# Evaporative loss differences between SDI and sprinkler irrigation – Southern High Plains experience

**Steven R. Evett, Research Soil Scientist**
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas, steve.evett@ars.usda.gov
**Gary W. Marek, Research Agricultural Engineer**
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas
**Paul D. Colaizzi, Research Agricultural Engineer**
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas
**David K. Brauer, Research Leader**
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas
**Susan A. O'Shaughnessy, Research Agricultural Engineer**
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas

***Abstract:*** Subsurface drip irrigation (SDI) has steadily gained ground despite being considerably more expensive to install than center pivot irrigation. SDI now serves greater than 8% of land irrigated by pressurized irrigation systems (sprinkler, surface and subsurface drip and other microirrigation methods) in the US. In the Texas High Plains, the most southern extension of the High Plains, 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 about one inch 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 – although growing. However, other factors influence acceptance of SDI, including larger yields, particularly with cotton, after conversion to SDI. Research has shown warmer soil temperatures obtained with SDI due to the reduced evaporative cooling early in the season, and crop rooting and early growth are improved in the warmer soil, particularly for cotton, which is one reason for larger yields. Not as well established is the degree to which the reduced soil water evaporation 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). Two of the lysimeters and surrounding fields were irrigated by subsurface drip irrigation (SDI) and the other two were irrigated by mid elevation spray application (MESA). Evaporative losses from SDI fields were two to five inches less than those from sprinkler irrigated fields. Differences were strongly affected by plant height, essentially disappearing when plant height reached the elevation of spray nozzles, indicating that 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 differences being exacerbated in dry years.

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

## Introduction

Irrigation application method is known to affect crop performance, including yield and water use efficiency, with subsurface drip irrigation (SDI) having some advantages over spray sprinkler irrigation for corn, cotton and sorghum production. Sprinkler has become the predominant irrigation method for crop production in the USA and Great Plains, with > 80 percent of the irrigated area in the Southern High Plains (SHP) being by center pivot irrigation system (Colaizzi et al., 2009; NASS, 2014). Microirrigation, which includes surface and subsurface drip irrigation, generally results in greater crop water productivity compared with sprinkler, where the greater crop water productivity is due to greater crop production, less consumptive use of irrigation water, or a combination of both (Camp, 1998), 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 has justified the greater capital costs per unit land area of microirrigation compared with sprinkler (Bordovsky et al., 2000; Bosch et al., 1992; Enciso et al., 2005; O'Brien et al., 1998), leading to > 200,000 acres irrigated by SDI in the SHP, almost entirely for cotton. As cotton, corn and sorghum prices fluctuate, and as other pressures to rotate out of cotton arise, this SDI ground may be planted to corn or even sorghum.

The advantage of SDI is thought to be due in part to decreased loss of water to evaporation (*E*) from the soil surface since the soil surface is directly wetted by spray sprinklers but not with SDI. Also, 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 vs. surface irrigation (sprinkler or gravity flow) that wets the entire soil surface was estimated using a mechanistic model (Evett et al., 1995), which would mean 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 crop water productivity, also known as crop water use efficiency (WUE) (Howell, 2001).

There are, however, very few direct daily measurements of differences in *E*, *T*, their sum the evapotranspiration (ET), and water and energy balances of crops grown using SDI compared with spray sprinkler irrigation. Instead, these differences and their effect on WUE have been indirectly inferred from numerous crop water productivity studies, particularly those 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 Osgodd, 1990), corn (Adamsen, 1992; Colaizzi et al., 2011), cotton (Bordovsky et al., 2000; Cetin and Bilgel, 2002; Colaizzi et al., 2010), lettuce (Sammis, 1980; Hanson 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 management 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 designs and configurations for sprinkler (e.g., solid set, center pivot, high pressure impact, low pressure spray) and microirrigation (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 crop water productivity compared with sprinkler, 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 understanding of the mechanisms contributing to improved crop WUE and limiting our ability to develop and test crop water use and water use efficiency models that include irrigation application method.

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

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

for periods during which $I$, $P$, $F$ and $R$ are known because the change in soil water storage ($\Delta S$) is known from the lysimeter mass change (Evett et al., 2012b). Energy and water balance modeling tells us that most of the difference in ET from SDI versus spray sprinkler occurs early in the season during pre-irrigation and the period before full cover is established (Evett et al., 1995). The ET difference is due primarily to differences in $E$, not $T$ from the relatively small plants, and can be determined from weighing lysimeter measurements.

In order to more fully understand water and energy balance and flux differences under SDI compared with spray 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., 2018). 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 water use efficiency, if any.

# 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 for grain in 2014 and 2015 at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas (35° 11’ N, 102° 06’ W, 1170 m elevation 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 Southern High Plains of the Great Plains and were thoroughly described by Evett et al. (2012a, 2018). 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 slope of the southern Rocky Mountains. Mean annual pan evaporation exceeds 2400 mm (Kohler et al., 1959).

## Agronomy

Crops were grown in four adjacent, square, 4.4-ha fields, in the center of each of which 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). Fields and the lysimeters within them were designated with reference to the cardinal directions as NE, SE, NW and SW. The crops were managed for high yield using practices common for the northern Texas Panhandle. Fertilizer was applied according to soil tests done by a commercial soil testing laboratory. In 2013, a medium season length corn (109 d) was planted in the four fields at 81,500 seeds $ha^{-1}$, fertilized with liquid N (32-0-0) and treated with herbicide. The hybrid corn was bred and engineered for water-limited conditions and so a test of this was conducted by irrigating the NW field 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). 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 June 22, 2015, again after cotton was hailed out, and fertilized and managed using typical methods for the region. Corn was planted May 10-11, 2016 at 87,475 seeds $ha^{-1}$.

Liquid fertilizer applications on the lysimeters were simulated by digging trenches 10 cm deep and spaced 38 cm apart to simulate the fertilizer applicator, then spraying the liquid in the trench 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 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. Deficit irrigation tests were conducted in NW or SW fields, alternating between fields.

## Lysimeter and soil water balance ET measurements

As shown in Eq. 1, crop water use (evapotranspiration, 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, but sprinkler irrigation metered amounts were verified by measuring the change in lysimeter mass caused by each irrigation. Precipitation was measured with rain gages 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., submitted). 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.

