CORN AND SORGHUM ET, E, YIELD, AND CWP AS AFFECTED BY IRRIGATION APPLICATION METHOD: SDI VERSUS MID-ELEVATION SPRAY IRRIGATION

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ABSTRACT. *Greater than 80% of the irrigated area in the Southern High Plains is served by center-pivot irrigation, but the area served by subsurface drip irrigation (SDI) is increasing due to several factors including declining well yields and improved yields and crop water productivity (CWP), particularly for cotton. Not as well established is the degree to which the reduced soil water evaporation (E) in SDI systems affects the soil water balance, water available to the crop, and overall water savings. Grain corn (*Zea mays *L.) and sorghum (*Sorghum bicolor *L. Moench) were grown on four large weighing lysimeters at Bushland, Texas, in 2013 (corn), 2014 and 2015 (sorghum), and 2016 (corn). Evapotranspiration (ET) was measured using the lysimeters and using a neutron probe in the surrounding fields. Two of the lysimeters and surrounding fields were irrigated with SDI, and the other two were irrigated with mid-elevation spray application (MESA). The lysimeter-measured evaporative losses were 149 to 151 mm greater from sprinkler-irrigated corn fields than from SDI fields. When growing sorghum, the lysimeter-measured evaporative losses were 44 to 71 mm greater from sprinkler-irrigated fields than from SDI fields. The differences were affected by plant height and became smaller when plant height reached the height of the spray nozzles, indicating that the use of LEPA or LESA nozzles could decrease the evaporative losses from sprinkler-irrigated fields in this region with its high evaporative demand. Annual weather patterns also influenced the differences in evaporative loss, with increased differences in dry years. SDI reduced overall corn water use by 13% to 15%, as determined by neutron probe, while either not significantly affecting yield (2016) or increasing yield by up to 19% (2013) and increasing CWP by 37% (2013) to 13% (2016) as compared with MESA full irrigation. However, sorghum yield decreased by 15% and CWP decreased by 14% in 2014 when using SDI compared with MESA full irrigation due to an overly wet soil profile in the SDI fields and deep percolation that likely caused nutrient losses. In 2015, there were no significant sorghum yield differences between irrigation methods. Sorghum CWP was significantly greater (by 14%) in one SDI field in 2015 compared with MESA fully irrigated sorghum. Overall, sorghum CWP increased by 8% for SDI compared with MESA full irrigation in 2015. These results indicate that SDI will be successful for corn production in the Texas High Plains, but SDI is unlikely to benefit sorghum production.*

Keywords. *Corn, Crop water productivity, Evaporative loss, Evapotranspiration, Irrigation application method, Sorghum, Water use efficiency, Weighing lysimeter.*

Irrigation application method is known to affect crop performance, including yield and crop water productivity (CWP, also known as water use efficiency), with subsurface drip irrigation (SDI) having some advantages over sprinkler irrigation for corn, cotton, and sorghum production. Sprinkler irrigation has become the pre-dominant irrigation method for crop production in the U.S. Great Plains, with >80% of the irrigated area in the Southern High Plains (SHP) irrigated with center-pivot systems (Colaizzi et al., 2009; NASS, 2014). Microirrigation, which includes surface and subsurface drip irrigation, generally results in greater CWP compared with sprinkler irrigation due to greater crop production, less consumptive use of irrigation water, or a combination of both (Camp, 1998), as well as less sensitivity to impaired irrigation water (Goldberg and Shmueli, 1970; Berstein and Francois, 1973; Goldberg et al., 1976; Adamsen, 1989, 1992; Wu et al., 2001) and warmer soil temperatures (Wang et al., 2000; Colaizzi et al., 2010). In some cases, this greater CWP has justified the greater capital costs per unit land area of microirrigation compared with sprinkler irrigation (Bordovsky et al., 2000; Bosch et al., 1992; Enciso et al., 2005; O'Brien et al., 1998), leading to at least 175,716 ha irrigated with SDI in the SHP in 2016, almost entirely for cotton

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(http://www.hpwd.org/other). For the High Plains Water Conservation District, the largest water conservation district in the Texas High Plains, SDI accounted for 20% of the total 898,615 ha irrigated with pressurized systems in 2016. As cotton, corn, and sorghum prices fluctuate, and as other incentives arise to rotate out of cotton production, these SDI fields may be planted to corn or even sorghum. Microirrigation now serves more than 8% of land irrigated with pressurized systems (sprinkler, surface and subsurface drip, and other microirrigation methods) in the U.S. (NASS, 2014).

In the Texas High Plains, the most southern extension of the SHP, irrigation water is completely derived from fossil aquifers, the most important of which is the declining Ogallala Aquifer, a fossil aquifer that is recharged at most by 2 to 3 cm per year. Well yields are steadily declining, making it difficult in some cases to find adequate capacity to serve a center-pivot irrigation system. An SDI system can be zoned to accommodate the smaller well yields. Although center-pivot variable-rate irrigation (VRI) systems can also accommodate declining well yields, the acceptance of VRI systems is relatively small. Other factors also influence the acceptance of SDI, including increased CWP for corn and cotton and larger yields for cotton after conversion to SDI (Lamm, 2016).

The advantage of SDI is thought to be due in part to decreased loss of water to evaporation (E) from the soil surface because the soil surface is directly wetted by sprinklers but not by SDI. In addition, there are no evaporative losses from wind drift or evaporation from sprinkler-wetted canopies using SDI. A 36% (81 mm) decrease in evaporative loss using SDI versus surface irrigation (sprinkler or gravity flow) that wetted the entire soil surface was estimated using a mechanistic model (Evett et al., 1995), which means that more of the applied irrigation water would be available for transpiration (T) by plants. Because yield is directly tied to transpiration (Doorenbos and Kassam, 1979), this increase in the T/E ratio should result in relatively more yield per unit of water applied with SDI, and a corresponding increase in CWP (Howell, 2001).

However, there are few direct daily measurements of the differences in E, T, their sum (evapotranspiration, or ET), and the water and energy balances of crops grown using SDI compared with sprinkler irrigation. Instead, these differences and their effects on CWP have been indirectly inferred from numerous CWP studies, particularly studies that included limited irrigation (i.e., irrigation rates below the crop ET obtained under full irrigation). Initial studies in the 1960s and 1970s were conducted in Israel (Goldberg and Shmueli, 1970; Goldberg et al., 1976) and California (Berstein and Francois, 1973; Peacock et al., 1977) for bell peppers, melons, cucumbers, tomatoes, and vineyards. Subsequent studies included other common crops, such as alfalfa (Bui and Osgood, 1990), corn (Adamsen, 1992; Colaizzi et al., 2011), cotton (Bordovsky et al., 2000; Cetin and Bilgel, 2002; Colaizzi et al., 2010), lettuce (Sammis, 1980; Hansona et al., 1997), onion (Al Jamal et al., 2001), peanut (Adamsen, 1989), potato (Sammis, 1980), sorghum (Colaizzi et al., 2004), soybean (Wang et al., 2000; Colaizzi et al., 2010), sugar beet (Tognetti et al., 2003), sunflower (Sezen et al., 2011), tree orchards (Middelton et al., 1979; Bielorai, 1982), and vineyards (Bowen et al., 2012). These studies were conducted under a wide range of climates (e.g., arid, Mediterranean, temperate, humid), soil textures (e.g., loamy sand to clay), water and soil quality (e.g., different pH, salinity, sodicity), and agronomic and irrigation practices that reflected commercial production in the study region (e.g., full and limited irrigation, irrigation scheduling criteria, tillage, fertilization). The cited studies included numerous variants of the design and configuration for sprinklers (e.g., solid set, center pivot, high-pressure impact, low-pressure spray) and microirrigation systems (surface drip, SDI, depth of SDI). Despite the wide range of crops and environmental and technological conditions, in nearly all cases microirrigation resulted in greater CWP compared with sprinkler irrigation, which was due to greater crop yield for a given irrigation rate or crop ET, the same crop yield for less irrigation water applied or less crop ET, or a combination of both. Still, direct measurements of evaporative losses and their contribution to the overall water balance are few, limiting our understanding of the mechanisms that contribute to improved CWP and limiting our ability to develop and test crop water use and CWP models that include irrigation application method.

Weighing lysimeters directly measure water losses from the soil (ΔS) due to ET when there is no precipitation (P) or irrigation (I) occurring and when deep flux (F) and runoff (R) are negligible. The crop ET can be calculated as the residual of the soil water balance equation:

$$\mathrm{ET} = P + I + R + F + \Delta S \tag{1}$$

where

ET = evapotranspiration

P = precipitation

I = irrigation

R = sum of runoff and runon

F = deep flux

ΔS = change in soil water storage.

The crop ET can be calculated for periods during which I, P, F, and R are known because the change in soil water storage (ΔS) is known from the lysimeter mass change, and equation 1 may also be solved when ΔS is determined using the neutron probe method (Evett et al., 2012b). Energy and water balance modeling tells us that most of the difference in ET from SDI versus sprinkler irrigation occurs early in the season during pre-irrigation and before full cover is established (Evett et al., 1995). The ET difference is due primarily to differences in E, rather than T from the relatively small plants, and can be determined from weighing lysimeter measurements.

To more fully understand the water and energy balance and flux differences with SDI compared with sprinkler irrigation, we modified the large weighing lysimeter facility at Bushland, Texas (Marek et al., 1988) during 2012 and early 2013 so that the eastern two of the four monolithic lysimeters and their surrounding fields could be irrigated using SDI (Evett et al., 2018a). Energy and water balances were measured on grain crops grown in 2013 through 2016 to determine the differences in evaporative loss and corresponding differences in yield and CWP.

MATERIALS AND METHODS

SITE DESCRIPTION

Grain corn (*Zea mays* L) was grown in 2013 and 2016, and grain sorghum (*Sorghum bicolor* (L.) Moench) was grown in 2014 and 2015 at the USDA-ARS Conservation and Production Research Laboratory (CPRL) in Bushland, Texas (35° 11′ N, 102° 6′ W, 1170 m above MSL) on a gently sloping (<0.3%) Pullman soil (fine, mixed, superactive, thermic Torrertic Paleustoll). The slowly permeable soil has a dense B22 horizon at 0.3 to 0.5 m depth and a caliche layer at approximately 1.4 m depth that restricts water movement in some seasons. The soil series is common to 1.2 million ha of land and one-third of the irrigated area in the Texas Panhandle (Musick et al., 1988). The plant-available water holding capacity is approximately 210 mm in the top 1.4 m of the profile. The research location and facilities are situated in the SHP and were thoroughly described by Evett et al. (2012a, 2018b). Winds are predominantly from the south and southwest during the growing season and often carry advective energy from dryland and rangeland fields and pastures. Additional energy is derived from their passage over the Chihuahuan Desert, followed by descent with adiabatic heating along the eastern slopes of the southern Rocky Mountains. Mean annual pan evaporation exceeds 2400 mm (Kohler et al., 1959).

