NebGuide

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Research-Based Information That You Can Use

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Ground-Based Thermal Sensing of Field Crops and Its Relevance to Irrigation Management

Tsz Him Lo, Graduate Research Assistant
Daran R. Rudnick, Irrigation Management Specialist, Assistant Professor
Yufeng Ge, Advanced Sensing Systems Engineer, Assistant Professor
Derek M. Heeren, Irrigation Engineer, Assistant Professor
Suat Irmak, Soil and Water Resources and Irrigation Engineer, Professor
J. Burdette Barker, Post-Doctoral Research Associate
Xin Qiao, Water and Irrigation Management Specialist, Assistant Professor
Tim M. Shaver, Nutrient Management Specialist, Associate Professor

This NebGuide discusses the use of ground-based thermal sensors to monitor crops and ultimately inform irrigation decisions.

Transpiration, Water Stress, and Canopy Temperature

By taking in carbon dioxide from the surrounding air and using energy captured from sunlight, plant leaves transform carbon dioxide into substances that serve as energy sources and building materials for plant maintenance and growth. To sustain this essential process that results in biomass and yield production, the microscopic openings on plant leaves—called stomata—are opened to allow carbon dioxide to enter. Unavoidably, water inside the leaves evaporates and exits through these same stomata, which is the phenomenon known as transpiration. To replenish the water loss via transpiration, plant roots extract water from the surrounding soil. Soils differ in the rate at which they can supply water to roots (e.g., generally faster in sandy, loose, well-structured soils than in clayey, compacted, poorly structured soils). However, as any soil dries, the rate at which it can supply water decreases. This decrease is generally larger in sand than in clay given the same amount of water extracted, which explains the usual need to irrigate more frequently in sandy soils.

Crop water stress begins when the soil can no longer supply water to the plant as fast as the leaves are losing water via transpiration. With the onset of water stress, plants activate short-term mechanisms to reduce water loss. One of these mechanisms is temporarily narrowing the stomata on the leaves. Yet just as the evaporation of our sweat cools us down, transpiration cools down plant leaves. Narrower stomata not only reduce water loss but also increase leaf and canopy temperature (i.e., the collective temperature of multiple leaves within consideration). Engaging this mechanism for significant durations hinders plant growth because the entry of carbon dioxide into leaves is also reduced and because the leaves can heat up to temperatures that are detrimental to plants. The combination of these two effects explains in part why prolonged water stress causes plants to be shorter, less leafy, and generally lower yielding.

For a given canopy and soil water status, canopy temperature varies depending on weather and sun position (Jackson et al., 1981). Canopy temperature tends to follow the overall trend of air temperature. Thus, during