At each of eight neutron probe access tubes in each field, 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 that. 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 measured soil layer was calculated by multiplying the volumetric water content by the layer depth. Profile water content as a depth was calculated by summing the water contents for each 0.20-m thick measured 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 for each field, the value of *R* was assumed equal to zero since 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 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. For each of the four fields, these were grouped into four mean ET values for purposes of WUE calculation. For each of the four fields, field ET values were used in calculations of water use efficiency using field combine yields (described in the section on Plant Sampling). Lysimeter-measured ET data were used primarily to illustrate the differences in ET between SDI and MESA irrigation application methods in terms of ET and evaporative losses over time.

## Irrigation systems and management

Spray sprinkler irrigation was applied to the NW and SW fields using a ten-span linear irrigation system (Lindsay Manufacturing, Inc., replaced after 2014 with a Valley system, Valmont Industries, Valley, NE)) moving in the E-W direction with spray plates at 1.5-m height (mid-elevation sprays, MESA) on weighted drops with 69 kPa pressure regulators on each drop. Drops were spaced at 1.52-m intervals. Irrigations were typically 19 to 25 mm depth, and occasionally as much as 38 mm. Nozzling was such that a 25-mm irrigation took 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 tubing (model Typhoon 990, 13 mil wall thickness, Netafim, Inc., Fresno, Calif.) spaced 1.52-m apart and injected 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 purposefully chosen to be relatively small so that the drip tape would act more as a line source and more uniformly wet the soil orthogonally to the drip line. The combination of emitter spacing, discharge rate and drip tube spacing was chosen so that application of a given depth of water would take approximately the same time as application of the same amount of water with the linear move irrigation system. 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, then pumped through sand filters with automatic flush out (waste stream returned to the reservoir) to remove sediments and algae. A variable frequency drive was used to provide constant supply line pressure downstream of the filters.

The SDI tubing on the lysimeters was buried at the same depth and row spacing as in the field and the same tubing was used as in the field. The two SDI tubes in each lysimeter were plumbed 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 was carefully controlled so that the number of emitters per unit area was the same on the lysimeters as in the field. The buried header in the lysimeter was connected to the field SDI supply so that when the field was irrigated the lysimeters were also 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 irrigation rate on the lysimeters 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 mass change of the lysimeter.

Later in 2014, the lysimeter irrigation system was changed so that lysimeter ET could be more clearly differentiated from mass gain due to irrigation (Evett et al., 2018). In each lysimeter, water storage tanks, larger in volume than needed for a 38-mm irrigation depth, were suspended from the monolith using a 4,448 N (1,000-lb) load cell. Charging the tanks required about five minutes, producing a step change in both the 4,448 N load cell and in the lysimeter load cell during which ET was negligible. The mass change determined using the two load cells was compared to verify equality and to verify that the correction irrigation amount was delivered. After the tanks were charged and the solenoid valves were closed, a separate solenoid valve was opened to allow a pressure-regulated pump and pressure tank system to supply water to the lysimeter SDI lines through a pressure regulator set to 69 kPa. Since the water supply tanks and pressure-regulated pump and pressure tank were all suspended from the soil monolith container, the irrigation itself 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. Pre-plant irrigations were applied in 2013 and 2014 due to dry pre-plant 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 pre-plant irrigation in those years. The NW and SW fields were managed together and separately 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 nozzle size reduced to apply approximately 75% of full irrigation beginning on 6 June. The deficit irrigation treatment in the SW field was applied to provide more data for a longer-term study of deficit sprinkler irrigation at Bushland. There is no similar long-term study using SDI, so 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 soil water in the NW and SW fields, so again the SW field was managed for a deficit irrigation of 75% of full, and in 2016 this was reversed with the deficit irrigation treatment 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 sampling

Plant counts after emergence were taken in two adjacent rows at each of two separate locations in each of the 10 linear move sprinkler spans, and in each adjacent pair of SDI zones (zones 1 and 2, 3 and 4, etc.). Counts in each row were in a 0.91-m row length. 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 leaf area index, LAI (-), and above-ground biomass determination 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 leaf area index (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 sampling was done both by hand and by combine. Yield samples were 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). Above-ground biomass was also collected from these sample areas for dry biomass determination. After drying, ear or head mass, and shelled or threshed seed mass were determined. On each replicate sample, the mass of 200 seeds was determined, and after oven drying (24 h at 60$^{o}$C), dry mass per seed was determined. Combine harvested grain was weighed and moisture content measured separately for each of the 10 linear-move sprinkler spans, and for every two SDI zones, resulting in five yield samples for each of the four lysimeter fields. The combine harvested yields were total yields for each subarea of each field. Reported yields are dry grain yields. 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 yields and crop water use values calculated from neutron probe data were used for the results presented in this paper.

# RESULTS and DISCUSSION

## 2013 corn

Despite a severe hailstorm during corn emergence, plant stand was 84,000 $ha^{-1}$ in the SDI fields 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 9.38 Mg $ha^{-1}$, which was significantly greater (30% greater) than the 7.19 Mg $ha^{-1}$ corn harvest resulting from limiting MESA irrigation to 75% of full irrigation. Yield differences translated to differences in water use efficiency. Full MESA irrigation resulted in WUE of 1.29 kg $m^{-3}$, which was significantly (11%) greater than the 1.16 kg $m^{-3}$ WUE of deficit MESA irrigated corn. Fully irrigated corn grown using SDI yielded on average 11.1 Mg $ha^{-1}$, which was significantly greater (18% greater) than the yield of MESA fully irrigated corn. The mean WUE (1.66 kg $m^{-3}$) for SDI corn was significantly greater (29%) than that of MESA fully irrigated corn.

Reasons for the differences in yield and water use are illustrated in Figure 1. For DOY 170 through 189, SDI corn used 48 mm less water than did MESA fully irrigated corn. Once the crop substantially covered the soil, by day of year (DOY) 175, the SW field, which was fully irrigated using MESA, used water at rates much greater than did the deficit irrigated NW field (Fig. 1A). Daily ET exceeded 12 mm several times and exceeded 14 mm once under full MESA irrigation. In contrast, peak water use of deficit irrigated corn was 10 mm $d^{-1}$. Water use of fully MESA irrigated corn exceeded that of the deficit irrigated crop through seed filling and senescence up until DOY 255. In contrast, the fully irrigated SDI corn exceeded 10 mm daily water use only once, and in fact appeared to use water at daily rates very close to those exhibited by the MESA deficit irrigated corn until DOY 230 when SDI irrigated corn began to use more water than the MESA deficit irrigated corn and began to closely match the water use of the MESA fully irrigated corn (Fig. 1B). This late season water use was likely important for completing grain filling. Overall, fully MESA irrigated corn used the most water (722 mm), deficit MESA irrigated corn used 620 mm, while corn irrigated using SDI used significantly less (649 to 677 mm) than did fully irrigated MESA corn, based on neutron probe readings.

