USDA-ARS Colorado Maize Water Productivity Data Set

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ABSTRACT

The USDA-Agricultural Research Service conducted a water productivity field trial for irrigated maize in northeastern Colorado in 2008 through 2011. The dataset, which is available online from the USDA National Agricultural Library, includes measurements of irrigation, precipitation, soil water storage, and plant growth; daily estimates of crop evapotranspiration; and seasonal measurement of crop water use and crop yield. Soil parameters and hourly and daily weather data are also provided. This paper describes the dataset and the methodology used to collect the data. The dataset can be useful to evaluate and improve maize crop models.

INTRODUCTION

The USDA-ARS Water Management Research Unit in Fort Collins, CO conducted water productivity field research near Greeley, CO from 2008 – 2011. We measured water productivity of a 4 crop rotation (winter wheat, maize, sunflower, dry bean) with 6 levels of irrigation. This dataset includes water balance, crop growth and yield measurements for maize (*Zea mays L.*) for 4 cropping seasons (2008-2011) under 6 levels of irrigation. The methodology includes detailed measurement of water balance components so crop water use (evapotranspiration) could be accurately estimated.

Data include:

- Soil texture and Water Retention vs. Water Potential
- Precipitation
- Irrigation application
- Soil water content
- Daily and hourly weather parameters (solar radiation, relative humidity, wind speed, air temperature)
- Phenology (growth stages, canopy ground cover, crop height, LAI)
- Final above ground biomass and grain yield
- Crop management activities, including tillage, seeding, fertility, and pest control
- Bowen ratio energy balance estimated crop evapotranspiration (only 2008, 2010, full irrigation)
- Biomass total carbon and nitrogen (only 2008, 2009)

Calculated, inferred, and estimated data include:

- Soil field capacity and plant available water

- Reference evapotranspiration
- Crop evapotranspiration
- Crop Transpiration
- Soil Evaporation

The dataset is available from the USDA National Agricultural Library data repository at https://data.nal.usda.gov/dataset/usda-ars-colorado-maize-water-productivity-dataset-2008-2011 . The data are presented in spreadsheet format. The primary data files are the four annual ***LIRF Maize 20xx.xlsx*** files that include the daily water balance and phenology, final yield and biomass data, and crop management logs. Annual ***LIRF Weather 20xx.xlsx*** files provide hourly and daily weather parameters including reference evapotranspiration. The ***LIRF Soils.xlsx*** file gives soil information. Each spreadsheet contains a *Data Descriptions* worksheet that provides worksheet or column specific information. Comments are embedded in cells with specific information. A ***LIRF photos.pdf*** file provides images of the experimental area, measurement processes and crop conditions.

MATERIALS AND METHODS

Field Site and Conditions

The field experiments were carried out at the USDA-ARS Limited Irrigation Research Farm (LIRF) (40°26’ N, 104°38’ W, and 1428 m asl) located NE of Greeley, CO (LIRF). The 16-ha facility near the western edge of the central High Plains was developed to conduct irrigated crop water requirements and response research. The average annual precipitation at the semi-arid site is 350 mm with 215 mm between May and Sept (PRISM, 2015). Annual and seasonal average precipitation during the 4 years of the study was near normal (340 and 220 mm, respectively). Irrigated maize is the dominant crop in the region and county maize grain yields (@15.5% grain moisture) averaged 11 Mg ha^{-1} during the 4 years of the experiment (USDA-NASS 2015).

Soils

The largest portion of the field experimental area contains Olney fine sandy loam soil (fine-loamy, mixed, superactive, mesic Ustic Haplargids). Other soils in the field are Nunn clay loam (fine, smectitic, mesic Aridic Argiustolls) (blocks 3 and 4 of section D (2008 Maize)), and Otero sandy loam (coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents) (most of section A (2010 Maize)) (USDA-NRCS 2015). The ***LIRF Soil*** spreadsheet shows soil maps and descriptions.

The surface soil at the site is fairly uniform due to a land levelling operation in 1980 in which the surface 20 - 30 cm was removed, stockpiled, and replaced. Below the surface layer, soil texture of the alluvial soil varies horizontally and vertically. Field soil variability was mapped by measuring electrical conductivity with a Veris resistivity machine (Veris Technologies, Salina, KS[1]). Sixteen soil cores, one from each block of each field section, were collected to 1.8 m depth (see ***LIRF Soils*** file for EC maps and soil sampling locations and data). Cores were divided into depth horizons by visual texture and color

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[1] Mention of products or trade names is provided for the benefit of the reader and does not imply endorsement of the product by the authors or USDA.

changes. Soil texture was measured with a hydrometer (Gee and Or 2002) and soil water content versus soil water potential was measured with a pressure plate apparatus (Klute 1986).

