or 45 centimeters depth, the results were not included. Thresholds at 29.5 and 30°C were also excluded due to the frequent occurrence of more than one zero stress value. Soil moisture tension at 20 and 45 centimeters deep exhibited similar linear relationships for the month of September, but the models using the 45 centimeter depth had stronger relationships as determined by the coefficient of determination (see Table 2.1). This could be attributed to a more developed root system at this time of the crop growing season which would indicate logical extension of roots deeper into the soil. Average tension at 20 centimeters during the month of August is highly correlated with total temperature difference calculated using all of the temperature thresholds examined, while tension at 45 centimeters is still significant albeit with weaker relationships. Incorporating canopy temperature measurements over a longer period of time increases the strength of the relationships between total temperature difference and soil moisture tension. Although a month-long time period is not practical for irrigation management, these results indicate that a longer time period for calculating total temperature difference produces the most accurate representation of soil moisture tension conditions.

Table 2.1. Results from regression analysis of monthly maize canopy temperature stress-threshold on soil moisture tension at both 20 and 45 centimeters deep.

		Temperature Threshold (degrees Celsius)				
Month	Depth	27°	27.5°	28°	28.5°	29°
				r^2		
August	20	0.94	0.96	0.96	0.96	0.95
August	45	0.68	0.72	0.74	0.76	0.75
September	20	0.78	0.81	0.82	0.82	0.82
September	45	0.78	0.82	0.82	0.82	0.81

Note: All results are significant at $\alpha = 0.05$ level.

General Discussion

Our results are similar to those presented by DeJonge et al. (2015), who found similar relationships between soil water deficit and canopy temperature based stress indices. They also observed that the indices they examined were more sensitive at higher temperatures. However, they did not find a relationship between soil water deficit and any index when the average canopy temperature at 14:00 hours, which Idso et al. (1978) demonstrated as the time most indicative of water stress, was less than 29°C. Our results contrast with this finding, because temperature thresholds above 29°C very rarely produced significant relationships. Regression analysis of the total temperature difference suggests that canopy temperature alone is not suitable during the vegetative growth stages for quantifying soil moisture tension variability when its standard deviation is relatively small. Due to a malfunction of the canopy temperature datalogger at the 120% ET water treatment, only five of the six points were available for statistical evaluation until July 29th. The lack of significant linear models in July may potentially be attributed to limited variability in soil moisture tension during that period of frequent precipitation. González-Dugo et al. (2006) observed that cotton canopy temperature variability was limited when crop stress was low, but was sensitive to water stress variability under conditions where moderate stress was prevalent. It’s also possible that our measurements earlier in the crop growth season were more affected by solar azimuth (Figure 2.12), similar to the observation of Nielsen et al. (1984) that the effect of solar azimuth angle became weaker in

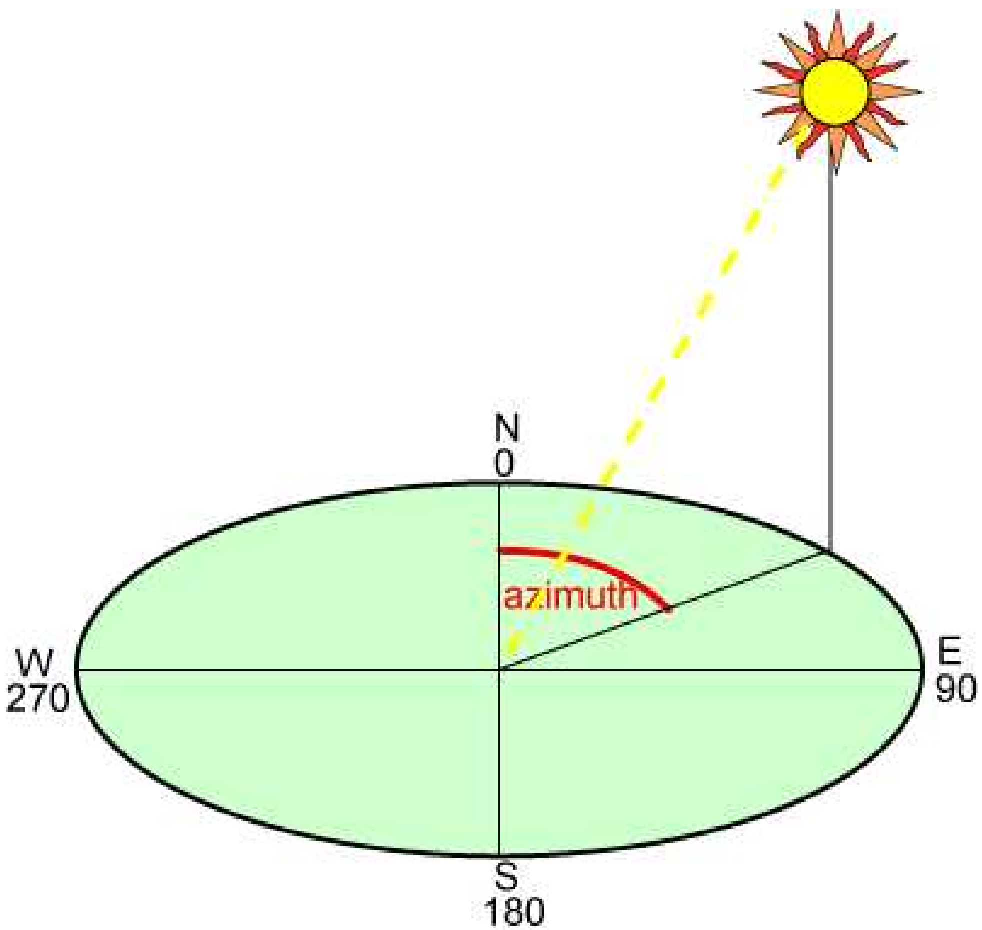

Figure 2.12. Solar azimuth represented by the red angle with solar incidence at the dotted yellow line. Adapted from Honsberg and Bowden (2016).

soybeans as they matured. They also found that changing the view direction of infrared thermometers results in a range of temperatures and suggested that an average viewed from multiple cardinal directions would be the most accurate approximation. However, they did not comment on the consistency of this effect across sensors pointing in the same direction as was the case with this study. In maize, Clawson and Blad (1982) did not find any dependence of canopy temperature on the sensor view direction. Canopy temperature is probably most suited for use with agronomic operations where moderate stress between irrigation events is not unusual and therefore canopy temperature variability is ample.

Berliner et al. (1984) demonstrated that blustery conditions have a cooling effect on the crop canopy and suggested that integrating temperature readings over a period of time would help to mitigate both atmospheric and windy conditions. Averaging the total temperature difference in this study over the months of August and September resulted in very strong relationships with synchronous soil moisture tension measured at 20 centimeters, which supports their suggestion. Using a threshold temperature for stress is principally similar to setting a time window (e.g. 8 hours above 28°C) for stress management as done with the Temperature-Time Threshold explored by Wanjura et al. (1995) in cotton and patented for irrigation scheduling (Upchurch et al., 1996). However, incorporating the total temperature difference as in our study adds value for gauging the severity of water stress. Not relying on a time window should eliminate any need to adjust a fixed time period for representative results throughout a growing season or different geographic location. A plant specific threshold for the total temperature difference would be the only parameter necessary to adjust.

Slight differences in the coefficient of determination as a result of using different canopy temperature thresholds suggests that it may not be necessary to select a highly specific threshold temperature for effective field use, but merely to utilize the spatial distribution of canopy temperature measurement to gauge varying degrees of stress. Using a threshold near the center of thermal kinetic window for maize appears to be adequate, and could therefore be adjusted to reflect water management goals specific to the agronomic operation. The same was suggested by Upchurch et al. (1996) in reference to the Temperature-Time Threshold method.

Using a one month interval for calculating total temperature difference is not practical from an irrigation management perspective, but does demonstrate that lengthening the time interval improves its relationship with soil moisture tension. Since the time between irrigation events can range from a few days to a few weeks, a running average of total temperature difference from the previous irrigation event (to maximize the measurement time period) would be the most practical if the infrared thermometers are stationary and provide continuous data. When water becomes available for an irrigation event, the temperature data since the last irrigation up until that point could be used to form a variable rate prescription. Implementation would require infrared thermometers to be strategically placed in areas of the field which tend to have extreme (i.e. high and low) soil moisture tension in order to incorporate the most complete spectrum of variability. Another option is for the stationary measurements to be scaled up to the entire field using the method demonstrated by Peters and Evett (2004).

Conclusions

Daily total temperature difference demonstrates some potential for utilizing canopy temperature to quantify variability of soil moisture tension, and could therefore be used for variable rate irrigation management with inexpensive sensors. However, the method is not suitable during the vegetative crop growth stages or for agronomic conditions where plant water stress is minimal. Averaging the total temperature difference over a longer time period may also be necessary for consistently strong relationships. It is essential to confirm repeatability of these results with other crops and study sites. Finally, an economic evaluation of the monetary implications of management at field scale would be necessary to transition these findings into industry.

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APPENDIX A

Table A1. Results from regression analysis of average soil moisture tension intervals for the three tensiometer depths (20, 45, and 75 centimeters) on selected indices from the crop stage V2 (two leaf) satellite image acquisition.

Average Tension Interval‡	Index†	Tensiometer Depth (cm)	r^2	p-value	RMSE (-kPa)
24 hours	RENDVI	20	0.052	0.665	10.240
		45	0.014	0.825	3.142
		75	0.098	0.546	1.192
	RECI	20	0.085	0.576	10.060
		45	0.010	0.853	3.149
		75	0.083	0.580	1.202
	RDVI	20	0.038	0.713	10.320
		45	0.019	0.797	3.135
		75	0.592	0.074	0.802
	OSAVI	20	0.040	0.703	10.300
		45	0.016	0.813	3.139
		75	0.648	0.053	0.745
	NDVI	20	0.043	0.694	10.300
		45	0.013	0.832	3.144
		75	0.691	0.040	0.698
	GRVI	20	0.347	0.219	8.501
		45	0.070	0.613	3.051
		75	0.830	0.012	0.517
	GNDVI	20	0.346	0.219	8.501
		45	0.075	0.600	3.043
		75	0.834	0.011	0.512
	GARI	20	0.059	0.644	10.200
		45	0.013	0.833	3.144
		75	0.891	0.005	0.415
	EVI	20	0.008	0.867	10.470
		45	0.006	0.884	3.155
		75	0.669	0.047	0.723
1 week	RENDVI	20	0.168	0.420	7.115
		45	0.021	0.785	1.838
		75	0.097	0.548	1.285
	RECI	20	0.218	0.351	6.937
		45	0.003	0.916	1.854
		75	0.080	0.586	1.297
	RDVI	20	0.001	0.906	7.841
		45	0.229	0.337	1.631
		75	0.655	0.051	0.795
	OSAVI	20	0.000	0.971	7.843
		45	0.205	0.367	1.656
		75	0.717	0.033	0.720
	NDVI	20	0.000	0.987	7.844

		45	0.176	0.407	1.686
		75	0.766	0.022	0.655
	GRVI	20	0.504	0.114	5.524
		45	0.145	0.457	1.718
		75	0.781	0.019	0.633
	GNDVI	20	0.501	0.116	5.542
		45	0.147	0.453	1.715
		75	0.784	0.019	0.628
	GARI	20	0.181	0.400	7.009
		45	0.002	0.939	1.856
		75	0.908	0.003	0.411
	EVI	20	0.018	0.802	7.775
		45	0.135	0.474	1.727
		75	0.724	0.032	0.711
PTD	RENDVI	20	0.210	0.361	1.930
		45	0.004	0.903	1.688
		75	0.052	0.665	1.460
	RECI	20	0.248	0.314	1.882
		45	0.008	0.864	1.685
		75	0.035	0.725	1.473
	RDVI	20	0.065	0.625	2.099
		45	0.413	0.169	1.296
		75	0.736	0.029	0.771
	OSAVI	20	0.066	0.624	2.098
		45	0.511	0.111	1.183
		75	0.816	0.014	0.644
	NDVI	20	0.064	0.629	2.100
		45	0.610	0.067	1.056
		75	0.882	0.005	0.515
	GRVI	20	0.664	0.048	1.259
		45	0.392	0.184	1.320
		75	0.530	0.101	1.028
	GNDVI	20	0.657	0.050	1.271
		45	0.389	0.186	1.323
		75	0.533	0.100	1.025
	GARI	20	0.363	0.205	1.732
		45	0.557	0.088	1.126
		75	0.808	0.015	0.658
	EVI	20	0.121	0.499	2.035
		45	0.421	0.164	1.288
		75	0.729	0.023	0.729

† RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized

Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index
‡ Average soil moisture tension over the three intervals listed as 24 hours, 1 week, and planting to date (PTD)

Table A2. Results from regression analysis of average soil moisture tension intervals for the three tensiometer depths (20, 45, and 75 centimeters) on selected indices from the crop stage V6 (six leaf) satellite image acquisition.

