CHARACTERIZING EVAPORATIVE LOSSES FROM SPRINKLER IRRIGATION USING LARGE WEIGHING LYSIMETERS

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HIGHLIGHTS

- Losses for MESA and LESA were comparable on the day of irrigation and oftentimes greater for the subsequent day.
- Losses were greater due to incomplete canopy conditions for both MESA and LESA on both days.
- Evaporative losses from irrigation extended to at least the subsequent day following irrigation in most cases.
- Losses over two days accounted for as much as 39.5% and 28.0% of irrigation depth for MESA and LESA, respectively.

ABSTRACT. *Effective irrigation systems that increase crop water productivity by minimizing evaporative losses are paramount for extending the longevity of finite groundwater resources in the semi-arid U.S. Southern High Plains (SHP). Although subsurface drip irrigation (SDI) acreage has increased in recent years, center-pivot sprinkler systems still account for greater than 85% of the irrigated area in the SHP. Modern sprinkler configurations are typically classified according to application height as either mid-elevation spray application (MESA) or low-elevation spray application (LESA). While application drift and evaporative losses are easily measured under fallow conditions, quantifying evaporative losses under cropped conditions is difficult. Lysimeter-derived daily evapotranspiration (ET) values for SDI-irrigated and sprinkler-irrigated fields planted to corn in 2016 (MESA) and 2018 (LESA) near Bushland, TX, were compared for days when sprinkler irrigation events occurred and for subsequent days, when possible. Differences (extra ET) were attributed to evaporative losses associated with MESA and LESA irrigation. Average daily extra ET values for both sprinkler irrigation methods were similar on the day of irrigation, although MESA was slightly larger than LESA at 1.4 and 1.2 mm, respectively. The average daily extra ET values for incomplete canopy conditions were 2.2 mm for MESA and 1.9 mm for LESA, while values were identical for both methods at 0.6 mm for full canopy conditions. Average daily extra ET values were also expressed as a percentage of daily standardized grass reference ET (ETos) values. Average values for MESA and LESA were 20.1% and 13.5%, respectively, for the season, with similar findings of 29.3% and 19.4% for incomplete canopy conditions. Average extra ET/ETos values for incomplete canopy conditions were similar at 7.5% and 7.7% for MESA and LESA, respectively. Evaporative irrigation losses, calculated as the percentage of extra ET to irrigation depth, were slightly larger overall for the day of irrigation for MESA (5.4%) than LESA (5.2%). Losses of 7.9% and 7.0% were observed for incomplete canopy conditions for MESA and LESA, respectively. Average losses for LESA (3.5%) under full canopy conditions were greater than those for MESA (1.9%). A comparison of extra ET values for days following irrigation revealed that evaporative losses from irrigation events extended beyond the day of irrigation. MESA extra ET values for the day following irrigations increased by 57.1% (2.2 mm) overall, 13.6% (2.5 mm) for incomplete canopy conditions, and 150.0% (1.5 mm) for full canopy conditions. The same was true for LESA, with increases of 125.0% (2.7 mm) overall, 78.9% (3.4 mm) for incomplete, and 216.7% (1.9 mm) for full canopy conditions. Summing of extra ET values for the day of irrigation and the subsequent day yielded average values more than double those for the day of irrigation only, at 3.9 and 4.3 mm for MESA and LESA, respectively. Similarly, values for extra ET as a percentage of irrigation depth were also more than double those for the day of irrigation only, with the greatest loss values of 39.5% for MESA and 28.0% for LESA. These findings suggest that although LESA appears to mitigate evaporative losses marginally more in corn than MESA on the day of irrigation, considerably more evaporative losses occurred for both methods during the subsequent day, with slightly increased losses for LESA, resulting in little difference between overall losses over the two days. This may in part be explained by*

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the temporary cooling effect of the irrigation inside the canopy on the day of irrigation, which is diminished by the second day. A greater discrepancy between evaporative losses for MESA and LESA is likely to be observed for crops having shorter stature or lower leaf density, such as cotton, although more study is needed to corroborate this claim. Knowledge of these findings provides useful information for both producers and water managers when considering irrigation management and water planning strategies.