Soil texture of most soil horizons classified as loamy sand (LS), sandy loam (SL) or sandy clay loam (SCL). Surface soils (approximately 0 – 30 cm) classified as SL or SCL with average sand, silt, and clay fractions of 71, 11, and 18%, respectively. From 30 – 60 cm, the soils were more variable with the majority being SCL. In the 60 – 90 cm depth, the texture varied similar to the overlying layer but tended to have slightly higher sand fraction. Below 90 cm, most samples classified as sandy loams and loamy sands. Table 1 shows the mean sand, silt, and clay fractions for each field section by 30 cm depth increments.

Soil bulk density was measured during annual neutron moisture meter (NMM) calibration on 10 cm long volumetric samples collected with a 33 mm diameter soil tube that was inserted into the soil with a hydraulic soil sampling machine (Giddings Machine Co., Windsor, CO). Bulk density data for 93 cores are given in the Bulk Density worksheet of the ***LIRF Soils*** file. Average bulk density was 1.48 in the surface 15 cm and 1.68 - 1.70 g cm^{-3} in subsurface horizons, and was relatively uniform spatially and with depth below the surface layer.

Table 1 Soil texture (mean sand (S), silt (Si), and clay (C) fractions in %) for the four sections of the LIRF water productivity field

	A (Maize 2010)			B (Maize 2009)			C (Maize 2011)			D (Maize 2008)		
Depth	**S**	**Si**	**C**	**S**	**Si**	**C**	**S**	**Si**	**C**	**S**	**Si**	**C**
0 – 30 cm	76	9	15	72	11	17	69	12	19	67	13	20
30 – 60 cm	72	7	21	70	10	20	62	15	23	68	13	19
60 – 90 cm	78	7	15	73	6	21	80	5	15	57	13	30
90 – 120 cm	81	5	14	78	7	15	84	6	10	74	7	19

Twenty-seven of the 122 soil horizon samples from the 16 core samples were selected to represent a range of soil textures to determine the soil water retention characteristics. Soil water retention at 3, 10, 33, 50, 100, and 1474 kPa pressure was measured in a pressure plate apparatus. The ***LIRF Soil*** spreadsheet file lists the soil water retention data for each of the soil horizon samples. Figure 1 shows the water release curves for the soils. As expected, soil water content at any pressure generally decreased with the coarseness of the soil texture represented by the percent sand. At 10 kPa, the volumetric soil water content (SWC) varied from 12 to 35%, and at 33 kPa, from 9 to 29%. In general, SWC at 1475 kPa (15 bars) was about 60% of SWC at 33 kPa (1/3 bar), and about 50% of the SWC at 10 kPa (field capacity for coarse textured soils)). For our water balance, we assumed permanent wilting point was 50% of field capacity, and thus total plant available water was 50% of field capacity.

Soil organic matter, pH, electrical conductivity and several chemical constituents were measured by the Colorado State University Soil Testing Laboratory (Self 2010) on the 2007 soil samples used for the soil water retention measurements and on annual pre-plant soil fertility samples. The organic matter content averaged 1.6% for the surface soils and 1% from 30 – 90 cm. Soil pH (saturated paste) averaged 7.8 from 0 – 60 cm and 8.0 below 60 cm. Soil electrical conductivity (saturated paste extract) averaged

1.4 dS m^{-1} from 0 – 60 cm and 0.9 dS m^{-1} at lower depths in these initial samples, but declined to 0.5 dS m^{-1} during the project.