MESA irrigation wetted the soil surface, which resulted in much greater evaporative loss during pre-plant irrigations and in the first 25 days after planting (DAP) when the crop was emerging and not yet covering much of the soil surface (Fig. 1C). As observed from weighing lysimeter data, total MESA irrigation water use in that period was 147 to 161 mm compared with the much smaller 113 to 115 mm water use of SDI irrigated corn. Most of this water was lost to evaporation from the soil surface since the plants were not emerged or were very small. The gross savings in evaporative loss from the use of SDI was 85 mm during this period (Fig. 1C). This is remarkably 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 suffered under MESA irrigation did not end at 25 days after planting, but continued until approximately day of year (DOY) 192 when the corn grew taller than the MESA sprays, totaling another 53 mm more water lost from full MESA irrigation than from full SDI.

Differences in water use did not always translate directly into differences in yield. The fully MESA irrigated corn yield was significantly greater (30%) than that from the deficit MESA irrigated corn. However, the corn irrigated with SDI, which used less water than the Full MESA irrigated treatment, out yielded both significantly with a mean yield of 11.0 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 extra yield from the SDI fields was partially due to more water available for transpiration, particularly during grain filling at season's end (Fig. 1C). Water use efficiency for the SDI fields was significantly greater than that for the MESA irrigated fields. And, WUE for the fully MESA irrigated field was significantly greater than that for the deficit MESA irrigated field. Yield loss for the deficit MESA irrigated field occurred even though measured water contents were within the management allowed depletion range (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 management allowed depletion level, 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 nearly constantly at or near the management allowed depletion level for a substantial part of the season, including during grain filling, which evidently had a substantial effect on final yield.

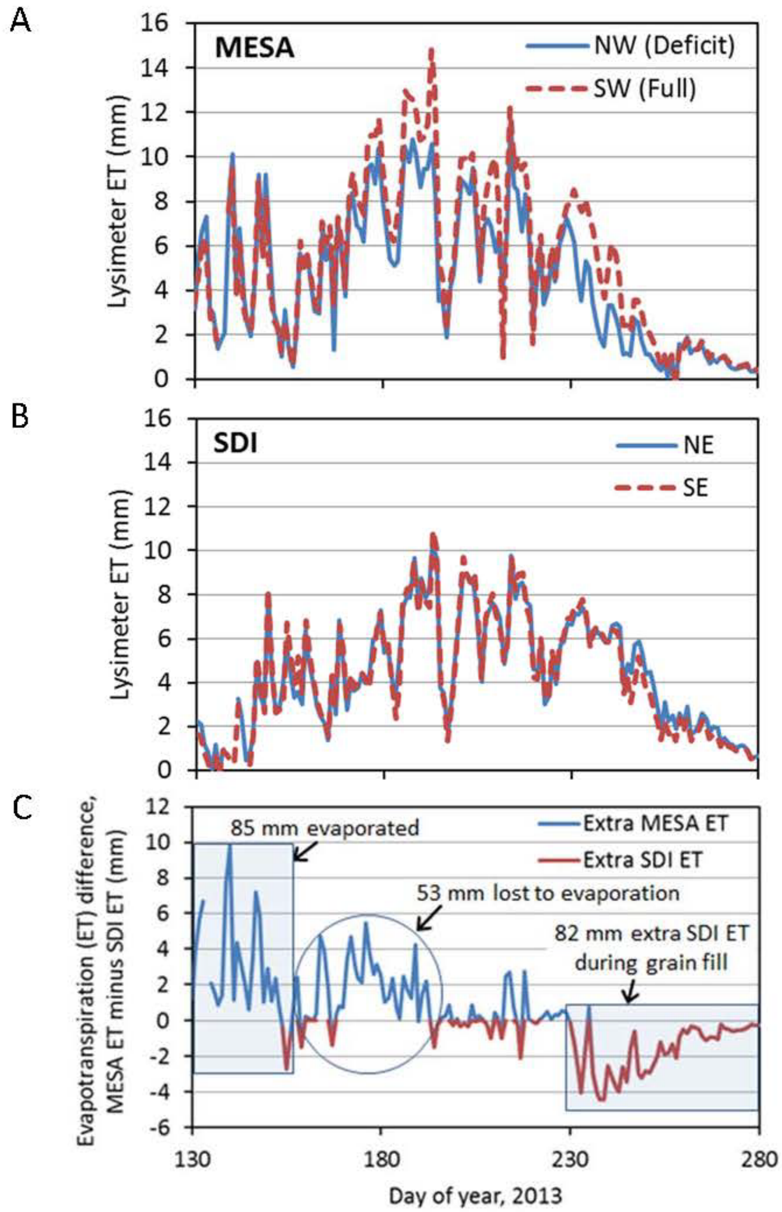


**Figure 1. (A) Corn evapotranspiration (ET) in the northwest (NW) and southwest (SW) lysimeter MESA irrigated fields in 2013. (B) Corn ET in the northeast (NE) and southeast (SE) SDI fields. (C) Difference in ET between MESA and SDI irrigation where values >0 are extra ET in the MESA irrigated fields and values <0 are extra ET in the SDI fields.**

Increased yield of the SDI irrigated corn may have been somewhat influenced by overall better soil water conditions (Fig. 2). While water storage in the top 1.5-m of soil for the fully irrigated MESA 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 was enough, in combination with the antecedent water to bring the soil to field capacity. This water remained in the profile and was available to the crop later in the season. There is evidence that corn rooting is enhanced when the Pullman soil is wetter (Tolk and Evett, 2012) because the soil strength (resistance to root penetration) increases greatly as the soil dries. The MESA irrigated fields were irrigated to replenish water content to field capacity, but the large evaporative losses prevented effective use of the irrigation water applied, so water content only increased gradually (Fig. 2A). This is why irrigation to replenish water content to field capacity in the MESA irrigation fields often did not result in measured water content being at field capacity in those fields. The other reason is that neutron probe measurements typically lagged irrigation events by two to three days in the MESA irrigated fields because the fields were too muddy for foot traffic in those fields. In contrast, the neutron probe was used in the SDI fields soon after irrigation because irrigations left the soil surface reasonably dry.