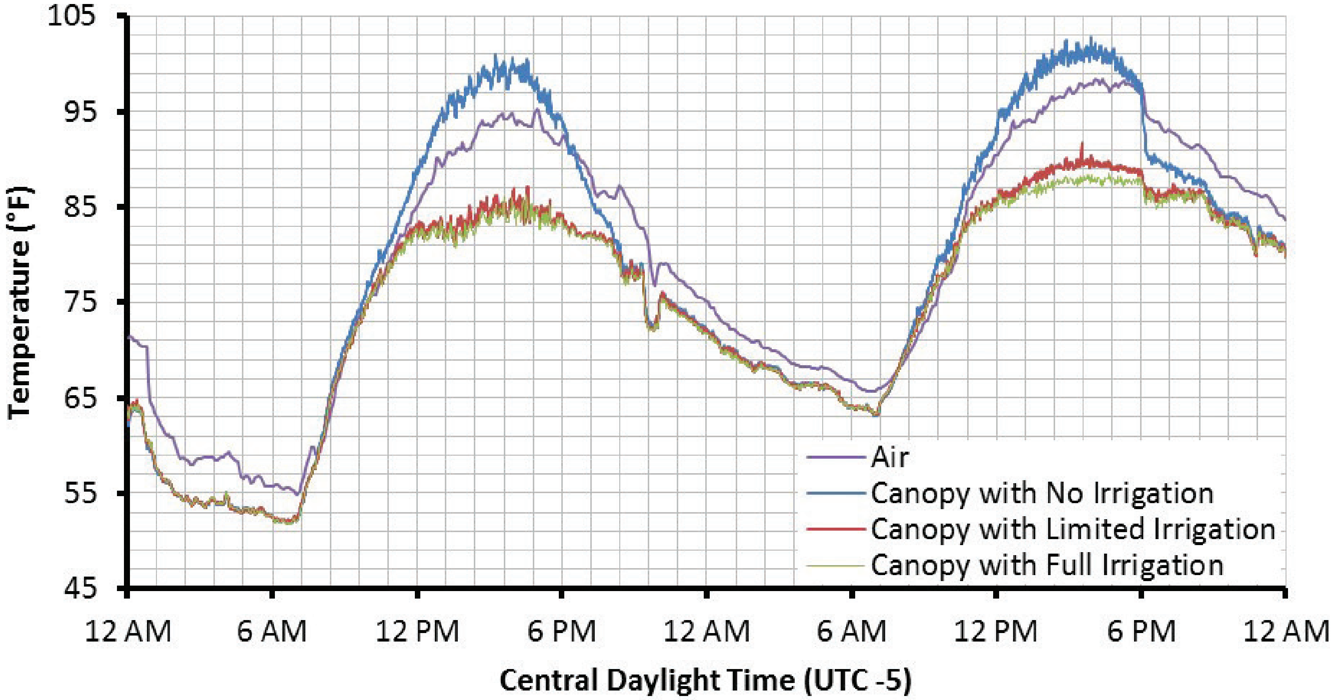

Figure 1. Air temperature reported by Nebraska State Climate Office weather station and canopy temperature sensed by infrared thermometers over corn in North Platte, Neb., on July 23 (calm, dry, and sunny until 7:30 p.m. CDT) and July 24 (moderately windy, dry, and sunny until 6 p.m. CDT), 2017. The average of three infrared thermometers represents each of the three irrigation treatments.

Figure 2. Image of a) a station of two infrared thermometers mounted over soybeans with the left sensor viewing the canopy at an oblique angle and the right sensor viewing straight downward, and b) a thermal infrared camera held over small grains.

most summer days in Nebraska, canopy temperature starts to rise rapidly in the early morning, peaks in the mid-afternoon, and declines gradually until the next early morning *(Figure 1)*.

The deviation of canopy temperature from air temperature, on the other hand, is determined jointly by the surroundings of the plant and by plant regulation of the stomata on its leaves. In calm and humid conditions, all plants transpire slowly, and canopy temperature is close to air temperature regardless of water stress severity; likewise, sweat evaporates slowly and cools us down minimally under such conditions.

In windy and dry conditions, however, plentifully watered plants transpire quickly and are cooler than the air temperature, whereas water-stressed plants transpire slowly and are warmer than the air temperature *(Figure 1)*. This disparity between plentifully watered and water-stressed plants in the latter scenario widens with cloudless skies and high sun position. Windy and dry conditions along with cloudless skies and high sun position are most typical of the middle part of the day during Nebraska summers. Therefore, increasing water stress severity lengthens the duration and amplifies the magnitude at which canopy temperatures rise above plentifully watered levels during the middle part of the day *(Figure 1)*.