AGRONOMIC PRACTICES

Crops were grown in four adjacent square 4.4 ha fields. In the center of each field was a large weighing lysimeter (nominally 3 m × 3 m in surface area and 2.4 m deep) (Evett et al., 2012b; Marek et al., 1988). The four fields and the lysimeters within them were designated with reference to the cardinal directions as northeast (NE), southeast (SE), northwest (NW), and southwest (SW). The NE and SE fields were irrigated with SDI, and the NW and SW fields were irrigated with mid-elevation spray application (MESA). The crops were managed for high yield using practices common for the northern Texas Panhandle. Rows were oriented in the E-W direction and spaced 0.76 m apart. Tables A1 through A4 in the Appendix show the timing of agronomic practices for the four cropping seasons.

Fertilizer was applied according to soil tests done by a commercial soil testing laboratory. In 2013, a medium-season (109 days) corn (Pioneer variety 1151AM AquaMax, ≤80% Bt) was planted in the four fields at 81,500 seeds ha^{-1}, fertilized with liquid N (32-0-0), and treated with herbicide. This hybrid corn was bred and engineered for water-limited conditions, so a test of this variety was conducted by irrigating at deficit levels in the NW or SW MESA-irrigated fields, alternating between fields in different years. In 2013, the NW field was irrigated at 75% of full irrigation (see the Irrigation Systems and Management section for a definition of "full"). The same variety was planted at 87,475 seeds ha^{-1} on 10-11 May 2016, fertilized with a combination of 32-0-0 and 10-34-0, and treated with herbicide. In 2016, the SW field was deficit irrigated at 75% of full irrigation.

In 2014, a short-season sorghum (Channel variety 5c35) was planted on 20 June at a rate of 210,000 seeds ha^{-1} on all fields after cotton failed due to heavy rain and hail (>200 mm in five days). The sorghum was fertilized and treated with herbicide following typical production practices in the area. After plant establishment, the SW field was deficit irrigated at 75% of full. The same sorghum variety was planted on 22 June 2015, again after cotton was hailed out, and was fertilized and managed using typical practices for the region.

Liquid fertilizer applications on the lysimeters were simulated by digging trenches 10 cm deep and spaced 38 cm apart, to simulate the fertilizer applicator, and then manually spraying the liquid fertilizer in the trenches and covering it with soil. Common tillage practices included stubble mulch tillage after harvest to close soil cracks in order to minimize rodent damage to the buried drip lines, followed by off-season shredding of stalks and incorporation of residue using a disc plow in the fields and by hand-tillage on the lysimeters.

ET DETERMINATION BY LYSIMETER AND SOIL WATER BALANCE

As shown in equation 1, crop water use (ET) is measured by the soil water balance of a control volume that includes the root zone. In this study, both weighing lysimeters and field soil water balance calculations based on neutron probe measurements were used to determine ET. Weighing lysimeters define the control volume as the depth of the lysimeter (2.3 m at Bushland). The lysimeter mass change is a direct measure of the change in soil water storage and thus of the water lost to evaporation and transpiration (ET) when P, I, R, and F are zero. Lysimeter mass changes were converted to a depth of water by dividing the mass change by the density of water at standard atmosphere and pressure and by the effective surface area of the lysimeter (9.15 m^2).

The lysimeters were drained under vacuum equivalent to 1 m of hanging water column into tanks suspended by load cells from the lysimeter soil tanks so that drainage did not change the total mass of the lysimeter. Irrigations were metered, and the metered amounts of sprinkler irrigation were verified by measuring the change in lysimeter mass caused by each irrigation. Precipitation was measured with rain gauges at each lysimeter and again verified (and corrected when precipitation events happened quickly) by observing changes in lysimeter mass (Marek et al., 2014; Evett et al., 2018b). The field was furrow diked to inhibit runoff and runon into the lysimeters, and the lysimeter soil boxes had approximately 0.05 m of freeboard that prevented runoff and runon for all irrigation events and almost all precipitation events, with notable exceptions discussed in the Results and Discussion section.

At each of eight neutron probe access tubes in each field, the soil profile water content was determined to 2.4 m depth using a neutron probe for measurements centered at 0.10 m depth and at depths in 0.20 m increments below 0.10 m. The neutron probe was operated and field calibrated to 0.01 m^3 m^{-3} accuracy using methods described by Evett et al. (2008), and a depth control stand (Evett et al., 2003) was used to ensure repeatedly accurate probe depth placement. The water content as a depth for each 0.20 m thick soil layer was calculated by multiplying the volumetric water content by the layer depth. The profile water content as a depth was calculated by summing the water contents for each 0.20 m thick soil layer. The change in storage for each period between neutron probe measurements (typically weekly) was calculated as the difference in profile water contents. The precipitation and irrigation amounts were taken as those measured by the lysimeters in each field, the value of R was assumed equal to zero because the fields were furrow diked, and the soil water flux (J_w, m s^{-1}) at the bottom of the control volume for the neutron probe was estimated using Darcy's law:

$$J_w = -K(\Delta H/\Delta z) \quad (2)$$

where

J_w = soil water flux (m s^{-1})

K = hydraulic conductivity (m s^{-1})

$\Delta H/\Delta z$ = hydraulic head gradient.

Soil water contents at the 2.10 and 2.30 m depths were used to estimate the hydraulic conductivity (K, m s^{-1}) and hydraulic gradient ($\Delta H/\Delta z$) for the 2.10 to 2.30 m soil layer using methods described in detail by Evett et al. (2012b).

Eight determinations of field ET by soil water balance were thus made in each field (NW, SW, NE, and SE) using the neutron probe. These were grouped into four mean ET values for each of the four fields. Because lysimeter data do not provide replication, the four neutron probe-based mean ET values for each field were used in combination with four combine-harvested yield values for each field (described in the Plant Sampling section) to determine four values of CWP for each field, which were used in statistical analysis of the differences between fields and treatments. The lysimeter-measured ET data were used primarily to illustrate the differences between SDI and MESA irrigation in terms of ET and evaporative losses over time.

IRRIGATION SYSTEMS AND MANAGEMENT

Irrigation with MESA was applied to the NW and SW fields using a ten-span linear-move irrigation system (Lindsay Manufacturing, Inc., replaced after 2014 with a Valley system, Valmont Industries, Valley, Neb.) moving in the E-W direction with spray plates at 1.5 m height (mid-elevation sprays) on weighted drops with 69 kPa pressure regulators on each drop. The drops were spaced at 1.52 m intervals in alternate interrows. Irrigation was typically 19 to 25 mm depth, and occasionally as much as 38 mm. Nozzling was such that a 25 mm irrigation required approximately 12 h. Proximal lateral end pressures were typically 242 kPa, and distal lateral end pressures were typically 173 kPa, ensuring that the pressure regulators set and operated correctly after system startup.

The SDI system was installed in the NE and SE fields and lysimeters before the 2013 cropping season using 25 mm diameter drip lines (Typhoon 990, 13 mil wall thickness, Netafim, Inc., Fresno, Cal.) spaced 1.52 m apart and buried at 0.30 to 0.36 m depth in the E-W direction. Emitters were spaced 0.30 m apart and had 0.68 L h^{-1} discharge at the 69 kPa regulated line pressure. Emitter spacing was purposely chosen to be relatively small so that each drip line would act more like a line source and wet the soil more uniformly orthogonal to the drip line. The combination of emitter spacing, discharge rate, and drip line spacing was chosen so that application of a given depth of water would require approximately the same time as application of the same amount of water with the linear-move system. The drip lines were 210 m long and designed for an emission uniformity of 98.6%. The field was divided into 20 zones, with each zone controlled with a separate valve, meter, and pressure regulator. The system applied 25 mm of irrigation in approximately 14 h. Water from multiple wells was stored in a reservoir and then pumped through sand filters with automatic flush out (waste stream returned to the reservoir) to remove sediment and algae. A variable-frequency pump drive was used to provide constant supply line pressure downstream of the filters.

The SDI lines in the lysimeters were buried at the same depth and row spacing as in the field, and the same drip line was used as in the field. The two SDI lines in each lysimeter were connected to a buried header at the west side of each lysimeter soil monolith and to a buried flush-out line at the east end of the monolith. The number of emitters and emitter spacing relative to the west and east sides of the monoliths were carefully controlled so that the number of emitters per unit area was the same in the lysimeters as in the field. The buried header in each lysimeter was connected to the field SDI supply so that the lysimeter was irrigated when the field was irrigated. Lysimeter mass gain in the hours just before and after midnight during overnight irrigations, when ET was essentially zero, was examined to verify that the irrigation rate in the lysimeter was equal to that in the field. The irrigation rate was verified to be practically constant, which was expected due to the pressure regulation, and ET during irrigations was calculated using the difference between mass added by the constant-rate irrigation and the mass change of the lysimeter.

Later in 2014, the lysimeter irrigation system was changed to use water storage tanks suspended from the monolith so that lysimeter ET could be more clearly differentiated from mass gain due to irrigation (Evett et al., 2018a). Charging the tanks for an irrigation required about 5 min, producing a step change in both the 4,448 N load cell from which the tanks were suspended and in the lysimeter load cell, during which ET was negligible. Because the water tanks and pressure-regulated pump and pressure tank were all suspended from the monolith, irrigation did not change the mass of the lysimeter, and any lysimeter mass change could be directly attributed to ET (or precipitation).

After crop emergence, irrigations were applied to replace soil water in the root zone to field capacity based on weekly neutron probe measurements. Note that irrigation scheduling was done in a feedback system guided by weekly replenishment of measured soil water depletion, rather than by the concept of management allowed depletion (MAD). Previous studies showed that the Pullman soil held enough plant-available water that weekly replenishment was sufficient to avoid crop stress (Howell et al., 1997). Even so, MAD values are shown in the Results and Discussion section for comparison to measurements. Irrigation depth was constrained by the objectives of avoiding runoff from the furrow-diked fields in the case of MESA irrigation and avoiding deep percolation losses in the case of SDI. Minimizing runoff and deep percolation losses aided the accurate computation of ET by the field soil water balance. This sometimes meant that more than one irrigation a week was needed to replenish the soil profile. Preplant irrigations were applied in 2013 and

2014 due to dry preplant soil conditions that would have prevented uniform germination and emergence. Dry spring conditions are common in the region, but early-season precipitation was plentiful in 2015 and 2016, avoiding the need for preplant irrigation in those years.

The NW and SW fields were managed together and were separate from the common management applied to the NE and SE fields. In 2013, the SW field was managed for full (100% replenishment) irrigation, replacing soil water used back to field capacity, while the NW field was irrigated on the same dates but with the nozzle size reduced to apply approximately 75% of full irrigation beginning on 7 June. The deficit irrigation treatment in the NW field was applied to provide more data for a longer-term study of deficit sprinkler irrigation at Bushland. A deficit treatment was not applied in the SDI fields. In 2014, the NW field was managed for full irrigation, while the SW field was managed for approximately 75% of full irrigation. In 2015, large precipitation events early in the year equalized the soil water in the NW and SW fields, so again the SW field was managed for deficit irrigation (75% of full); in 2016 this was reversed, with the deficit irrigation treatment (75% of full) in the NW field. In all years, the NE and SE fields were both managed for full irrigation. With a minimum of four crop water use and yield samples in each field, there were sufficient replications for statistical validity.

