The Northern Colorado Limited Irrigation Research Farm: Past and Future Experiments

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Abstract: *Agricultural water research has been conducted for over 100 years at the USDA-ARS Limited Irrigation Research Farm (LIRF) near Greeley, Colorado. Recent experiments since 2008 have focused on deficit irrigation of commodity crops, primarily corn. Experimental design and facilities are described, as well as water production function (yield vs. evapotranspiration) data obtained from 2008-2016. Water balance is determined using several inputs including on-site reference evapotranspiration, canopy cover, and feedback from soil water content using neutron probe measurements. Physiological measurements, from root length density to plant transpiration via sap-flow, have been taken and example results are also shown. Ground-based remote sensing is an important component of the program, from continuous infrared canopy temperature readings in focused plots to less frequent multispectral and thermal imaging taken from a high clearance tractor with a customized boom. Results and publications from previous projects are briefly highlighted, and the current research focus outlined.*

Keywords. Deficit irrigation, limited irrigation, water productivity, water use efficiency, water stress, infrared thermometry, IRT, CWSI, remote sensing, image processing, root growth, sap flow, plant traits

Introduction

Irrigation water supplies in the Great Plains and much of the western U.S. are declining. Supplies originally developed for irrigated agriculture are being diverted to growing urban areas and for ecosystem restoration. Groundwater use in many areas has exceeded sustainable amounts and must decrease to prevent aquifer depletion. Temperature increases due to climate change will likely reduce mountain snowpack accumulation that is critical to irrigation water supplies and may increase watershed evapotranspiration and crop water requirements. Irrigated agriculture will likely have less water available in the future than it had in the past. Sustaining irrigated agriculture and meeting future food and fiber needs of the growing global population will require increasing productivity per unit of water.

To respond to these needs, the Limited Irrigation Research Farm (LIRF) was established near Greeley, CO in 2008. Managed by the USDA-ARS (Agricultural Research Service) Water Management and Systems Research Unit (formerly Water Management Research Unit), this farm and research group have the overall goal of defining management strategies to sustain irrigated agriculture with limited water supplies. Specific objectives include:

- Determining potential for crop evapotranspiration (ET) savings from growth-stage based strategic deficit irrigation.
- Improving irrigation scheduling by developing crop coefficients from ground-based remote sensing.
- Understanding physiological responses to crop water stress.

This paper provides an overview of the LIRF, the datasets collected and works published since 2008, and goals/aims going forward.

Farm and Experiment Description

The LIRF is located northeast of Greeley, CO (40°26’50” N, 104°38’10” W, 1425 m asl). The 16-ha facility was developed to conduct research on irrigated crop water requirements and crop response. Annual and seasonal average precipitation at this semi-arid site is 340 and 220 mm, respectively. A 4.7-ha experimental field was divided into 4 equal crop sections. From 2008 to 2011, maize (*Zea mays* L., the dominant crop in the region) was grown in rotation with sunflower (*Helianthus annuus*), dry bean (*Phaseolus vulgaris*), and winter wheat (*Triticum aestivum*), as shown in Figure 1. Each field section was divided into 4 replicate blocks, and each block was divided into six 9 x 43 m plots containing 12 N-S oriented crop rows (0.76 m row spacing) on which six irrigation treatments were randomly assigned (randomized block design). From 2012 to 2016, the western two sections and eastern two sections were combined and used to grow maize and sunflower (*H. annuus*) in rotation, with 12 irrigation treatments. Irrigations were applied using surface drip tubing, placed next to each plant row. The east and west edges of each crop section contained a 6 row buffer, with all measurements taking place in the middle 4 to 6 rows. While several crops were evaluated in the overall experiment, the results shown in this paper will be exclusively for maize. All treatments of the same crop were planted at the same population and received the same nitrogen applications. Minimum tillage was used to maintain surface residue from the previous crop and minimize surface evaporation.

Figure 1. Aerial view of the water productivity plots at LIRF on August 1, 2008. Crops from left to right are dry beans, winter wheat (post-harvest), sunflower, and maize. Note visible treatment effects in maize, which was at a more advanced growth stage and has more aboveground biomass than dry bean and sunflower.

Irrigation and Water Balance

The full irrigation treatment was irrigated such that water availability (irrigation plus precipitation plus stored soil water) was adequate to meet crop water requirements, as predicted by the reference evapotranspiration and crop coefficients from FAO-56 methodology (Allen et al., 1998). Adequacy was monitored by ensuring the soil water content remained in the readily available water range. The remaining treatments were irrigated to achieve total water applications (irrigation plus precipitation) that approximated the target treatment amounts. In the 2008-2011 experiment (Trout, 2016), the scaling of the remaining treatments was typically done throughout the season; in the 2012-2016 experiment there were varying levels of water stress and ET reduction imposed from V7 (7 leaves) until VT (tasseling), and from R4 (dough) to maturity. During the sensitive reproductive stages between VT and R4, the crop was irrigated to eliminate water stress. Irrigation applications to each treatment were measured with turbine flow meters (Badger Recordall Turbo 160 with RTR transmitters). Soil water content, SWC, was measured 2 or 3 times each week on the days before and/or after irrigation in the crop row near the center of each plot. Soil water content was measured in 30 cm depth increments between 30 and 150 cm depth, and at 200 cm depth with a neutron soil moisture meter, NMM, (CPN-503 Hydroprobe, InstroTek, San Francisco, CA). The NMM was calibrated gravimetrically at the site. The calibration was used to convert instrument relative counts to volumetric soil water content (SWC). The NMM measures SWC within an approximately 15 cm radius from the measurement point, and was assumed to represent the soil profile within 15 cm of the measurement depth (eg. the 30 cm depth measurement represented the 15 – 45 cm depth). The SWC in the surface 15 cm was measured in the row near the NMM access tube with a portable time domain reflectometer (Minitrase, Soilmoisture Equipment Corp, Santa Barbara, CA) with 15 cm long rods.

By assuming zero runoff due to relatively small field slopes, adequate soil infiltration and surface residue, and drip irrigation, the crop ET (ETc) was estimated as

$$ETc = I + P - \Delta S - DP \qquad \text{Eq. 1}$$

Full details of water balance are described in Trout and DeJonge (2013). An example of soil water trends under two irrigation treatments is shown in Figure 2.