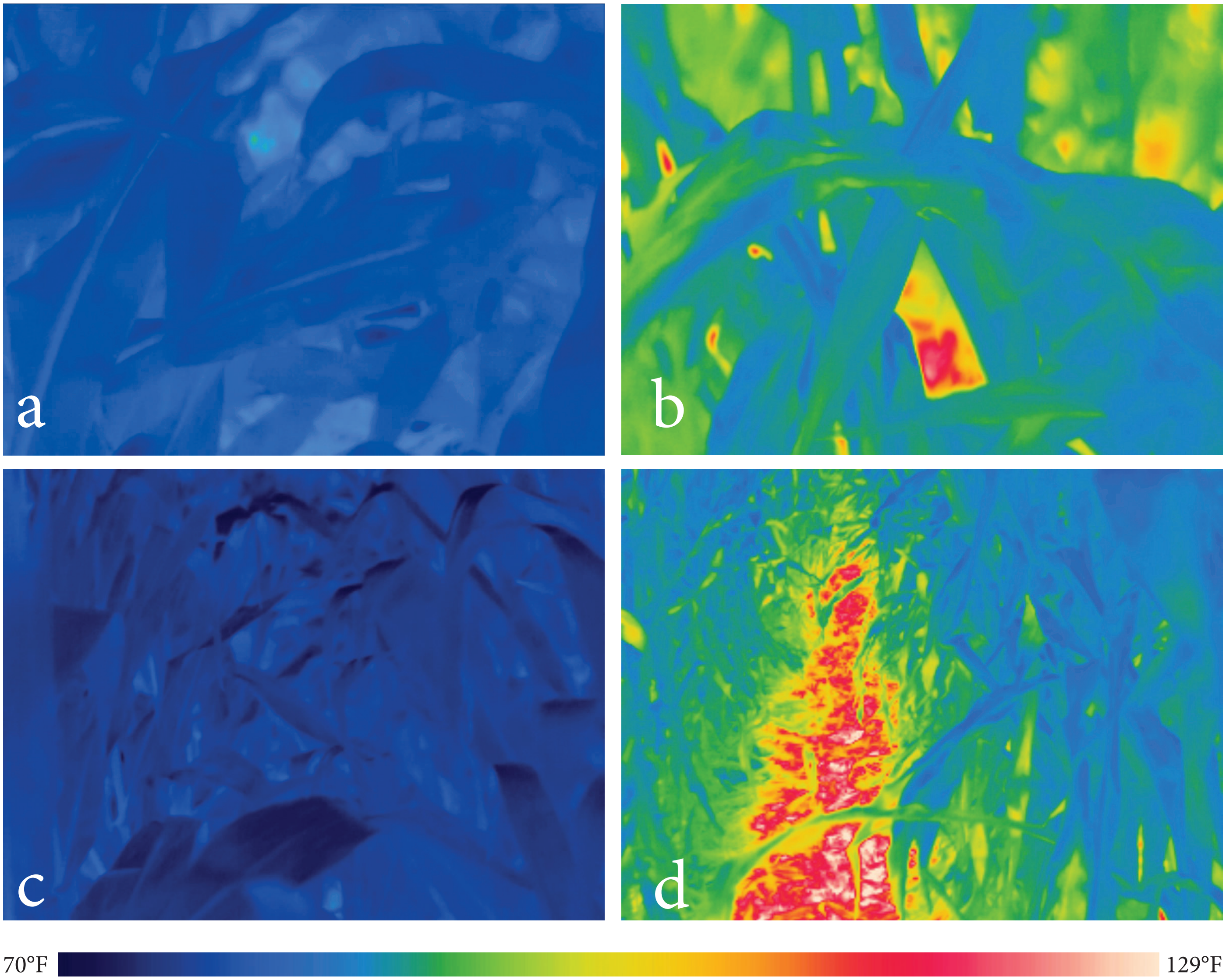

Figure 3. Temperature images of a) plentifully watered corn leaves, b) water-stressed corn leaves, c) two plentifully watered corn rows, and d) two water-stressed corn rows as captured by a thermal infrared camera around 4 p.m. CDT on August 23, 2016, near Brule, Neb. (air temperature ≈ 86°F).

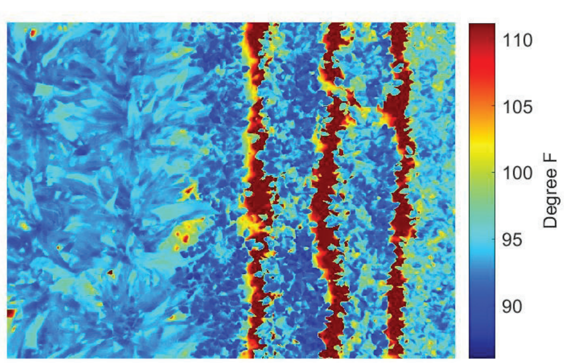

Figure 4. Overhead temperature image of corn (left) and soybean (right) rows as captured by a thermal infrared camera at 2:34 p.m. CDT on July 21, 2017, near Mead, Neb. (air temperature ≈ 94°F).