PLANT COUNTS AND SAMPLING

Plant counts after emergence were taken in 0.91 m row segments in two adjacent rows at two separate locations in each of the ten linear-move sprinkler spans and in each adjacent pair of SDI zones (zones 1 and 2, zones 3 and 4, etc.). The locations were in opposite halves of each field in the E-W direction. On an approximately biweekly basis, as weather allowed, destructive plant samples for determination of leaf area index (LAI) and above-ground biomass were taken in two adjacent rows, each 0.91 m long, in three replicate locations in each field, and leaf area was determined using a calibrated leaf area meter. Specific LAI (leaf area per unit leaf mass, m^2 kg^{-1}) was computed as a conservative crop development parameter and an internal data check. Crop height and width were measured in the same locations and on each lysimeter. Both fresh mass and dry mass were determined. Yield data reported in this article were from combine harvesting. Yield samples were also taken by hand by removing ears or heads in two rows, each 3.28 m long, in three replicates for each of the four fields and for all plants on each lysimeter (four rows, 2.25 m^2 per row) to determine seed number and mass. Above-ground biomass was collected from these sample areas for determination of dry biomass and harvest index. After drying, the ear or head mass and the shelled or threshed seed mass were determined. On each replicate sample, the mass of 200 seeds was determined, and dry mass per seed was determined after oven-drying (24 h at 60°C). Combine-harvested grain was weighed, and moisture content was measured separately for each of the ten linear-move sprinkler spans and for every two SDI zones, resulting in five yield samples for each of the four fields. The combine-harvested yields were total yields for each area of each field. Yields from the northernmost and southernmost sprinkler spans (or two SDI zones) were omitted from the statistical analysis to avoid edge effects, leaving four yield values for each of the four fields. Reported yields are dry grain yields, adjusted to zero moisture. Statistical calculations were performed using t-tests assuming unequal variances and by ANOVA using the Holm-Sidak method for means comparisons. Means were considered significantly different at the 5% level. Combine-harvested yields and crop water use values calculated from neutron probe data were used for the results presented in this article.

RESULTS AND DISCUSSION

2013 CORN

Despite a severe hailstorm on 28 May 2013 during corn emergence, the plant stand was 84,000 ha^{-1} in the SDI fields, where hail damage reduced the stand, and 96,600 ha^{-1} in the MESA fields. The fully irrigated SW field received 583 mm of MESA irrigation, while the deficit-irrigated NW field received 447 mm of MESA irrigation. Corn fully irrigated using MESA yielded 9.35 Mg ha^{-1}, which was significantly (30%) greater than the 7.24 Mg ha^{-1} corn harvest resulting from limiting MESA irrigation to 75% of full (table 1). The yield differences translated to differences in CWP. MESA

Table 1. Irrigation, precipitation, evapotranspiration (ET), yield, and crop water productivity for corn in 2013. Yields are combine-harvested and adjusted to zero water content (dry). The NE and SE fields were irrigated with SDI, and the NW and SW fields were irrigated with MESA. The NE, SE, and SW fields were fully irrigated. The NW field was irrigated at 75% of the SW field beginning on DOY 158 (7 June).[a]

	Field and Lysimeter (and Irrigation Method)			
2013 Corn	NE (SDI)	SE (SDI)	NW (MESA 75%)	SW (MESA Full)
Preplant irrigation (60 days before planting) (mm)	10	8	112	113
Irrigation from planting to initiation of deficit (DOY 157) (mm)	229	231	21	23
Irrigation after deficit irrigation had begun (DOY 157) (mm)	293	295	314	448
Total irrigation (mm)	532	533	447	583
Preplant precipitation (60 days before planting) (mm)	44	29	29	32
Precipitation from planting to DOY 157 (mm)	38	33	41	45
Precipitation after DOY 157 (mm)	214	208	203	211
Total growing season precipitation (mm)	251	241	245	256
ET from planting to 25 DAP (mm)	104	108	143	137
ET from first preplant irrigation to 25 DAP (mm)	132	131	231	218
Total lysimeter ET (mm)[b]	682	667	708	814
Total field ET (neutron probe basis, same date ranges) (mm)	678 b	643 d	660 c	762 a
Dry grain yield (Mg ha^{-1})	11.38 a	10.87 b	7.24 d	9.35 c
Crop water productivity (CWP) (kg m^{-3})	1.68 a	1.69 a	1.10 c	1.23 b

[a] Field ET, yield, and CWP values followed by different letters are significantly different across the row at $p = 0.05$ using the Holm-Sidak method.

[b] DOY 142 to 296 for east lysimeters, and DOY 136 to 288 for west lysimeters.

full irrigation resulted in CWP of 1.23 kg m^{-3}, which was significantly (12%) greater than the 1.10 kg m^{-3} CWP for MESA deficit-irrigated corn. Fully irrigated corn using SDI yielded on average 11.1 Mg ha^{-1}, which was significantly (19%) greater than the yield of MESA fully irrigated corn. The mean CWP (1.68 kg m^{-3}) for SDI corn was significantly greater (37%) than that for MESA fully irrigated corn. The CWP for MESA deficit-irrigated corn was significantly smaller than that for all other treatments.

Details of the differences in water use and evaporative loss are shown in figure 1. From the first preplant irrigation to 25 days after planting (DAP), MESA fully irrigated corn used 93 mm more water than SDI corn. From day of year (DOY) 167 (25 DAP) through DOY 189, SDI corn used 46 mm less water than MESA fully irrigated corn. Once the crop substantially covered the soil (by DOY 175), the SW field, which was fully irrigated using MESA, used water at rates much greater than the deficit-irrigated NW field (fig. 1a). Under MESA full irrigation, daily ET exceeded 12 mm several times and exceeded 14 mm once. In contrast, the peak water use of deficit-irrigated corn was 10 mm d^{-1}. The water use of MESA fully irrigated corn exceeded that of deficit-irrigated corn through seed filling and senescence until DOY 255. In contrast, the SDI fully irrigated corn exceeded 10 mm of daily water use only once, and in fact appeared to use water at daily rates close to those exhibited by the MESA deficit-irrigated corn until DOY 230, when the SDI irrigated corn began to use more water than the MESA deficit-irrigated corn and began to closely match the water use of MESA fully irrigated corn (fig. 1). We postulate that the increased late-season use of water in SDI was related to deeper wetting of the profile and easier deep root growth and water uptake with SDI. This late-season water use was likely important for complete grain filling. From field ET calculations based on neutron probe readings and equation 1, MESA fully irrigated corn used the most water (780 mm), MESA deficit-irrigated corn used 666 mm, while SDI irrigated corn used significantly less water (666 to 678 mm) than MESA fully irrigated corn.

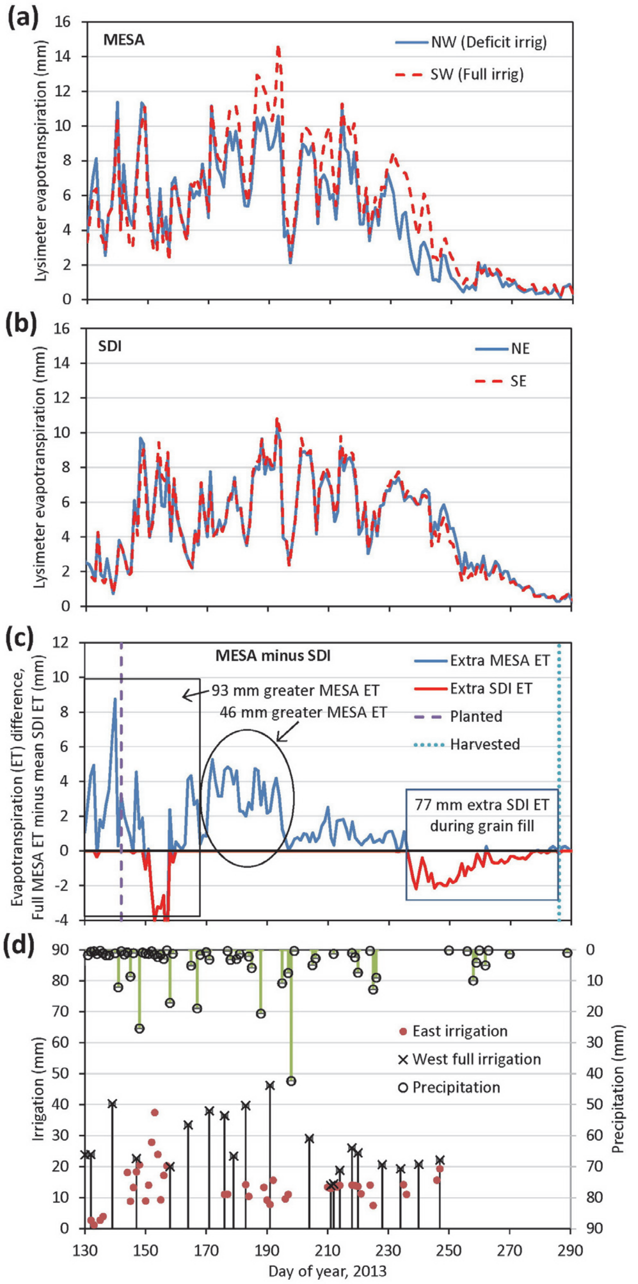

Figure 1. Corn evapotranspiration (ET) in 2013 in (a) MESA irrigated fields (NW and SW) and (b) SDI fields (NE and SE), (c) differences in ET between MESA and SDI fields (values >0 indicate extra ET in MESA fields, and values <0 indicate extra ET in SDI fields), and (d) mean precipitation, mean irrigation in east fields (SDI), and mean full irrigation in west fields (MESA).

MESA irrigation wetted the soil surface, which resulted in much greater evaporative loss during preplant irrigations and in the first 25 DAP when the crop was emerging and not yet covering much of the soil surface (fig. 1c). As observed from the weighing lysimeter data, total MESA irrigation water use in that period was 218 and 231 mm, compared with the much smaller water use (131 and 132 mm) of SDI irrigated corn. Most of this water was lost to evaporation from the soil surface because the plants had not emerged or were very small. The gross savings in evaporative loss from the use of SDI was 93 mm during this period (fig. 1c). This is close to the savings estimated by Evett et al. (1995), who used the ENWATBAL simulation model to estimate an evaporative loss reduction of 81 mm for SDI compared with surface irrigation of corn in a relatively dry year. The greater evaporative losses under MESA irrigation did not end at 25 DAP but continued until approximately DOY 196, when the corn had grown taller than the MESA sprays, totaling another 46 mm more water lost from MESA full irrigation than from full SDI during that period.

Differences in water use did not always translate directly into yield differences. The MESA fully irrigated corn yield was significantly (30%) greater than the MESA deficit-irrigated corn yield. However, the SDI irrigated corn, which used less water than the MESA fully irrigated corn, significantly exceeded both MESA treatment yields with a mean yield of 11.1 Mg ha^{-1}. Overall yields were not as large as expected, partly due to corn earworms that invaded nearly every ear despite the Bt variety grown. The larger yields from the SDI fields were partially due to more water available for transpiration, particularly during the late-season grain filling stage (fig. 1c). The CWP for the SDI fields was significantly greater than that for the MESA fields, and the CWP for the MESA fully irrigated field was significantly greater than that for the MESA deficit-irrigated field. Yield loss for the MESA deficit-irrigated field occurred even though the measured water contents were greater than the MAD value (fig. 2). There are two reasons for this. First, the water content values plotted in figure 2 are means, and some individual values were less than the MAD value, which means that some areas of the field were dry enough to cause yield reduction. Second, the mean values in the deficit-irrigated field were almost constantly at or near the MAD level for much of the season, including during grain filling, which evidently had a substantial effect on final yield.