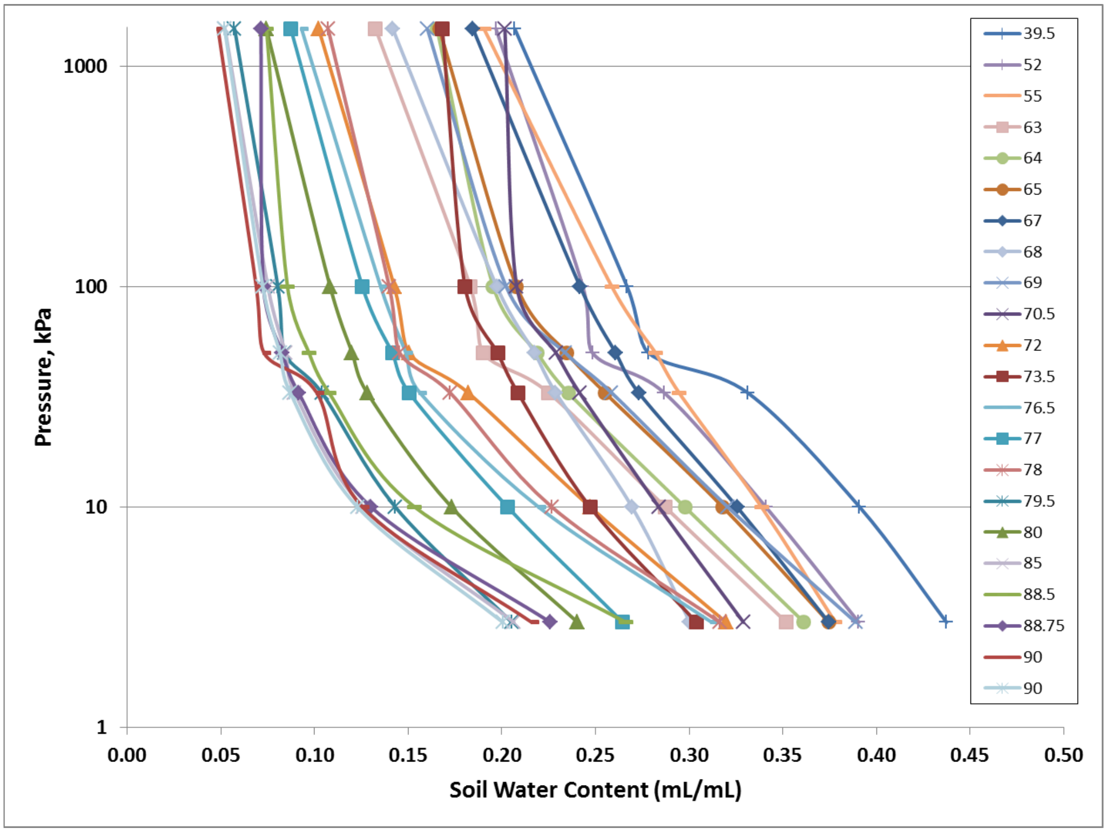


Figure 1 Water retention curves for LIRF Water Productivity Field. Legend lists percent sand content.

Field SWC measurements indicated that the variability present in the field could not be adequately represented by the pressure plate data. In some SWC measurement locations, SWC 24 hrs after irrigation substantially exceeded the 33 kPa value expected to represent the area, while at other locations, the SWC never reached the 33 kPa value even after drainage occurred at deeper levels. Thus, the field capacity, FC, values presented in the ***LIRF Maize*** files and used in the water balance calculations were measured in the field for each field SWC measurement site (neutron tube location) and each measurement depth. The field capacity was set at the soil water content measured approximately 24 hours after a large irrigation or precipitation event when SWC increased lower in the soil profile (ie. FC was exceeded and drainage occurred). Thus, this value is equivalent to a 24 hr drain down SWC and represents the upper limit of water stored and available for plant uptake. After 24 hrs, water uptake by the plant in the active root zone generally halted downward water movement. The FC values in the dataset are correlated with the pressure plate SWC data that was collected nearby (see ***LIRF Soils*** file). For field areas with sand content above 80%, the field measured FC values are similar to the 10 kPa values; in areas with sand content below 80%, FC is similar to the 33 kPa values.

Experimental Design

The experiment was laid out in a randomized block design with 4 replications and 6 treatments (Fig 2). A 5 Ha field at LIRF was divided into 4 sections - one for each crop of a 4 crop rotation: winter wheat, maize, sunflower, pinto bean). Maize was in a different section each year (see Fig 2) following winter wheat that was harvested the previous July. Each section was divided into 4 blocks (replications), and each block into six 9 x 40 m plots that contained 12 N-S rows planted on 0.76 m spacing. Each section included 6 border rows on the edges. All soil and plant measurements were collected from the center 6 rows of the plots.