Noncontact Measurement of Canopy Temperature

As discussed previously, knowledge of canopy temperature sheds light on the severity of water stress because canopy temperature increases as water stress severity increases for a given sun position and set of weather conditions. Canopy temperature is relatively easy to measure compared with transpiration or the rate at which a soil can supply water. A noncontact (i.e., without touching the leaves) method of measuring canopy temperature is to use sensors that detect the thermal infrared energy produced by the canopy (i.e., array of leaves) invisible to the human eye. Every object above-460°F (i.e., absolute zero) produces energy, and the intensity of the energy produced increases as the temperature of the object increases. Canopy temperature can be calculated by quantifying the intensity of the thermal infrared energy produced by the canopy. Many commercially available sensors that detect thermal infrared energy can measure canopy temperature, but growers and their consultants should consider the following questions when choosing a thermal infrared sensor for their particular application(s):

- Is an infrared thermometer (i.e., a non-imaging sensor) or a thermal infrared camera (i.e., an imaging sensor) more appropriate?

An infrared thermometer obtains one temperature value when it makes a measurement *(Figures 1* and *2a)*, whereas a thermal infrared camera obtains one temperature value for each pixel when it captures an image *(Figures 2b, 3,* and *4)*. This difference is especially relevant in situations where it may be difficult to avoid detecting the ground while detecting the canopy (e.g., when canopies are sparse). Because ground temperature is usually warmer than canopy temperature *(Figures 3* and *4),* partial detection of the ground usually causes overestimation of canopy temperature and, consequently, of water stress.

An infrared thermometer alone does not provide a straightforward means of isolating canopy temperature from the measured temperature value. Therefore, infrared thermometers are typically oriented to view the crop canopy at oblique angles with respect to the ground and the crop rows (yet without viewing above the horizon) rather than straight downward. The temperature value measured at this orientation is less influenced by ground temperature and thus closer to canopy temperature.

In contrast, a thermal infrared camera allows users to extract only the temperature values from pure canopy pixels *(Figures 3* and *4)*. Challenges of using a thermal infrared camera may be the correct identification of pure canopy pixels in the images or the proper representation of a whole plant with multiple leaf-scale (or finer) temperature values. If using a thermal infrared camera that automatically differentiates between canopy and non-canopy pixels, users should verify that the classification procedure is performing well. If using a thermal infrared camera without this capability, users would be wholly responsible for the correct identification of pure canopy pixels.

- What is an appropriate field of view of the thermal infrared sensor?

Usually expressed as an angle, the field of view of a thermal infrared sensor is set by the manufacturer. The target area that is detected by the sensor depends on the field of view of the sensor, the distance between the sensor and the canopy, and the orientation of the sensor. The size of the target area increases as the field of view increases, the distance from the canopy increases, and the sensors point farther away from perpendicular to the ground. It is generally ideal to maximize the target area of infrared thermometers so that the measured temperature value is representative of many typical plants instead of one particular leaf. However, the target area of the sensor should be chosen to exclude unrepresentative targets (e.g., ground, sky, sensor-mounting structure, barren or other anomalous spots, field/plot edges). At the same time, the distance from the canopy should be chosen to avoid the potential interference by other objects in the field (e.g., machinery hitting the sensor mounting structure, plants blocking wireless sensor communication).

When comparing thermal infrared cameras, users also need to consider the total number of pixels in each image, whose maximum is set by the manufacturer as well. With the same distance from the canopy and the same field of view, a larger total number of image pixels results in a smaller area corresponding to each pixel and thus a higher level of spatial detail. If two thermal infrared cameras have the same field of view, the camera with the larger total number of image pixels can be farther from the canopy while still obtaining pure canopy pixels.

- What are the minimum requirements for numerical resolution and accuracy?

An appropriate thermal infrared sensor offers users sufficient confidence in the quality of the temperature values measured during crop monitoring (i.e., as opposed to medical or high-temperature industrial scenarios). The numerical resolution of a sensor is the smallest temperature difference the sensor can distinguish theoretically. The manufacturer sets this specification. On the other hand, the numerical accuracy of a sensor is the expected closeness of the measured temperature values to the true temperature values, which is sometimes expressed as a range of expected magnitudes of error.

A manufacturer may report numbers that claim to represent the numerical accuracy of its sensor, but not every manufacturer actually conducts a meaningful assessment of numerical accuracy. Such an assessment involves a rigorous experiment that subjects both the sensor and its target to the full range of temperatures encountered in the field. Furthermore, this experiment must be repeated for each sensor unit and over time because minute differences in sensor hardware can produce large differences in sensor response and because sensor response can drift with wear and tear.