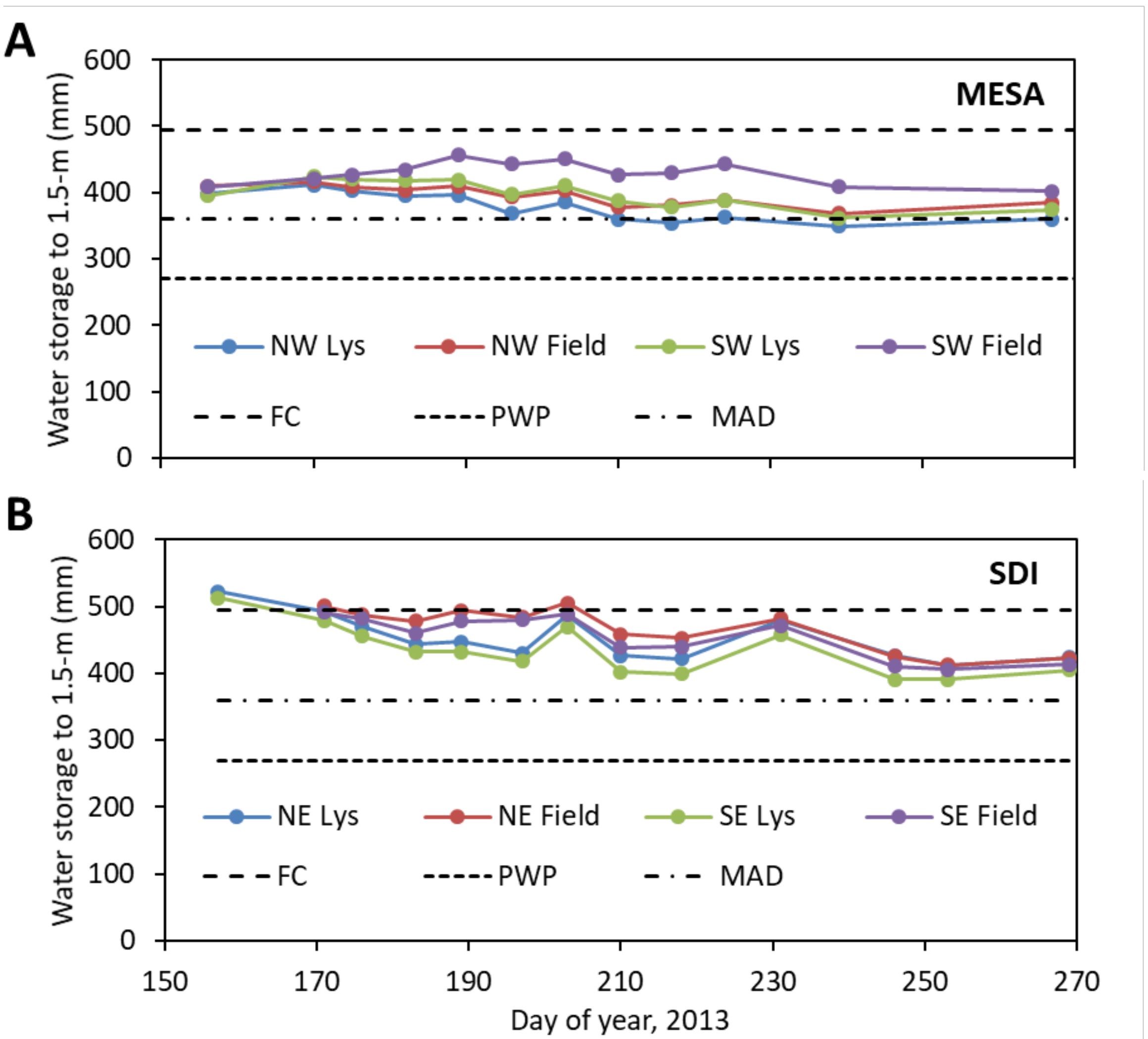


**Figure 2. (A) Water storage in the top 1.5 m of soil in 2013 for (A) the northwest (NW) and southwest (SW) MESA irrigated fields and lysimeters (Lys), and (B) the northeast (NE) and southeast (SE) SDI fields and lysimeters. FC is field capacity, PWP is permanent wilting point, and MAD is the maximum allowed depletion.**

## 2014 short season sorghum

Due to a dry spring and dry soil profile, pre-plant irrigations were conducted on all lysimeter fields in 2014. MESA irrigation on the west fields began on May 1, 2014 (DOY 121) and totaled 105 mm before sorghum was planted. SDI applications began on May 12, 2014 (DOY 132) in the east fields and totaled 177 mm before planting due to the drier soil profile in the east fields. Immediately after pre-plant irrigations were ended, precipitation totaling 119 mm occurred over six days (DOY 141-146). Cotton was planted on DOY 154 but failed soon after due to torrential rains. Short season sorghum (Channel 5c35) was planted on June 20 (DOY 171) and emerged five days later. Black layer was noted on DOY 272 and fully developed by DOY 290. The deficit irrigation treatment on the SW field did not begin until August 1 and resulted in only a 73 mm reduction in total irrigation, not enough to much 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 to August 1. Hot, dry weather in July and August required 256 mm of irrigation for the fully irrigated treatment in the NW field to finish the season. A large rain (>50 mm) on September 3 finished the irrigation season.

Despite the 73 mm difference in total irrigation, season total sorghum water use (ET) did not differ importantly or significantly between the fully MESA irrigated (694 mm) and deficit irrigated (670 mm) crops (Fig. 3). Even though yield from deficit irrigated sorghum was 4.4% less than that for fully irrigated sorghum, yield was not significantly different (7.31 Mg $ha^{-1}$ for full irrigation and 6.96 Mg $ha^{-1}$ for deficit irrigation). Similar depression of yield when water is limited during grain filling has been reported previously. In the NE and SE fields, yields were smaller for sorghum produced using SDI, 6.76 and 6.19 Mg $ha^{-1}$, respectively, which did not differ significantly. However, the SDI yields were significantly smaller (9% overall) than those obtained using MESA irrigation. For the same sorghum variety, O'Shaughnessy et al. (2014) reported 8.04 Mg $ha^{-1}$ for 533 mm of ET in 2009, but only an average 6.42 Mg $ha^{-1}$ for an average ET of 648 mm of ET in 2010 and 2011. For one field under SDI, water use efficiency was numerically greater than that for MESA irrigation, but there were no significant differences in WUE amongst the four fields and two irrigation application method treatments.

Water use in the SDI fields was typically less than that in the MESA irrigated fields throughout the season (Fig. 3A,3B). The MESA fully irrigated sorghum used 53 mm more water than did the SDI sorghum during the period from initiation of pre-plant irrigation until 25 days after planting (Fig 3C). Unlike the result for the previous year's tall corn crop, losses to evaporation continued throughout the season for the MESA irrigated sorghum, totaling another 52 mm by season's end for a season-long total of 105 mm lost to evaporation. The likely cause for the greater ET from the MESA irrigated crop through August 1 (DOY 213) is that the sorghum did not reach a height greater than the elevation of the spray plates and so the entire leaf area was wetted by each irrigation.