Keywords. *Evaporation, Evapotranspiration, LESA, MESA, Semi-arid, Sprinkler Irrigation, Subsurface Drip Irrigation, Transpiration, Weighing Lysimeters.*

Irrigation is used to supplement inadequate and erratic precipitation for agricultural crop production in arid and semi-arid lands. Although subsurface drip irrigation (SDI) acreage has increased, sprinkler irrigation remains the predominant method in the U.S. Great Plains, with greater than 85% of the Southern High Plains (SHP) irrigated area served by center-pivot systems (USDA-NASS, 2019). A recent study identified over 50,000 center pivots covering 2.67 million ha in the SHP, with the Texas Panhandle accounting for 58% of the total area (Hassani et al., 2021). Fossil water from the High Plains Aquifer, also known as the Ogallala Aquifer, has served as the primary source of irrigation in the SHP since development began in the 1950s. Decades of pumping coupled with minimal recharge have resulted in decreased saturated thickness and reduced well capacities throughout most of the region. The seemingly inevitable depletion of the Ogallala has motivated efforts to develop more efficient irrigation methods and management strategies. In the early 1980s, a paradigm shift from high-pressure impact sprinkler systems to low-pressure (207 kPa) spray systems resulted in significant reductions in wind drift losses and pumping energy requirements, in part because spray nozzles were typically suspended below the irrigation system lateral pipe and closer to the crop canopy where wind speeds were less, whereas impact sprinklers were typically mounted on top of the system lateral pipe.(Howell et al., 1991; Schneider and Howell, 1995a, b, c). Subsequent low energy precision application (LEPA) modifications increased application efficiency and reduced wind drift and evaporation losses by avoiding canopy wetting and applying water directly to the soil (Lyle and Bordovsky, 1983). However, the concentrated application of water using LEPA often led to ponding and runoff on sloped or slowly permeable soils, requiring mitigation using furrow dikes or more frequent, smaller irrigations (Schneider and Howell, 1995b, 1998, 1999). Alternatively, low-pressure sprinkler systems provided a compromise by allowing increased drift losses as compared to LEPA but increasing infiltration with reduced runoff potential by expanding the spray footprint while also improving application uniformity (Peters et al., 2016; Schneider and Howell, 1998, 1999). The advent of low-pressure sprinkler systems gave rise to a new era of sprinkler innovation and design, drop configurations, and system management. With such advancements came the need for evaluation and comparison methods. Irrigation application efficiency (AE), a measure commonly used to quantify losses during irrigation events, can be defined as:

$$AE = \frac{I_E}{I_A} \tag{1}$$

where

AE = irrigation application efficiency (fraction)

I_E = depth of effective irrigation remaining in the root zone after application and available for root uptake

I_A = depth of applied irrigation.

Most modern low-pressure sprinkler spray pattern designs aim to increase AE by optimizing droplet size and velocity to limit drift and evaporative losses, thereby increasing infiltration and minimizing runoff. Sprinkler drop and spacing configurations are numerous but are typically characterized in one of two categories based on the height of application from the ground surface: mid-elevation sprinkler application (MESA) having a nominal application height of ~1.5 to 2.0 m, and low-elevation sprinkler application (LESA) having an application height of ~0.5 m. In general, systems with greater AE require less applied irrigation (I_A) to achieve a targeted effective irrigation depth (I_E). This concept is important because even small increases in AE can translate to large water savings when considering the irrigated acreage of the SHP.

Sarwar et al. (2019) used catch cans to determine water application efficiency (WAE), defined as the fraction of irrigation water that reached the ground, for both MESA and LESA irrigation systems over uncropped fields near Prosser, Washington. Their results showed that, on average, 21% more irrigation water reached the ground with LESA than with MESA over a three-year period with varying climatic conditions. Using short-duration, high-intensity rainfall events as surrogates for irrigation events, Marek et al. (2016) used data from large weighing lysimeters near Bushland, TX, to show that nearly all the water from 20 to 30 mm events on fallow was lost to evaporation within three to four days under typical summer conditions, with standardized grass reference ET (ETos) (ASCE, 2005) values of 0.5 to 1.0 mm hr^{-1}. Although such information is insightful, similar evaluations for cropped areas are needed to provide more comprehensive measures of effective AE. Factors affecting AE include climate, soil type, canopy density, canopy height, length of the vegetative growth stage, practices that reduce (furrow dikes) or enhance (furrow compaction) runoff, and sprinkler height. As such, the determination of AE values for both individual irrigations and seasonal performance can be challenging.

Somewhat complicating matters is an important distinction between "losses" associated with measures of AE and other measures of efforts to increase crop yield. For example, crop water productivity (CWP), also known as water use efficiency (WUE), is commonly defined as:

$$CWP = \frac{Y}{ET} \tag{2}$$

where

CWP = crop water productivity

Y = marketable yield

ET = water used to produce the yield, evapotranspiration (ET).