The increased yields of the SDI irrigated corn may have been influenced by better overall soil water conditions (fig. 2). While water storage in the top 1.5 m of the soil for the MESA fully irrigated field was always considerably greater than the maximum allowed depletion, water storage in the SDI fields was greater and often near field capacity for the first half of the season (fig. 2b). This was due to two factors. One is that the SDI fields were heavily irrigated (220 mm) after planting in order to bring water to the surface to germinate the corn. This irrigation was enough, in combination with the antecedent water, to bring the soil to field capacity. Calculated deep percolation losses were small, as was measured lysimeter drainage, so this water remained in the profile and was available to the crop later in the season. Field-calculated deep percolation at the 2.20 m depth for the period from DOY 171 to 269 totaled <1 mm in the NE field and 26 mm in the SE field. For the period from DOY 156 to 267, field-calculated deep percolation was 9 mm in the NW field and 24 mm in the SW field. Measured lysimeter drainage over the same periods was 8 mm in the NE lysimeter and zero in the SE, NW, and SW lysimeters.

There is evidence that corn rooting is enhanced when the Pullman soil is wet (Tolk and Evett, 2012). This likely occurs because the soil strength (resistance to root penetration) is much less in wetter soil. The MESA fields were irrigated to replenish water content to field capacity, but the large evaporative losses likely prevented effective use of the applied irrigation water, so the water content only increased gradually (fig. 2a). This is why irrigation to replenish the water content to field capacity in the MESA fields often did not result in the measured water content being at field capacity in those fields. The other reason is that the neutron probe measurements typically lagged irrigation events by two to three days in the MESA fields because the fields were too muddy for foot traffic. In contrast, the neutron probe could be used in the SDI fields soon after irrigation because SDI left the soil surface reasonably dry.

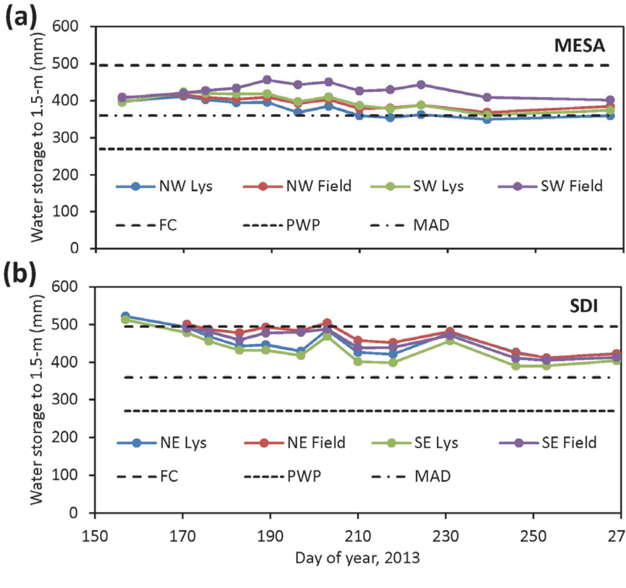

Figure 2. Water storage in top 1.5 m of soil in 2013 for (a) NW (deficit) and SW (full) MESA irrigated fields and lysimeters (Lys) and (b) NE and SE SDI fields and lysimeters. FC = field capacity, PWP = permanent wilting point, and MAD = management allowed depletion.

2014 SHORT-SEASON SORGHUM

Due to a dry spring and dry soil profile, preplant irrigations were conducted on all lysimeter fields in 2014 in preparation for cotton planting but were terminated due to heavy rains (121 to 125 mm) that delayed planting. Cotton was planted on 3 June 2014 (DOY 154) but failed soon after due to torrential rains totaling >120 mm during emergence (DOY 156 to 159, fig. 3d). Short-season sorghum (Channel 5c35) was planted on 20 June 2014 (DOY 171) and emerged five days later. Black layer was noted on DOY 272 and was fully developed by DOY 290. MESA irrigation on the west fields began on 1 May 2014 (DOY 121) and totaled 98 mm before sorghum was planted (table 2). SDI applications began on 12 May 2014 (DOY 132) in the east fields and averaged ~171 mm before sorghum planting due to the drier soil profile in the seed zone in the east fields and the need to bring water to the soil surface to promote germination. The deficit irrigation treatment on the SW field did not begin until 1 August and resulted in only a 73 mm reduction in total irrigation, not enough to influence crop yield given the full soil profile that resulted from the plentiful rains. Due to the full profile, only 34 mm of MESA irrigation was required from planting through July. Hot, dry weather in July and August required 256 mm of irrigation for the fully irrigated treatment in the NW field. A large rainfall (>60 mm) on September 3 finished the irrigation season.

Runoff during and after a rainfall of >60 mm in 25 min before midnight on 5 June 2014 (DOY 156) and continuing into DOY 157 compromised ET measurements on the SE, NW, and SW lysimeters for those two days. Runoff was not detected on the NE lysimeter but may have occurred. Runon also likely occurred. The field soil water balance based on neutron probe data was also likely compromised due to runoff losses. Runoff losses from the lysimeters were limited by the ~0.05 m freeboard of the lysimeter walls, but the field had not yet been furrow diked to prevent runoff losses. Deep percolation losses were calculated for both fields throughout the season, with the largest in the SDI fields. Other large precipitation events of ~53 mm on DOY 197 and 62 mm on DOY 248 (fig. 3d) occurred over longer periods and did not result in runoff from the lysimeters but may have caused runoff in the fields. The following discussion of water use, yields, and CWP should be understood in the context of this uncertainty in ET.

Although there was a 72 mm difference in total irrigation,

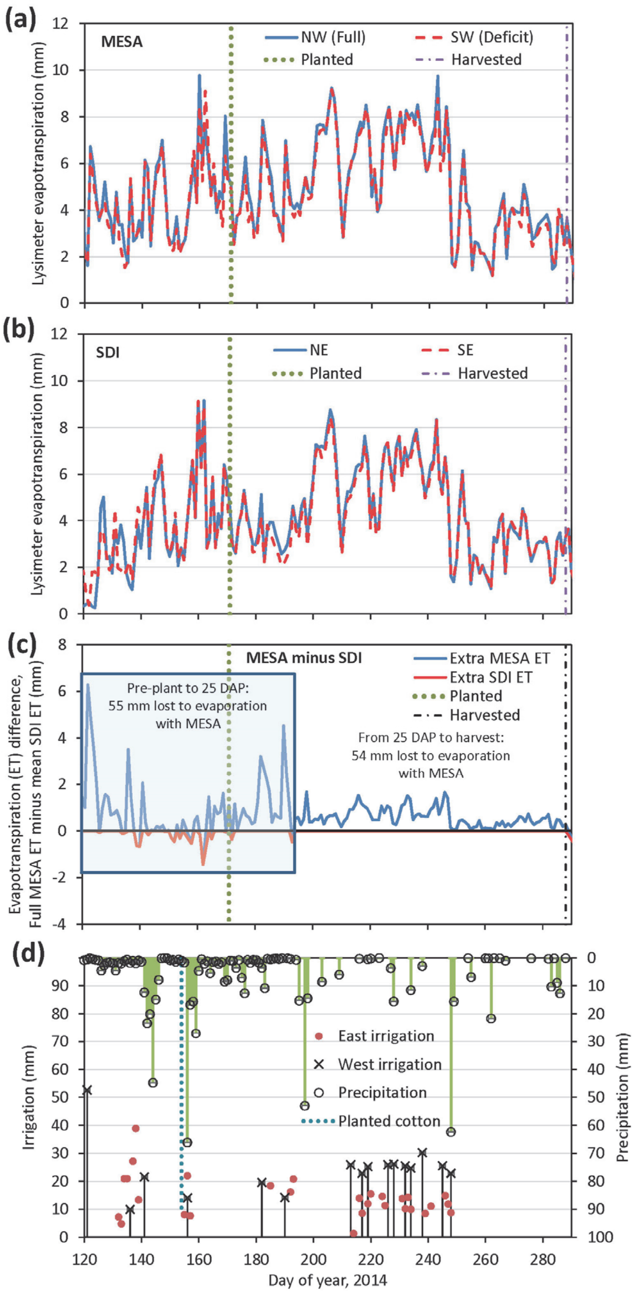

Figure 3. Sorghum evapotranspiration (ET) in 2014 in (a) MESA irrigated fields (NW and SW) and (b) SDI fields (NE and SE), (c) differences in ET between MESA and SDI fields (values >0 indicate extra ET in MESA fields, and values <0 indicate extra ET in SDI fields), and (d) mean precipitation, mean irrigation in east fields (SDI), and mean full irrigation in west fields (MESA).

the season-total sorghum water use (ET) did not differ much between the MESA fully irrigated (596 mm by lysimeter, 552 mm by neutron probe) and deficit-irrigated (574 mm by lysimeter and 518 by neutron probe) crops (fig. 3a; table 2). Even though the yield from deficit-irrigated sorghum was 7.0% less than that for fully irrigated sorghum, the yields were not significantly different (table 2). Similar depression of yield when water is limited during grain filling has been reported previously (Sehgal et al., 2018). In the NE and SE SDI fields, yields were smaller (6.41 and 6.19 Mg ha^{-1}, respectively) and did not differ significantly. However, the SDI yields were significantly smaller (15% overall) than those obtained using MESA full irrigation. For the same sorghum variety, O'Shaughnessy et al. (2014) reported a yield of 8.04 Mg ha^{-1} for 533 mm of ET in 2009 but only an average of 6.42 Mg ha^{-1} for an average ET of 648 mm in 2010 and 2011. For one of the SDI fields in the present study, CWP was significantly smaller than that for MESA full irrigation; otherwise, there were no significant differences in CWP among the four fields and two irrigation methods.

Water use recorded with the lysimeters in the SDI fields was typically less than that in the MESA irrigated fields throughout the season (fig. 3c). The MESA fully irrigated sorghum used 55 mm more water than the SDI sorghum during the period from initiation of preplant irrigation until 25 DAP (fig. 3c). Unlike the results for the previous year's tall corn crop, losses to evaporation continued throughout the season for the MESA irrigated sorghum, totaling another 54 mm by season's end, for a season-long total of 109 mm lost to evaporation. The likely cause for the greater ET for the MESA irrigated crop through 1 August (DOY 213) is that the sorghum did not reach a height that was appreciably greater than the elevation of the spray plates, so the entire leaf area was wetted by each irrigation event. Note that water use calculated using equation 1 and the neutron probe data did not follow the same trends as the lysimeter-based ET (table 2).

There are several possible reasons for the smaller sorghum yields with SDI. The large rainfalls may have leached fertilizer from the already full soil profile in the SDI fields, depressing yields. Supporting this idea is the fact that the lysimeters in the SDI fields drained considerably more water than those in the MESA irrigated fields (mean of 298 mm for SDI vs. <4 mm for MESA), indicating larger deep percolation losses in the SDI fields. Preplant irrigation with the SDI system was larger than with the MESA system in order to bring water to the seedbed for cotton germination. This proved unnecessary due to the large rains just after cotton planting, and it left the soil profile full of water prior to the large rains. Depressed sorghum grain yield under full irrigation, when "full" is defined as 100% replenishment of the soil water to field capacity, is why the sorghum experiments by O'Shaughnessy et al. (2012, 2014) used 80% replenishment as the maximum. It is also one reason why a 75% replenishment treatment was included in the MESA deficit-irrigated fields in the present study.