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 did those in the MESA irrigated fields, indicating larger deep percolation losses in the SDI fields. Pre-plant irrigation with the SDI system was larger than that for the MESA system in order to bring water to the seed bed for cotton germination. This proved unnecessary due to the large rains just after cotton planting, but it did leave the soil profile full of water prior to the large rains.

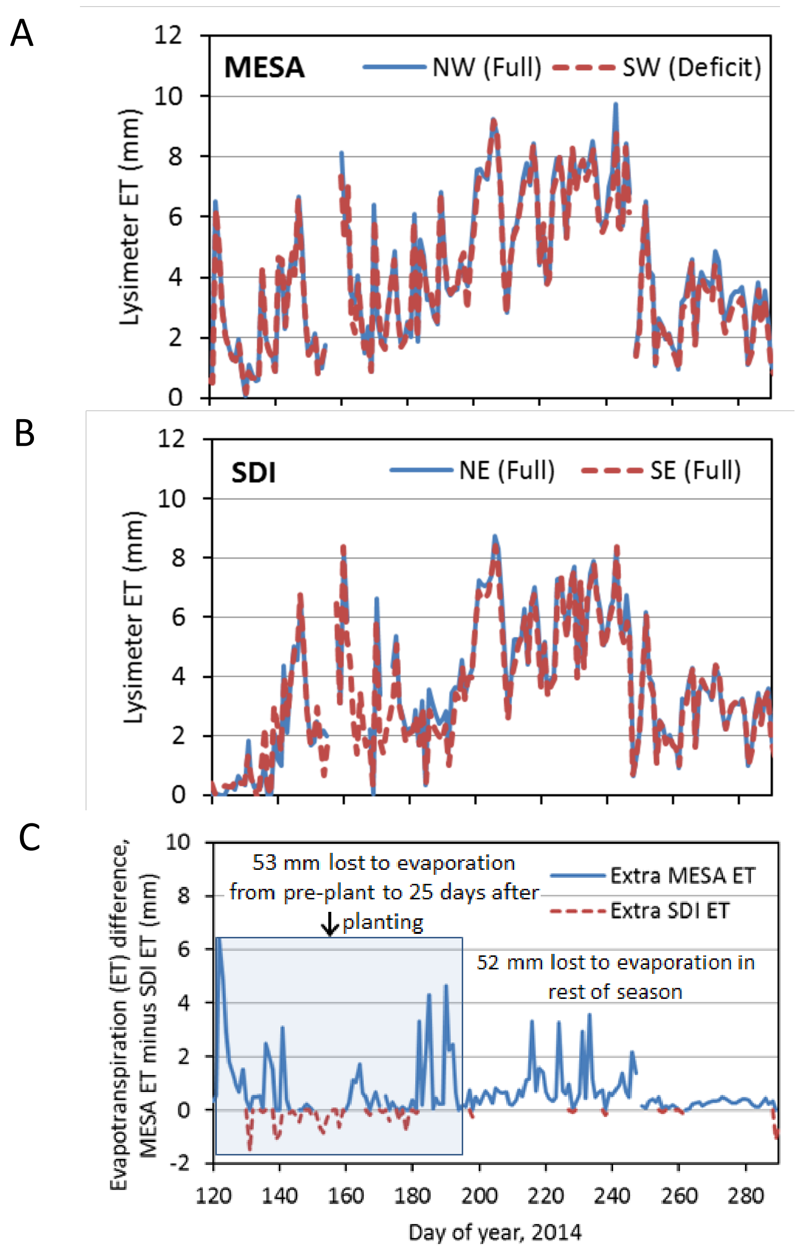


**Figure 3. (A) Sorghum evapotranspiration (ET) in the northwest (NW) and southwest (SW) lysimeter fields irrigated with MESA in 2014. (B) Sorghum ET in the NE and SE SDI fields. (C) Difference in ET between MESA and SDI irrigation where values >0 are extra ET in the MESA irrigated fields and values <0 are extra ET in the SDI fields.**

Despite the larger pre-plant irrigation, evaporative losses before planting and through 25 DAP were on average 53 mm smaller in the SDI fields compared with the MESA irrigated fields. Season long irrigation using SDI averaged 21 mm more than that for full irrigation using MESA. But, season long water use for SDI sorghum averaged 112 mm less than that for MESA fully irrigated sorghum, mostly due to 84 mm less irrigation in the SDI fields after August 1, which caused water content to decrease to near the management allowed depletion value (Fig. 4). The relatively less irrigation of the SDI fields in August was due to an error in neutron probe readings that went undetected until too late to take correction action.

Although water content did not decrease to less than the management allowed depletion, it is possible that less irrigation in the SDI fields after August 1 combined with loss of nutrients due to deep percolation led to the 9% yield depression in SDI fields. As for the deficit irrigated corn crop in 2013, mean values of soil water content being at the management allowed depletion level indicated that some values were well less than that level and some areas of the field were thus water stressed. It is known from previous studies that deficit irrigation during grain filling can reduce sorghum yields.