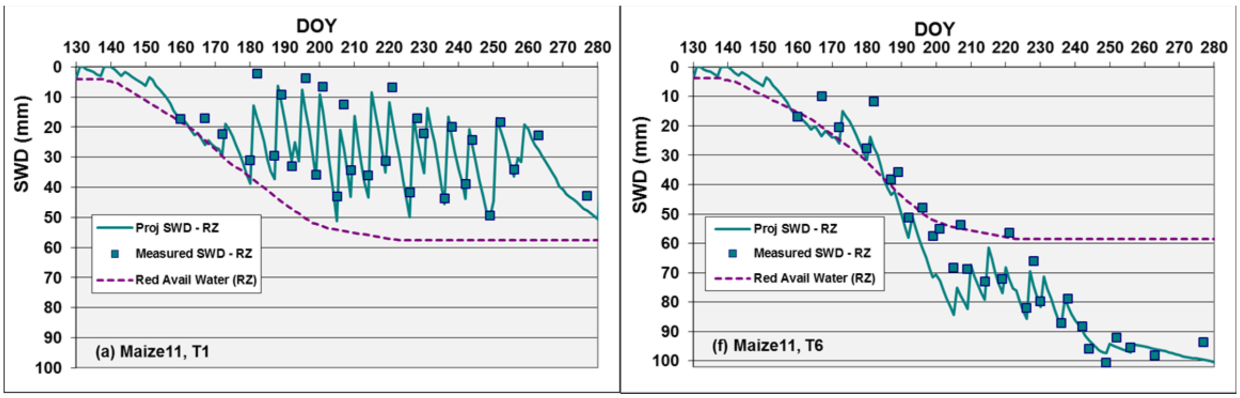

Figure 2. Soil water deficit (SWD, mm) for LIRF 2011 maize fully irrigated treatment (T1, left) and deficit irrigated treatment (T6, right). Squares are the measured SWD in the active root zone, solid line is the modeled SWD, and the dashed line represents the readily available water for the active root zone.

Water Production Function

Crop productivity and its relationship with water is often considered either in terms of yield vs. water applied, or yield vs. ET, the latter of which is called a water production function (WPF). The productivity of maize in the 2008-2011 experiment is shown below (Figure 3). . Results from 2012-2016 have shown similar WPF among treatments with the same deficit target between the two stress periods (late vegetative and maturation periods) with evidence that different deficit targets between these periods (e.g. substantial deficit in either period with near full irrigation in the other) can cause departures (Comas et al., 2014).

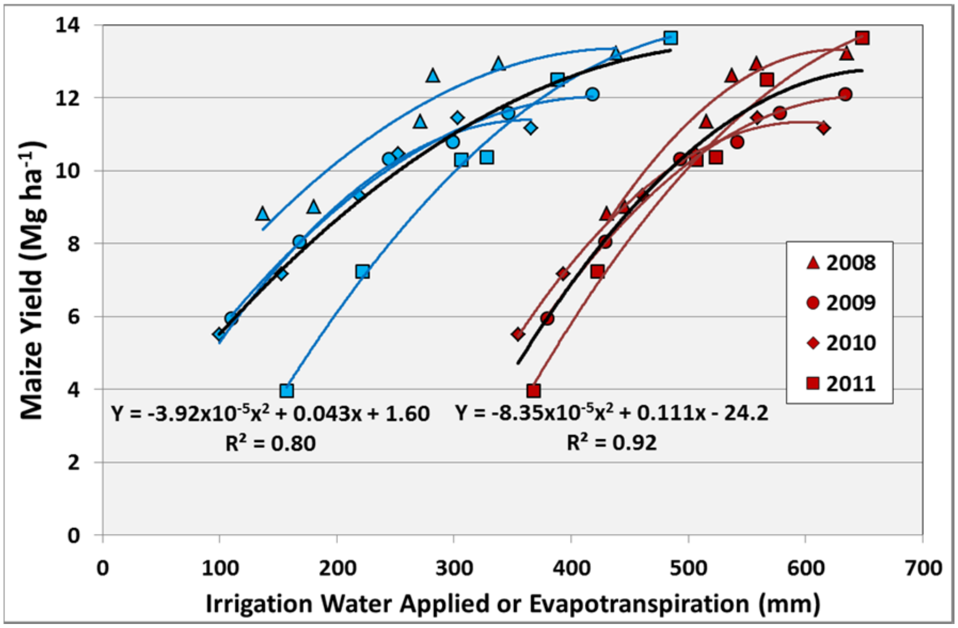

Figure 3. Maize grain yield (@15.5% moisture content) vs. irrigation water applied (left curves, blue symbols) and crop evapotranspiration (right curves, red symbols). Narrow (colored) lines are 2nd degree polynomial regression fits to the mean yield data for each year. Thick (black) lines and equations are regression fits to the combined 4 years of data.

The water production function based on applied irrigation water is fairly flat at full irrigation and curves downward as the water application decreases, showing that the decrease in yield for each unit decrease in water applied is relatively small when the deficit is small, but the rate of yield decrease gets larger as the deficit increases. This means that the marginal productivity of irrigation water (additional yield per unit additional water) is relatively low near full irrigation, showing the potential benefit to the farmer of reducing irrigation and transferring water to higher-valued uses. The water use efficiency, or productivity per unit of irrigation water applied, increases from about 29 kg ha^{-1} mm^{-1} of water applied at full irrigation to about 40 kg ha^{-1} mm^{-1} when irrigation is reduced by 50%. This is because irrigation is more efficient, precipitation is more effectively used by the crop, and the crop extracts more water from the soil.

However, the water production function for grain yield based consumptive use or ET (the right curves in Fig 6) moves to the right and is relatively straight and consistent until at maximum ET, where it levels and spreads some. This implies that the corn is equally efficient in its use of every additional unit of water consumed. The water use efficiency in terms of ET is about 20 kg ha^{-1} mm^{-1} at full irrigation. This is smaller than when based on irrigation water because it also counts precipitation used by the crop. The water use efficiency based on ET stays relatively constant for deficits up to about 15%, and then decreases. Because corn requires about 250-300 mm of water to produce any yield, the water use efficiency declines with deficit irrigation.

Infrared Thermometry

Canopy temperature has been used as an indicator of crop water stress, since a reduction in plant available water results in lower transpiration rates and consequently higher canopy temperatures. The LIRF experiment has provided a framework to collect comprehensive datasets of canopy temperature. Temperature of the corn canopy was acquired on a continuous basis (Figure 4) using infrared thermal radiometer (IRT, model: SI-121, Apogee Instruments Inc., Logan UT) with a 36° field of view and ±0.2 °C accuracy. The IRTs were attached to telescoping posts and angled 23° below horizontal and 45° from north (looking northeast) to ensure viewing primarily crop canopy once canopy cover was nearly complete. Data was typically omitted when canopy was less than 80% total ground cover, to limit view of soil background. Measurements were sampled every 5s and averaged over 30 min intervals.