Despite the larger preplant irrigation, evaporative losses before planting and through 25 DAP were on average 55 mm smaller in the SDI fields compared with the MESA irrigated fields. Growing season irrigation with SDI averaged 128 mm less than that for MESA full irrigation, but season-long water use for SDI sorghum averaged 77 mm less than that for MESA fully irrigated sorghum, mostly due to 75 mm less irrigation in the SDI fields after August 1. Water content in the SDI fields remained near field capacity for the rest of the season (fig. 4). It is possible that plentiful water in the SDI fields after 1 August, combined with the loss of nutrients due to deep percolation, led to the 9% yield depression in SDI fields.

This result is in line with those of Colaizzi et al. (2004), who reported that yields for both long-season and short-sea-

Table 2. Irrigation, precipitation, evapotranspiration (ET), yield, and crop water productivity for sorghum in 2014. Yields are combine-harvested and adjusted to zero water content (dry). The NE and SE fields were irrigated with SDI, and the NW and SW fields were irrigated with MESA. The NE, SE, and SW fields were fully irrigated. The SW field was irrigated at 75% of the NW field beginning on DOY 213 (1 August).[a]

	Field and Lysimeter (and Irrigation Method)			
2014 Sorghum	NE (SDI)	SE (SDI)	NW (MESA Full)	SW (MESA 75%)
Preplant irrigation (mm)	175	168	98	99
Irrigation from planting through DOY 212 (mm)	52	59	34	33
Irrigation after DOY 212 (mm)	181	181	256	185
Total irrigation (planting to harvest) (mm)	233	240	290	217
Preplant precipitation (mm)	298	316	364	316
Precipitation from planting through DOY 212 (mm)	148	147	153	134
Precipitation DOY 213 to harvest (mm)	180	172	172	175
Total growing season precipitation (mm)	328	319	325	308
ET from 50 days before planting to 25 DAP (mm)	270	264	322	303
Total growing season lysimeter ET (mm)	534	515	596	574
Total growing season ET (neutron probe basis) (mm)	566 a	518 c	552 b	518 c
Dry grain yield (Mg ha^{-1})	6.41 b	6.19 b	7.45 a	6.93 ab
Crop water productivity (CWP) (kg m^{-3})	1.13 b	1.20 ab	1.35 a	1.34 ab

[a] Field ET, yield, and CWP values followed by different letters are significantly different across the row at p = 0.05.

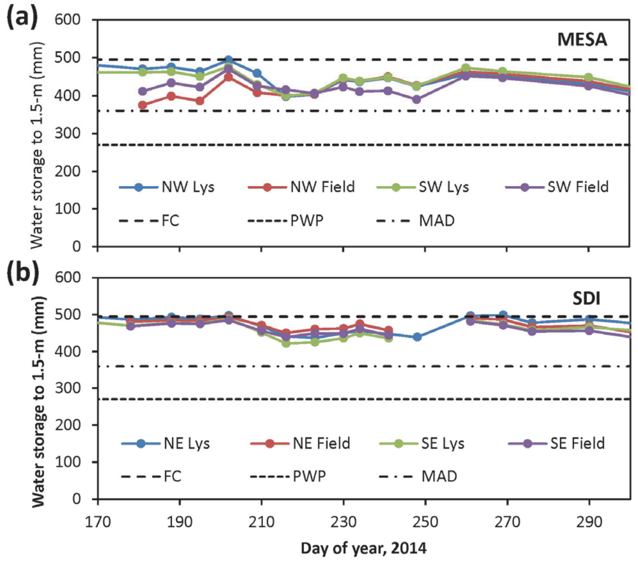

Figure 4. Water storage in top 1.5 m of soil in 2014 for (a) NW (full) and SW (deficit) MESA irrigated fields and lysimeters (Lys) and (b) NE and SE SDI fields and lysimeters. FC = field capacity, PWP = permanent wilting point, and MAD = management allowed depletion.

son grain sorghum were on average 12% less for SDI compared with MESA for 75% and 100% of full irrigation. They also attributed this yield depression to leaching of nutrients, which was supported by measurements of increasing volumetric water content deep (>1.8 m) in the soil profile. In their study, leaching was caused by overirrigation due to irrigation management based on crop coefficients developed for sprinkler irrigation, which did not take into account the reduced crop water use with SDI. For sorghum irrigated with SDI at Colby, Kansas, Lamm et al. (2010) reported smaller grain yields at all irrigation levels compared with irrigation using low-energy precision applicators (LEPA), but they did not suggest a cause. Interestingly, for 25% and 50% irrigation rates, Colaizzi et al. (2004) reported that SDI resulted in an average of 36% greater grain yields compared with MESA. This implied that SDI resulted in greater partitioning of water to plant transpiration and less to soil evaporation, especially early in the season. The present study confirms the supposition of Colaizzi et al. (2004) of reduced evaporative loss with direct measurements, which reinforces their supposition of greater partitioning of water to plant transpiration.

Despite the fact that spray irrigation can reduce leaf temperature and in some cases promote greater yields (Hatfield and Prueger, 2015; Hatfield et al., 2011), yields in the SDI fields were likely not adversely affected by greater leaf temperatures. The mean daily air temperatures in 2013 and 2014 were not greatly different; they varied from 20°C to 30°C through the middle part of the growing season, when the weather was warmest, but not enough to incur large yield effects. Plant height and width were not noticeably or significantly different between the SDI and MESA irrigated fields (data not shown). However, LAI reached greater values in the MESA fields than in the SDI fields, and the difference at maximum LAI (before DOY 230) was statistically significant for the MESA fully irrigated field (data not shown). Because the water content in the SDI fields before DOY 230 was not deficient (fig. 4), and because leaf expansion is known to be influenced by nitrogen fertility, the smaller LAI in the SDI fields was likely due to loss of N fertilizer due to leaching, which resulted in decreased LAI and yield.

2015 SHORT-SEASON SORGHUM

The year 2015 was the wettest year in >70 years of record at Bushland, with >970 mm of precipitation. Precipitation in the 60 days before sorghum planting averaged 412 mm, nearly the yearly mean for Bushland, which is why preplant irrigations were not conducted in 2015 (table 3; fig. 5d). The 41 mm range in lysimeter catch precipitation during this period was representative of the precipitation variability caused by convective thunderstorms with their well-defined rain shafts, which are characteristic of the region (Evett et al., 2018b). As in 2014, cotton was planted and hailed out, followed by planting short-season sorghum (Channel 5c35) at 210,000 seeds ha^{-1} on 22-23 June 2015 (DOY 173-174). Dry surface soil and shallow hand-planting necessitated hand-watering of the east lysimeters on 2 July 2015 (DOY 183) to promote emergence (fig. 5d). The fully emerged crop was severely damaged by hail on 8 July 2015 (DOY 189) but survived, reached full bloom on 20 August, and was harvested on 20 October (DOY 293). Grasshoppers and sugarcane aphids infested the crop in August but were controlled

Table 3. Irrigation, precipitation, evapotranspiration (ET), yield, and crop water productivity for sorghum in 2015. Yields are combine-harvested and adjusted to zero water content (dry). The NE and SE fields were irrigated with SDI, and the NW and SW fields were irrigated with MESA. The NE, SE, and NW fields were fully irrigated. The SW field was irrigated at 75% of the NW field beginning on DOY 182 (1 July).[a]

	Field and Lysimeter (and Irrigation Method)			
2015 Sorghum[b]	NE (SDI)	SE (SDI)	NW (MESA Full)	SW (MESA 75%)
Preplant irrigation (mm)	0	0	0	0
Irrigation from planting to 25 DAP (mm)	55	56	42	51
Irrigation after 25 DAP (mm)	175	171	244	183
Total irrigation (mm)	230	227	286	234
Preplant precipitation (60 days before) (mm)	433	420	402	392
Precipitation from planting to 25 DAP (mm)	157	153	135	144
Precipitation after 25 DAP (mm)	255	256	262	266
Total growing season precipitation (mm)	412	409	397	411
ET from planting to 25 DAP (mm)	97	93	105	95
Total lysimeter ET (planting to harvest) (mm)	548	542	594	594
Total field ET (neutron probe basis) (mm)	555 b	508 c	601 a	558 c
Dry grain yield (Mg ha^{-1})	7.46 a	7.54 a	7.88 a	7.83 a
Crop water productivity (CWP) (kg m^{-3})	1.34 b	1.49 a	1.31 b	1.40 a

[a] Field ET, yield, and CWP values followed by different letters are significantly different across the row at p = 0.05 using the Holm-Sidak method.

[b] Irrigation values do not reflect hand-watering on the NE and SE lysimeters on DOY 183 to aid germination.

using pesticides. Deficit irrigation of the SW field began on 1 July 2015 (DOY 182). Precipitation during the growing season averaged 405 mm, and total growing season irrigation amounts were correspondingly small: 286 mm for MESA full irrigation and an average of 228 mm in the field for SDI (hand-watering to promote emergence on the east lysimeters on DOY 183 is excluded from this average).

Irrigation from planting to 25 DAP was not much different between the MESA full irrigation and SDI treatments, ranging from 51 to 56 mm (table 3; fig. 5d). ET to 25 DAP was only slightly larger (10 mm) for MESA irrigation compared with SDI, in part because hand-watering of the east lysimeters caused subsequently larger ET for three days (fig. 5d). Full-season ET was 50 mm larger for MESA full irrigation compared with SDI (fig. 5c). In this wet year, ET rates were less than 10 mm d^{-1} and almost always less than 8 mm d^{-1} (figs. 5a and 5b). ET rates were only slightly less for SDI than for MESA full irrigation throughout the season. Soil water content remained greater than the MAD value in the SDI fields and was similar for the fully irrigated MESA field (fig. 6). Soil water content in the MESA deficit-irrigated field approached MAD late in the season, but too late to have an appreciable effect on yield. Yields averaged 7.51 Mg ha^{-1} for SDI versus 7.88 Mg ha^{-1} for MESA full irrigation and 7.86 ha^{-1} for MESA deficit irrigation. Yields were not significantly different across the four fields, although the mean yield of 7.85 Mg ha^{-1} for the MESA irrigated fields was numerically larger than the mean SDI yield of 7.51 Mg ha^{-1}. At 1.49 kg m^{-3}, the CWP of the SE SDI field was statistically greater than the CWP of the NW MESA fully irrigated field at 1.31 kg m^{-3}. The CWP of the SE SDI field was also significantly greater than that of the NE SDI field and the SW MESA deficit-irrigated field. The mean CWP of 1.42 kg m^{-3} for SDI was numerically larger than the 1.31 kg m^{-3} value for MESA full irrigation and close to the 1.40 kg m^{-3} value for MESA deficit irrigation.