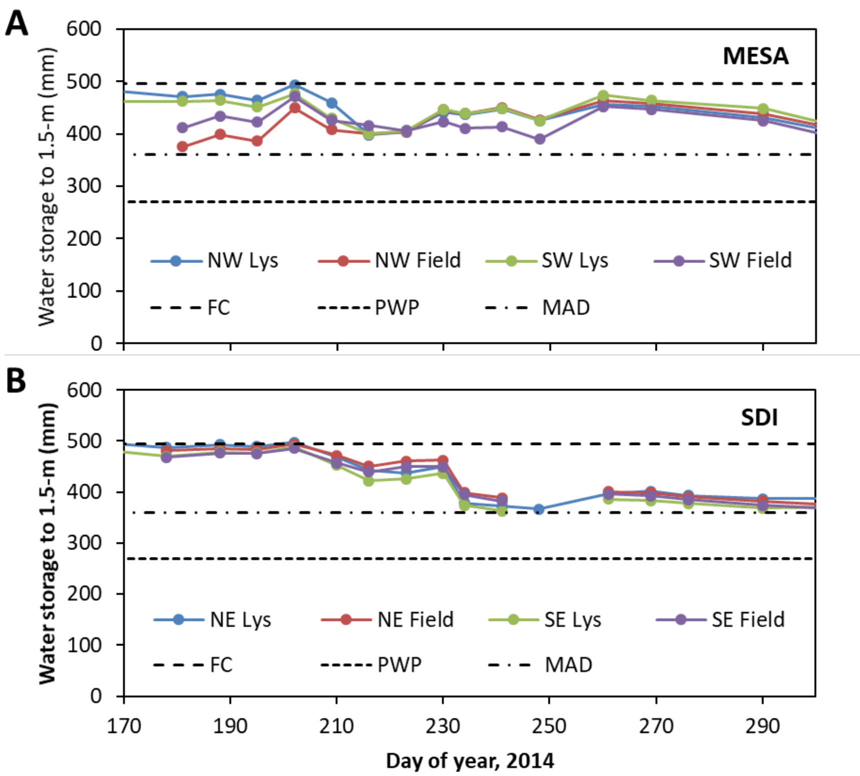


**Figure 4. (A) Water storage in the top 1.5 m of soil in 2014 for (A) the northwest (NW) and southwest (SW) MESA irrigated fields and lysimeters (Lys), and (B) the northeast (NE) and southeast (SE) SDI fields and lysimeters. FC is field capacity, PWP is permanent wilting point, and MAD is the maximum allowed depletion.**

This result is in line with those of Colaizzi et al. (2004) who reported that yields for both long and short season grain sorghum were on average 12% less for SDI compared with MESA for 75% and 100% of full irrigation rates. They too 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 case, leaching was caused by over irrigation due to irrigation management being based on crop coefficients developed for sprinkler irrigation, which did not take into account the reduced crop water use with SDI. 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 study reported herein confirms their supposition 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 lower leaf temperature and in some cases promote greater yields, yield in the SDI fields was likely not adversely affected by greater leaf temperatures. The mean daily air temperatures in 2013 and 2014 were not greatly different, and they varied from 20 to 30$^{o}$C through the middle part of the growing season when it was warmest, not great enough to incur large yield effects. The under irrigation of SDI fields late in the season did not affect plant height and width, both of which were not noticeable or significantly different between the SDI and MESA irrigated fields. Leaf area index, LAI (-), did, however, reach numerically greater values in the MESA irrigated fields than in the SDI fields, and the difference at maximum LAI (before DOY 230) was statistically significant for the fully MESA irrigated field. Since water content in the SDI fields before DOY 230 was not deficient, and since 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

2015 was the wettest year in >70 years of record at Bushland with >870 mm of precipitation. Due to a wet spring, pre-plant irrigations were not conducted in 2015. As in 2014, cotton was planted and hailed out, followed by planting short season sorghum (Channel 5c35) at 210,000 seeds ha$^{-1}$ on June 22-23, 2015 (DOY 173-174). The fully emerged crop was severely damaged by hail on July 8, 2015 (DOY 189), but survived and reached full bloom on August 20 and was harvested on October 20$^{th}$ (DOY 293). Grasshoppers and sugar cane aphids infested the crop in August but were controlled successfully using pesticides. Deficit irrigation of the SW field began on July 1, 2015 (DOY 182).

Irrigation from planting to 25 DAP was not much different between full MESA and SDI irrigation treatments, ranging from 51 to 61 mm. Precipitation in the 60 days before sorghum planting averaged 412 mm, nearly the yearly mean for Bushland. Additional precipitation during the growing season averaged 407 mm. Total season irrigation amounts were correspondingly small, being 286 mm for full MESA irrigation and 262 mm for SDI. ET to 25 DAP was only slight larger (10 mm) for MESA irrigation compared with SDI, and full season ET was 50 mm larger for full MESA irrigation compared with SDI (Fig. 5C). In the wet year, ET rates were less than 10 mm d$^{-1}$ and almost always less than 8 mm d$^{-1}$ (Fig. 5). ET rates for SDI were only slightly less than that for full MESA irrigation throughout the season. Soil water content remained within management allowed depletion in the SDI fields and was similar for the fully irrigated MESA field (Fig. 6). Soil water content in the deficit MESA field approached MAD late in the season, but too late to have appreciable effect on yield. Yields averaged 7.54 Mg ha$^{-1}$ for SDI versus 7.60 ha$^{-1}$ for full MESA and 7.74 ha$^{-1}$ for deficit MESA irrigated fields. Neither yields nor WUE were significantly different across the four fields, although WUE of 1.39 kg m$^{-3}$ was numerically larger than that of 1.28 kg m$^{-3}$ for full MESA and 1.31 kg m$^{-3}$ for deficit MESA irrigation.