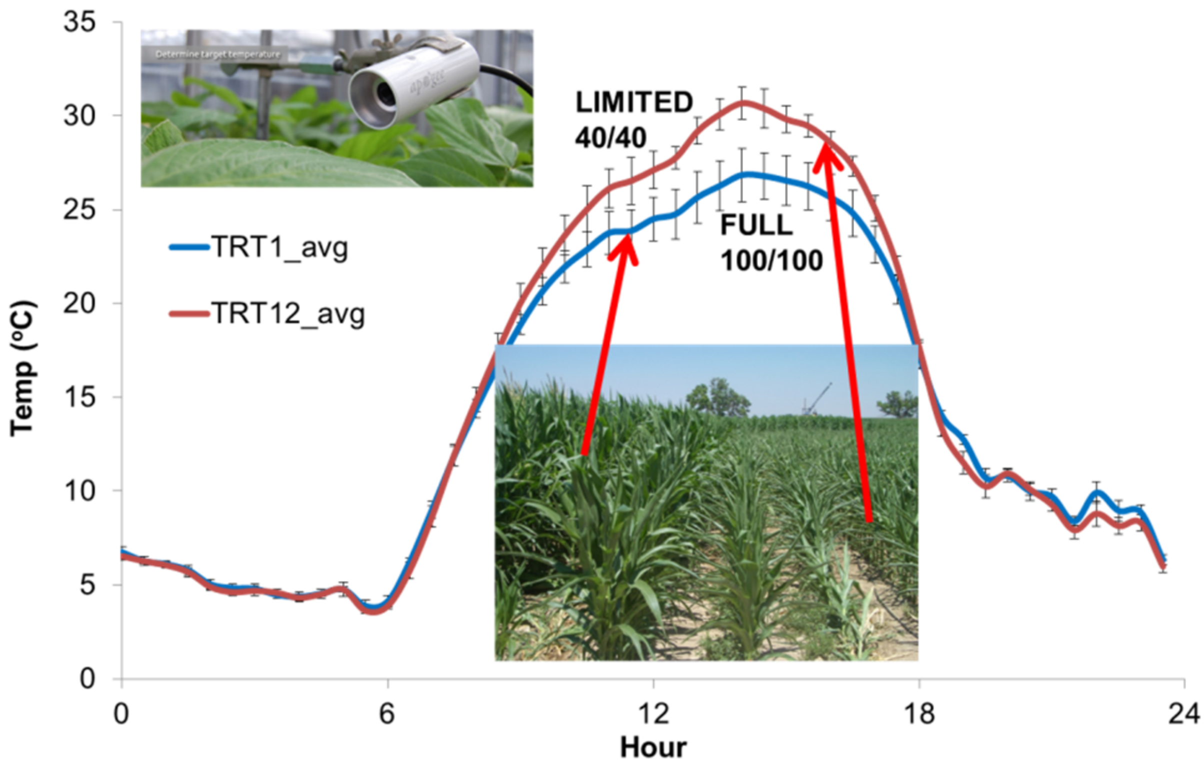

Figure 4. Representative single-day canopy temperature for fully irrigated maize (blue) and limited irrigation maize (red). Error bars indicate standard deviation from four replicates.

Several indices have been developed for monitoring and quantifying water stress from infrared thermometry, using canopy temperature (Tc) as a main driver. The most famous of these is the Crop Water Stress Index (CWSI) established in the early 1980s (Idso et al., 1981; Jackson et al., 1981). While this index is often considered the gold standard, it has additional meteorological requirements which include onsite air temperature and humidity, as well as creation of site or region-specific baselines. Our research recently showed that canopy temperature alone can be strongly correlated with plant physiological measurements of crop water stress such as leaf water potential (DeJonge et al., 2015), which is discussed in more detail later.

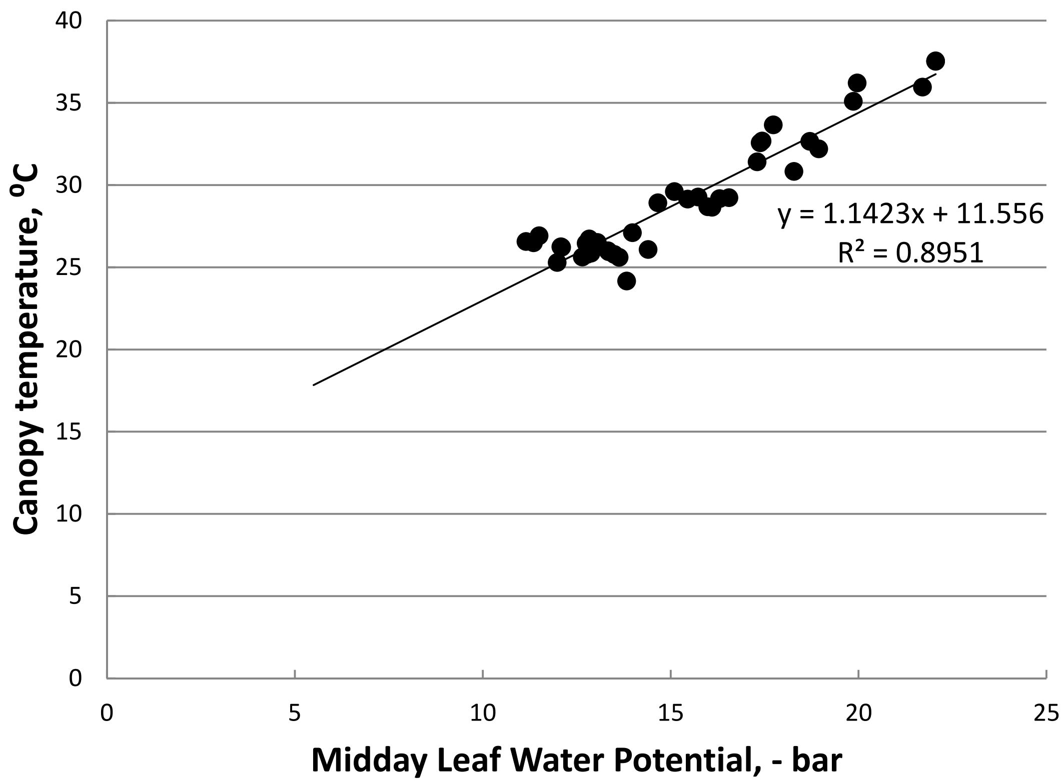

Figure 5. Canopy temperature at 1400 h (Tc) vs. midday leaf water potential (Ψ_L) taken on leaves collected in a two hour window straddling 1400 h on three dates in 2013 (growth stage in parentheses): 23 July (vegetative), 15 August (anthesis), and 3 September (grain-filling). Adapted from DeJonge et al. (2015).