Average Tension Interval‡	Index†	Tensiometer Depth (cm)	r^2	p-value	RMSE (-kPa)
24 hours	RENDVI	20	0.850	0.009	4.291
		45	0.067	0.619	6.283
		75	0.066	0.624	1.426
	RECI	20	0.850	0.009	4.280
		45	0.060	0.641	6.310
		75	0.068	0.619	1.425
	RDVI	20	0.218	0.350	9.780
		45	0.108	0.525	6.146
		75	0.384	0.190	1.158
	OSAVI	20	0.150	0.448	10.200
		45	0.103	0.536	6.163
		75	0.435	0.155	1.110
	NDVI	20	0.091	0.561	10.550
		45	0.095	0.552	6.189
		75	0.477	0.129	1.067
	GRVI	20	0.610	0.067	6.907
		45	0.063	0.630	6.297
		75	0.146	0.454	1.363
	GNDVI	20	0.612	0.066	6.894
		45	0.065	0.625	6.291
		75	0.151	0.446	1.359
	GARI	20	0.141	0.464	10.260
		45	0.176	0.408	5.906
		75	0.360	0.208	1.180
	EVI	20	0.136	0.473	10.280
		45	0.162	0.429	5.956
		75	0.331	0.232	1.207
1 week	RENDVI	20	0.285	0.276	7.790
		45	0.024	0.771	4.647
		75	0.022	0.780	1.400
	RECI	20	0.243	0.321	8.015
		45	0.013	0.827	4.672
		75	0.011	0.841	1.407
	RDVI	20	0.661	0.049	5.361
		45	0.044	0.690	4.598
		75	0.138	0.469	1.314
	OSAVI	20	0.659	0.050	5.381
		45	0.078	0.591	4.515
		75	0.214	0.356	1.255
	NDVI	20	0.639	0.056	5.536

		45	0.121	0.499	4.410
		75	0.300	0.260	1.184
	GRVI	20	0.049	0.675	8.985
		45	0.004	0.902	4.693
		75	0.002	0.934	1.414
	GNDVI	20	0.046	0.682	8.995
		45	0.004	0.907	4.694
		75	0.001	0.944	1.414
	GARI	20	0.304	0.257	7.685
		45	0.004	0.907	4.694
		75	0.080	0.588	1.385
	EVI	20	0.613	0.066	5.735
		45	0.005	0.889	4.690
		75	0.079	0.589	1.358
PTD	RENDVI	20	0.020	0.787	2.520
		45	0.008	0.869	1.191
		75	0.007	0.878	1.342
	RECI	20	0.045	0.686	2.488
		45	0.003	0.916	1.194
		75	0.005	0.931	1.345
	RDVI	20	0.065	0.626	2.462
		45	0.426	0.160	0.906
		75	0.197	0.379	1.207
	OSAVI	20	0.064	0.627	2.463
		45	0.492	0.121	0.853
		75	0.281	0.280	1.142
	NDVI	20	0.063	0.633	2.466
		45	0.549	0.092	0.804
		75	0.373	0.198	1.066
	GRVI	20	0.327	0.236	2.089
		45	0.182	0.399	1.082
		75	0.001	0.948	1.345
	GNDVI	20	0.327	0.236	2.089
		45	0.185	0.395	1.080
		75	0.002	0.937	1.345
	GARI	20	0.046	0.685	2.488
		45	0.441	0.151	0.894
		75	0.133	0.477	1.253
	EVI	20	0.022	0.781	2.519
		45	0.382	0.191	0.940
		75	0.129	0.485	1.256

† RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized

Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index
‡ Average soil moisture tension over the three intervals listed as 24 hours, 1 week, and planting to date (PTD)

Table A3. Results from regression analysis of average soil moisture tension intervals for the three tensiometer depths (20, 45, and 75 centimeters) on selected indices from the crop stage V9 (nine leaf) satellite image acquisition.

Average Tension Interval‡	Index†	Tensiometer Depth (cm)	r^2	p-value	RMSE (-kPa)
24 hours	RENDVI	20	0.913	0.003	3.779
		45	0.413	0.169	10.740
		75	0.327	0.314	4.540
	RECI	20	0.796	0.017	5.792
		45	0.476	0.129	10.150
		75	0.544	0.155	3.734
	RDVI	20	0.475	0.130	9.292
		45	0.228	0.338	12.330
		75	0.006	0.900	5.516
	OSAVI	20	0.361	0.207	10.250
		45	0.258	0.303	12.080
		75	0.011	0.864	5.501
	NDVI	20	0.176	0.407	11.640
		45	0.271	0.290	11.980
		75	0.024	0.804	5.467
	GRVI	20	0.116	0.509	12.050
		45	0.303	0.257	11.710
		75	0.024	0.804	5.467
	GNDVI	20	0.117	0.406	11.630
		45	0.304	0.257	11.700
		75	0.029	0.784	5.452
	GARI	20	0.177	0.406	11.630
		45	0.051	0.666	13.660
		75	0.334	0.308	4.516
	EVI	20	0.334	0.229	10.460
		45	0.046	0.684	13.700
		75	0.179	0.477	5.012
1 week	RENDVI	20	0.400	0.178	4.982
		45	0.099	0.544	4.336
		75	0.187	0.391	14.290
	RECI	20	0.264	0.298	5.521
		45	0.186	0.394	4.151
		75	0.362	0.207	12.670
	RDVI	20	0.623	0.062	3.951
		45	0.157	0.437	4.224
		75	0.030	0.743	15.620
	OSAVI	20	0.568	0.084	4.229
		45	0.293	0.268	3.868
		75	0.076	0.598	15.240
	NDVI	20	0.413	0.169	4.931

		45	0.533	0.099	3.143
		75	0.174	0.410	14.410
	GRVI	20	0.499	0.117	4.553
		45	0.059	0.642	4.461
		75	0.136	0.472	14.740
	GNDVI	20	0.488	0.123	4.605
		45	0.063	0.631	4.452
		75	0.136	0.473	14.740
	GARI	20	0.534	0.099	4.391
		45	0.010	0.853	4.578
		75	0.012	0.838	15.760
	EVI	20	0.431	0.157	0.852
		45	0.029	0.748	4.533
		75	0.000	0.975	15.850
PTD	RENDVI	20	0.016	0.812	2.038
		45	0.071	0.611	0.767
		75	0.173	0.412	2.548
	RECI	20	0.025	0.766	2.029
		45	0.024	0.770	0.786
		75	0.292	0.268	2.357
	RDVI	20	0.129	0.485	1.917
		45	0.004	0.909	0.794
		75	0.067	0.620	2.706
	OSAVI	20	0.214	0.356	1.822
		45	0.009	.0856	0.791
		75	0.119	0.504	2.630
	NDVI	20	0.347	0.219	1.661
		45	0.114	0.514	0.749
		75	0.207	0.365	2.495
	GRVI	20	0.236	0.328	1.795
		45	0.011	0.842	0.791
		75	0.057	0.648	2.720
	GNDVI	20	0.250	0.313	1.780
		45	0.011	0.846	0.791
		75	0.059	0.644	2.718
	GARI	20	0.001	0.958	2.054
		45	0.106	0.530	0.752
		75	0.037	0.717	2.750
	EVI	20	0.036	0.720	2.017
		45	0.181	0.401	0.720
		75	0.050	0.671	2.731

† RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized

Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index
‡ Average soil moisture tension over the three intervals listed as 24 hours, 1 week, and planting to date (PTD)

Table A4. Results from regression analysis of average soil moisture tension intervals for the three tensiometer depths (20, 45, and 75 centimeters) on selected indices from the crop stage R3 (milk) satellite image acquisition.

Average Tension Interval‡	Index†	Tensiometer Depth (cm)	r^2	p-value	RMSE (-kPa)
24 hours	RENDVI	20	0.422	0.163	8.243
		45	0.327	0.236	19.470
		75	0.693	0.040	11.850
		75§	0.964	0.007	4.692
	RECI	20	0.592	0.074	6.922
		45	0.455	0.142	17.530
		75	0.057	0.648	7.299
	RDVI	20	0.206	0.366	9.659
		45	0.142	0.462	21.990
		75	0.167	0.421	6.861
	OSAVI	20	0.344	0.222	8.783
		45	0.235	0.330	20.760
		75	0.097	0.547	7.143
	NDVI	20	0.509	0.111	7.594
		45	0.347	0.219	19.180
		75	0.032	0.736	7.398
	GRVI	20	0.049	0.674	10.570
		45	0.032	0.733	23.350
		75	0.002	0.939	7.512
	GNDVI	20	0.045	0.688	10.600
		45	0.029	0.747	23.390
		75	0.000	0.999	7.519
	GARI	20	0.017	0.808	10.750
		45	0.009	0.856	23.620
		75	0.093	0.556	7.160
	EVI	20	0.003	0.917	10.820
		45	0.001	0.944	23.720
		75	0.000	0.980	7.518
1 week	RENDVI	20	-	-	-
		45	0.394	0.182	18.400
		75	0.551	0.091	10.330
	RECI	20	-	-	-
		45	0.524	0.104	16.310
		75	0.472	0.312	11.190
	RDVI	20	-	-	-
		45	0.195	0.380	21.200
		75	0.461	0.138	11.310
	OSAVI	20	-	-	-
		45	0.296	0.265	19.830
		75	0.385	0.188	12.080

	NDVI	20	-	-	-
		45	0.407	0.173	18.200
		75	0.266	0.295	13.190
	GRVI	20	-	-	-
		45	0.048	0.676	23.050
		75	0.036	0.720	15.130
	GNDVI	20	-	-	-
		45	0.045	0.686	23.090
		75	0.044	0.689	15.060
	GARI	20	-	-	-
		45	0.013	0.832	23.480
		75	0.005	0.890	15.360
	EVI	20	-	-	-
		45	0.005	0.898	23.580
		75	0.158	0.436	14.140
PTD	RENDVI	20	0.772	0.021	2.143
		45	0.827	0.012	4.190
		75	0.109	0.523	7.098
	RECI	20	0.861	0.008	1.672
		20§	0.910	0.027	1.556
		45	0.851	0.009	3.891
		75	0.057	0.648	7.299
	RDVI	20	0.547	0.093	3.019
		45	0.754	0.025	4.992
		75	0.167	0.421	6.861
	OSAVI	20	0.645	0.054	2.670
		45	0.799	0.016	4.514
		75	0.097	0.547	7.143
	NDVI	20	0.699	0.038	2.461
		45	0.767	0.022	4.862
		75	0.032	0.736	7.398
	GRVI	20	0.329	0.234	3.673
		45	0.330	0.233	8.247
		75	0.002	0.939	7.512
	GNDVI	20	0.315	0.247	3.711
		45	0.346	0.219	8.144
		75	0.000	0.999	7.519
	GARI	20	0.315	0.247	3.711
		45	0.094	0.555	9.590
		75	0.093	0.556	7.160
	EVI	20	0.300	0.261	3.751
		45	0.120	0.501	9.448
		75	0.000	0.980	7.518

† RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference

Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

‡ Average soil moisture tension over the three intervals listed as 24 hours, 1 week, and planting to date (PTD)

§ Designates a quadratic regression, which is included for RENDVI and RECI due to vast improvement over the linear model.

Table A5. Results from regression analysis of average soil moisture tension intervals for the three tensiometer depths (20, 45, and 75 centimeters) on selected indices from the bare soil (crop emergence) satellite image acquisition.