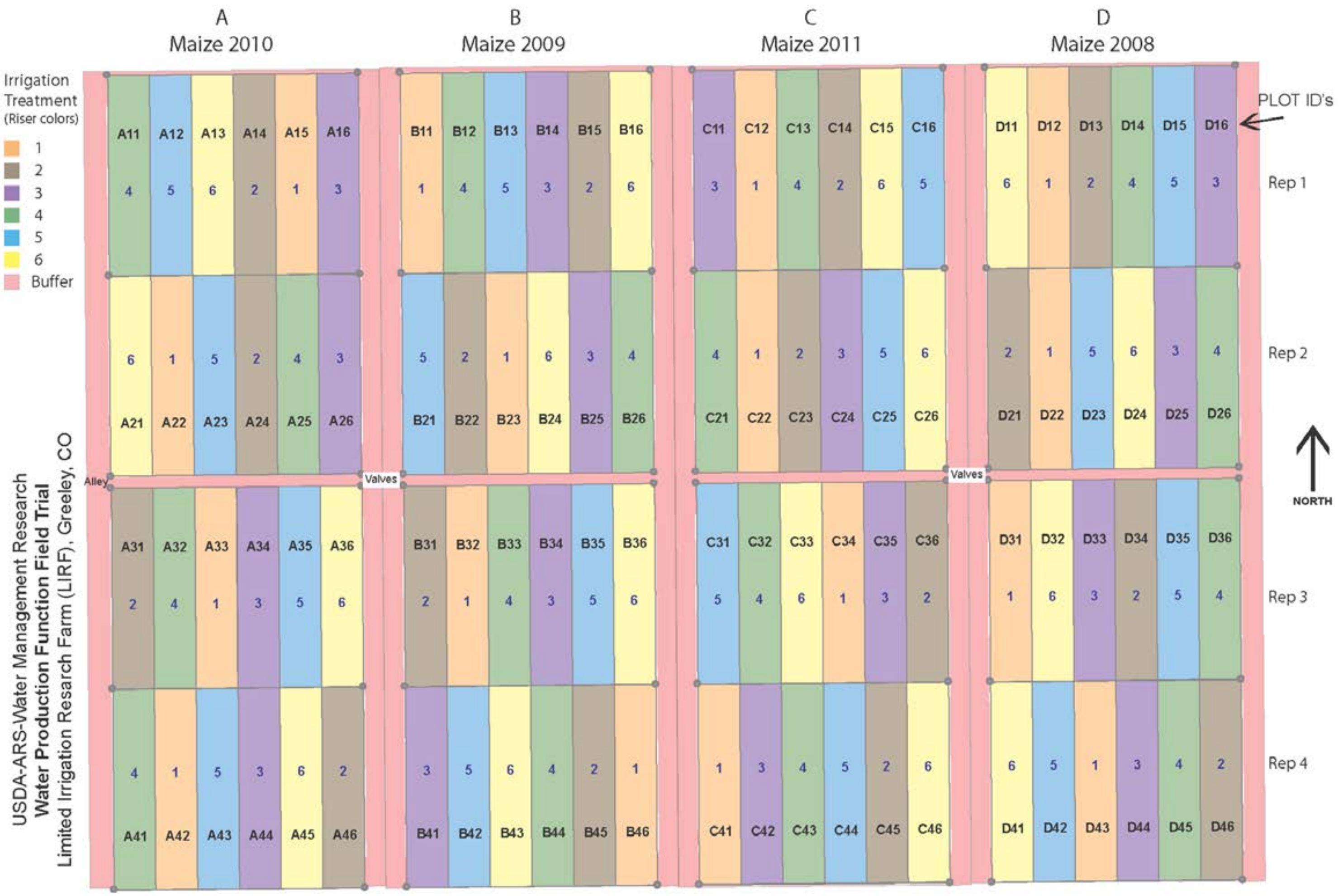
Six irrigation treatments were randomly assigned to each block. The 6 treatments were designed to meet portions of full crop water requirements.

- T1: 100% of crop water requirements (no stress)
- T2: 85% of T1
- T3: 75% of T1
- T4: 70% of T1
- T5: 55% of T1
- T6: 40% of T1

The full irrigation treatment, T1, 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 (FAO-56 methodology, Allen et al. 1998). Adequacy was monitored by insuring the soil water content remained in the plant readily available range. The remaining treatments were irrigated to achieve total water applications (irrigation plus precipitation) that approximated the target treatment amounts.