Research conducted at LIRF has resulted in several simpler alternative indices such as the canopy temperature ratio Tcratio (Bausch et al., 2010), degrees above non-stressed canopy temperature DANS (Taghvaeian et al., 2014), and degrees above canopy temperature threshold DACT (DeJonge et al., 2015). These simpler indices may have promise for use by producers given the advantages of less data needs (Table 1), and can be converted to a stress coefficient to reduce crop transpiration under water stress (Kullberg et al., 2016). New methods are being created to process nadir thermal images in new quantifiers of water stress (Han et al., 2016), with more discussion to follow. Additional work is being conducted to create smartphone-based tools for farmers to quantify water stress and ET reduction.

Table 1. Comparison of basic data required for each K_s method tested and associated ET_c estimation RMSE. From Kullberg et al. (2016).

Category	**Requirement**	***K_s* method**			
		CWSI	**DANS**	**DACT**	**T_{cratio}**
Canopy Temperature	Target	X	X	X	X
	Non-Stressed Reference		X		X
Environmental	Relative Humidity	X			
	Air Temperature	X			
	Clear Sky	X	X	X	X
Pre-Calculation	Baselines (locally calibrated)	X			
	Threshold Temperature			X	
	Scaling Coefficient (locally calibrated)		X	X	
	Daily ET_c RMSE (mm/day)	0.77	0.80	0.80	0.83
	Daily ET_c RMSE (%)	14.6	15.2	15.2	15.6

Ground-Based Remote Sensing

Remote sensing data has been collected for crop irrigation management. Ground-based digital RGB, multispectral and thermal imagery were taken with a highboy tractor with a customized boom (Figure 6) using a Canon RGB camera, Tetracam Mini MCA multispectral camera (Tetracam, Inc.) and a FLIR IR camera A645s (FLIR Systems, Inc., Portland, USA). Canopy cover was estimated by separating transpiring (green) from nontranspiring (soil, non-green canopy) using RGB or multispectral images, and near real-time crop coefficient was determined based on crop canopy cover measurements (Trout and Johnson, 2007). We are developing an unmanned aerial system equipped with multispectral and thermal cameras to monitor vegetation, quantify crop water status, and estimate crop coefficient and crop ET at desirable spatial and temporal resolutions.

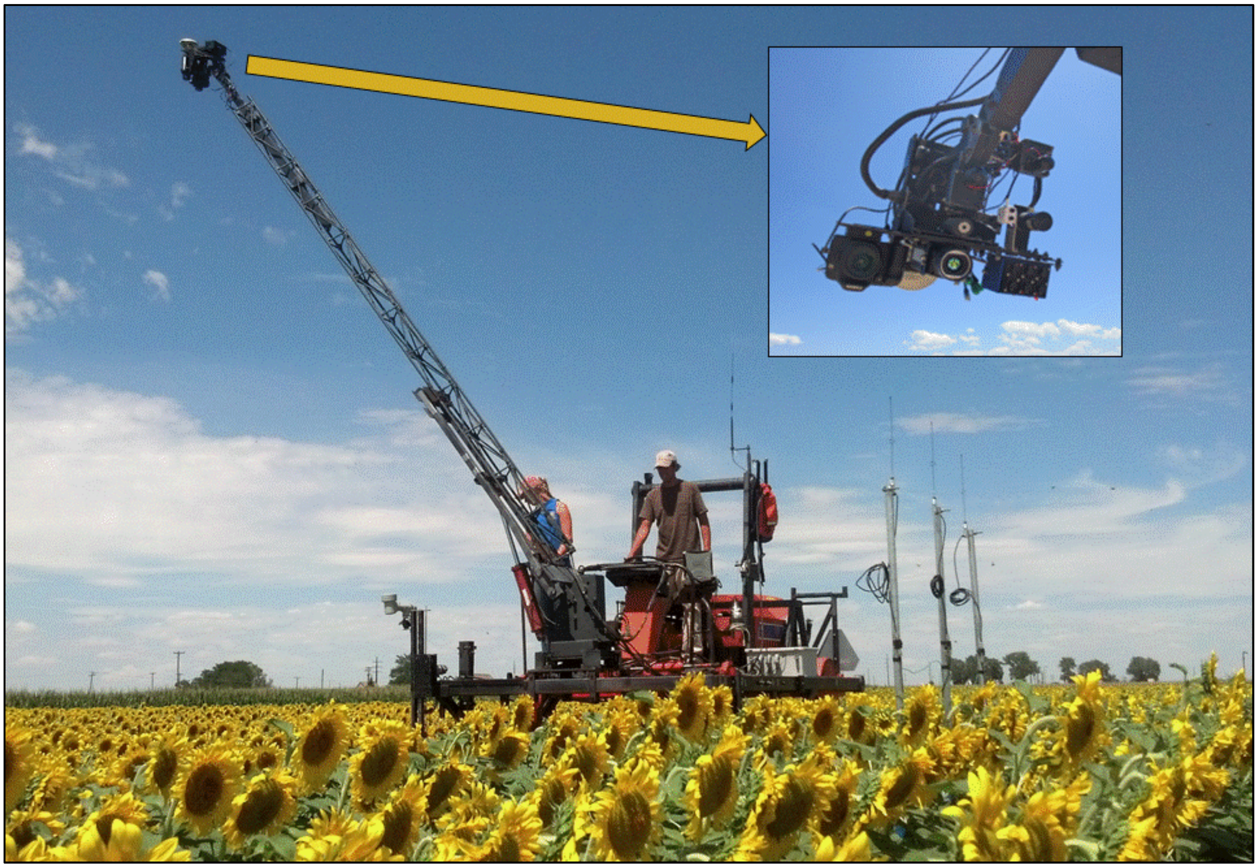

Figure 6. High clearance tractor ground-based remote sensing data collection platform. The tractor drives in "border rows" between plots where no samples are taken, and captures nadir images of adjacent plots without direct contact or disturbance.

Using high resolution thermal imagery (Figure 7), we also developed a methodology to obtain canopy temperature distribution, and proved that canopy temperature standard deviation (CTSD) could be used for maize water stress detection and be a potential tool for irrigation scheduling (Han et al., 2016).