Average Tension Interval‡	Index†	Tensiometer Depth (cm)	r^2	p-value	RMSE (-kPa)
24 hours	RENDVI	20	0.808	0.015	0.423
		45	0.506	0.113	1.366
		75	0.510	0.111	1.008
	RECI	20	0.803	0.016	0.428
		45	0.500	0.116	1.376
		75	0.485	0.124	1.034
	RDVI	20	0.647	0.054	0.572
		45	0.347	0.219	1.571
		75	0.427	0.160	1.091
	OSAVI	20	0.642	0.055	0.576
		45	0.343	0.222	1.576
		75	0.410	0.171	1.106
	NDVI	20	0.637	0.057	0.581
		45	0.339	0.226	1.581
		75	0.395	0.182	1.121
	GRVI	20	0.776	0.020	0.456
		45	0.458	0.140	1.432
		75	0.493	0.120	1.026
	GNDVI	20	0.786	0.019	0.446
		45	0.462	0.137	1.426
		75	0.485	0.124	1.034
	GARI	20	0.711	0.035	0.518
		45	0.417	0.166	1.484
		75	0.242	0.321	1.254
	EVI	20	0.652	0.052	0.568
		45	0.356	0.211	1.560
		75	0.362	0.206	1.150
1 week	RENDVI	20	0.672	0.046	0.748
		45	0.556	0.089	1.169
		75	0.642	0.055	0.687
	RECI	20	0.697	0.039	0.720
		45	0.544	0.094	1.185
		75	0.653	0.052	0.677
	RDVI	20	0.554	0.090	0.873
		45	0.375	0.196	1.387
		75	0.637	0.057	0.693
	OSAVI	20	0.556	0.089	0.871
		45	0.369	0.201	1.394
		75	0.635	0.058	0.694
	NDVI	20	0.558	0.088	0.869

		45	0.363	0.206	1.401
		75	0.633	0.058	0.696
	GRVI	20	0.812	0.014	0.567
		45	0.494	0.119	1.248
		75	0.565	0.085	0.758
	GNDVI	20	0.812	0.014	0.567
		45	0.499	0.116	1.241
		75	0.569	0.083	0.755
	GARI	20	0.664	0.048	0.757
		45	0.430	0.157	1.324
		75	0.648	0.053	0.682
	EVI	20	0.554	0.090	0.873
		45	0.380	0.193	1.382
		75	0.648	0.053	0.682
PTD	RENDVI	20	0.727	0.031	0.536
		45	0.648	0.053	1.015
		75	0.714	0.034	0.714
	RECI	20	0.749	0.026	0.514
		45	0.623	0.062	1.050
		75	0.721	0.033	0.705
	RDVI	20	0.601	0.070	0.647
		45	0.446	0.147	1.276
		75	0.730	0.030	0.693
	OSAVI	20	0.602	0.070	0.646
		45	0.435	0.154	1.285
		75	0.726	0.031	0.698
	NDVI	20	0.603	0.069	0.646
		45	0.425	0.160	1.296
		75	0.721	0.032	0.704
	GRVI	20	0.854	0.008	0.392
		45	0.535	0.099	1.166
		75	0.615	0.827	0.827
	GNDVI	20	0.853	0.008	0.392
		45	0.541	0.096	1.159
		75	0.619	0.063	0.823
	GARI	20	0.694	0.039	0.567
		45	0.459	0.140	1.258
		75	0.690	0.041	0.742
	EVI	20	0.650	0.072	0.650
		45	0.443	0.149	1.276
		75	0.732	0.030	0.691

† RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized

Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index
‡ Average soil moisture tension over the three intervals listed as 24 hours, 1 week, and planting to date (PTD)

Table A6. Vegetation index values derived from satellite image acquired at the V2 (two leaf) crop growth stage.

% ET†	RENDVI	RECI	RDVI	OSAVI	NDVI	GRVI	GNDVI	GARI	EVI
40	0.178	0.656	0.206	0.330	0.290	2.058	0.346	0.160	0.104
60	0.168	0.607	0.209	0.337	0.298	2.110	0.357	0.181	0.107
80	0.186	0.694	0.213	0.342	0.300	2.110	0.357	0.187	0.111
100	0.182	0.682	0.210	0.338	0.298	2.153	0.366	0.196	0.109
120	0.167	0.615	0.198	0.321	0.284	2.074	0.349	0.161	0.100
140	0.177	0.653	0.200	0.322	0.283	2.097	0.354	0.163	0.102

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding pixel values.

‡ RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

Table A7. Average soil moisture tension at the V2 (two leaf) crop growth stage.

	Soil Moisture Tension (-kPa)								
	20 centimeters			45 centimeters			75 centimeters		
% ET†	24 hour	Week	PTD‡	24 hour	Week	PTD	24 hour	Week	PTD
40	34.439	21.502	10.612	21.219	10.898	9.732	14.169	13.651	12.059
60	37.852	22.186	10.969	15.449	12.689	12.264	16.468	16.077	14.714
80	38.583	24.257	11.031	14.566	12.785	10.160	16.075	15.700	14.305
100	54.676	37.763	15.283	17.962	14.306	12.051	16.688	16.230	14.226
120	40.036	22.392	10.033	15.861	14.485	9.699	14.239	13.682	12.114
140	56.440	33.939	12.752	13.264	15.563	8.336	14.964	14.204	11.804

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding tensiometers.

‡ Soil moisture tension is grouped by the interval previous to image acquisition, which was used for the average calculations: 24 hour, one week, and planting to date (PTD).

Table A8. Vegetation index values derived from satellite image acquired at the V6 (six leaf) crop growth stage.

% ET†	RENDVI	RECI	RDVI	OSAVI	NDVI	GRVI	GNDVI	GARI	EVI
40	0.320	1.616	0.403	0.659	0.590	3.515	0.557	0.581	0.230
60	0.308	1.509	0.381	0.622	0.556	3.376	0.543	0.525	0.212
80	0.330	1.708	0.396	0.645	0.574	3.545	0.560	0.554	0.222
100	0.322	1.619	0.404	0.659	0.588	3.576	0.563	0.584	0.231
120	0.318	1.605	0.397	0.650	0.582	3.526	0.558	0.549	0.220
140	0.311	1.534	0.394	0.645	0.577	3.393	0.545	0.555	0.223

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding pixel values.

‡ RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

Table A9. Average soil moisture tension at the V6 (six leaf) crop growth stage.

	Soil Moisture Tension (-kPa)								
	20 centimeters			45 centimeters			75 centimeters		
% ET†	24 hour	Week	PTD‡	24 hour	Week	PTD	24 hour	Week	PTD
40	18.868	16.217	17.674	43.814	50.092	20.812	15.826	12.628	13.195
60	30.883	22.440	18.877	54.944	47.361	18.412	19.506	15.246	16.005
80	9.846	14.845	18.786	55.143	50.451	17.966	18.923	14.786	15.536
100	21.735	16.850	22.707	56.064	50.808	19.704	18.698	14.836	15.511
120	25.764	27.990	19.681	58.329	56.856	19.728	17.931	12.733	13.665
140	38.405	35.893	23.243	60.670	58.028	18.532	18.972	12.633	13.750

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding tensiometers.

‡ Soil moisture tension is grouped by the interval previous to image acquisition, which was used for the average calculations: 24 hour, one week, and planting to date (PTD).

Table A10. Vegetation index values derived from satellite image acquired at the V9 (nine leaf) crop growth stage.

% ET†	RENDVI	RECI	RDVI	OSAVI	NDVI	GRVI	GNDVI	GARI	EVI
40	0.396	2.859	0.476	0.802	0.742	4.751	0.652	0.843	0.283
60	0.394	2.861	0.480	0.811	0.754	4.599	0.643	0.867	0.291
80	0.418	3.318	0.486	0.816	0.754	4.789	0.655	0.867	0.293
100	0.403	2.971	0.489	0.824	0.763	4.961	0.664	0.892	0.296
120	0.398	3.010	0.476	0.806	0.752	4.745	0.652	0.829	0.275
140	0.413	3.185	0.492	0.827	0.766	4.604	0.643	0.858	0.296

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding pixel values.

‡ RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

Table A11. Average soil moisture tension at the V9 (nine leaf) crop growth stage.

	Soil Moisture Tension (-kPa)								
	20 centimeters			45 centimeters			75 centimeters		
% ET†	24 hour	Week	PTD‡	24 hour	Week	PTD	24 hour	Week	PTD
40	38.418	58.059	25.581	40.501	62.707	28.056	-	18.831	14.340
60	43.948	59.406	27.136	36.403	71.932	28.136	34.281	47.845	20.676
80	13.251	49.416	23.868	26.581	70.854	27.669	45.202	53.957	21.300
100	27.427	44.754	26.639	41.774	70.624	28.855	38.423	32.486	18.032
120	39.818	57.389	26.735	28.454	73.823	29.641	45.585	54.385	19.831
140	25.519	52.235	29.442	8.012	73.780	28.790	42.212	49.168	19.146

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding tensiometers.

‡ Soil moisture tension is grouped by the interval previous to image acquisition, which was used for the average calculations: 24 hour, one week, and planting to date (PTD).

Table A12. Vegetation index values derived from satellite image acquired at the R3 (milk) crop growth stage.

% ET†	RENDVI	RECI	RDVI	OSAVI	NDVI	GRVI	GNDVI	GARI	EVI
40	0.428	2.968	0.519	0.849	0.760	5.064	0.670	0.872	0.324
60	0.419	2.897	0.513	0.844	0.761	4.948	0.664	0.851	0.313
80	0.453	3.539	0.531	0.869	0.780	5.742	0.703	0.936	0.334
100	0.437	3.274	0.517	0.849	0.765	4.821	0.656	0.865	0.322
120	0.454	3.621	0.531	0.872	0.785	5.339	0.684	0.867	0.319
140	0.454	3.508	0.529	0.864	0.773	5.178	0.676	0.872	0.327

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding pixel values.

‡ RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

Table A13. Average soil moisture tension at the R3 (milk) crop growth stage.

	Soil Moisture Tension (-kPa)								
	20 centimeters			45 centimeters			75 centimeters		
% ET†	24 hour	Week	PTD‡	24 hour	Week	PTD	24 hour	Week	PTD
40	38.617	29.594	31.631	64.458	63.102	44.109	23.498	17.671	17.528
60	27.948	20.830	31.926	23.749	25.469	39.473	59.189	44.972	30.025
80	19.762	13.957	22.778	16.035	15.534	28.104	16.029	24.613	30.271
100	14.608	10.499	24.740	10.244	11.578	37.006	12.593	18.245	27.943
120	11.995	7.054	23.676	10.622	8.372	23.405	8.899	7.493	17.462
140	21.788	13.533	26.018	9.929	7.988	22.493	9.818	8.188	16.716

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding tensiometers.

‡ Soil moisture tension is grouped by the interval previous to image acquisition, which was used for the average calculations: 24 hour, one week, and planting to date (PTD).

Table A14. Vegetation index values derived from the bare soil (crop emergence) satellite image.

% ET†	RENDVI	RECI	RDVI	OSAVI	NDVI	GRVI	GNDVI	GARI	EVI
40	0.090	0.289	0.103	0.166	0.146	1.624	0.238	0.002	0.050
60	0.077	0.245	0.086	0.139	0.122	1.588	0.227	-0.022	0.042
80	0.088	0.284	0.095	0.152	0.134	1.633	0.240	-0.004	0.046
100	0.087	0.279	0.101	0.163	0.144	1.618	0.236	-0.005	0.049
120	0.098	0.329	0.123	0.202	0.180	1.708	0.262	0.051	0.061
140	0.104	0.347	0.123	0.200	0.178	1.749	0.273	0.038	0.060

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding pixel values.

‡ RENDVI, Red Edge Normalized Difference Vegetation Index; RECI, Red Edge Chlorophyll Index; RDVI, Renormalized Difference Vegetation Index; OSAVI, Optimized Soil Adjusted Vegetation Index; NDVI, Normalized Difference Vegetation Index; GRVI, Green Ratio Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; GARI, Green Atmospherically Resistant Index; EVI, Enhanced Vegetation Index

Table A15. Average soil moisture tension at the time of the bare soil (crop emergence) satellite image acquisition.

	Soil Moisture Tension (-kPa)								
	20 centimeters			45 centimeters			75 centimeters		
% ET†	24 hour	Week	PTD‡	24 hour	Week	PTD	24 hour	Week	PTD
40	6.085	8.709	7.286	10.650	9.760	8.383	12.829	12.433	11.502
60	6.882	8.711	7.439	13.406	12.361	11.410	13.865	14.316	13.767
80	5.136	7.417	6.459	10.910	9.942	8.877	14.029	13.816	13.310
100	6.065	9.142	7.723	14.358	12.920	11.214	12.675	14.471	13.508
120	4.830	6.804	5.929	10.756	9.928	8.826	13.400	12.344	11.406
140	4.701	6.301	5.429	10.110	9.095	7.747	10.494	12.326	11.214

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the corresponding tensiometers.

‡ Soil moisture tension is grouped by the interval previous to image acquisition, which was used for the average calculations: 24 hour, one week, and planting to date (PTD).

APPENDIX B

Table B1. Results from regression analysis of daily maize canopy temperature stress-threshold on soil moisture tension at 20 centimeters deep.