All treatments were fully irrigated until growth stage V7 (Abendroth et al., 2011) to insure good crop stands and proper formation of reproductive organs. Water stress was partially reduced for all treatments during the reproductive (VT – R2) growth stages to ensure adequate pollination and seed initiation. Irrigation was often terminated earlier in low water treatments than in the high water treatments due to earlier senescence. Due to the above stress regulation, unanticipated precipitation, and uptake from soil water storage, actual average seasonal crop evapotranspiration, ETc, amounts for the 6 treatments were:

- T1: 100% of crop water requirements
- T2: 89% of T1
- T3: 83% of T1
- T4: 78% of T1
- T5: 67% of T1
- T6 61% of T1



Plot size: Width 9m (12 row at 0.76m spacing), Length 44m. Total Area (5ha); 6 row or 4.5m buffers between crops and on field edges
4 Crop rotation: Dry Beans, Winter Wheat, Corn, Sunflower.

Figure 2 Field experimental plot layout showing 4 field sections, 4 replicated blocks, and 6 randomly assigned treatments. Numbers in the plots refer to treatments T1 – T6. Plot identifiers refer to field section (A – D), replication block (1 – 4), and location within the block (1 – 6).

Crop and Irrigation Management

The crop was managed to achieve high yields under fully-irrigated conditions. All treatments were planted at the same population and received the same nitrogen applications (exception: 2011, T5 and T6). Economically-based recommendations would likely be to reduce plant population and nitrogen application for reduced yield conditions associated with water stress. However, evidence from the literature indicated that, under the experimental conditions, plant population and fertility targeted at high yields would not negatively impact yields under deficit irrigation so only water availability was varied among treatments. Minimum tillage (no tillage in 2009, strip tillage in 2010 and 2011) was used to maintain surface residue from the previous wheat crop and minimize surface evaporation.

DeKalb brand 52-59 (VT3) maize seed was planted with a John Deere Maxiplex planter in early May at 80,000-to-82,000 seeds ha^{-1}. Final plant populations varied from 77,000 to 82,000 plants ha^{-1}, but did not vary significantly by treatment. The genetically modified variety allowed good herbicide-based weed control (glyphosate resistant) and minimized lepidopteran (ear and root borer) insect damage. Planting dates, harvest dates, and pest management are given in the crop logs worksheet in the ***LIRF Maize*** files.

In 2008, the soil water content at planting was too low to assure good germination, so a portable sprinkler system was used to apply a small irrigation (21 mm) to insure a good crop stand. This application is listed in the water balance spreadsheet as precipitation on day of year, DOY, 142. In other years soil water content was adequate for good germination or drip irrigation was used to provide good conditions for germination.

Nitrogen fertilizer (Urea ammonium nitrate, UAN, 32%) was sidedress applied near the seed at planting at 34 kg ha^{-1} N. Additional nitrogen was applied through the irrigation water (fertigation) to meet fertility requirements based on pre-plant soil tests, expected yields, and nitrogen concentration in the groundwater used for water supply. Nitrogen applications are listed in the ***LIRF Maize*** files. Note that, due to the high nitrate concentration in the groundwater (25 mg L^{-1} N which is equivalent to 0.25 kg N ha^{-1} mm^{-1} of water applied), low water treatments received as much as 50 kg ha^{-1} less N than the high water treatments.

Irrigation water from a groundwater well was applied through a surface drip irrigation system with drip tubing along each row. The irrigation system was installed each season after planting and removed before harvest to avoid impact on farming operations. Although the groundwater was relatively high in soluble salts (EC = 1.9 dS m^{-1}), there was no evidence of salinity levels in the soils that would impact yield (soil (1:1 extraction) EC < 0.5 dS m^{-1}). Irrigations were applied once or twice each week. Irrigation amount for the T1 treatment was based on predicted crop water use as calculated by the dual crop coefficient method (Allen et al. 1998, Allen and Jensen 2016) and adjusted as needed for measured soil water deficits to maintain SWC in the readily available range. Irrigations were reduced based on received or anticipated precipitation. Irrigation amounts for the remaining treatments were reduced relative to the T1 treatment to achieve the targeted ETc reductions. If required irrigation amount was less than 12 mm, the irrigation was skipped and the amount was added to the following irrigation.

A log of miscellaneous crop management operations is listed on the Crop Log worksheet of the ***LIRF Maize*** files. Entries include tillage, planting, harvest, and pest management operations, along with some irrigation and crop phenology observations that are also listed in the water balance sheets.