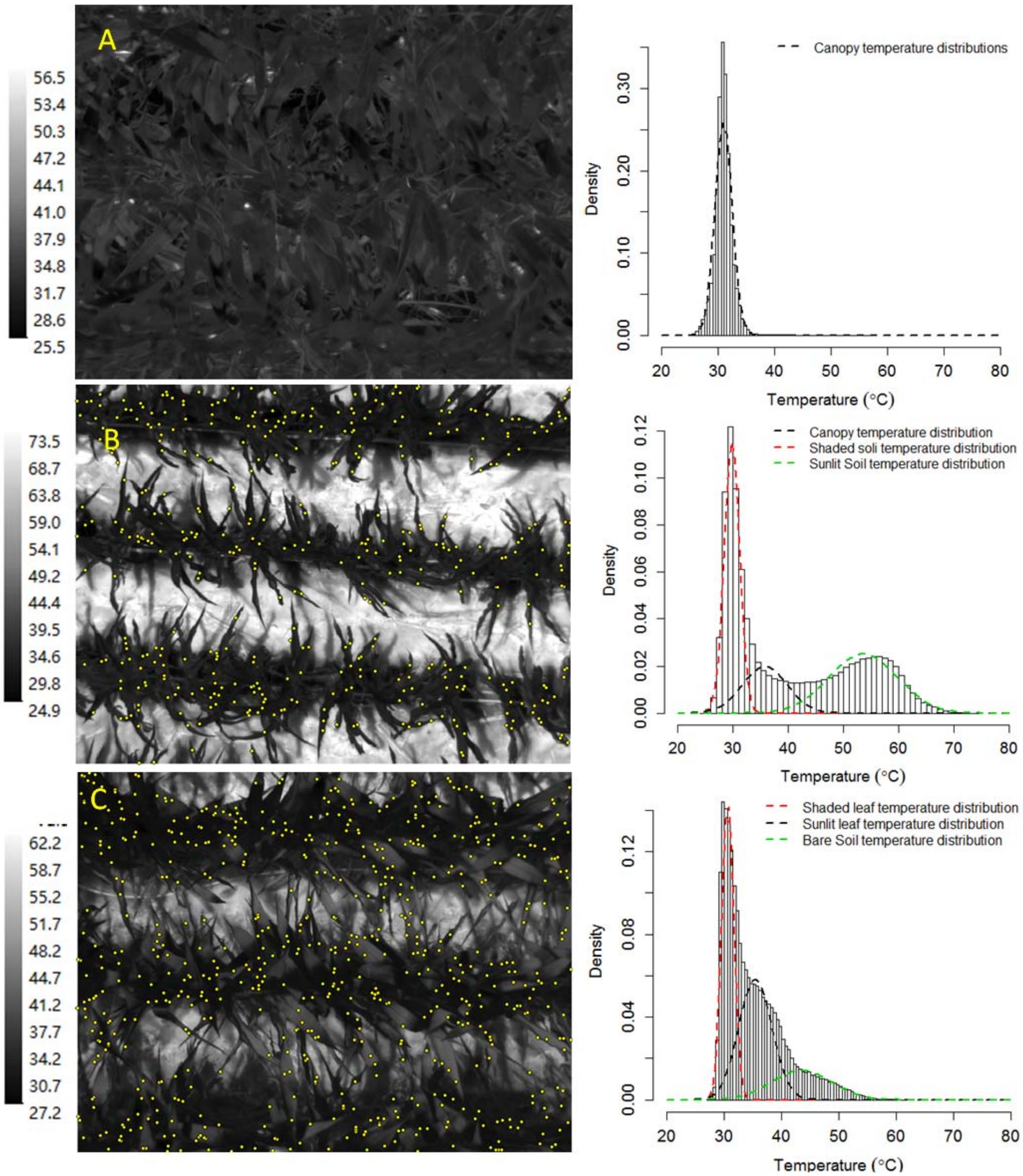

Figure 7. Examples of thermal images of maize taken in 2013 and their temperature distributions (A: DOY 241, Treatment 1: 100% ET; B: DOY 183, Treatment 12: 40% ET; C: DOY 204, Treatment 10: 65% ET). Yellow points were manually selected for calibration of the methods used. From Han et al. (2016).

Physiological Measurements

Physiological measurements are taken to understand plant responses underlying effects of deficit irrigation on yield, document plant stress and water use, and ground-truth the remote sensing of stress. Leaf water potential, Ψ_L, taken with a Scholander pressure chamber, is the standard measure of plant stress (Figure 9). Measurements are typically taken at midday within a two hour window past solar noon to document the maximum daily stress achieved. Measurements of canopy development, root system development (Figure 10 and Figure 11), leaf level transpiration, stomatal conductance, carbon fixation and fluorescence (indicating electron transport through photosystem II) under varying levels of water availability are made to quantify plant development above and below ground, water use and the acclimation of photosynthesis to water limitations. Measurements have documented roots deeper in the soil profile in crops well adapted for drought such as sunflower compared to maize (Figure 11). Measurements have also shown that root growth stimulation under deficit irrigation mainly occurred at middle depths in the rooting profile (30-70 cm) under frequent (4-5 d) surface drip irrigation (Figure 11). Measurements of sap flow with heat-balance type sap flow gages are made to quantify whole plant water use (Figure 12). Crop transpiration determined from water balance is closely aligned with measurements from sap flow (data not shown).

Figure 9. Midday leaf water potential (Ψ_L) measured with a pressure chamber. A distal portion of a leaf is cut, put in a zippered plastic bag, and transported in an insulated cooler to the pressure chamber, where it is trimmed with a razor blade, covered with a damp cloth, and place in the chamber for measurement.