	Temperature threshold (degrees Celsius)								
Date	26°	26.5°	27°	27.5°	28°	28.5°	29°	29.5°	30°
					r^2				
July 1	0.05	0.06	0.07	0.10	0.12	0.15	0.19	0.23	0.28
July 11	0.35	0.42	0.46	0.38	-	-	-	-	-
July 12	0.16	0.17	0.17	0.19	0.21	0.25	0.31	0.39	0.48
July 13	0.25	0.29	0.30	0.30	0.35	-	-	-	-
July 14	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.03	0.04
July 15	0.00	0.01	0.01	0.02	0.03	0.03	0.05	0.06	0.05
July 16	0.15	0.15	0.14	0.12	0.10	0.07	0.05	0.04	0.03
July 17	0.26	0.25	0.26	0.23	0.22	0.16	0.11	0.07	0.05
July 18	0.09	0.06	0.04	0.05	0.05	0.05	0.06	-	-
July 19	0.22	0.10	0.05	0.10	-	-	-	-	-
July 22	0.65	0.62	0.58	0.57	0.53	0.47	0.44	0.42	0.40
July 23	0.58	0.55	0.55	0.59	0.56	0.51	0.54	0.20	-
July 24	0.24	0.15	0.01	0.05	0.00	0.02	-	-	-
July 25	0.02	0.10	0.14	0.11	0.34	0.36	-	-	-
July 26	0.07	0.06	0.04	0.04	0.03	0.02	0.00	0.01	-
July 27	0.41	0.42	0.43	0.41	0.41	0.40	0.42	0.46	0.43
August 1	0.70*	0.71*	0.76*	0.80*	0.84*	0.87**	0.88**	-	-
August 2	0.77*	0.59	0.56	0.43	0.62	-	-	-	-
August 4	0.90**	0.85**	0.92**	-	-	-	-	-	-
August 5	0.91**	0.89**	0.88**	0.87**	0.84*	0.81*	0.80*	0.78*	-
August 6	0.29	0.21	0.16	-	-	-	-	-	-
August 29	0.56	0.51	0.77*	-	-	-	-	-	-
August 30	0.40	0.38	0.39	0.39	0.41	0.40	0.36	-	-
September 1	0.53	0.56	0.59	0.60	0.59	0.54	-	-	-
September 2	0.02	0.01	0.00	0.00	0.01	-	-	-	-
September 5	0.69*	0.64	0.77*	-	-	-	-	-	-
September 10	0.65*	0.74*	0.81*	0.75*	-	-	-	-	-

September 13	0.66*	0.73*	0.80*	0.86**	-	-	-	-	-
September 14	0.75*	0.74*	0.77*	0.77*	-	-	-	-	-
September 15	0.86**	0.83*	0.83**	-	-	-	-	-	-
September 21	0.49	0.54	0.60	0.68*	0.74*	-	-	-	-
September 24	0.42	0.50	0.63	-	-	-	-	-	-
September 27	0.88**	0.59	0.63	0.66*	0.71*	0.77*	-	-	-

- Value is not included because the temperature threshold produced too many zero values (more than one) for meaningful statistical comparison.

* Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

Table B2. Results from regression analysis of daily maize canopy temperature stress-threshold on soil moisture tension at 45 centimeters deep.

	Temperature threshold (degrees Celsius)								
Date	26°	26.5°	27°	27.5°	28°	28.5°	29°	29.5°	30°
					r^2				
July 1	0.63	0.64	0.66	0.68	0.69	0.71	0.73	0.74	0.75
July 3	0.14	0.13	0.13	0.07	-	-	-	-	-
July 4	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04
July 5	0.06	0.07	0.10	0.13	0.17	0.23	0.29	0.31	-
July 11	0.02	0.02	0.02	0.02	-	-	-	-	-
July 12	0.12	0.10	0.09	0.07	0.06	0.03	0.01	0.00	0.00
July 13	0.01	0.00	0.00	0.00	0.01	-	-	-	-
July 14	0.05	0.06	0.05	0.04	0.03	0.02	0.02	0.01	0.00
July 15	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00
July 16	0.01	0.00	0.01	0.02	0.02	0.02	0.02	0.02	0.01
July 17	0.03	0.03	0.02	0.02	0.01	0.01	0.00	0.00	0.00
July 18	0.04	0.04	0.06	0.07	0.06	0.04	0.01	-	-
July 19	0.20	0.41	0.42	0.29	-	-	-	-	-
July 26	0.42	0.40	0.37	0.37	0.34	0.30	0.19	0.09	-
July 27	0.36	0.37	0.37	0.36	0.34	0.33	0.33	0.34	0.28
July 29	0.55	0.54	0.52	-	-	-	-	-	-
July 30	0.09	0.11	0.22	0.30	0.37	0.41	0.44	-	-
July 31	0.43	0.46	0.56	0.61	0.60	-	-	-	-
August 1	0.71*	0.77*	0.82*	0.83*	0.80*	0.75*	0.69*	-	-
August 2	0.61	0.52	0.56	0.40	0.37	0.44	-	-	-
August 4	0.52	0.55	0.60	-	-	-	-	-	-
August 5	0.55	0.58	0.61	0.63	0.67*	0.72*	0.75*	0.75*	-
August 6	0.09	0.05	0.03	-	-	-	-	-	-
August 12	0.05	0.05	0.05	0.06	0.09	0.12	0.12	-	-
August 13	0.69*	0.68*	0.67*	0.66*	0.66*	0.66	0.64	0.65	0.65
August 14	0.13	0.11	0.10	0.10	0.11	0.12	0.04	0.00	-

August 15	0.40	0.46	0.51	0.58	0.64	0.66	0.66	0.64	0.54
August 16	0.30	0.40	0.74*	-	-	-	-	-	-
August 21	0.40	0.55	0.65	-	-	-	-	-	-
August 29	0.21	0.29	0.57	-	-	-	-	-	-
August 30	0.77*	0.84*	0.87**	0.89**	0.94**	0.98**	-	-	-
September 1	0.92**	0.95**	0.97**	0.98**	0.97**	0.93**	-	-	-
September 2	0.04	0.02	0.00	0.01	0.03	-	-	-	-
September 5	0.82*	0.76*	0.85**	-	-	-	-	-	-
September 10	0.46	0.63	0.78*	0.84*	-	-	-	-	-
September 13	0.65	0.70*	0.75*	0.77*	-	-	-	-	-
September 14	0.75*	0.74*	0.79*	0.78*	-	-	-	-	-
September 15	0.80*	0.77*	0.77*	-	-	-	-	-	-
September 21	0.66*	0.71*	0.77*	0.83*	0.87**	-	-	-	-
September 24	0.33	0.40	0.51	-	-	-	-	-	-

- Value is not included because the temperature threshold produced too many zero values (more than one) for meaningful statistical comparison.

* Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

Table B3. Daily total temperature differences for the 26° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	30.19	170.29	95.06	104.01	-	67.62
July 2	1.55	59.65	45.35	0.63	-	3.59
July 3	0.00	50.35	65.49	69.46	-	8.77
July 4	46.30	139.22	137.12	136.20	-	100.48
July 5	21.90	71.47	54.48	41.74	-	46.20
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.44	18.64	24.16	19.63	-	2.41
July 11	11.36	25.59	33.77	18.58	-	10.05
July 12	51.81	123.81	149.03	93.06	-	96.34
July 13	11.15	40.79	50.60	27.29	-	19.20
July 14	40.37	69.94	78.87	40.33	-	55.65
July 15	56.81	92.14	110.38	65.36	-	70.66
July 16	67.90	88.87	99.05	62.93	-	74.42
July 17	101.13	120.70	130.88	97.50	-	111.42
July 18	34.47	43.92	51.52	37.54	-	29.49
July 19	9.30	15.16	13.16	8.37	-	15.05
July 20	34.05	44.32	51.05	32.49	-	35.75
July 21	7.77	9.53	10.74	5.77	-	6.05
July 22	69.93	66.10	25.95	40.82	-	34.68
July 23	63.56	77.03	67.80	67.61	-	41.00
July 24	20.99	36.40	26.66	18.34	-	20.70
July 25	36.00	45.56	40.71	34.52	-	34.37
July 26	66.51	80.44	85.33	57.22	-	36.62
July 27	97.44	124.00	95.69	72.79	-	75.72
July 28	30.57	46.26	18.41	3.09	-	0.38
July 29	32.37	40.57	29.23	9.85	8.15	18.57
July 30	78.62	68.67	79.48	33.20	50.75	71.92
July 31	45.69	47.43	42.82	23.87	29.06	35.28
August 1	87.49	70.14	70.27	39.08	44.23	39.92
August 2	22.79	21.16	19.66	12.07	15.84	10.76
August 3	1.82	0.00	0.35	0.87	0.53	0.00
August 4	39.93	36.46	25.67	11.62	13.31	23.94
August 5	95.50	85.96	67.42	42.45	46.90	62.98
August 6	27.36	19.78	18.64	5.40	8.39	26.92
August 7	39.96	40.55	34.56	10.67	16.05	28.61

August 8	2.97	1.72	5.71	1.32	1.16	0.77
August 9	26.37	9.88	4.11	7.16	11.28	8.78
August 10	25.25	21.13	10.80	7.42	6.44	20.47
August 11	15.26	7.37	11.94	13.83	4.31	28.17
August 12	49.49	60.45	41.75	35.17	31.47	60.36
August 13	64.64	60.65	41.88	37.95	37.12	38.50
August 14	74.58	69.29	50.43	62.98	73.56	54.62
August 15	74.78	73.63	47.88	50.89	45.84	63.85
August 16	6.27	12.44	3.09	4.81	5.53	3.05
August 17	0.09	0.35	0.15	0.21	0.62	2.63
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	7.61	3.20	0.50	1.35	6.74	2.30
August 21	24.68	22.52	0.23	5.87	11.08	14.12
August 22	0.00	0.09	11.65	0.62	0.03	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	21.57	9.48	5.96	7.80	9.33	15.96
August 25	47.46	36.33	27.78	34.27	50.74	43.60
August 26	11.08	7.02	3.57	4.84	11.79	7.90
August 27	1.32	3.40	1.61	2.31	1.05	0.49
August 28	0.03	0.00	6.13	0.00	0.00	0.00
August 29	12.50	5.31	6.20	5.66	9.46	11.65
August 30	66.76	58.17	31.88	33.01	42.93	40.30
August 31	0.47	1.28	0.00	0.00	0.94	1.59
September 1	56.56	42.92	15.57	17.83	24.54	18.58
September 2	35.04	30.61	42.83	16.44	43.01	39.03
September 3	0.17	0.00	0.00	0.00	0.00	0.00
September 4	3.52	1.45	17.49	1.20	5.45	8.71
September 5	15.43	4.79	4.19	3.19	7.56	3.66
September 6	13.18	0.51	4.57	0.11	0.39	1.59
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	4.49	0.05	0.61	0.00	0.00	0.00
September 9	15.61	3.38	10.37	0.26	9.06	18.52
September 10	31.38	23.45	10.04	6.75	14.22	23.75
September 11	0.27	0.00	0.00	0.00	0.00	0.00
September 12	23.61	0.58	5.16	0.11	10.00	14.90
September 13	37.12	20.44	3.68	9.59	23.20	15.58
September 14	48.26	14.07	4.89	4.89	16.69	14.23
September 15	64.83	11.03	10.18	0.36	9.08	9.08
September 16	39.65	3.88	14.11	4.23	13.08	11.63
September 17	0.15	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	23.54	0.23	1.72	0.00	12.49	0.00
September 21	87.20	32.90	49.42	12.96	39.92	15.50
September 22	6.28	1.93	1.03	0.97	1.10	0.00
September 23	22.84	1.48	15.70	2.06	13.21	1.82
September 24	45.85	10.26	25.02	4.70	29.68	9.42
September 25	19.76	0.00	2.39	0.00	5.14	2.35
September 26	6.81	0.00	0.00	0.00	0.00	0.00
September 27	94.13	39.78	59.83	28.11	54.36	31.46
September 28	7.55	0.00	0.00	0.09	0.35	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B4. Daily total temperature differences for the 26.5° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	22.45	156.68	81.59	91.58	-	55.89
July 2	0.32	48.77	36.27	0.00	-	0.44
July 3	0.00	35.51	52.20	55.67	-	2.74
July 4	36.78	124.31	122.36	122.33	-	87.30
July 5	15.38	59.57	42.69	31.19	-	36.20
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	11.25	17.16	11.87	-	0.17
July 11	6.83	17.19	26.21	12.40	-	5.71
July 12	38.76	105.70	130.76	75.14	-	78.83
July 13	6.39	29.26	39.97	18.52	-	11.98
July 14	32.06	59.26	68.64	31.83	-	47.15
July 15	44.46	77.66	96.57	53.39	-	56.93
July 16	54.90	72.52	84.20	49.07	-	58.49
July 17	84.53	101.91	113.24	81.21	-	93.71
July 18	26.42	35.18	43.52	30.54	-	21.32
July 19	4.71	7.37	8.52	5.06	-	9.29
July 20	25.55	32.50	42.68	23.99	-	26.70
July 21	5.27	5.96	7.95	3.40	-	3.56
July 22	61.09	55.20	18.77	31.82	-	26.36
July 23	49.01	59.45	53.15	52.61	-	27.00
July 24	12.77	21.74	18.02	9.52	-	11.17
July 25	23.75	29.08	28.32	23.90	-	23.29
July 26	51.04	64.67	69.39	42.71	-	24.49
July 27	81.33	106.51	79.73	59.29	-	60.94
July 28	20.16	33.81	9.67	0.03	-	0.00
July 29	21.96	28.31	20.59	4.54	2.86	11.35
July 30	64.84	50.76	67.75	25.53	36.47	56.92
July 31	31.89	31.96	29.84	13.53	18.06	21.97
August 1	71.52	57.56	56.68	28.65	30.67	25.72
August 2	14.42	12.19	13.06	6.77	10.19	5.20
August 3	0.82	0.00	0.00	0.37	0.03	0.00
August 4	30.53	22.29	17.26	6.04	6.21	15.06
August 5	81.65	71.99	55.42	31.24	34.35	49.26
August 6	17.70	11.31	11.49	1.62	3.54	18.88
August 7	28.97	27.78	24.39	4.86	7.14	18.03