Drainage occurred in all four lysimeters but on average was larger (210 mm) in the east (SDI) lysimeters than the average 165 mm in the west (MESA) lysimeters. Drainage in the MESA deficit-irrigated lysimeter was least at 150 mm. Drainage in the east began on DOY 141 in response to the 412 mm of precipitation in the 60 days before sorghum planting, while drainage in the west began on DOY 190 in response to the larger rains after planting. As in 2014, lysimeter drainage is indicative of deep percolation losses in the field, and the larger drainage in the east lysimeters likely corresponded to larger deep percolation and fertilizer losses in the east fields than in the west fields. The calculated deep percolation at 2.20 m depth over the period from DOY 197 to 289 was not as large as the drainage in the lysimeters and was 5 mm for the NE field, 35 mm for the SE field, 21 mm for the NW field, and 30 mm for the SW field. The corresponding drainage over the same period in the lysimeters was 78 mm for the NE lysimeter, 67 mm for the SE lysimeter, 99 mm for the NW lysimeter, and 122 mm for the SW lysimeter. Considering that the standard deviation of calculated deep percolation in a field can be >5 times its magnitude, these differences between means of field calculated deep percolation losses (*N* = 8) and the single values from each lysimeter do not seem problematic.

As shown by Evett et al. (2012b), there can be differences between lysimeter and field soil water balances. In figure 6, water storage is shown for the top 1.5 m of the profile because that is the rooting zone, and the storage value in that depth was used for irrigation management. However, the soil water content in the lysimeters between 1.5 and 2.3 m depths was typically greater than the field soil water contents because lysimeters cannot reproduce field soil water conditions near their bottoms, even with vacuum drainage equivalent to 1 m of water head. Because hydraulic conductivity increases logarithmically with soil water content, the wetter 1.5 to 2.3 m profile in the lysimeters could drain more easily during the very wet 2015 season. Based on the data presented here, there is no reason to conclude that either the neutron probe method or the lysimeter method are inaccurate; they simply represent different systems.

2016 CORN

A drought-tolerant corn variety (Pioneer 1151AM) was planted on 10-11 May 2016 (DOY 131) at 87,475 seeds ha^{-1} and had emerged by 21 May (DOY 137). Due to precipitation averaging 99 mm in the 60 days before planting, no preplant irrigation was required. The 75% deficit irrigation treatment on the NW field began on 9 June 2016 (DOY 161).

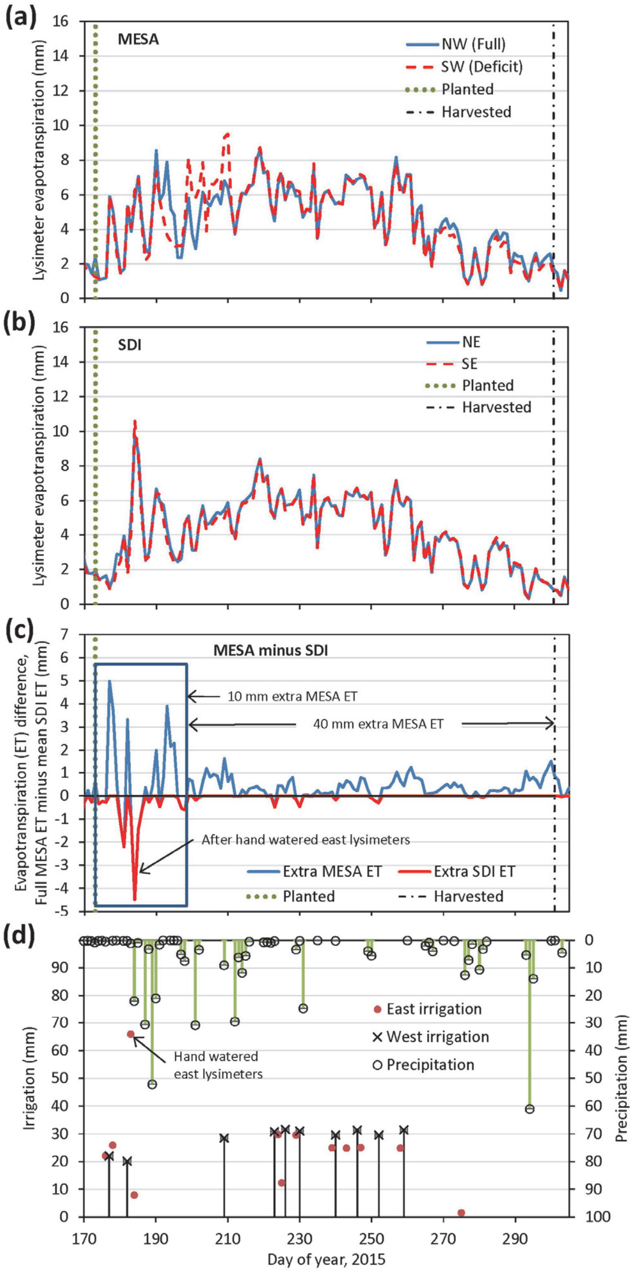

Figure 5. Sorghum evapotranspiration (ET) in 2015 in (a) MESA irrigated fields (NW and SW) and (b) SDI fields (NE and SE), (c) differences in ET between MESA and SDI (values >0 indicate extra ET in MESA fields, and values <0 indicate extra ET in SDI fields), and (d) mean precipitation, mean irrigation in east fields (SDI), and mean full irrigation in west fields (MESA).

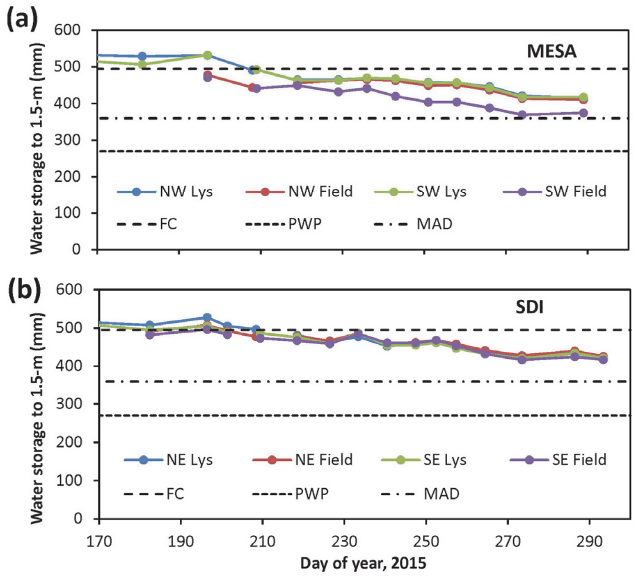

Figure 6. Water storage in top 1.5 m of soil in 2015 for (a) NW (full) and SW (deficit) MESA irrigated fields and lysimeters (Lys), and (b) NE and SE SDI fields and lysimeters. FC = field capacity, PWP = permanent wilting point, and MAD = management allowed depletion.

Along with growing season precipitation that averaged 238 mm and moderate weather, total irrigation averaged 504 mm for SDI (table 4). MESA full irrigation was 22% larger and MESA full irrigation ET was 21% larger than for SDI. For MESA deficit irrigation, the ET was 9% larger than the ET for SDI, even though the total irrigation (392 mm) was 22% less than the SDI mean of 504 mm. This result indicates that sprinkler irrigation was relatively inefficient in delivering water to the crop in the deficit regime. Due to timely rains, the soil water content under MESA deficit irrigation approached the MAD level only twice during the growing season. Daily ET exceeded 15 mm once and reached 12 mm a few times for MESA fully irrigated corn (fig. 7a) but reached and exceeded 12 mm only once for SDI (fig. 7b).

Because little irrigation was applied before 25 DAP (<40 mm), there was not much difference in ET between MESA full irrigation and SDI during that period, but ET was consistently larger for MESA full irrigation for the rest of the season (fig. 7c), resulting in 150 mm more ET over the entire growing season for MESA full irrigation than for SDI. Soil water storage throughout the season indicated a no-stress regime for MESA fully irrigated corn and corn under SDI (figs. 8a and 8b). The MESA deficit-irrigated corn approached the MAD level twice during critical growth stages (fig. 8a), resulting in the MESA deficit-irrigated yield of 9.76 Mg ha^{-1} being significantly less than that for MESA full irrigation or either SDI field (table 4). The SDI yields were significantly less than the yield for MESA full irrigation; MESA full irrigation resulted in 9% (0.92 Mg ha^{-1}) larger yield than the average for SDI. The largest CWP of 1.71 kg m^{-3} for the SE SDI field was significantly greater than the CWP for either full or deficit irrigation with MESA.

There was no drainage in the SE, SW, and NW lysimeters during the growing season and 50 mm of drainage in the NE lysimeter. The calculated deep percolation was <50 mm. This indicates that deep percolation was likely unimportant in the fields.

DISCUSSION

Evapotranspiration during the preplant irrigation period and in the first 25 DAP was mostly due to evaporation from the soil surface. By that measure, the SDI system saved 85 and 93 mm of the water that was lost to evaporation early in the season (preplant to 25 DAP) from the MESA fully irrigated crop in 2013 and 2014, respectively, which was consistent with the estimate of evaporative loss reduction for SDI made using the ENWATBAL model (Evett et al., 1995).

Table 4. Irrigation, precipitation, evapotranspiration (ET), yield, and crop water productivity for corn in 2016. Yields are combine-harvested and adjusted to zero water content (dry). The NE and SE fields were irrigated with SDI, and the NW and SW fields were irrigated with MESA. The NE, SE, and SW fields were fully irrigated. The NW field was irrigated at 75% of the SW field beginning on DOY 161 (9 June).[a]

	Field and Lysimeter (and Irrigation Method)			
2016 Corn	NE (SDI)	SE (SDI)	NW (MESA 75%)	SW (MESA Full)
Preplant irrigation (mm)	0	0	0	0
Irrigation from planting to 25 DAP (mm)	34	34	33	36
Irrigation after 25 DAP (mm)	464	476	358	580
Total irrigation (mm)	498	510	392	616
Preplant precipitation (60 days before) (mm)	108	99	102	88
Precipitation from planting to 25 DAP (mm)	41	38	43	38
Precipitation after 25 DAP (mm)	198	195	195	202
Total growing season precipitation (mm)	238	233	239	241
ET from planting to 25 DAP (mm)	51	50	68	62
ET from DOY 157 to 285 (mm)	677	685	728	819
Total lysimeter ET (mm)	728	736	796	882
Total field ET (neutron probe basis) (mm)	750 b	718 c	717 c	860 a
Dry grain yield (Mg ha^{-1})	11.92 b	12.31 b	9.76 c	13.04 a
Crop water productivity (CWP) (kg m^{-3})	1.59 b	1.71 a	1.36 c	1.52 b

[a] Field ET, yield, and CWP values followed by different letters are significantly different across the row at p = 0.05 using the Holm-Sidak method.

In 2015 and 2016, when the spring weather was wetter and preplant irrigation was not needed, the ET savings with SDI to 25 DAP were small (≤11 mm). Between 25 DAP and midseason, another 53 and 52 mm of water was lost with MESA irrigation compared with SDI in 2013 and 2014, respectively. In 2015 and 2016, from 25 DAP to harvest, there were ET savings of 39 and 139 mm, respectively, using SDI compared with MESA full irrigation. For corn grown in 2013, much of the water saved due to smaller evaporative losses was used during grain filling, when SDI corn used 82 mm more water than MESA fully irrigated corn. In the relatively dry 2013 season, SDI reduced overall corn water use by 12% while increasing yields by 19% and CWP by 35% compared with MESA full irrigation. In the relatively wet 2016 season, SDI reduced overall corn water use by 125 mm while increasing CWP by 9% compared with MESA full irrigation, although the SDI yield was 9% less than the yield for MESA full irrigation.