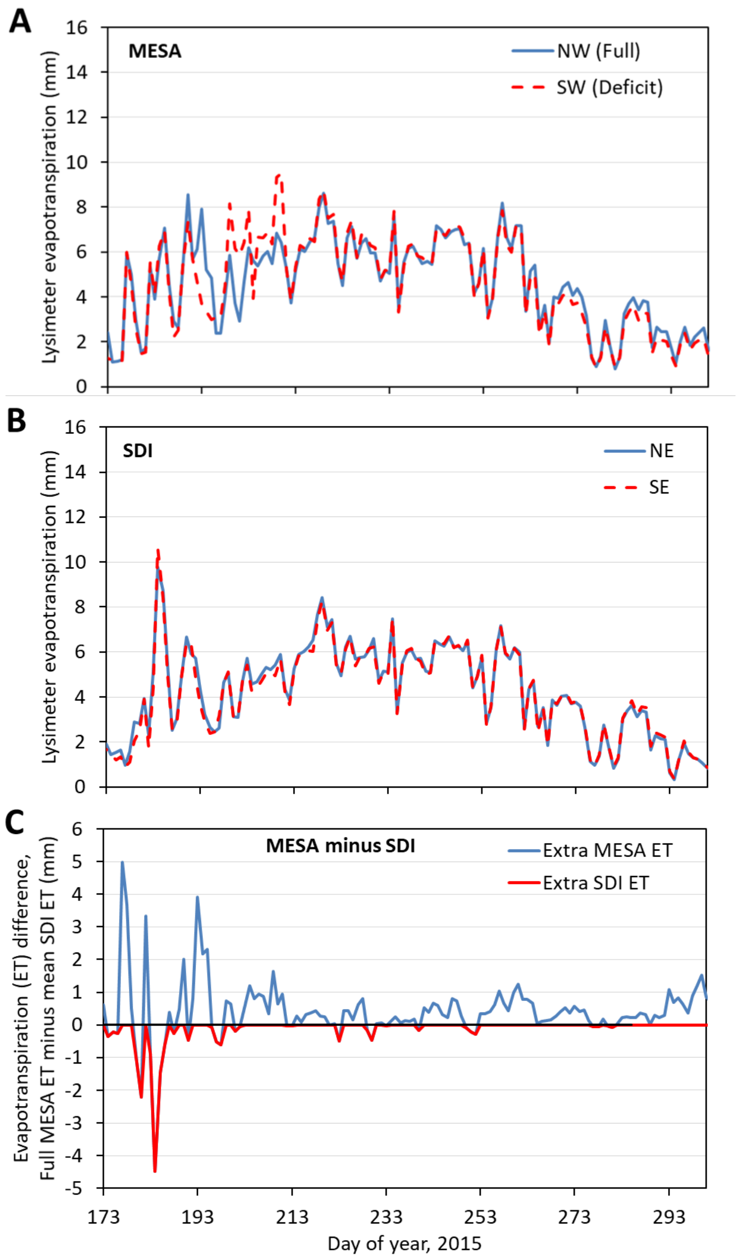


**Figure 5. (A) Sorghum evapotranspiration (ET) in the northwest (NW) and southwest (SW) lysimeter fields irrigated with MESA in 2015. (B) Sorghum ET in the NE and SE SDI fields. (C) Difference in ET between MESA and SDI irrigation where values >0 are extra ET in the MESA irrigated fields and values <0 are extra ET in the SDI fields.**

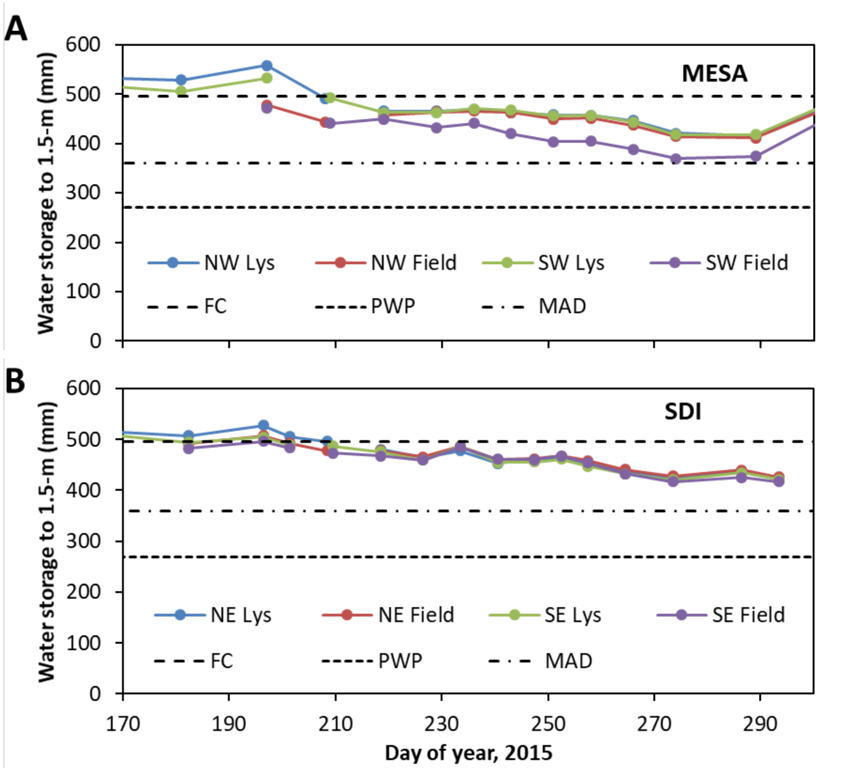


**Figure 6. (A) Water storage in the top 1.5 m of soil in 2015 for (A) the northwest (NW) and southwest (SW) MESA irrigated fields and lysimeters (Lys), and (B) the northeast (NE) and southeast (SE) SDI fields and lysimeters. FC is field capacity, PWP is permanent wilting point, and MAD is the maximum allowed depletion.**

## 2016 corn

A drought tolerant corn variety (Pioneer 1151) was planted May 10-11, 2016 (DOY 131) at 87,475 seeds $ha^{-1}$ and had emerged by May 21 (DOY 137). Due to pre-plant precipitation averaging 99 mm, no pre-plant irrigation was required. The 75% deficit irrigation treatment on the NW field began on June 9, 2016 (DOY 161). Along with growing season precipitation that averaged 238 mm and moderate weather, total irrigation averaged 504 mm for SDI. Full MESA irrigation was 18% larger and full MESA ET was 17% larger than for SDI. For deficit irrigated MESA the ET was 8% larger than ET for SDI, even the though total irrigation (392 mm) was 22% less than that for SDI (mean of 504 mm). This result indicates that spray irrigation was relatively inefficient in delivering water to the crop in the deficit regime. Due to timely rains, soil water content under deficit MESA irrigation approached the MAD only twice during the growing season, and the crop ET was relatively larger than that for SDI. Daily ET exceeded 15 mm once and reached 12 mm a few times for fully MESA irrigated corn, but only reached and exceeded 12 mm once for SDI (Fig. 7). Because irrigation before 25 DAP was relatively little (<40 mm), there was not much difference in ET between full MESA and SDI during that period, but ET was consistently larger for full MESA irrigation for the rest of the season (Fig. 7C), resulting in 150 mm more ET over the entire growing season for full MESA irrigation than for SDI. Soil water storage throughout the season indicated a no-stress regime for fully MESA irrigation corn and corn under SDI (Fig. 8A,B). The deficit MESA irrigated corn approached the management allowed depletion level twice during critical growth stages (Fig. 8B).