August 8	2.21	0.00	3.89	0.32	0.35	0.27
August 9	19.10	1.21	1.77	3.07	5.75	4.51
August 10	18.90	11.00	5.13	2.43	2.97	12.64
August 11	10.62	2.10	7.30	8.10	1.43	19.94
August 12	36.53	44.57	29.66	25.29	19.32	46.15
August 13	55.73	47.40	32.93	30.04	30.39	30.21
August 14	58.68	50.44	37.70	48.48	57.70	40.33
August 15	61.62	58.14	36.88	39.35	33.71	49.77
August 16	2.89	6.27	1.82	2.46	1.91	1.19
August 17	0.00	0.00	0.00	0.00	0.03	1.54
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	3.51	0.00	0.00	0.53	2.77	0.77
August 21	16.59	14.24	0.00	1.96	4.59	7.29
August 22	0.00	0.00	10.15	0.03	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	13.81	3.18	1.37	2.13	3.36	7.88
August 25	35.82	24.61	17.11	22.01	37.50	30.42
August 26	6.64	3.01	1.76	1.96	7.12	4.21
August 27	0.35	0.52	1.11	0.96	0.11	0.00
August 28	0.00	0.00	3.63	0.00	0.00	0.00
August 29	6.88	0.46	2.46	1.70	3.72	5.27
August 30	57.76	45.66	23.27	22.88	32.78	28.59
August 31	0.00	0.00	0.00	0.00	0.21	1.09
September 1	48.98	32.11	9.43	9.88	16.21	11.58
September 2	26.50	18.74	31.05	7.27	31.77	28.66
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	2.52	0.00	12.70	0.21	1.60	4.08
September 5	11.08	0.04	2.69	1.23	2.62	1.37
September 6	9.64	0.00	3.10	0.00	0.00	0.12
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	1.54	0.00	0.00	0.00	0.00	0.00
September 9	9.07	0.07	4.86	0.00	2.64	10.45
September 10	25.38	15.50	6.31	2.31	7.72	14.31
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	14.97	0.00	2.42	0.00	3.48	7.38
September 13	28.12	11.13	0.32	3.60	14.09	7.30
September 14	41.59	6.85	2.17	2.19	9.66	7.88
September 15	56.33	3.16	4.14	0.00	3.19	4.86
September 16	31.15	0.13	9.34	0.82	6.18	6.46
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	15.17	0.00	0.87	0.00	6.91	0.00
September 21	75.20	21.17	34.82	4.71	28.49	7.41
September 22	3.28	0.00	0.05	0.47	0.21	0.00
September 23	15.89	0.00	8.35	0.20	5.68	0.42
September 24	35.82	4.41	14.01	1.15	20.15	3.51
September 25	11.80	0.00	0.51	0.00	0.75	0.98
September 26	2.74	0.00	0.00	0.00	0.00	0.00
September 27	83.90	28.98	47.09	19.47	44.29	20.79
September 28	5.05	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B5. Daily total temperature differences for the 27° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	15.31	144.53	69.44	79.70	-	44.54
July 2	0.00	39.48	27.84	0.00	-	0.00
July 3	0.00	25.82	39.76	44.10	-	0.03
July 4	28.10	111.19	108.80	108.98	-	76.09
July 5	9.68	50.12	31.45	21.92	-	26.54
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	6.42	10.90	5.83	-	0.00
July 11	3.54	12.91	20.40	6.86	-	2.42
July 12	26.24	89.11	113.38	58.80	-	62.39
July 13	3.24	22.28	30.60	12.21	-	6.48
July 14	24.53	50.97	59.65	24.58	-	38.65
July 15	32.98	65.30	83.30	41.98	-	43.43
July 16	43.85	58.95	71.06	37.22	-	43.88
July 17	69.77	85.45	96.56	66.07	-	77.23
July 18	20.57	28.76	35.66	24.48	-	14.30
July 19	2.04	4.25	4.62	2.50	-	4.97
July 20	17.45	26.38	34.68	15.97	-	18.05
July 21	2.77	5.24	5.45	1.46	-	1.73
July 22	54.05	50.23	13.26	24.01	-	19.49
July 23	35.46	47.56	39.29	38.29	-	14.57
July 24	6.72	15.71	12.91	4.95	-	5.76
July 25	13.37	20.42	18.00	15.23	-	13.09
July 26	38.98	51.49	56.84	31.05	-	15.20
July 27	66.75	91.21	64.79	45.79	-	47.13
July 28	11.36	23.64	4.11	0.00	-	0.00
July 29	13.16	19.03	13.25	1.10	0.28	5.42
July 30	52.24	46.66	56.85	18.03	24.31	42.44
July 31	20.69	20.82	19.47	6.33	9.01	11.14
August 1	57.22	49.29	44.12	19.49	18.65	14.93
August 2	7.55	8.05	7.88	3.32	5.08	2.35
August 3	0.23	0.00	0.00	0.00	0.00	0.00
August 4	22.51	16.60	9.70	1.27	1.26	7.78
August 5	68.54	59.40	44.21	20.68	23.01	36.67
August 6	9.57	6.81	6.15	0.06	0.85	11.88
August 7	19.18	21.00	15.94	1.49	3.04	11.36

August 8	1.71	0.00	2.39	0.00	0.00	0.00
August 9	13.97	0.78	0.68	0.37	2.77	1.66
August 10	13.17	7.60	1.51	0.49	1.47	6.41
August 11	7.18	1.05	4.71	3.38	0.25	12.10
August 12	27.28	31.80	20.12	17.34	11.20	35.46
August 13	47.44	39.46	24.81	23.13	23.89	23.07
August 14	46.00	36.12	28.77	36.10	44.88	28.72
August 15	49.75	47.58	27.95	30.13	24.22	38.04
August 16	1.62	2.61	0.99	1.16	0.40	0.03
August 17	0.00	0.00	0.00	0.00	0.00	0.54
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	1.63	0.00	0.00	0.03	1.02	0.00
August 21	9.78	8.62	0.00	0.24	1.64	2.83
August 22	0.00	0.00	8.65	0.00	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	6.93	0.74	0.14	0.05	0.41	1.70
August 25	25.35	14.83	7.43	11.63	24.85	19.39
August 26	3.35	1.07	0.76	0.36	4.14	1.84
August 27	0.00	0.15	0.61	0.25	0.00	0.00
August 28	0.00	0.00	1.40	0.00	0.00	0.00
August 29	2.83	0.00	0.37	0.11	0.36	1.56
August 30	48.76	36.07	15.22	14.04	22.78	19.55
August 31	0.00	0.00	0.00	0.00	0.00	0.59
September 1	41.98	25.61	4.83	4.62	8.95	6.33
September 2	19.99	10.90	20.23	1.93	21.34	19.23
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	1.52	0.00	8.74	0.00	0.11	1.96
September 5	7.08	0.14	1.42	0.21	0.40	0.49
September 6	7.03	0.00	2.10	0.00	0.00	0.00
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	0.14	0.00	0.00	0.00	0.00	0.00
September 9	4.06	0.00	2.12	0.00	0.70	6.71
September 10	20.06	10.00	3.23	0.15	3.03	7.17
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	8.37	0.00	1.42	0.00	0.54	1.77
September 13	20.04	4.99	0.00	0.92	7.09	3.23
September 14	35.19	4.45	0.95	0.24	4.66	2.74
September 15	47.83	1.07	0.95	0.00	0.40	2.43
September 16	23.44	0.00	5.35	0.00	2.40	3.42
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	7.68	0.00	0.37	0.00	3.20	0.00
September 21	63.20	11.69	21.78	0.50	18.14	2.78
September 22	1.24	0.00	0.00	0.00	0.00	0.00
September 23	9.49	0.00	3.59	0.00	1.45	0.00
September 24	26.69	0.87	5.42	0.21	11.15	0.67
September 25	5.58	0.00	0.00	0.00	0.00	0.00
September 26	0.88	0.00	0.00	0.00	0.00	0.00
September 27	73.90	20.61	35.21	11.98	34.79	11.42
September 28	2.73	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B6. Daily total temperature differences for the 27.5° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	10.22	132.31	57.79	68.83	-	33.86
July 2	0.00	30.28	20.21	0.00	-	0.00
July 3	0.00	14.85	28.30	33.25	-	0.00
July 4	20.77	98.39	95.95	96.23	-	65.60
July 5	5.71	40.28	21.55	13.71	-	18.33
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	2.66	5.82	1.88	-	0.00
July 11	1.02	8.76	15.84	3.54	-	0.46
July 12	15.75	72.82	96.80	44.53	-	47.22
July 13	1.30	15.05	22.50	7.86	-	2.26
July 14	18.00	42.94	51.15	17.94	-	30.42
July 15	22.60	52.59	70.65	31.81	-	30.37
July 16	33.42	46.24	59.19	27.15	-	31.31
July 17	55.28	69.78	81.61	52.43	-	62.59
July 18	15.07	22.76	29.36	18.75	-	8.63
July 19	0.50	1.54	2.65	0.95	-	2.00
July 20	10.69	18.46	26.72	9.58	-	10.22
July 21	0.87	3.45	3.21	0.46	-	0.52
July 22	48.26	43.47	8.48	17.52	-	13.13
July 23	23.34	34.10	26.93	25.23	-	5.69
July 24	3.79	9.75	9.77	2.77	-	2.47
July 25	6.30	11.19	11.28	7.64	-	5.82
July 26	30.02	40.31	46.49	22.17	-	8.27
July 27	53.28	76.71	51.98	33.43	-	35.34
July 28	4.91	13.28	0.72	0.00	-	0.00
July 29	7.26	11.03	7.29	0.00	0.00	1.98
July 30	40.72	38.93	46.54	10.77	15.15	29.13
July 31	11.68	12.67	10.91	1.52	2.69	4.23
August 1	43.23	39.80	32.21	11.08	9.53	7.57
August 2	3.11	4.12	4.35	1.39	2.44	1.04
August 3	0.00	0.00	0.00	0.00	0.00	0.00
August 4	15.01	9.61	3.40	0.00	0.00	2.21
August 5	56.27	47.94	34.21	10.75	13.76	24.35
August 6	4.02	3.21	2.79	0.00	0.00	6.37
August 7	12.50	14.54	9.21	0.73	1.34	6.43