Sorghum, particularly short-season sorghum, is not a crop ordinarily considered for SDI; in this study, sorghum was grown in two years after cotton crop failure. When sorghum was grown using SDI, yields and water use efficiencies were comparable to other studies reported for short-season sorghum at Bushland. However, sorghum yield was significantly (15%) less for SDI than for MESA full irrigation in 2014. The 2014 SDI results were likely due to leaching of applied fertilizer and an overly wet soil profile caused by a combination of preplant irrigation in a dry spring followed by large precipitation events. The CWP was 14% smaller for SDI than for MESA full irrigation, and significantly so for one of the two SDI fields. In 2015, the yield differences were smaller and statistically insignificant. Although 2015 was the wettest year on record, precipitation was less intense than in 2014, and deep percolation losses and runoff were less important. SDI used significantly (12%) less water than MESA full irrigation in 2015, and CWP was 8% to 14% larger for SDI than for MESA. The sorghum yield reduction with SDI was similar to that reported by Colaizzi et al. (2004, 2005) at Bushland for full irrigation and 75% of full irrigation, when full irrigation was defined by reference ET multiplied by crop coefficient values determined using sprinkler irrigation. Lamm et al. (2010) also reported sorghum yield reductions for SDI at Colby, Kansas, but for all irrigation levels, and O'Shaughnessy et al. (2012, 2014) chose replenishment of soil water depletion to 80% of field capacity as their "full" sorghum irrigation treatment due to yield reductions previously observed with more plentiful irrigation regimes. Combined, these results point to a need to further investigate sorghum yield response to irrigation regime and application method, including both how much water is in the soil profile and the location of the water in relation to the root zone.

Crop ET calculated using neutron probe data generally followed the same ranking as ET determined by weighing lysimeter except for the 2014 season, when runoff and deep percolation losses influenced the accuracy of ET calculated using the soil water balance. The largest differences in ET from the two methods were for the MESA fully irrigated treatment in 2016 and for the MESA deficit-irrigated treatments in 2013 and 2016. The absolute differences for MESA were 48 mm for deficit irrigation and 61 mm for full irrigation in 2013 (7.3% and 8.0%), 56 mm for deficit irrigation and 44 mm for full irrigation in 2014 (10.9% and 8.0%), 21 mm for deficit irrigation and 23 mm for full irrigation in 2015 (3.5% and 4.1%), and 78 mm for deficit irrigation and 22 mm for full irrigation in 2016 (9.8% and 2.5%).

The absolute ET differences between the neutron probe and lysimeter methods for SDI were 5 and 23 mm in 2013 (0.7% and 3.6%), 20 and 40 mm in 2014 (3.6% and 7.2%), 14 and 24 mm in 2015 (2.6% and 4.7%), and 22 and 17 mm in 2016 (3.0% and 2.3%). Differences between the ET values determined using the lysimeters and the neutron probe were expected, given that the neutron probe data represented a mean of eight values and each lysimeter rendered a single value (Evett et al., 2012b). Except for the SE field in 2014, the differences for SDI were <5%, which is reasonable, given that the standard deviation of field ET (determined using the neutron probe) ranged from 2.5% to 4.9%. Differences between the lysimeter and neutron probe ET values for the MESA fields were reasonable for full irrigation in 2015 and 2016, but not so much in 2013 and 2014. Except for 2015, the differences for MESA deficit irrigation were less reasonable, given the standard deviation of field-determined ET.

The yield increases in some years and the water savings

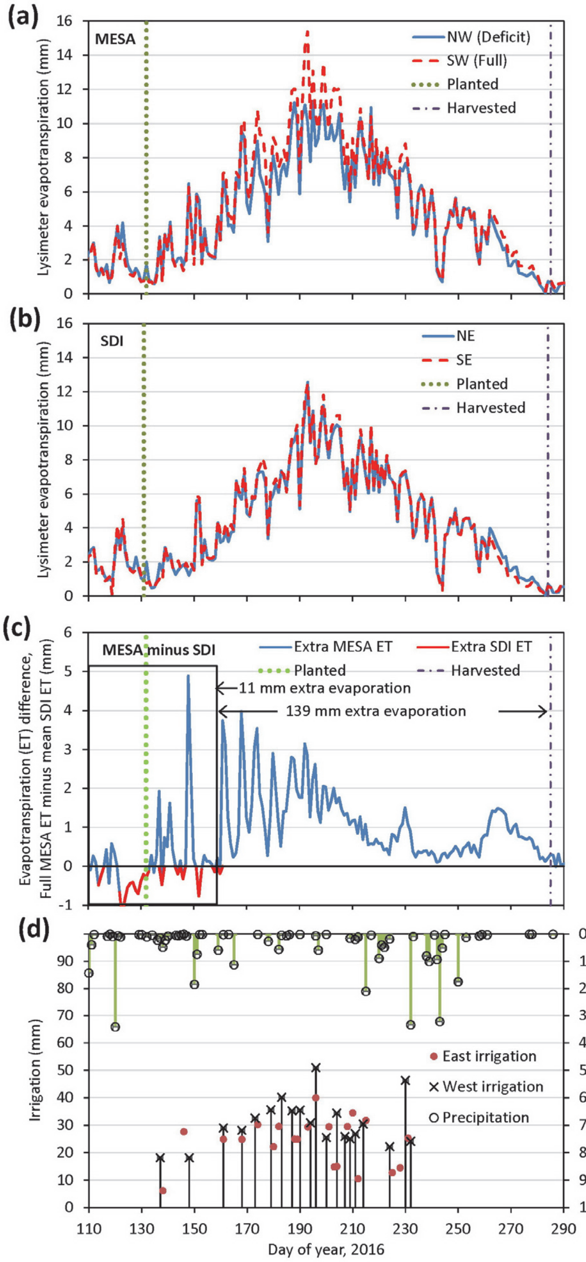

Figure 7. Corn evapotranspiration (ET) in 2016 in (a) MESA irrigated fields (NW and SW) and (b) SDI fields (NE and SE), (c) differences in ET between MESA and SDI fields (values >0 indicate extra ET in MESA fields, and values <0 indicate extra ET in SDI fields), and (d) mean precipitation, mean irrigation in east fields (SDI), and mean full irrigation in west fields (MESA).

in three of four years using SDI point to important economic advantages in revenue and reduced pumping costs, particularly for corn. These advantages were more apparent for corn production and much less for sorghum production. Extreme weather events in 2014 and an abnormally wet year in 2015 impacted the relevance of the sorghum results for this region.

CONCLUSIONS

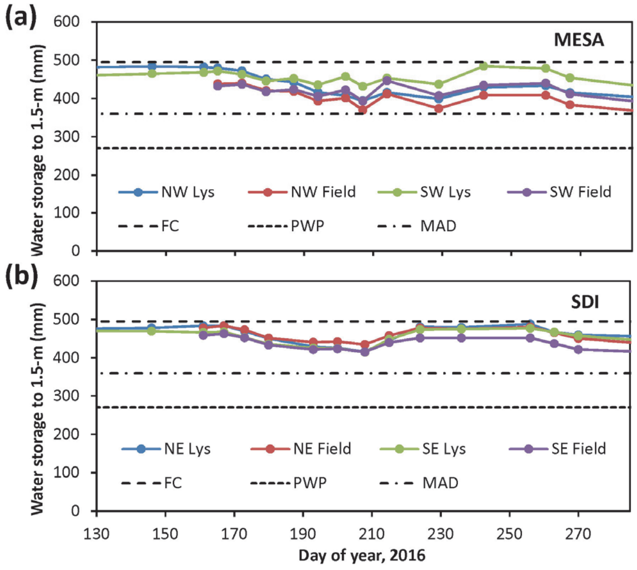

Figure 8. Water storage in top 1.5 m of soil in 2016 for (a) NW (deficit) and SW (full) MESA irrigated fields and lysimeters (Lys), and (b) NE and SE SDI fields and lysimeters. FC = field capacity, PWP = permanent wilting point, and MAD = management allowed depletion.

Using SDI instead of MESA sprinkler irrigation reduced evaporative losses and saved important amounts of water during the preplant irrigation period (if any) and during the post-plant period through at least 25 DAP regardless of the crop. Savings decreased when precipitation was plentiful during these periods but can be important in semi-arid West Texas. Savings ranged from 93 to 55 mm in the dry springs of 2013 and 2014, but were <11 mm in the wet springs of 2015 and 2016.

Water savings using SDI rather than MESA sprinkler irrigation continued after 25 DAP and even when leaf area had reached its maximum. These additional savings were 46, 54, 40, and 139 mm of water in 2013, 2014, 2015, and 2016, respectively. Therefore, considerable water was lost to evaporation from the wetted canopy and soil with MESA sprinkler irrigation, even when the crops had reached full height.

Total water savings using SDI rather than MESA sprinkler irrigation were 139, 109, 50, and 150 mm in 2013, 2014, 2015, and 2016, respectively. Given that 2015 was the wettest year on record at Bushland, the 50 mm of water savings was meaningful. Given variable pumping costs of $10.70 per ha-cm for MESA (Amosson et al., 2011), the data from the four years translate to an extra cost of $57 to $171 ha^{-1} for MESA, with a mean of $128 ha^{-1}. For a center-pivot system irrigating 50.8 ha (1/4 mile pivot without end gun), the annual variable cost savings with SDI range from $2,899 to $8,697 and would average $6,494 for the four years.

Corn yield and CWP were both substantially improved with SDI as compared with MESA sprinkler irrigation. Using SDI did not significantly affect yield in 2016 but increased yield by 19% in 2013, and CWP was increased in both years, by 37% in 2013 and 13% in 2016.

Sorghum yield decreased by 15% and CWP decreased by 14% in 2014 using SDI compared with MESA full irrigation due to an overly wet soil profile in the SDI fields and deep percolation that likely caused nutrient losses. Overall, sorghum CWP increased by 8% for SDI compared with MESA full irrigation in 2015, while yields were not significantly different.

Problems with overly wet soil profiles and drainage occurred in years with dry springs, when heavy irrigation with SDI was required to bring water to the seedbed for germination but was followed by large precipitation events. Under such conditions, incorporation or injection of fertilizer before planting can lead to fertilizer loss in deep percolation, which can be partly mitigated by the use of slow-release formulations. As precipitation events become larger but more infrequent with climate change, SDI management can be expected to become more difficult.

Overall, these results indicate that SDI can be successful for corn production in the Texas High Plains, but SDI is unlikely to benefit sorghum production.

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APPENDIX

AGRONOMIC PRACTICES IN 2013, 2014, 2015, AND 2016

Table A1. Corn crop management in 2013.