Once this experiment has been performed, a calibration (i.e., a set of mathematical procedures to correct the error in the measured temperature values) can be developed to remove the predictable or systematic portion of the errors, but the unpredictable or random portion of the errors will remain and continue to limit the accuracy of the sensor. Growers and their consultants are unlikely to engage heavily in calibration activities. Therefore, the recommendation is to select sensors for which calibration services are accessible and the magnitude of random error has been shown to be generally within acceptable levels.

- What are the necessary software capabilities of the sensor or its companion devices?

Besides the scientific considerations mentioned above, the convenience of a thermal infrared sensor is a practical consideration that is extremely important, especially if the sensor is to be used routinely for informing irrigation decisions. However, what is actually most convenient can vary greatly among applications. The most convenient way to instruct the sensor to take a measurement may be pressing a button on the sensor, sending a remote command (e.g., from a phone or computer), or scheduling automatic measurements at a desired time interval. The most convenient way to process the measurements may be performing manual computations afterwards or programming a complex series of operations that include applying calibrations, filtering, averaging, analyzing, and recommending action. The most convenient way to record the measurements may be writing temperature values on a piece of paper or storing temperature values along with date, time, and location information in digital memory. The most convenient way to transfer the measurements elsewhere may be entering numbers into a spreadsheet or scheduling automatic uploading to a server via a cellular data network. If an infrared thermometer or a thermal infrared camera does not have all the necessary software capabilities for an application, the missing capabilities can be outsourced as long as the sensor is compatible with companion devices that can provide those missing capabilities.

- What is the financial budget for the sensor?

Thermal infrared cameras tend to be more expensive than infrared thermometers of similar merit, while sensors marketed towards researchers tend to be more expensive than those marketed towards the general public. Nonetheless, some studies have concluded that a substantial price difference does not guarantee a substantial performance difference, and that two infrared thermometers of unequal cost may be equally appropriate for some applications (Mahan and Yeater, 2008; Mahan et al., 2010).

The above list of questions should be considered holistically when choosing a thermal infrared sensor. Additionally, for any application, the alternative(s) to ground-based thermal sensing should be explored also.

Application of Canopy Temperature to Irrigation Scheduling

Ground-based thermal sensing can serve as the primary means by which irrigation is scheduled. Because of the strong and direct physical relationship between canopy temperature and water stress under a given sun position and set of weather conditions, irrigation scheduling based on canopy temperature is quite close to monitoring and responding to water stress itself, especially compared with calendar-based or weather-based irrigation scheduling.

Furthermore, the noncontact nature of canopy temperature sensing creates opportunities to inform variable rate irrigation management by mounting infrared thermometers and thermal infrared cameras either to multiple stationary structures (e.g., poles) or to vehicles (e.g., center pivots, high-clearance applicators) that can move across the field throughout the irrigation season (Sadler et al., 2002).

Although many research studies monitor canopy temperature with thermal infrared sensors, few studies actually schedule irrigation using ground-based thermal sensing. The remainder of this section focuses on the latter type of studies. Field-tested approaches to irrigation scheduling that are based on at most one set of temperature measurements per day include irrigating whenever:

- the canopy temperature range spanned by multiple replicate measurements exceeds a threshold (Clawson and Blad, 1982);
- the difference between actual canopy temperature and plentifully watered canopy temperature exceeds a threshold (Clawson and Blad, 1982); or
- the value of the Crop Water Stress Index (CWSI; Idso et al., 1981; Jackson et al., 1981; see equation) exceeds a threshold (Nielsen, 1990; Stegman and Soderlund, 1992) where T_c is canopy temperature and T_a is air temperature.

$$CWSI = \frac{(T_c - T_a)_{\text{actual}} - (T_c - T_a)_{\text{plenty of water}}}{(T_c - T_a)_{\text{no water}} - (T_c - T_a)_{\text{plenty of water}}}$$

Field-tested approaches to irrigation scheduling that are based on continuous temperature data (which some studies predicted by temporal scaling according to Peters and Evett [2004]) include:

- the Temperature-Time Threshold approach, which recommends irrigation whenever the accumulated time above a temperature threshold exceeds a time threshold (Wanjura et al., 1990; Wanjura et al., 1995; Upchurch et al., 1996; Peters and Evett, 2008; O'Shaughnessy et al., 2012); and
- the Integrated Crop Water Stress Index approach, which recommends irrigation whenever the running total of Crop Water Stress Index exceeds an index-time threshold (O'Shaughnessy et al., 2013; O'Shaughnessy et al., 2015; O'Shaughnessy et al., 2017).