Water Balance Measurements

Weather parameters were measured with a standard ET weather station located on a 0.4 Ha irrigated grass plot adjacent to the experimental field. The station, part of the Colorado Agricultural Meteorological Network, CoAgMet (http://www.coagmet.com/ , station GLY04), measured solar radiation, relative humidity, wind speed and direction, air temperature, and precipitation.

Both hourly and daily weather parameters are given in the ***LIRF Weather*** files. The weather data were checked for errors by comparing with nearby instrumentation and expected ranges. When errors were detected, data were corrected. Missing data were likewise replaced by measurements from a nearby weather station, as noted in the data files. Thus, this dataset will differ slightly from that provided from the CoAgMet site. Reference evapotranspiration was calculated from hourly weather data by the ASCE Standardized Penman-Monteith equation (ASCE-EWRI, 2005). Both tall (alfalfa), ETr, and short (grass), ETo, reference ET are presented in the ***LIRF Weather*** files. Daily values are sum of hourly values.

Two additional precipitation gauges were located inside the experimental field. Daily precipitation data is the median of the three gauges or the average of two if one gauge malfunctioned. Generally, 2 or 3 gauges recorded precipitation events within 1 mm. The tipping bucket gauges do not accurately measure winter snow, so winter precipitation was estimated from other gauges in the local area (CoCoRahs: http://www.cocorahs.org/ ; NOAA UNC; http://met.unco.edu/esci/met/wxlinks/index.html ; Northern Water Eaton station: http://www.northernwater.org/WaterConservation/WeatherandETData.aspx). These corrected precipitation data are given in the Daily worksheet (Precip).

Irrigation applications to each treatment were measured with turbine flow meters (Badger Recordall Turbo 160 with RTR transmitters). The meters were tested by the manufacturer to within ± 1.5% accuracy. We cross calibrated the new meters in our hydraulics laboratory to within ±2% at the beginning of the study, and to within ±3% after 8 years of use (2015). Irrigation applications were controlled by and recorded with Campbell Scientific CR1000 data loggers. Irrigation water was delivered to the corner of each plot through underground PVC pipe, and applied to the crop from microirrigation tubing (16 mm diameter, thick walled tubing with 1.1 L h^{-1} conventional inline emitters spaced 30 cm apart) placed on the soil surface near each row. A constant pressure water supply controlled with a variable speed drive booster pump, low pressure loss in the delivery system, and relatively flat topography resulted in predicted water distribution uniformity exceeding 95%.

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 at the site with volumetric soil cores collected during access tube installation. Calibration data collected each year at

15% of the NMM measurement sites indicated no variation in the calibration with location or depth and no drift in the response of the NMM with time. 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. Because SWC was measured in the crop row near the drip tubing, one-dimensional soil water models will likely predict smaller fluctuations in SWC with time between irrigation events.

In 2008 and 2010, a Bowen Ratio Energy Balance, BREB, system was used to measure maize evapotranspiration near the center of fields directly south of the experimental plots. Mkhwanazi etal. (2015) provides details of the BREB instrumentation, operation, and data analysis. These data are presented in the ***LIRF Maize*** files with the T1 treatment for the two years. The approximately 120 m x 150 m fields were planted within 2 days of the plots and were irrigated to meet full irrigation requirements. BREB ETc was calculated over 30-min intervals throughout the day and summed to obtain daily values. Photo 16 in the ***LIRF Photo Log*** shows the BREB instrumentation.

A limitation with the BREB estimates of ET is the limited (60-to-80m) fetch distance within the fields and potential sources of sensible heat advection from beyond the field boundaries. The fields are bordered by irrigated fields except for of the SW corner in 2008 and the south side and NW corner in 2010. There are unirrigated roadways on 3 sides of the field. Photos 1 and 2 in the ***LIRF Photo Log*** show the layout of the surrounding fields in 2010. An analysis of advective conditions indicated sensible heat measurements were acceptable on most days.

Plant Measurements

The ***LIRF Maize*** files contain periodic measurements through the seasons of plant growth stage, plant height, and canopy ground cover; and seasonal measurements of plant population, maximum leaf area index, above ground biomass, harvest index, grain yield, and grain mass. Plant measurements were made on individual plots (4 replications), unless otherwise noted. Mean values are presented in the daily data worksheets; means and standard deviation values along with individual plot data are presented in the seasonal worksheets.