Date (2013)	Day of Year	Action
NW and SW fields (MESA)		
23-24 April	113-114	Applied 32-0-0 fertilizer at a rate of 236 kg N ha^{-1} and incorporated using disc plow.
2 May	122	Built beds using disk bedder.
16-17 May	136-137	Planted Pioneer corn variety 1151HR Aqua Max with Bt at a rate of 81,500 seeds ha^{-1} using row planter. Hand-planted lysimeters at slightly greater rate. Measured plant stand was greater than the seeding rate set in the planter (stand was 96,600 ha^{-1}). Overseeding during hand-planting of the lysimeters allowed thinning to match the field plant stand.
24 May	144	Corn fully emerged. Thinned lysimeter areas to match field plant density.
28 May	148	Hail resulted in approximately 13% stand loss, more on east fields than on west fields.
7 June	158	Started treatment irrigations using Nelson #20 nozzles on the NW field to target applications at 75% of full (100%) irrigation applied to the SW field using #23 nozzles.
11 June	162	Sprayed west fields with Roundup Power Max (glyphosate) and GMAX Lite (atrazine and S-metolachlor), mixed at active ingredient rates of 771 and 631 g ha^{-1}, respectively.
12 June	163	Furrow diked west fields.
30 July	211	Applied 27 kg N ha^{-1} as liquid 32-0-0 fertilizer using Nelson #22 nozzles for uniform irrigation.
31 July	212	Applied 29 kg N ha^{-1} as liquid 32-0-0 fertilizer using Nelson #22 nozzles for uniform irrigation.
25 June	254	Staged plants and harvested for biomass and LAI six times, ending on 11 September.
15 October	288	Hand-harvested lysimeters and random replicated field locations.
21 October	294	Combine-harvested field in ten approximately equal-sized sections (measured areas).
NE and SE fields (SDI)		
23-24 April	113-114	Applied 172 kg N ha^{-1} as liquid 32-0-0 fertilizer on east field and incorporated using disc plow.
22-23 May	142-143	Planted Pioneer corn variety 1151HR Aqua Max with Bt at a rate of 81,500 seeds ha^{-1} using row planter. Hand-planted lysimeters at slightly greater rate. Measured plant stand was greater than the seeding rate set in the planter (stand was 84,000 ha^{-1}). Overseeding during hand-planting of the lysimeters allowed thinning to match the field plant stand.
31 May	151	Rotary hoed east field to break up crust and allow emergence.
2 June	153	Corn fully emerged on lysimeters, spotty in fields.
21 June	172	Sprayed Roundup Power Max (glyphosate) at active ingredient rate of 756 g ha^{-1}.
25 June	254	Staged plants and harvested for biomass and LAI six times, ending on 11 September.
15 October	288	Hand-harvested lysimeters and random replicated field locations.
23 October	296	Combine-harvested field in ten approximately equal-sized sections (measured areas).

Table A2. Sorghum crop management in 2014.

Date (2014)	Day of Year	Action
NW and SW fields (MESA)		
5 March	64	Incorporated stubble using offset disk.
16 April	106	Applied 101 kg N ha^{-1} as liquid 32-0-0 fertilizer using knife applicator. Did not apply any fertilizer to spans 2 and 6 for reduced-N trial.
18 April	108	Spread and disked in residue that had concentrated behind the combine.
13 May	133	Used disk bedder to bed the field.
14 May	134	Used cultipacker to break up clods and pack beds.
15 May	135	Sprayed Charger Max (S-metolachlor) at active ingredient rate of 1,392 g ha^{-1} for pre-emergent weed control.
2 June	154	Planted Delta-Pine cotton variety 1219b2RF at 205,000 seeds ha^{-1}.
18 June	169	Ran rod weeder over beds to terminate remaining cotton after crop failure.
19 June	170	Ran cultipacker to break up clods and pack beds.
20 June	171	Replanted with Channel sorghum variety NC+5C35 at a rate of 210,000 seeds ha^{-1}.
25 June	176	Sorghum emergence.
26 June	177	Full emergence; thinned lysimeter areas to match field plant density.
14 July	195	Furrow diked field.
17 August	229	West field in full bloom.
20 October	293	Harvest.
NE and SE fields (SDI)		
5 March	64	Incorporated stubble using offset disk.
10 April	100	Applied 101 kg N ha^{-1} as liquid 32-0-0 fertilizer using knife applicator. Did not apply any fertilizer to zones 3 and 4 nor to zones 11 and 12 for reduced-N trial.
18 April	108	Disked field to incorporate residue.
3 June	154	Planted Delta-Pine cotton variety 1219b2RF at a rate of 205,000 seeds ha^{-1}.
4 June	155	Sprayed Section 2ec (clethodim) at active ingredient rate of 168 g ha^{-1} to burn down volunteer corn and Charger Max (S-metolachlor) at active ingredient rate of 1,392 g ha^{-1} for pre-emergent weed control.
20 June	171	Replanted with Channel sorghum variety NC+5C35 at a rate of 210,000 seeds ha^{-1}.
25 June	176	Sorghum emergence.
26 June	177	Full emergence; thinned lysimeter areas to match field plant density.
8 July	189	Sprayed Strut (diglycolamine salt of 3,6-dichloro-o-anisic acid) herbicide at active ingredient rate of 302 g ha^{-1} to terminate cotton and weeds.
11 July	192	Furrow diked field.
19 August	231	East field in full bloom.
20 October	293	Harvest.

Table A3. Sorghum crop management in 2015.

Date (2015)	Day of Year	Action
NW and SW fields (MESA)		
3 April	93	Applied 32-0-0 and 10-34-0 to both lysimeters at a rate totaling 168 kg N ha^{-1} and 49 kg P ha^{-1}.
13 April	103	Applied 168 kg N ha^{-1} and 49 kg P ha^{-1} to fields using a blend of 32-0-0 and 10-34-0.
16 April	106	Ran disk bedder to build beds.
18 May	138	Sprayed Charger Max (S-metolachlor) at active ingredient rate of 1,391 g ha^{-1} for pre-emergent weed control and Roundup Power Max (glyphosate) at active ingredient rate of 648 g ha^{-1} to kill emerged weeds.
2 June	153	Planted cotton.
14 June	165	Cotton hailed out.
19 June	170	Sprayed with Roundup (glyphosate) and Sharpen (saflufenacil) at active ingredient rates of 864 and 25 g ha^{-1}, respectively, to kill volunteer sorghum and the remainder of the cotton.
22 June	173	Planted Channel sorghum variety 5c35 at a rate of 210,000 seeds ha^{-1}.
27 June	178	Sorghum fully emerged.
7 July	188	Thinned lysimeters.
8 July	189	Crop severely damaged by 74 mm of rain and hail.
24 July	205	Diked west field using Bigham Bros diker.
14 August	226	Peak bloom.
29 August	241	Controlled grasshoppers and sugarcane aphids using Prevathon (chlorantraniliprole) at active ingredient rate of 25 g ha^{-1} and Sivanto 200 SL (flupyradifurone and propylene carbonate) at active ingredient rate of 7.3 g ha^{-1}.
28 October	301	Final hand-harvest on lysimeters and random replicated field locations.
12 November	316	Combine harvest in ten approximately equal-sized areas (measured) covering entire field.
NE and SE fields (SDI)		
2 April	92	Applied 32-0-0 and 10-34-0 to both lysimeters at a rate totaling 168 kg N ha^{-1} and 49 kg P ha^{-1}.
8 April	98	Applied 168 kg N ha^{-1} and 49 kg P ha^{-1} to fields using a blend of 32-0-0 and 10-34-0.
10 April	100	Ran disk plow over the east field.
18 May	138	Sprayed Charger Max (S-metolachlor) at active ingredient rate of 1,391 g ha^{-1} for pre-emergent weed control and Roundup Power Max (glyphosate) at active ingredient rate of 648 g ha^{-1} to kill emerged weeds.
3 June	154	Planted cotton.
14 June	165	Cotton hailed out.
19 June	170	Sprayed with Roundup (glyphosate) and Sharpen (saflufenacil) at active ingredient rates of 864 and 25 g ha^{-1}, respectively, to kill volunteer sorghum and the remainder of the cotton.
23 June	174	Planted Channel sorghum variety 5c35 today at a rate of 210,000 seeds ha^{-1}.
28 June	179	Sorghum fully emerged.
29 June	180	Started hand-watering lysimeters due to dry conditions.
4 July	185	Lysimeters fully emerged.
8 July	189	Crop severely damaged by hail.
20 July	201	Diked east field using Bigham Bros diker.
20 August	232	Peak bloom.
29 August	241	Controlled grasshoppers and sugarcane aphids using Prevathon (chlorantraniliprole) at active ingredient rate of 25 g ha^{-1} and Sivanto 200 SL (flupyradifurone and propylene carbonate) 200 at active ingredient rate of 7.3 g ha^{-1}.
20 October	293	Final hand-harvest on lysimeters and random replicated field locations.
9 November	313	Combine harvest in ten approximately equal-sized areas (measured) covering entire field.

Table A4. Corn crop management in 2016.

Date (2016)	Day of Year	Action
NW and SW fields (MESA)		
6 April	97	Fertilized NW field at a rate of 202 kg N ha^{-1} and 84 kg P ha^{-1} using a combination of 32-0-0 and 10-34-0. Fertilized SW field at a rate of 135 kg N ha^{-1} and 84 kg P ha^{-1} using a combination of 32-0-0 and 10-34-0. The SW field received less N because it would be irrigated at the full rate and would receive more in-season fertilizer through the MESA sprinkler.
11 April	102	Disked west field.
11 May	132	Planted Pioneer variety 1151AM AquaMax (≤80% Bt) at a rate of 87,475 seeds ha^{-1} according to planter settings. Actual stand count after emergence was approximately 93,900 plants ha^{-1}.
16 May	137	Sprayed both fields with Charger Max ATZ (S-metolachlor, atrazine) at active ingredient rates of 1,610 and 2,080 g ha^{-1}, and Roundup Power Max (glyphosate) at active ingredient rate of 864 g ha^{-1}, respectively.
21 May	142	Corn emerged.
8 June	160	Diked west fields using Bigham Bros diker.
17 June	169	Fertigated 39 kg N ha^{-1} of 32-0-0.
1 July	183	Fertigated 40 kg N ha^{-1} of 32-0-0.
12 July	194	Fertigated 40 kg N ha^{-1} of 32-0-0.
17 October	291	Started combine harvest.
NE and SE fields (SDI)		
5 April	96	Fertilized with liquid at a rate of 202 kg N ha^{-1} and 84 kg P ha^{-1} using a combination of 32-0-0 and 10-34-0.
11 April	102	Disked east field.
10 May	131	Planted Pioneer variety 1151AM AquaMax (≤0% Bt) at a rate of 87,475 seeds ha^{-1} according to planter settings. Actual stand count after emergence was approximately 93,900 plants ha^{-1}.
16 May	137	Sprayed both fields with Charger Max ATZ (S-metolachlor, atrazine) active ingredient rates of 1,610 and 2,080 g ha^{-1}, and Roundup Power Max (glyphosate) at active ingredient rate of 864 g ha^{-1}, respectively.
17 May	138	Hand-watered lysimeters and area around the outside of the box.
21 May	142	Corn emerged.
9 June	161	Diked east fields using Bigham Bros diker.
16 June	168	Fertigated 38 kg N ha^{-1} of 32-0-0.
7 July	189	Fertigated 38 kg N ha^{-1} of 32-0-0.
14 July	196	Fertigated 38 kg N ha^{-1} of 32-0-0.
13 October	287	Started combine harvest.