Field testing of irrigation scheduling approaches using ground-based thermal sensing has been scarce in Nebraska. The Clawson and Blad (1982) study cited previously was conducted on corn in 1979 at the university's Sandhills Agricultural Laboratory near Tryon, Neb. More information from new Nebraska research will be shared once it becomes available. In the meantime, growers and consultants who are interested in trying this technology are encouraged to contact the authors.

Final Remarks

Despite the rich history of research on this topic, irrigation scheduling based on canopy temperature has a disadvantage. Canopy temperature provides no predictive information about the imminence of future water stress, yet many irrigation systems are designed to require two to four days to complete one application across an entire field. If an irrigation application is started only after water stress can be confidently confirmed in the presence of temperature measurement uncertainties, the part of the field that is irrigated last may suffer significant water stress. Withholding irrigation before confirmed water stress might not pose a problem for crops whose yield quantity (e.g., cotton) or yield quality (e.g., wine grape) is maximized under some water stress. Thus, irrigation scheduling based on canopy temperature may be most suitable for these crops and for fields where the water supply is inadequate for full irrigation.

However, withholding irrigation before confirmed water stress is inappropriate for crops that achieve maximum yield in the absence of water stress and are growing on fields with adequate water supply for full irrigation. Growers who delay irrigation in this manner not only may be incurring yield loss due to water stress but also may be violating the terms of their irrigated crop insurance policies. Where the water supply is adequate for full irrigation, university recommendations encourage growers to maintain generous amounts of soil moisture while leaving room for capturing mid-season rainfall and then to draw down soil moisture towards the end of the growing season. These recommendations account for the typical multiday duration of an irrigation application and for possible adverse conditions (e.g., equipment breakdown, days with extremely high evaporative demand).

Under the current circumstances of irrigated crop production in Nebraska, the appropriateness of irrigation scheduling based on canopy temperature is uncertain at this time. However, some research has found optimistic results in a location more humid than Nebraska (Bockhold et al., 2011). This would imply a climate where increases in canopy temperature are even smaller and more difficult to confirm. Irrigation scheduling based on canopy temperature warrants further research in Nebraska so that its application in the Nebraska context can be more clearly determined (Payero and Irmak, 2006).

Opportunities also exist to combine thermal infrared sensors with simulation models and soil moisture sensors to complement the strengths and weaknesses of each technology for irrigation management. For example, while thermal infrared sensors may be used to quantify the severity of water stress, soil moisture sensors may be used to track soil water status and to decide irrigation application depths (Irmak et al., 2000). Such eventual integration of technologies would benefit both conventional irrigation and variable rate irrigation (Barker et al., 2018).

In the meantime, the following Nebraska Extension resources can provide information about other irrigation management tools:

- EC3002, *Soil Water Sensors for Irrigation Management*
- EC783, *Principles and Operational Characteristics of Watermark Granular Matrix Sensor to Measure Soil Water Status and Its Practical Applications for Irrigation Management in Various Soil Textures*
- G1579, *Using Modified Atmometers (ETgage®) for Irrigation Management*
- Nebraska ETgage® weekly data map (*https://nawmn.unl.edu/ETdata/DataMap*)
- G1850, *Irrigation Management for Corn*
- G1367, *Irrigating Soybean*
- G1871, *Predicting the Last Irrigation of the Season*
- EC2000, *Variable Rate Application of Irrigation Water with Center Pivots*

- CornSoyWater: a weather-based irrigation scheduling tool (*http://cornsoywater.unl.edu*)

DISCLAIMER

Reference to commercial products or trade names is made with the understanding that no discrimination is intended of those not mentioned and no endorsement by Nebraska Extension or the authors is implied for those mentioned.

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