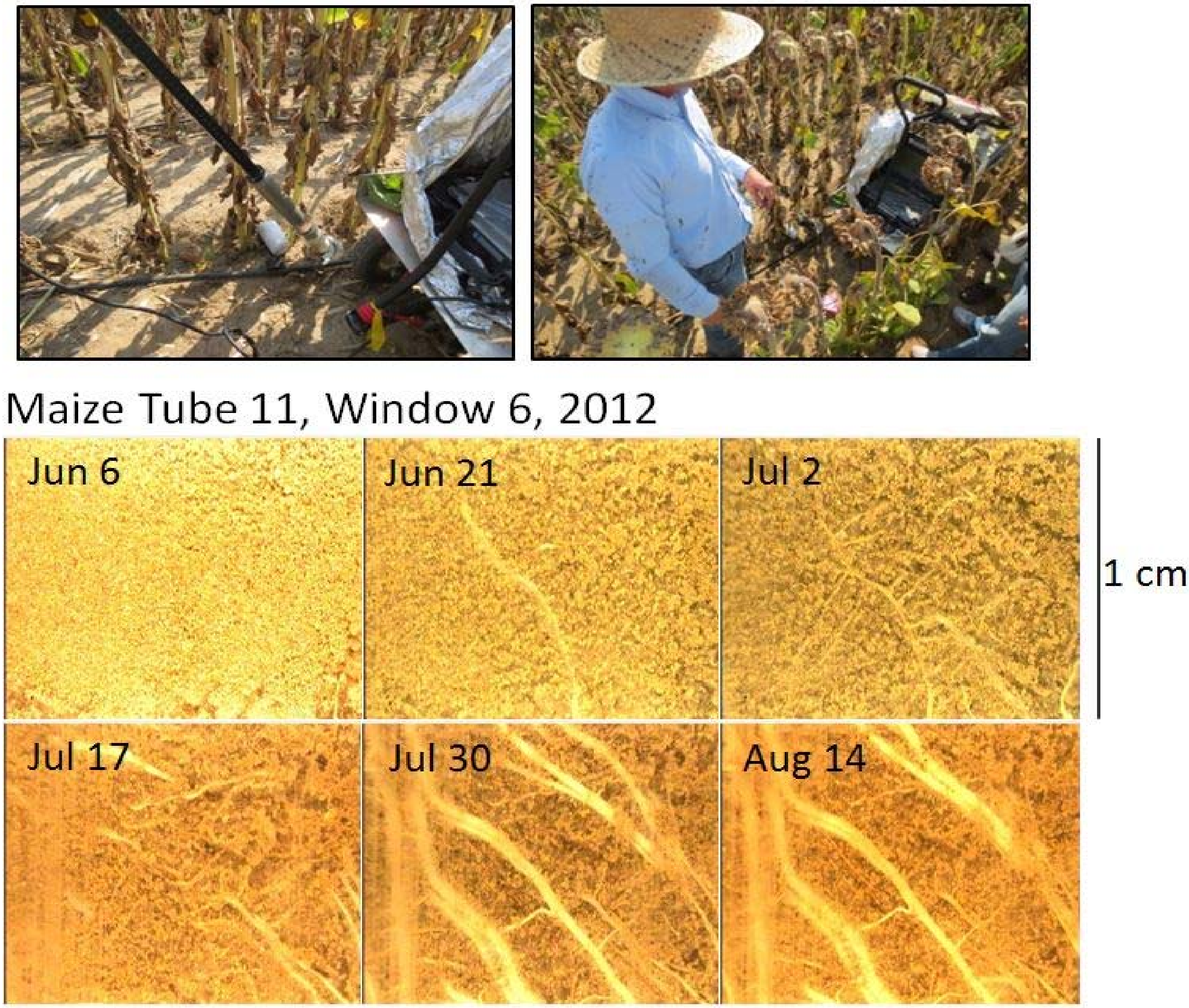

Figure 10. Minirhizotron camera system (Bartz Technology Corporation, Carpinteria, CA, USA) and root images recorded over the season. Upper left picture shows camera inserted into a clear acrylic tube installed in the field in a stand of sunflower. Upper right picture shows the computer system used to record images from a mobile cart. The lower pictures show a series of images with flushes of root growth recorded over the season from one position on the root tube.

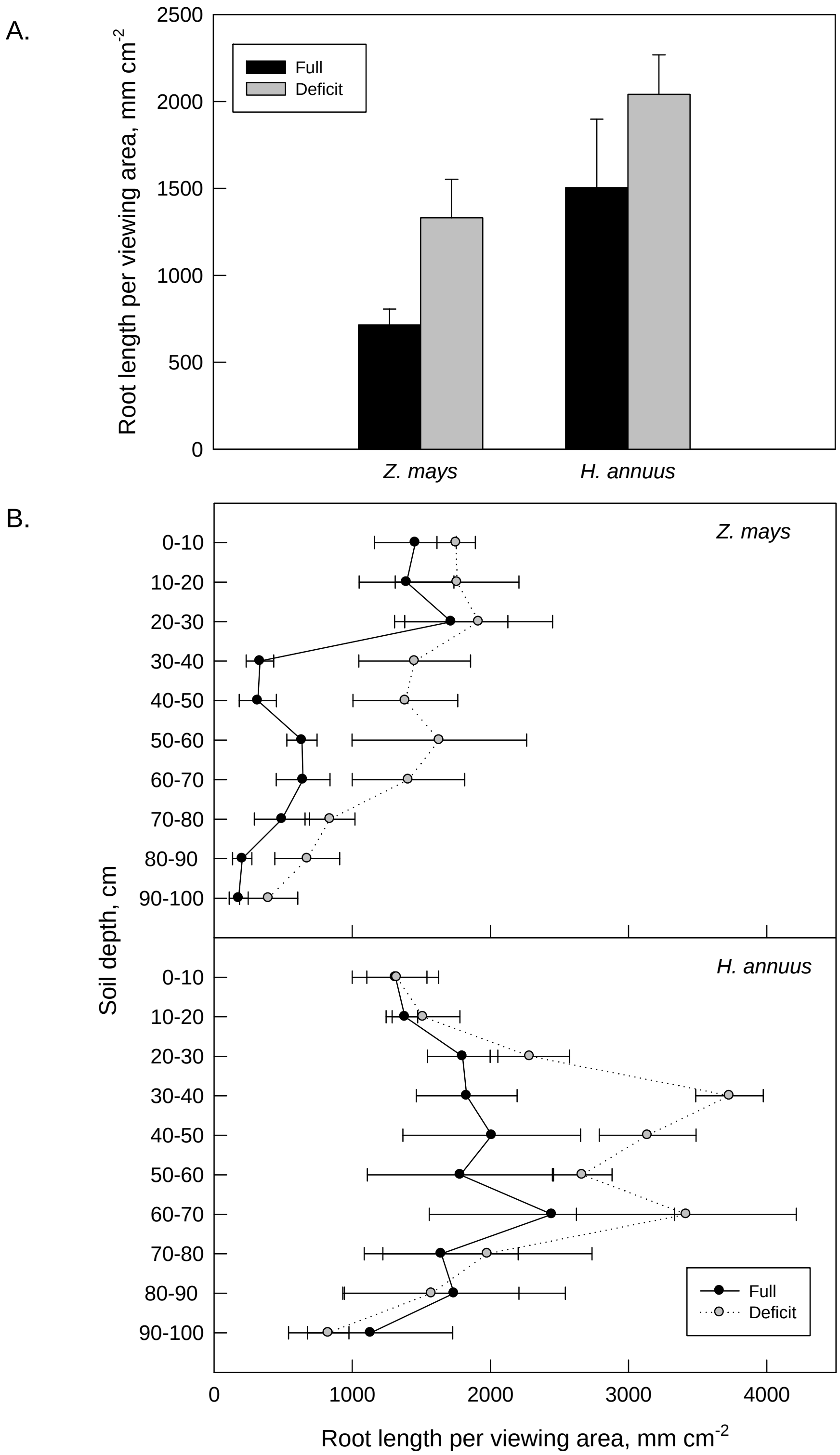

Figure 11. Annual root production (A) and distribution (B) in maize (Zea mays) and sunflower (Helianthus annuus) in 2012 from Comas et al. (2013). Root growth is expressed in terms of root length per viewing area of the minirhizotron window. Each bar and point represents root growth averaged among four minirhizotron tubes per treatment, with each tube installed in a different treatment plot. Error bars represent standard error of the mean.