Growth stage was periodically evaluated visually based on guidelines presented in Abendroth et al. 2011. Plant height was measured throughout the season with a measurement rod to the top of the leaf canopy. Leaf Area Index, LAI, was estimated by measuring the length and width of each leaf on 5 plants, and multiplying the average leaf area (m^2 per plant) by the plant population (plants m^{-2}). LAI was measured throughout the season on treatments T1, T3, T4, and T5 in 2009 and 2010, and on all treatments at the maximum LAI in 2011.

Crop canopy ground cover, fc, was measured approximately weekly near solar noon with a digital camera from a nadir view six meters above the ground surface (see photos 13 and 17 in the ***Photo Log*** file). The camera field of view encompassed 4 rows x 4 m. The digital image pixels were differentiated between green plant canopy and background (soil, surface residue, and senesced leaves) with manually-trained image analysis software. The ***LIRF Maize*** spreadsheets include daily fc estimates interpolated between measured data. Canopy ground cover in stressed corn is influenced by the amount of leaf curl, which occurs with high evaporative demand primarily in the afternoon. Since the intent of the measurement was to measure the impact of crop canopy on evapotranspiration, fc measurements below canopy expansion trends were assumed to result from leaf curl were not included in the interpolation.

Plant population was measured before harvest by counting the total number of plants in the plot yield area (described below).

Above ground biomass was measured before harvest in all years. Ten or fifteen complete corn plants were cut 2 cm above the soil surface, ears were removed, and the remaining stover dried in an oven at 60^oC for 48 hours and weighed. Ears were likewise dried, grain was removed from the cobs, and both components redried and then weighed. Measurement of grain moisture content after drying indicated that the dried grain contained 5-to-6% water, so biomass grain weight was appropriately reduced. (Note that this adjustment to 0% grain moisture is not normally done for biomass reported in the literature.) Above ground biomass included stover, cobs, and grain. Plot above ground biomass was calculated as the average total weight per plant (stover, cobs, and grain; kg per plant) multiplied by the plot plant population (plants ha^{-1}). Harvest Index was calculated as the ratio of dry grain weight to total above ground biomass. Average seed mass was measured by weighing 1000 seed subsamples (2010, 2011).

Grain yield was measured by hand harvesting the ears from the middle 15 m of the center 4 rows of each plot (46 m^2). In 2011, yield sample area was increased to 23 m length (70 m^2). Grain was threshed with a stationary thresher (Wintersteiger Classic ST, Wintersteiger AG, Ried, Austria), weighed and subsampled for moisture content determination. Grain moisture content at harvest was measured with a Dickey-john GAC500-XT Moisture Tester (Dickey-john Corp, Aubern, Ill). Yield (kg ha^{-1}) was normalized to 15.5% moisture content (commercial yield standard), and was also converted to dry weight.

Rooting depth was not measured, but was estimated based on observed soil water uptake (measured SWC decrease). Soil water uptake was not measured below 105 cm, so the final root zone depth for maize in the experimental field was estimated to be 105 cm (represented by the 0 – 15, 30, 60, and 90 cm SWC measurements), and the root zone expansion during the growing season was estimated to be an S curve between planting (5 cm) and full cover (105 cm). Although the assumed small initial rooting depth sometimes resulted in predicted high root zone soil water deficits early in the season, there were no visible signs of early plant stress.

When available, additional plant data is provided in the final worksheet of the ***LIRF Maize*** files. Total carbon and nitrogen in the above ground biomass components were measured in 2008 and 2009 with a LECO TrueSpec CN analyzer (LECO, St. Joseph, MI). Leaf water potential was measured in Block 4 on four dates in 2008 measured with a Scholander pressure cell. Chlorophyll fluorescence (photon yield, electron transfer rate, and photosynthetically active radiation) was measured on 10 dates in 2011 on treatments T1,T3, and T5 with a Licor 6400 gas exchange instrument.

Water balance Calculations

Evapotranspiration was calculated based on the water balance (all units in equivalent depth (mm)):

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

where:

- ΔS = change (increase) in soil water content in the root zone
- I = irrigation application
- P = precipitation
- DP = deep percolation loss of soil water below the root zone
- RO = surface runoff of precipitation or irrigation, and
- ETc = crop evapotranspiration, the loss of water to the atmosphere.