August 8	1.21	0.00	0.90	0.00	0.00	0.00
August 9	10.13	0.00	0.00	0.00	1.25	0.66
August 10	7.67	2.90	0.00	0.00	0.35	1.96
August 11	4.18	0.09	2.40	0.73	0.00	5.61
August 12	21.49	21.77	12.42	11.68	5.97	26.09
August 13	40.52	31.53	18.85	17.05	17.74	17.01
August 14	35.87	24.71	20.68	24.38	33.39	19.40
August 15	39.90	36.35	19.91	21.63	15.88	27.26
August 16	0.89	0.14	0.49	0.49	0.00	0.00
August 17	0.00	0.00	0.00	0.00	0.00	0.00
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	0.25	0.00	0.00	0.00	0.17	0.00
August 21	4.68	3.91	0.00	0.00	0.57	0.23
August 22	0.00	0.00	7.15	0.00	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	2.41	0.09	0.00	0.00	0.00	0.13
August 25	15.99	6.15	1.80	4.18	13.44	10.17
August 26	1.78	0.00	0.05	0.00	2.28	0.25
August 27	0.00	0.00	0.11	0.00	0.00	0.00
August 28	0.00	0.00	0.09	0.00	0.00	0.00
August 29	0.34	0.00	0.00	0.00	0.00	0.28
August 30	39.94	26.96	8.49	6.19	13.90	11.59
August 31	0.00	0.00	0.00	0.00	0.00	0.09
September 1	34.98	18.50	2.02	2.16	3.60	2.56
September 2	14.49	4.68	12.16	0.61	12.52	11.76
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	0.73	0.00	6.04	0.00	0.00	1.41
September 5	4.35	0.00	0.89	0.00	0.00	0.00
September 6	4.53	0.00	1.10	0.00	0.00	0.00
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	0.00	0.00	0.00	0.00	0.00	0.00
September 9	1.69	0.00	0.40	0.00	0.00	4.67
September 10	15.06	4.41	0.94	0.00	0.63	2.05
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	3.75	0.00	0.55	0.00	0.00	0.00
September 13	12.04	1.36	0.00	0.05	1.88	1.20
September 14	29.70	1.85	0.45	0.00	1.17	0.34
September 15	39.33	0.00	0.00	0.00	0.00	1.38
September 16	16.65	0.00	1.89	0.00	0.54	1.51
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	2.01	0.00	0.00	0.00	1.21	0.00
September 21	51.48	4.12	10.64	0.00	8.33	0.76
September 22	0.24	0.00	0.00	0.00	0.00	0.00
September 23	4.86	0.00	0.94	0.00	0.11	0.00
September 24	18.97	0.11	1.01	0.00	3.43	0.00
September 25	2.33	0.00	0.00	0.00	0.00	0.00
September 26	0.23	0.00	0.00	0.00	0.00	0.00
September 27	63.90	12.03	24.46	5.72	25.29	5.05
September 28	1.47	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B7. Daily total temperature differences for the 28° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	5.64	120.81	46.77	58.41	-	24.34
July 2	0.00	21.94	13.86	0.00	-	0.00
July 3	0.00	5.84	18.35	23.68	-	0.00
July 4	14.74	86.57	83.72	84.06	-	55.73
July 5	3.21	31.74	12.95	7.45	-	11.48
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	0.45	2.58	0.01	-	0.00
July 11	0.00	5.09	11.84	1.49	-	0.00
July 12	7.02	57.29	81.74	31.49	-	33.61
July 13	0.43	9.45	16.02	4.78	-	0.31
July 14	12.73	35.21	42.86	12.61	-	22.88
July 15	13.11	40.40	58.22	22.41	-	19.28
July 16	23.99	35.54	49.00	18.59	-	21.10
July 17	42.13	55.11	67.48	39.60	-	48.09
July 18	10.02	17.42	23.83	13.46	-	4.20
July 19	0.00	0.39	1.22	0.00	-	0.70
July 20	4.86	11.78	19.85	4.56	-	3.54
July 21	0.00	2.28	1.84	0.00	-	0.00
July 22	44.12	37.38	5.14	12.96	-	8.30
July 23	13.98	21.24	17.08	14.90	-	0.63
July 24	1.93	5.22	7.72	1.27	-	0.69
July 25	2.16	4.42	6.72	2.68	-	2.46
July 26	22.16	31.28	37.53	14.50	-	3.03
July 27	41.43	63.00	39.98	22.38	-	25.34
July 28	1.16	6.05	0.00	0.00	-	0.00
July 29	3.13	4.81	2.55	0.00	0.00	0.27
July 30	30.14	31.58	36.99	4.91	7.07	17.70
July 31	5.20	6.49	5.02	0.11	0.76	1.48
August 1	30.89	31.19	21.62	5.19	4.16	3.56
August 2	1.32	2.21	1.41	0.17	0.98	0.25
August 3	0.00	0.00	0.00	0.00	0.00	0.00
August 4	7.97	3.30	0.67	0.00	0.00	0.00
August 5	44.77	36.94	25.92	3.92	6.79	13.55
August 6	1.20	0.81	1.03	0.00	0.00	2.68
August 7	7.64	9.59	5.27	0.23	0.34	2.90

August 8	0.71	0.00	0.00	0.00	0.00	0.00
August 9	7.04	0.00	0.00	0.00	0.75	0.00
August 10	3.58	0.30	0.00	0.00	0.00	0.06
August 11	1.79	0.00	0.86	0.05	0.00	2.80
August 12	17.30	14.06	6.78	7.38	1.85	18.68
August 13	34.67	25.68	13.74	11.69	12.24	11.96
August 14	26.62	15.21	13.15	14.69	23.28	11.21
August 15	32.01	26.22	13.36	14.20	9.11	18.38
August 16	0.39	0.00	0.00	0.00	0.00	0.00
August 17	0.00	0.00	0.00	0.00	0.00	0.00
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	0.00	0.00	0.00	0.00	0.00	0.00
August 21	1.57	1.19	0.00	0.00	0.07	0.00
August 22	0.00	0.00	5.65	0.00	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	0.76	0.00	0.00	0.00	0.00	0.00
August 25	8.36	1.54	0.53	1.31	5.56	3.79
August 26	0.78	0.00	0.00	0.00	1.28	0.00
August 27	0.00	0.00	0.00	0.00	0.00	0.00
August 28	0.00	0.00	0.00	0.00	0.00	0.00
August 29	0.00	0.00	0.00	0.00	0.00	0.00
August 30	32.25	18.05	3.37	1.56	6.05	5.68
August 31	0.00	0.00	0.00	0.00	0.00	0.00
September 1	28.32	11.50	0.72	0.54	1.01	0.90
September 2	8.99	1.29	7.09	0.11	5.98	6.10
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	0.23	0.00	4.19	0.00	0.00	0.91
September 5	2.13	0.00	0.39	0.00	0.00	0.00
September 6	2.28	0.00	0.43	0.00	0.00	0.00
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	0.00	0.00	0.00	0.00	0.00	0.00
September 9	0.85	0.00	0.00	0.00	0.00	3.17
September 10	10.80	0.88	0.00	0.00	0.00	0.52
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	1.63	0.00	0.05	0.00	0.00	0.00
September 13	5.47	0.05	0.00	0.00	0.27	0.45
September 14	24.70	0.95	0.00	0.00	0.00	0.00
September 15	31.04	0.00	0.00	0.00	0.00	0.38
September 16	10.75	0.00	0.31	0.00	0.00	0.48
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	0.25	0.00	0.00	0.00	0.23	0.00
September 21	41.16	0.43	3.24	0.00	1.73	0.23
September 22	0.00	0.00	0.00	0.00	0.00	0.00
September 23	1.57	0.00	0.05	0.00	0.00	0.00
September 24	11.83	0.00	0.00	0.00	0.16	0.00
September 25	0.07	0.00	0.00	0.00	0.00	0.00
September 26	0.00	0.00	0.00	0.00	0.00	0.00
September 27	54.29	5.05	15.28	2.28	16.62	1.89
September 28	0.97	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B8. Daily total temperature differences for the 28.5° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	2.25	109.80	36.63	48.91	-	16.68
July 2	0.00	14.60	8.23	0.00	-	0.00
July 3	0.00	0.78	10.41	14.75	-	0.00
July 4	9.22	75.79	72.16	72.76	-	46.54
July 5	1.50	23.96	7.11	3.16	-	6.15
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	0.00	0.58	0.00	-	0.00
July 11	0.00	1.84	8.29	0.25	-	0.00
July 12	1.67	43.18	67.74	20.32	-	21.53
July 13	0.00	5.14	10.52	1.91	-	0.00
July 14	8.54	27.89	35.14	8.98	-	16.33
July 15	6.59	29.02	46.71	14.44	-	10.64
July 16	15.92	26.61	39.61	12.37	-	13.59
July 17	29.86	41.60	54.40	28.88	-	33.83
July 18	5.64	12.42	18.82	8.98	-	1.48
July 19	0.00	0.00	0.45	0.00	-	0.00
July 20	1.20	5.98	13.52	1.44	-	0.29
July 21	0.00	1.28	0.84	0.00	-	0.00
July 22	40.12	31.71	3.63	8.96	-	4.85
July 23	6.61	12.17	9.42	7.70	-	0.00
July 24	0.89	2.66	5.72	0.45	-	0.00
July 25	0.34	1.04	3.05	1.22	-	0.63
July 26	15.35	23.61	29.08	8.03	-	0.14
July 27	30.10	50.07	28.41	12.77	-	16.21
July 28	0.00	1.99	0.00	0.00	-	0.00
July 29	0.33	1.08	0.52	0.00	0.00	0.00
July 30	20.96	24.69	27.86	0.80	2.20	9.53
July 31	1.09	2.78	1.46	0.00	0.00	0.47
August 1	19.84	22.82	13.05	1.80	1.81	1.59
August 2	0.39	0.98	0.79	0.00	0.09	0.00
August 3	0.00	0.00	0.00	0.00	0.00	0.00
August 4	3.14	0.61	0.00	0.00	0.00	0.00
August 5	33.53	26.31	18.03	0.58	2.33	5.75
August 6	0.09	0.00	0.53	0.00	0.00	0.77
August 7	4.20	6.70	2.85	0.00	0.00	0.79

August 8	0.21	0.00	0.00	0.00	0.00	0.00
August 9	4.47	0.00	0.00	0.00	0.25	0.00
August 10	1.38	0.00	0.00	0.00	0.00	0.00
August 11	0.73	0.00	0.35	0.00	0.00	1.13
August 12	13.30	8.21	3.18	3.38	0.29	12.00
August 13	29.34	20.68	9.18	7.19	8.23	7.30
August 14	18.62	7.45	7.72	8.26	15.08	4.64
August 15	25.13	17.39	8.00	7.97	4.65	11.13
August 16	0.00	0.00	0.00	0.00	0.00	0.00
August 17	0.00	0.00	0.00	0.00	0.00	0.00
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	0.00	0.00	0.00	0.00	0.00	0.00
August 21	0.20	0.21	0.00	0.00	0.00	0.00
August 22	0.00	0.00	4.15	0.00	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	0.00	0.00	0.00	0.00	0.00	0.00
August 25	2.38	0.39	0.03	0.81	2.20	0.92
August 26	0.27	0.00	0.00	0.00	0.28	0.00
August 27	0.00	0.00	0.00	0.00	0.00	0.00
August 28	0.00	0.00	0.00	0.00	0.00	0.00
August 29	0.00	0.00	0.00	0.00	0.00	0.00
August 30	25.29	10.21	0.87	0.67	0.95	2.29
August 31	0.00	0.00	0.00	0.00	0.00	0.00
September 1	22.32	5.71	0.15	0.03	0.03	0.39
September 2	4.11	0.00	3.42	0.00	1.64	2.48
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	0.00	0.00	2.69	0.00	0.00	0.41
September 5	0.63	0.00	0.00	0.00	0.00	0.00
September 6	0.35	0.00	0.00	0.00	0.00	0.00
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	0.00	0.00	0.00	0.00	0.00	0.00
September 9	0.35	0.00	0.00	0.00	0.00	1.80
September 10	7.29	0.00	0.00	0.00	0.00	0.00
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	0.29	0.00	0.00	0.00	0.00	0.00
September 13	1.60	0.00	0.00	0.00	0.00	0.00
September 14	19.70	0.45	0.00	0.00	0.00	0.00
September 15	23.29	0.00	0.00	0.00	0.00	0.00
September 16	6.07	0.00	0.00	0.00	0.00	0.00
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	0.00	0.00	0.00	0.00	0.00	0.00
September 21	31.82	0.00	0.50	0.00	0.45	0.00
September 22	0.00	0.00	0.00	0.00	0.00	0.00
September 23	0.13	0.00	0.00	0.00	0.00	0.00
September 24	5.77	0.00	0.00	0.00	0.00	0.00
September 25	0.00	0.00	0.00	0.00	0.00	0.00
September 26	0.00	0.00	0.00	0.00	0.00	0.00
September 27	44.90	1.22	8.56	0.53	9.20	0.28
September 28	0.47	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B9. Daily total temperature differences for the 29° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	0.57	99.17	27.94	39.64	-	10.00
July 2	0.00	8.10	3.12	0.00	-	0.00
July 3	0.00	0.00	3.70	7.66	-	0.00
July 4	5.03	65.52	61.54	62.01	-	38.29
July 5	0.93	17.24	3.25	0.65	-	2.58
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	0.00	0.00	0.00	-	0.00
July 11	0.00	0.35	4.79	0.00	-	0.00
July 12	0.03	30.28	54.75	11.63	-	11.64
July 13	0.00	2.07	6.03	0.26	-	0.00
July 14	4.55	21.39	28.14	5.98	-	11.11
July 15	2.07	19.14	35.45	8.88	-	4.50
July 16	9.46	18.63	31.11	7.25	-	7.25
July 17	18.91	29.39	42.39	19.44	-	21.16
July 18	1.90	7.91	14.13	5.07	-	0.00
July 19	0.00	0.00	0.00	0.00	-	0.00
July 20	0.00	1.60	8.65	0.03	-	0.00
July 21	0.00	0.45	0.05	0.00	-	0.00
July 22	36.88	27.27	2.13	5.45	-	2.85
July 23	2.44	5.61	3.64	2.37	-	0.00
July 24	0.39	1.15	4.01	0.00	-	0.00
July 25	0.00	0.19	1.32	0.25	-	0.00
July 26	8.94	16.29	21.50	3.54	-	0.00
July 27	20.18	38.46	18.21	5.64	-	8.11
July 28	0.00	0.15	0.00	0.00	-	0.00
July 29	0.00	0.00	0.00	0.00	0.00	0.00
July 30	12.92	18.19	19.23	0.00	0.17	4.19
July 31	0.00	0.82	0.18	0.00	0.00	0.00
August 1	11.26	15.32	6.93	0.21	0.51	0.44
August 2	0.00	0.09	0.29	0.00	0.00	0.00
August 3	0.00	0.00	0.00	0.00	0.00	0.00
August 4	0.45	0.11	0.00	0.00	0.00	0.00
August 5	23.91	17.71	11.11	0.00	0.68	1.93
August 6	0.00	0.00	0.03	0.00	0.00	0.05
August 7	1.70	4.70	1.35	0.00	0.00	0.00