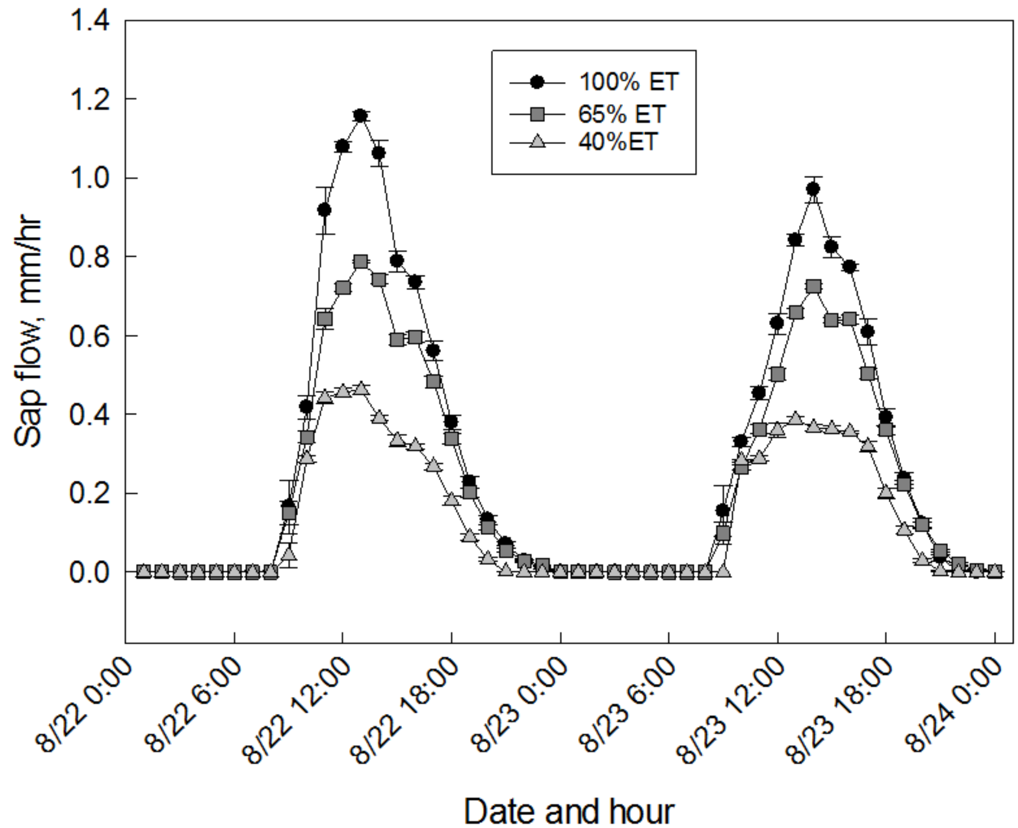

Figure 12. Hourly whole plant transpiration over two days in 2015. Each point is the hourly average of sap flow gages placed in four plots per treatment. Treatments are designated by the target ET. Error bars represent standard error of the mean.

Plant Traits

Drought is defined as a long-term absence of water, whereas deficit irrigation is a strategic management of water supplies based on critical growth stages. Improved production under drought periods of different lengths and timing within the growth season, as well as under regulated deficit irrigation will require different trait characteristics. Plants with higher water use efficiency (WUE), i.e. carbon income per unit water used, are best suited to deficit irrigation environments, whereas plants exhibiting resistance to short but extreme periods of water stress are best suited to dry environments. Greater water use efficiency can be achieved via either higher rates of growth or lower rates of water loss. In contrast with traits conferring higher WUE, the traits associated with improved drought tolerance are still poorly understood, but are likely to include: 1) robust water transport tissues that are less susceptible to dysfunction, 2) deeper or more efficient root systems, and 3) photosynthetic activities and apparatus that are less susceptible to damage during stress. At LIRF we evaluate different genetic varieties of maize to achieve a better understanding of which traits lead to better performance under drought and deficit irrigation. We take both a practical approach comparing commercially available genotypes that are available to farmers, as well as a biologically-informed approach, using an open-source “mapped” population that facilitates understanding performance~trait and trait~genetic relationships.

Published and preliminary data show that photochemical, stomatal, and water transport functioning are closely aligned during water stress in maize (Figure 13), with significant intrinsic variation existing in each of these traits across maize genotypes (Figure 14). This evidence strongly supports the idea that improved performance of maize in under both deficit irrigation as well as rain-fed environments will require improved water transport networks, which currently are not considered a priority for maize improvement (Gleason et al., 2012). Future work at LIRF will dig deeper into this issue.