For the experimental field, RO is assumed zero due to relatively small field slope and precipitation amounts, adequate soil infiltration, surface residue, and drip irrigation. Deep percolation was assumed to occur when precipitation exceeded the soil water deficit (SWD) in the full root zone at the time of precipitation and was calculated as the precipitation amount minus soil water deficit. Evidence of DP was an increase in SWC below the root zone following precipitation. Irrigation amounts never exceeded the SWD. Due to the semi-arid climate and careful irrigation scheduling, deep percolation losses occurred (by these criteria) only in 2008 following two large precipitation events.

Thus, for this study, ETc was estimated as:

$$ETc = I + P - \Delta S - DP \qquad \text{Eq 2}$$

Although ETc can conceptually be calculated each time SWC is measured, small inaccuracies in SWC measurements result in relatively larger errors in differences between two SWC measurements measured over time intervals in which cumulative ETc is small, resulting in relatively large scatter in calculated ETc over short time intervals. Thus, although this method can accurately estimate seasonal ETc, and fairly accurately estimate ETc over two or more weeks, it cannot be used to confidently estimate daily ETc. Therefore, a daily time step water balance model was created based on the FAO-56 dual crop coefficient approach (Allen et al., 1998) to estimate daily ETc. This model predicted the daily soil evaporation, transpiration, deep percolation, and soil water deficit. When the model-predicted SWD trend deviated from the measured SWD, the basal crop coefficient, Kcb, was manually adjusted for a preceding time period so that predicted and measured SWD trended similarly. The resulting daily ETc values were thus “calibrated” to match the long-term water balance measured ETc, and the sum of these daily values was equal to the cumulative ETc predicted by Eq 2 over multi-week and seasonal time intervals. Thus, although the daily ETc values must be considered model estimates, cumulative ETc values were based on the measured water balance parameters.

Crop evapotranspiration, ETc, calculated by Eq 2 includes surface evaporation. Surface evaporation was estimated for the field conditions by assuming that the total evaporable water, TEW (assumed 12 mm), or the depth of irrigation or precipitation if less than TEW, evaporates from the wetted sunlit soil surface between each wetting event. The entire surface is wetted by precipitation events, but only the portion of the soil along the drip tube is wetted during irrigations. The sunlit soil is reduced by the crop canopy, fc, and residue on the surface. Since the drip tube is near the plant row, the plant canopy shades much of the irrigation wetted surface for much of the season. For our reduced tillage condition, residue is assumed to shade 25% of the surface. When the surface soil is wet, we assume daily ETc is limited to 100% of ETr, so daily soil evaporation is limited to (1.0 – Kcb)*ETr. Estimates of daily evaporation and transpiration (calculated as ETc – E) are given in the ***LIRF Maize*** files. Crop models that do not adjust surface evaporation for partial surface wetting or soil shading may overestimate E and thus ETc measured in these field studies.

DISCUSSION

Because irrigations were carefully scheduled and precipitation events were generally small, deep percolation loss was assumed to occur during only one week in 2008. Because soil water storage capacity was not large (average total available water in the root zone = 110 mm), ΔS was generally less than 10% of the estimated seasonal ETc. Thus, accuracy of the seasonal ETc prediction is primarily based on the accuracy and uniformity of the irrigation applications and precipitation. We estimate that seasonal estimated ETc is within ±10% of the true value. For the days in 2008 and 2010 in which the BREB system provided data, the cumulative ETc from the water balance for the T1 treatment was 8% higher and 6% lower, respectively than that measured by the BREB system in the adjoining field.

Yields for the full irrigation treatment averaged 12.5 Mg ha^{-1} and for the lowest irrigation level averaged 6.0 Mg ha^{-1} over the 4 seasons. Yields were impacted in 2009 by a hail event just before VT growth stage that shredded leaves (see photo 15 in the ***Photo Log*** file). The relatively low yield at full irrigation in 2010 was likely due to early termination of irrigation and the resulting soil water stress 25 days prior to physiological maturity.

Seasonal ETc at full irrigation (T1) varied from 616 to 650 mm and averaged 632 mm. Approximately one-third of T1 ETc was supplied by precipitation each year, so seasonal irrigation amounts typically varied from 420 mm for T1 to 120 mm for T6. Yields decreased with each decrement of ETc in every case except for 2010 when the T2 yield was slightly higher than T1 (see paragraph above for likely reason). Yields decreased more than proportional to the ETc at deficits above 30% (T4 – T6). For the managed irrigation applications, harvest index did not vary consistently with treatment. For the surface drip irrigation and residue management used, wet soil surface evaporation was estimated to vary between 60 and 80 mm or about 10 - 12% of ETc.

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