August 8	0.00	0.00	0.00	0.00	0.00	0.00
August 9	2.46	0.00	0.00	0.00	0.00	0.00
August 10	0.09	0.00	0.00	0.00	0.00	0.00
August 11	0.23	0.00	0.00	0.00	0.00	0.39
August 12	9.47	3.70	0.59	0.71	0.00	6.59
August 13	25.16	16.03	5.70	3.29	4.73	3.65
August 14	12.03	2.62	3.95	4.18	11.37	1.10
August 15	19.13	10.81	4.38	3.55	1.55	5.98
August 16	0.00	0.00	0.00	0.00	0.00	0.00
August 17	0.00	0.00	0.00	0.00	0.00	0.00
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	0.00	0.00	0.00	0.00	0.00	0.00
August 21	0.00	0.00	0.00	0.00	0.00	0.00
August 22	0.00	0.00	2.68	0.00	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	0.00	0.00	0.00	0.00	0.00	0.00
August 25	0.39	0.00	0.00	0.31	0.29	0.29
August 26	0.00	0.00	0.00	0.00	0.00	0.00
August 27	0.00	0.00	0.00	0.00	0.00	0.00
August 28	0.00	0.00	0.00	0.00	0.00	0.00
August 29	0.00	0.00	0.00	0.00	0.00	0.00
August 30	18.79	3.84	0.00	0.17	0.00	0.37
August 31	0.00	0.00	0.00	0.00	0.00	0.00
September 1	17.43	1.21	0.00	0.00	0.00	0.00
September 2	2.31	0.00	1.58	0.00	0.24	0.39
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	0.00	0.00	1.36	0.00	0.00	0.00
September 5	0.00	0.00	0.00	0.00	0.00	0.00
September 6	0.00	0.00	0.00	0.00	0.00	0.00
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	0.00	0.00	0.00	0.00	0.00	0.00
September 9	0.00	0.00	0.00	0.00	0.00	0.80
September 10	4.63	0.00	0.00	0.00	0.00	0.00
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	0.00	0.00	0.00	0.00	0.00	0.00
September 13	0.35	0.00	0.00	0.00	0.00	0.00
September 14	14.70	0.00	0.00	0.00	0.00	0.00
September 15	16.02	0.00	0.00	0.00	0.00	0.00
September 16	3.09	0.00	0.00	0.00	0.00	0.00
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	0.00	0.00	0.00	0.00	0.00	0.00
September 21	23.18	0.00	0.00	0.00	0.00	0.00
September 22	0.00	0.00	0.00	0.00	0.00	0.00
September 23	0.00	0.00	0.00	0.00	0.00	0.00
September 24	1.67	0.00	0.00	0.00	0.00	0.00
September 25	0.00	0.00	0.00	0.00	0.00	0.00
September 26	0.00	0.00	0.00	0.00	0.00	0.00
September 27	36.24	0.37	3.81	0.00	3.95	0.00
September 28	0.00	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B10. Daily total temperature differences for the 29.5° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	0.07	88.67	19.94	31.02	-	4.82
July 2	0.00	3.98	0.49	0.00	-	0.00
July 3	0.00	0.00	0.46	2.41	-	0.00
July 4	2.37	56.52	52.08	52.42	-	31.23
July 5	0.43	11.92	0.93	0.07	-	1.03
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	0.00	0.00	0.00	-	0.00
July 11	0.00	0.00	1.86	0.00	-	0.00
July 12	0.00	19.04	42.50	5.19	-	4.08
July 13	0.00	0.62	2.94	0.00	-	0.00
July 14	2.23	15.51	21.45	3.17	-	6.96
July 15	0.05	11.05	26.32	4.91	-	2.09
July 16	4.78	12.28	23.50	3.03	-	2.57
July 17	9.63	19.17	31.89	11.77	-	10.61
July 18	0.00	3.98	10.08	2.18	-	0.00
July 19	0.00	0.00	0.00	0.00	-	0.00
July 20	0.00	0.00	4.75	0.00	-	0.00
July 21	0.00	0.00	0.00	0.00	-	0.00
July 22	34.88	23.84	0.84	3.34	-	1.49
July 23	0.24	1.31	1.09	0.62	-	0.00
July 24	0.00	0.33	2.52	0.00	-	0.00
July 25	0.00	0.00	0.43	0.00	-	0.00
July 26	3.99	10.09	14.65	0.88	-	0.00
July 27	11.99	28.52	10.48	2.82	-	2.34
July 28	0.00	0.00	0.00	0.00	-	0.00
July 29	0.00	0.00	0.00	0.00	0.00	0.00
July 30	6.53	11.69	11.57	0.00	0.00	0.59
July 31	0.00	0.15	0.00	0.00	0.00	0.00
August 1	6.10	8.70	2.85	0.00	0.01	0.00
August 2	0.00	0.00	0.00	0.00	0.00	0.00
August 3	0.00	0.00	0.00	0.00	0.00	0.00
August 4	0.00	0.00	0.00	0.00	0.00	0.00
August 5	15.86	9.85	5.82	0.00	0.01	0.46
August 6	0.00	0.00	0.00	0.00	0.00	0.00
August 7	0.73	3.52	0.09	0.00	0.00	0.00

August 8	0.00	0.00	0.00	0.00	0.00	0.00
August 9	0.82	0.00	0.00	0.00	0.00	0.00
August 10	0.00	0.00	0.00	0.00	0.00	0.00
August 11	0.00	0.00	0.00	0.00	0.00	0.00
August 12	6.45	1.14	0.00	0.21	0.00	2.89
August 13	21.21	11.53	3.25	1.29	1.79	1.49
August 14	7.24	0.16	1.05	1.82	9.14	0.00
August 15	14.17	5.68	1.90	1.16	0.01	2.49
August 16	0.00	0.00	0.00	0.00	0.00	0.00
August 17	0.00	0.00	0.00	0.00	0.00	0.00
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	0.00	0.00	0.00	0.00	0.00	0.00
August 21	0.00	0.00	0.00	0.00	0.00	0.00
August 22	0.00	0.00	1.68	0.00	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	0.00	0.00	0.00	0.00	0.00	0.00
August 25	0.00	0.00	0.00	0.00	0.00	0.00
August 26	0.00	0.00	0.00	0.00	0.00	0.00
August 27	0.00	0.00	0.00	0.00	0.00	0.00
August 28	0.00	0.00	0.00	0.00	0.00	0.00
August 29	0.00	0.00	0.00	0.00	0.00	0.00
August 30	12.45	0.44	0.00	0.00	0.00	0.00
August 31	0.00	0.00	0.00	0.00	0.00	0.00
September 1	12.93	0.00	0.00	0.00	0.00	0.00
September 2	1.08	0.00	0.69	0.00	0.00	0.00
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	0.00	0.00	0.36	0.00	0.00	0.00
September 5	0.00	0.00	0.00	0.00	0.00	0.00
September 6	0.00	0.00	0.00	0.00	0.00	0.00
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	0.00	0.00	0.00	0.00	0.00	0.00
September 9	0.00	0.00	0.00	0.00	0.00	0.25
September 10	2.51	0.00	0.00	0.00	0.00	0.00
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	0.00	0.00	0.00	0.00	0.00	0.00
September 13	0.00	0.00	0.00	0.00	0.00	0.00
September 14	10.48	0.00	0.00	0.00	0.00	0.00
September 15	9.49	0.00	0.00	0.00	0.00	0.00
September 16	1.04	0.00	0.00	0.00	0.00	0.00
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	0.00	0.00	0.00	0.00	0.00	0.00
September 21	15.30	0.00	0.00	0.00	0.00	0.00
September 22	0.00	0.00	0.00	0.00	0.00	0.00
September 23	0.00	0.00	0.00	0.00	0.00	0.00
September 24	0.09	0.00	0.00	0.00	0.00	0.00
September 25	0.00	0.00	0.00	0.00	0.00	0.00
September 26	0.00	0.00	0.00	0.00	0.00	0.00
September 27	28.24	0.00	0.96	0.00	1.05	0.00
September 28	0.00	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B11. Daily total temperature differences for the 30° Celsius threshold.

	% ET†					
Date	40	60	80	100	120	140
July 1	0.00	78.54	12.55	23.54	-	1.41
July 2	0.00	1.48	0.00	0.00	-	0.00
July 3	0.00	0.00	0.00	0.36	-	0.00
July 4	0.88	47.55	43.43	44.01	-	24.82
July 5	0.00	7.03	0.29	0.00	-	0.53
July 6	0.00	0.00	0.00	0.00	-	0.00
July 7	0.00	0.00	0.00	0.00	-	0.00
July 8	0.00	0.00	0.00	0.00	-	0.00
July 9	0.00	0.00	0.00	0.00	-	0.00
July 10	0.00	0.00	0.00	0.00	-	0.00
July 11	0.00	0.00	0.64	0.00	-	0.00
July 12	0.00	9.55	31.33	1.54	-	0.65
July 13	0.00	0.00	0.86	0.00	-	0.00
July 14	1.27	11.21	16.20	1.47	-	3.76
July 15	0.00	6.38	18.49	1.95	-	0.62
July 16	1.98	6.59	16.76	0.90	-	0.45
July 17	3.48	10.35	21.82	5.33	-	3.45
July 18	0.00	1.35	6.39	0.67	-	0.00
July 19	0.00	0.00	0.00	0.00	-	0.00
July 20	0.00	0.00	1.25	0.00	-	0.00
July 21	0.00	0.00	0.00	0.00	-	0.00
July 22	33.13	21.27	0.33	1.34	-	0.99
July 23	0.00	0.00	0.05	0.00	-	0.00
July 24	0.00	0.00	1.81	0.00	-	0.00
July 25	0.00	0.00	0.00	0.00	-	0.00
July 26	1.21	4.95	8.46	0.00	-	0.00
July 27	5.44	19.72	5.28	1.91	-	0.31
July 28	0.00	0.00	0.00	0.00	-	0.00
July 29	0.00	0.00	0.00	0.00	0.00	0.00
July 30	2.47	5.77	5.71	0.00	0.00	0.00
July 31	0.00	0.00	0.00	0.00	0.00	0.00
August 1	2.94	3.97	0.71	0.00	0.00	0.00
August 2	0.00	0.00	0.00	0.00	0.00	0.00
August 3	0.00	0.00	0.00	0.00	0.00	0.00
August 4	0.00	0.00	0.00	0.00	0.00	0.00
August 5	8.56	3.55	1.89	0.00	0.00	0.00
August 6	0.00	0.00	0.00	0.00	0.00	0.00
August 7	0.23	2.52	0.00	0.00	0.00	0.00

August 8	0.00	0.00	0.00	0.00	0.00	0.00
August 9	0.25	0.00	0.00	0.00	0.00	0.00
August 10	0.00	0.00	0.00	0.00	0.00	0.00
August 11	0.00	0.00	0.00	0.00	0.00	0.00
August 12	4.35	0.45	0.00	0.00	0.00	0.83
August 13	17.86	7.48	1.75	0.53	0.03	0.39
August 14	3.76	0.00	0.03	0.14	7.14	0.00
August 15	9.85	2.38	0.40	0.15	0.00	1.06
August 16	0.00	0.00	0.00	0.00	0.00	0.00
August 17	0.00	0.00	0.00	0.00	0.00	0.00
August 18	0.00	0.00	0.00	0.00	0.00	0.00
August 19	0.00	0.00	0.00	0.00	0.00	0.00
August 20	0.00	0.00	0.00	0.00	0.00	0.00
August 21	0.00	0.00	0.00	0.00	0.00	0.00
August 22	0.00	0.00	0.91	0.00	0.00	0.00
August 23	0.00	0.00	0.00	0.00	0.00	0.00
August 24	0.00	0.00	0.00	0.00	0.00	0.00
August 25	0.00	0.00	0.00	0.00	0.00	0.00
August 26	0.00	0.00	0.00	0.00	0.00	0.00
August 27	0.00	0.00	0.00	0.00	0.00	0.00
August 28	0.00	0.00	0.00	0.00	0.00	0.00
August 29	0.00	0.00	0.00	0.00	0.00	0.00
August 30	7.81	0.00	0.00	0.00	0.00	0.00
August 31	0.00	0.00	0.00	0.00	0.00	0.00
September 1	8.85	0.00	0.00	0.00	0.00	0.00
September 2	0.11	0.00	0.19	0.00	0.00	0.00
September 3	0.00	0.00	0.00	0.00	0.00	0.00
September 4	0.00	0.00	0.00	0.00	0.00	0.00
September 5	0.00	0.00	0.00	0.00	0.00	0.00
September 6	0.00	0.00	0.00	0.00	0.00	0.00
September 7	0.00	0.00	0.00	0.00	0.00	0.00
September 8	0.00	0.00	0.00	0.00	0.00	0.00
September 9	0.00	0.00	0.00	0.00	0.00	0.00
September 10	1.46	0.00	0.00	0.00	0.00	0.00
September 11	0.00	0.00	0.00	0.00	0.00	0.00
September 12	0.00	0.00	0.00	0.00	0.00	0.00
September 13	0.00	0.00	0.00	0.00	0.00	0.00
September 14	6.63	0.00	0.00	0.00	0.00	0.00
September 15	4.09	0.00	0.00	0.00	0.00	0.00
September 16	0.00	0.00	0.00	0.00	0.00	0.00
September 17	0.00	0.00	0.00	0.00	0.00	0.00

September 18	0.00	0.00	0.00	0.00	0.00	0.00
September 19	0.00	0.00	0.00	0.00	0.00	0.00
September 20	0.00	0.00	0.00	0.00	0.00	0.00
September 21	9.60	0.00	0.00	0.00	0.00	0.00
September 22	0.00	0.00	0.00	0.00	0.00	0.00
September 23	0.00	0.00	0.00	0.00	0.00	0.00
September 24	0.00	0.00	0.00	0.00	0.00	0.00
September 25	0.00	0.00	0.00	0.00	0.00	0.00
September 26	0.00	0.00	0.00	0.00	0.00	0.00
September 27	20.59	0.00	0.00	0.00	0.00	0.00
September 28	0.00	0.00	0.00	0.00	0.00	0.00
September 29	0.00	0.00	0.00	0.00	0.00	0.00

Note: Due to a malfunction of the datalogger, no data is included for 120% ET until July 29th.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the infrared thermometer.