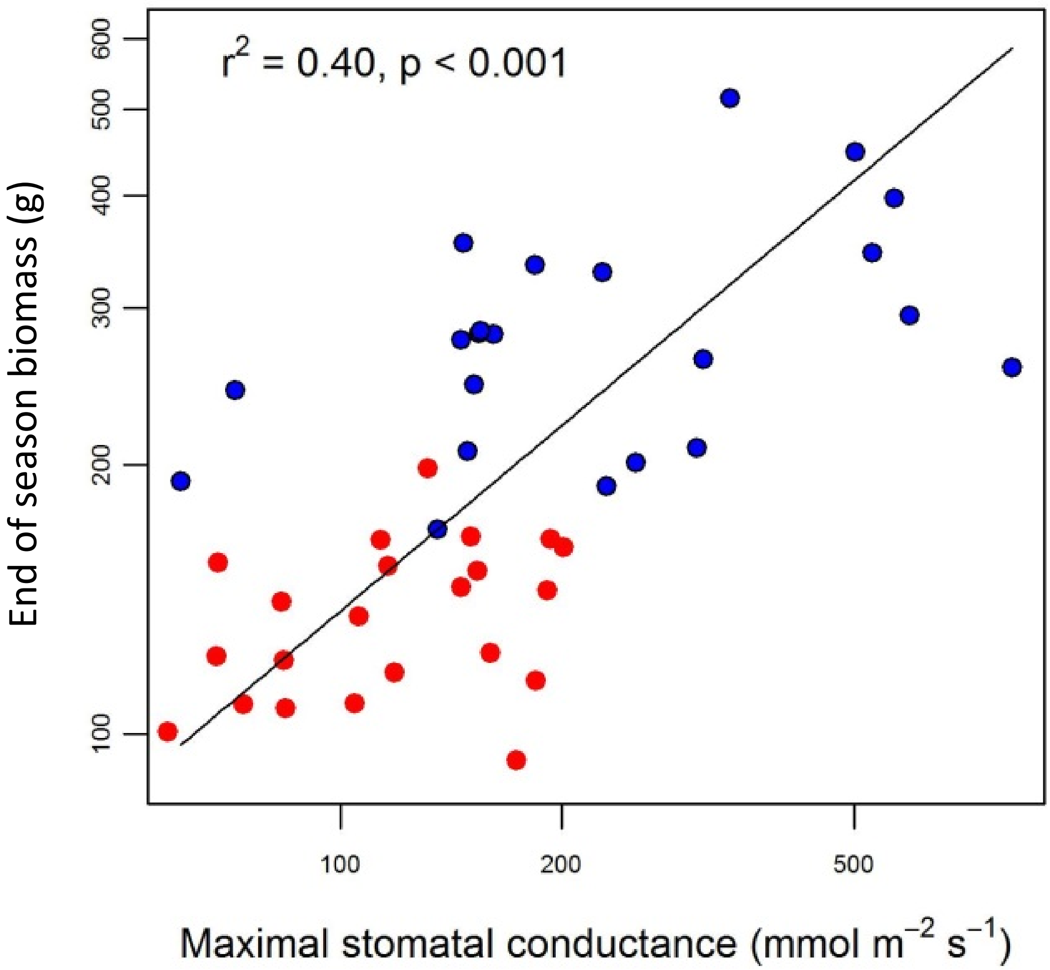

Figure 13. Relationship between maximal stomatal conductance (water loss at a given atmospheric demand) and end of season biomass. Each symbol represents a different maize genotype. Closed red and blue circles denote deficit-irrigated and fully-irrigated treatments, respectively. Note that maximal stomatal conductance explains ~40% of the total variation in end of season biomass across genotypes and treatments. This suggests that research focusing on the traits necessary to maintain high rates of stomatal conductance under water stress will also result in higher yield. It also suggests that much variation in these traits exists among maize varieties, and therefore, better performance can likely be achieved via trait-informed plant breeding and gene editing efforts.

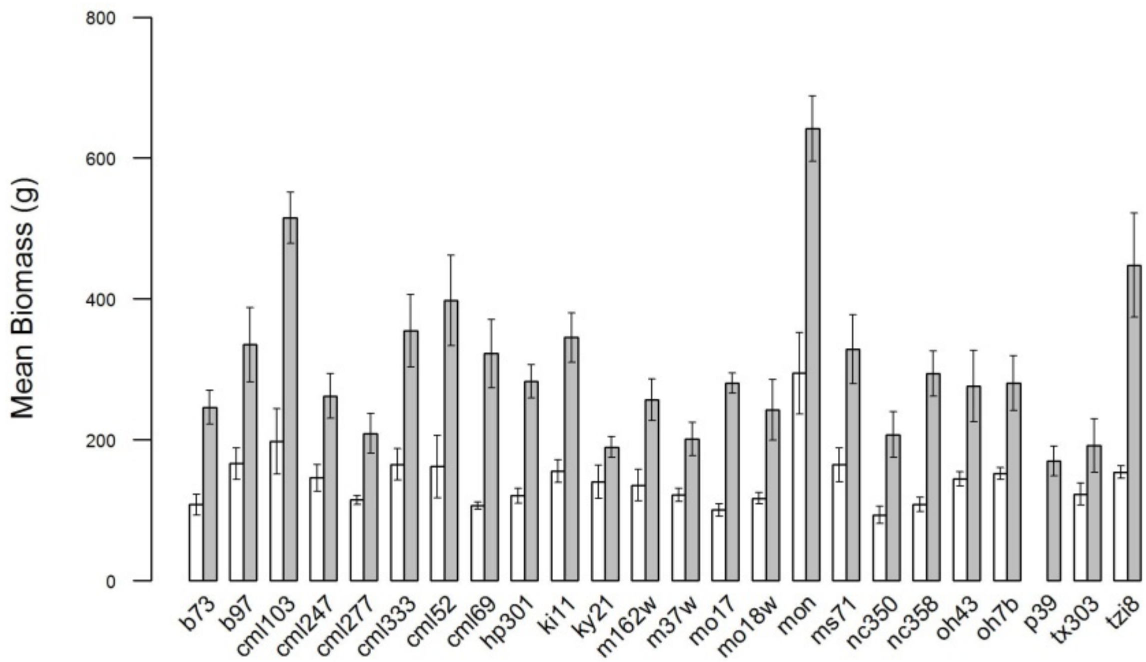

Figure 14. End-of-year biomass increment in fully-irrigated (gray bars) and deficit-irrigated (white bars) treatments across 24 inbred maize genotypes grown in Greeley, Colorado, USA. Note that the response to deficit irrigation (percentage reduction in biomass when grown under deficit vs full irrigation) varies markedly across genotypes. This suggests that response to deficit irrigation depends critically on the variety of maize that is grown.

Future Goals/Aims

Future work at LIRF will continue to explore new questions and objectives, which include:

1. Improve water use efficiency (WUE) by identifying plant traits, mechanisms, and agronomic practices that increase productivity per unit of water used by the crop.

2. Develop simple and accurate methods to quantify evapotranspiration (ET) in agricultural systems under limited water availability to improve the efficiency of irrigation scheduling.

3. Create Water Production Functions (WPF, yield per ET) for alternative crops under limited water availability.

Conclusions

The Limited Irrigation Research Farm (LIRF) near Greeley, CO is an agricultural experiment station that is exploring the management of limited or deficit irrigation, and gaining understanding on how this management affects crops at multiple levels, from satellite and ground-based remote sensing scales, to plant-based scales such as sap flow and root growth. Focus is also placed on quantifying water balance and evapotranspiration under water stress, and identifying plant traits that may be resistant to water limitations. The research Unit and farm has an annual Field Day, and welcomes tours throughout the field season – please contact us if you are interested in a field tour.

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