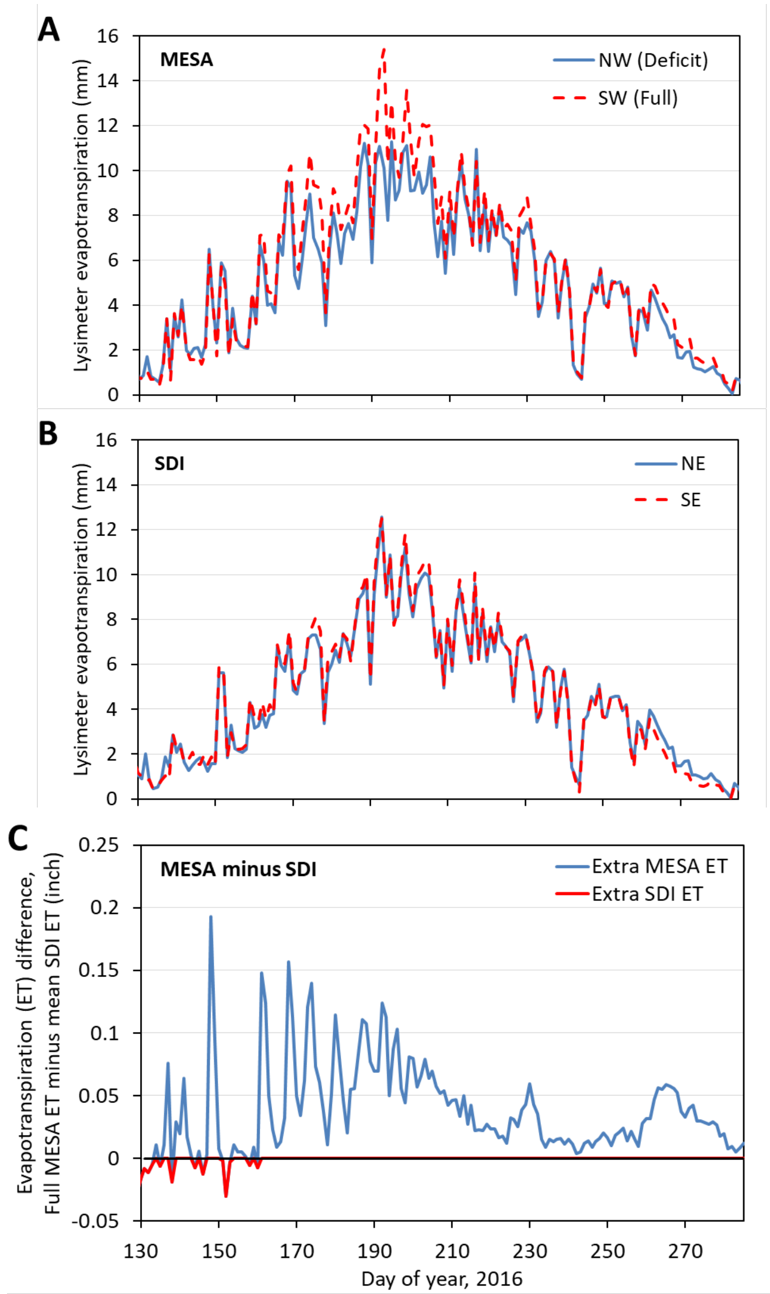


**Figure 7. (A) Corn evapotranspiration (ET) in the northwest (NW) and southwest (SW) lysimeter fields irrigated with MESA in 2016. (B) Corn ET in the NE and SE SDI fields. (C) Difference in ET between MESA and SDI irrigation where values >0 are extra ET in the MESA irrigated fields and values <0 are extra ET in the SDI fields.**

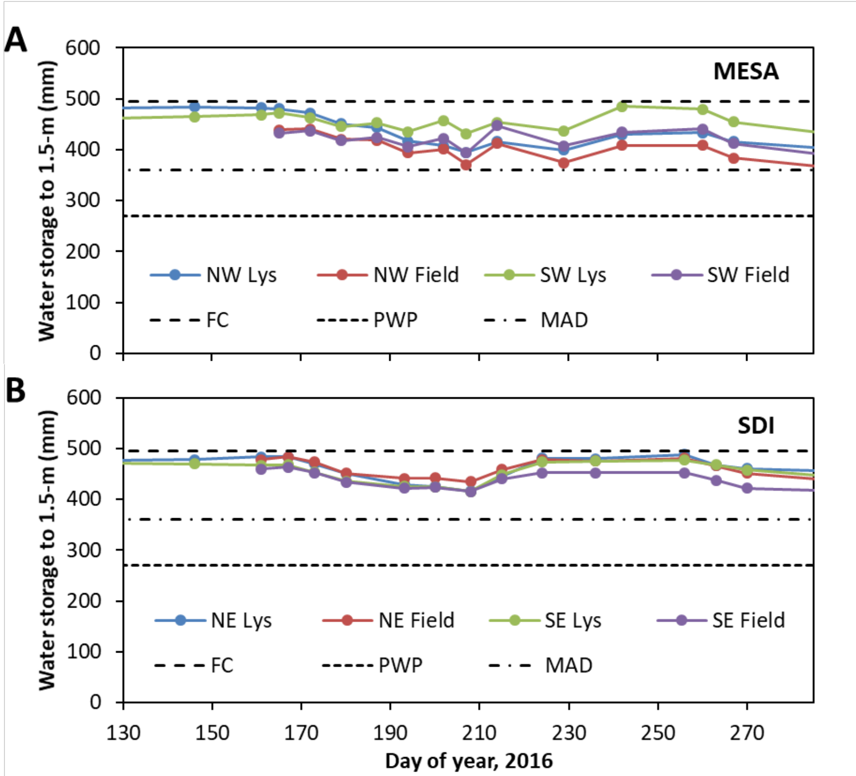


**Figure 8. (A) Water storage in the top 1.5 m of soil in 2016 for (A) the northwest (NW) and southwest (SW) MESA irrigated fields and lysimeters (Lys), and (B) the northeast (NE) and southeast (SE) SDI fields and lysimeters. FC is field capacity, PWP is permanent wilting point, and MAD is the maximum allowed depletion.**

## SUMMARY

The SDI system saved on average from 85 to 53 mm of water that was lost to evaporation early in the season (pre-plant to 25 DAP) from the fully MESA irrigated crop in the 2013 and 2014, respectively, which was consistent with the estimate of evaporative loss reduction for SDI made using the ENWATBAL model. In 2015 and 2016, when spring weather was wetter, the ET savings with SDI to 25 DAP were small (<= 11 mm). Between 25 DAP and mid season, another 53 to 52 mm of water was lost with the MESA irrigation system compared with the SDI system 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 full MESA irrigation. For corn grown in 2013, much of the water saved due to smaller evaporative losses was used during grain fill when SDI corn used 82 mm more water than did MESA fully irrigated corn. In the relatively dry 2013 season, SDI reduced overall corn water use by 147 mm while increasing yields by 1.88 Mg ha$^{-1}$ (20%) and WUE by 0.64 kg m$^{-3}$ (61%) compared with MESA full irrigation. In the relatively wet 2016 season, SDI reduced overall corn water use by 150 mm while increasing WUE by 0.24 kg m$^{-3}$ (17%) compared with MESA full irrigation, although with no significant yield difference. While sorghum, particularly short season sorghum, is not a crop ordinarily considered for SDI, it was grown successfully using SDI with yields and water use efficiencies comparable to others reported for short season sorghum at Bushland. The yield increases in some years and water savings in all years using SDI point to important economic advantages in revenue and reduced pumping costs.

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