Table B12. Daily average soil moisture tension for the 20 centimeter depth.

	% ET†					
Date	40	60	80	100	120	140
July 1	62.74	62.43	68.61	67.86	69.61	70.98
July 8	17.01	18.11	22.66	14.65	33.27	35.59
July 9	7.84	14.34	4.89	11.53	25.57	35.02
July 10	15.91	27.60	8.50	19.85	24.76	37.41
July 11	26.20	37.58	13.02	25.24	29.31	40.71
July 12	36.80	44.67	19.05	29.08	35.69	43.92
July 13	47.54	52.04	28.88	34.65	43.47	48.85
July 14	54.52	56.23	39.47	38.53	49.36	52.41
July 15	59.28	59.38	49.46	42.39	54.25	55.45
July 16	62.81	61.79	56.92	45.69	58.63	58.23
July 17	64.94	63.70	62.31	48.77	62.00	60.37
July 18	67.21	66.19	66.89	52.63	65.00	62.68
July 19	68.42	67.60	69.28	55.20	66.75	63.38
July 22	40.14	46.84	11.84	30.77	49.51	37.02
July 23	36.09	42.57	15.39	24.67	14.99	7.18
July 24	44.30	52.90	17.35	32.82	24.92	14.63
July 25	42.84	25.35	8.46	30.97	16.78	10.02
July 26	44.88	36.03	10.52	30.41	8.55	8.40
July 27	50.17	50.36	17.81	32.38	18.49	16.01
July 28	55.55	58.38	25.07	35.03	29.04	24.95
August 1	67.19	67.37	20.88	14.20	11.81	11.80
August 2	68.08	64.03	24.85	5.49	3.61	5.25
August 3	68.77	64.07	24.37	9.18	8.26	12.04
August 4	69.30	64.46	24.76	11.01	14.26	21.75
August 5	69.85	65.31	26.46	11.83	24.04	35.40
August 6	69.91	63.73	33.41	3.08	5.87	2.92
August 28	9.37	7.40	5.95	5.45	5.11	6.76
August 29	17.23	14.20	12.43	11.75	12.18	15.91
August 30	27.66	24.35	21.92	20.79	22.11	27.83
August 31	38.37	35.34	32.60	30.97	33.47	40.62
September 1	59.26	53.03	45.21	30.30	31.48	47.56
September 2	52.48	46.56	12.51	8.85	3.03	6.35
September 3	54.55	39.19	17.69	9.27	7.67	15.57
September 4	45.87	10.78	5.13	4.27	2.78	3.81
September 5	47.53	25.31	11.74	9.83	6.48	10.89
September 6	53.14	39.25	21.15	16.75	12.86	21.59
September 7	58.17	47.09	28.32	20.83	18.28	29.33
September 8	61.78	51.25	32.54	23.03	19.86	32.24

September 9	62.93	53.97	17.59	13.11	2.64	4.60
September 10	63.71	54.55	9.39	8.57	7.47	12.55
September 11	65.65	44.88	13.37	11.65	13.10	19.64
September 12	60.15	12.91	4.36	4.61	2.29	4.44
September 13	60.28	28.31	8.51	10.29	6.53	11.78
September 14	62.04	40.10	14.41	15.95	12.15	21.63
September 15	63.59	36.03	16.65	15.70	17.50	27.55
September 16	60.61	12.99	4.64	5.09	2.54	5.83
September 17	61.38	25.74	8.12	10.91	5.15	11.43
September 18	53.58	8.06	3.28	3.50	2.78	4.24
September 19	52.92	12.35	5.76	6.33	5.85	8.03
September 20	53.86	22.12	8.70	10.39	9.96	14.20
September 21	55.70	33.84	12.38	15.35	15.54	23.36
September 22	58.18	34.25	14.94	16.43	22.02	31.17
September 23	57.46	11.15	4.41	3.90	1.89	3.70
September 24	58.75	23.64	8.05	9.12	4.11	8.22
September 25	48.41	8.63	3.01	3.62	2.42	3.38
September 26	46.37	11.95	5.08	6.18	4.85	6.55
September 27	47.29	20.73	7.46	10.16	7.90	11.89
September 28	50.11	31.88	10.57	15.35	11.73	18.91
September 29	53.08	39.31	13.67	18.57	14.19	23.22

Note: The dates not included were removed during data cleaning due to sensor dehydration.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the tensiometer.

Table B13. Daily average soil moisture tension for the 45 centimeter depth.

	% ET†					
Date	40	60	80	100	120	140
July 1	31.14	28.05	29.88	31.33	33.09	32.29
July 2	35.97	32.99	35.21	36.73	39.20	38.67
July 3	41.02	38.38	40.83	42.34	45.67	45.17
July 4	46.92	44.87	47.34	48.81	52.99	52.54
July 5	52.61	51.08	53.32	54.72	58.95	58.62
July 9	50.86	53.09	53.60	54.71	54.73	55.99
July 10	53.79	56.00	56.53	57.40	58.30	59.42
July 11	57.21	59.41	59.85	60.47	61.93	62.91
July 12	60.02	62.17	62.47	62.90	64.64	65.38
July 13	62.71	64.72	64.93	65.27	67.10	67.56
July 14	64.79	66.69	66.84	67.14	68.85	69.14
July 15	66.47	68.26	68.37	68.70	70.22	70.38
July 16	67.95	69.66	69.74	70.09	71.42	71.48
July 17	69.00	70.64	70.71	71.10	72.25	72.21
July 18	70.90	72.50	72.55	73.07	74.16	74.05
July 19	72.12	73.66	73.71	74.25	75.14	75.06
July 26	38.74	33.18	25.38	28.05	10.37	10.56
July 27	42.82	37.81	30.79	32.14	16.27	17.01
July 28	48.50	44.25	38.32	38.89	25.14	27.00
July 29	53.64	50.10	45.23	45.48	33.94	36.26
July 30	54.59	51.08	46.27	45.78	33.83	34.59
July 31	45.73	40.31	32.82	27.89	7.15	7.43
August 1	47.21	42.09	35.35	30.87	11.85	11.56
August 2	43.99	38.14	30.66	26.37	5.33	5.99
August 3	45.74	40.16	33.07	29.17	9.66	10.17
August 4	47.40	42.07	35.34	31.55	13.42	14.19
August 5	49.84	44.85	38.68	35.19	18.98	20.17
August 6	45.61	39.74	32.20	26.14	5.90	6.09
August 12	44.45	40.50	34.97	33.47	20.75	20.47
August 13	44.97	40.69	34.49	37.04	26.44	24.65
August 14	35.31	28.78	19.11	22.57	5.80	5.72
August 15	38.34	32.24	23.18	25.00	10.97	10.98
August 16	40.81	34.99	26.30	26.31	14.03	12.76
August 17	42.31	36.68	28.25	26.80	15.81	13.88
August 18	44.38	39.02	31.03	28.83	19.47	17.05
August 19	32.22	24.25	15.14	18.09	5.55	3.28
August 20	31.91	23.91	15.46	17.52	7.88	7.75
August 21	32.56	24.66	16.57	17.66	10.27	10.31

August 22	21.22	10.88	9.95	11.53	4.65	4.51
August 23	23.45	13.30	11.91	12.29	8.19	7.98
August 27	24.90	18.29	12.67	10.67	9.54	9.87
August 28	17.74	8.98	7.74	5.14	4.39	4.24
August 29	20.62	12.00	10.22	8.63	8.67	8.49
August 30	24.94	16.90	13.86	12.61	12.85	12.38
August 31	30.28	22.95	18.50	17.17	17.50	16.60
September 1	34.63	27.89	22.54	20.93	21.04	20.63
September 2	26.66	18.14	8.87	9.23	4.66	4.40
September 3	27.53	19.05	10.52	10.42	8.93	8.68
September 4	18.00	7.50	4.03	4.09	3.48	3.24
September 5	21.69	11.88	8.00	7.89	7.75	7.86
September 6	26.27	17.21	12.17	11.77	11.57	11.65
September 7	29.52	21.00	14.84	14.07	13.66	13.72
September 8	31.81	23.66	16.76	15.67	15.02	15.52
September 9	28.51	19.63	12.71	8.92	4.37	4.27
September 10	29.73	21.01	15.24	11.17	9.29	9.31
September 11	31.73	23.25	16.25	12.97	11.82	11.39
September 12	25.19	15.38	5.32	5.51	3.93	4.03
September 13	28.03	18.79	8.93	8.86	8.48	8.66
September 14	30.88	22.19	12.55	12.36	12.16	12.27
September 15	31.45	22.86	14.43	14.81	14.55	14.01
September 16	23.15	12.85	6.13	6.68	4.42	4.39
September 17	25.40	15.49	8.64	8.65	7.25	7.42
September 18	17.92	6.44	4.71	5.22	4.01	3.80
September 19	20.97	10.10	7.40	7.69	7.50	7.39
September 20	24.55	14.41	10.40	10.77	10.87	10.71
September 21	28.32	18.98	13.76	14.30	14.78	14.41
September 22	31.69	23.03	16.70	17.65	18.39	17.06
September 23	25.34	15.44	5.92	6.19	3.62	3.66
September 24	27.48	17.94	8.09	8.22	6.77	7.10

Note: The dates not included were removed during data cleaning due to sensor dehydration.

† Percent of evapotranspiration (ET) irrigation treatment at the ground location of the tensiometer.

Figure B1. Java code used to read the temperature data.

```java
public class ImportAndDerive {
    static int arrLength = 10500;
    public static void main(String[] args) throws FileNotFoundException {
        // Create separate arrays for data
        int[] month = new int[arrLength];
        int[] day = new int[arrLength]; ;
        int[] year = new int[arrLength];
        int[] hour = new int[arrLength];
        int[] min = new int[arrLength];

        double[] soilTemp = new double[arrLength];
        double[] canopyTemp = new double[arrLength];
        double[] ambientTemp = new double[arrLength];

        //Open file
        Scanner scanner = new Scanner(new File("temperatureData.csv"));
        scanner.useDelimiter(",|\\s|/|:|\n");

        //Skip headers
        scanner.nextLine();
        int arrIndex = 0;

        //Loop through all lines in the data
        while (scanner.hasNext()) {
            for (int i = 0; i < 8; i++) {
                //Allocate one line into arrays
                month[arrIndex] = Integer.valueOf((scanner.nextInt()));
                day[arrIndex] = Integer.valueOf((scanner.next()));
                year[arrIndex] = Integer.valueOf((scanner.next()));
                hour[arrIndex] = Integer.valueOf((scanner.next()));
                min[arrIndex] = Integer.valueOf((scanner.next()));

                soilTemp[arrIndex] = Double.valueOf(scanner.nextDouble());
                canopyTemp[arrIndex] = Double.valueOf(scanner.nextDouble());
                ambientTemp[arrIndex] = Double.valueOf(scanner.nextDouble());
                if (scanner.next() != null) {
                    break;
                }
            }
        arrIndex++;
        }
        scanner.close();
```

Figure B2. Java code (continued from B1) used to calculate total temperature difference.

```
        double sum = 0;
        double tempDiff = 0;
        final double threshold = 28.5;
        int currentDay = 0;

        for (int i = 0; i <= arrIndex; i++){
            currentDay = day[i];
            if (currentDay == day[i+1]){
                //Normal calculations for entire day
                tempDiff = ambientTemp[i] - canopyTemp[i];

                if (canopyTemp[i] > threshold) {
                    tempDiff = canopyTemp[i] - threshold;
                    sum+= tempDiff;
                }
            } else {
                //Print total temperature difference result
                System.out.println(month[i] + "\t" + day[i] + "\t" + sum);
                sum = 0;  //Reset for the next day
            }
        }
    }
}
```