Drift and evaporative losses that occur during the conveyance and application of irrigation fail to reach the intended soil or plant surfaces, which is why those losses, while important, are not accounted for in CWP calculations. Measurement or estimation of crop ET is required for such calculations. Several methods are used for estimating ET, including eddy covariance, the Bowen ratio, surface renewal, and scintillometry. However, direct measurement of ET using properly designed and managed weighing lysimeters is considered the most accurate method. Although the beneficial effects of sprinkler irrigation on microclimate are debated (Cavero et al., 2009; Tolk et al., 1995), evaporation (E) from both the soil and plant surfaces is often considered a loss, while transpiration (T) is deemed an effective use of water in photosynthesis. As such, knowledge of the relative proportions of E and T aid in the evaluation of irrigation systems. However, empirical methods of partitioning E and T from Bushland lysimeter ET_c (crop ET) measurements are not currently possible. Further complicating matters is that the irrigation application itself changes the in-canopy and soil surface water dynamics, obfuscating the subsequent baseline conditions required for comparisons. One approach for alleviating this issue is to compare daily ET values from the adjacent sprinkler and SDI lysimeters having similar crop and management, including well-watered irrigation conditions. Evett et al. (2019) used such an approach to evaluate and compare the impacts of MESA and SDI on ET and yield for corn and sorghum grown in the Texas Panhandle. Although not a perfect analog, ET measurements from the SDI lysimeters can provide a close approximation of T because the relative proportion of E is typically minor because SDI does not wet plant surfaces and rarely wets the soil surface. Our overall objective was to characterize sprinkler irrigation losses (extra ET) by comparing lysimeter-derived daily ET values for MESA and LESA sprinkler irrigations with those from adjacent SDI lysimeter fields planted to corn grown near Bushland, TX, in 2016 and 2018. Additional analyses included a comparison of losses measured during incomplete and full canopy conditions in both years. Comparisons were limited primarily to the day of irrigation, but losses in subsequent days are discussed for a limited number of cases.

Materials and Methods

Study Area

A drought-tolerant grain corn (*Zea mays* L) hybrid (Pioneer 1151 AQUAMax) was grown in weighing lysimeter fields in 2016 and 2018 at the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, Texas. (35° 11′ N, 102° 6′ W, 1170 m above MSL). The approximately square field was subdivided into four quadrants of ~4.4 ha each, each having a lysimeter located in its center, designated according to its position relative to the cardinal directions: NE, SE, NW, or SW (fig. 1). The fields were gently sloping (< 0.3%) Pullman soil (fine, mixed, superactive, thermic Torrertic Paleustoll). The slowly permeable soil has a dense B2 horizon at 0.3 to 0.5 m depth and a caliche layer below approximately 1.4 m depth that restricts water movement in some seasons. Nominal lysimeter dimensions were 3 m × 3 m in surface area and 2.3 m in depth, each containing an undisturbed Pullman monolith, obtained on site (Marek et al., 1988). The regional climate was classified as semiarid and characterized by warm summers and cold winters with an annual pan evaporation of > 2400 mm and an annual short crop reference ET (ETos) of ~1700 mm (Evett et al., 2020).

Irrigation and Crop Management

In both years, the west fields (NW, SW) were irrigated using an N-S oriented, ten-span, 457 m linear-move sprinkler system equipped with spray drops positioned on 1.52 m spacing, each equipped with pressure regulators and drop weights, as further described by Evett et al. (2019) and Marek et al. (2021). In 2016, sprinkler irrigation was characterized as MESA, with spray drops positioned approximately 1.5 m above the ground surface. Sprinkler drops were lowered to approximately 0.5 m above the soil surface in 2018, constituting low-elevation spray application (LESA). The east fields (NE, SE) were irrigated by SDI using 25 mm diameter lines installed at a depth of 0.30 to 0.36 m in the center of interrows and on 1.52 m spacing (Evett et al., 2019). The east lysimeters were equipped with an independent lysimeter SDI system whose installation geometry was identical to that of the surrounding fields (Evett et al., 2018a). The SDI lines in the lysimeter boxes were plumbed to a pumping system, and water storage was attached to the lysimeter soil tank so that the subsystems became part of the lysimeter mass (Evett et al., 2018a). This design allowed for the onboarding of lysimeter irrigation water within minutes, resulting in practically a step increase in the water storage tank and lysimeter mass that was easily quantified and accounted for. Other advantages included tank filling at any time of day and meaningful measurement of ET during irrigation events. Corn was planted with 0.76 m row spacing, with sprinkler drops (west fields) and SDI lines (east fields) strategically placed in every other interrow. In both years, corn grown in the SDI (NE, SE) and sprinkler (SW) fields was fully irrigated, defined as not allowing management allowed depletion (MAD) of soil water content in the top 1.5 m of soil greater than 55%, although irrigations for the sprinkler and SDI fields did not typically occur within the same day. Soil profile water was monitored at least once a week, weather permitting, using a field calibrated (0.01 $m^3\ m^{-3}$ accuracy) neutron probe meter with a depth control stand to take readings centered at 0.2 m depth to 2.3 m depth in 0.2 m depth increments (Evett et al., 2003; Hignett and Evett, 2002) (fig. 2). In both years, the east (SDI) and west (sprinkler) fields were planted within one day of each other and managed for high yield production. Values for leaf area index

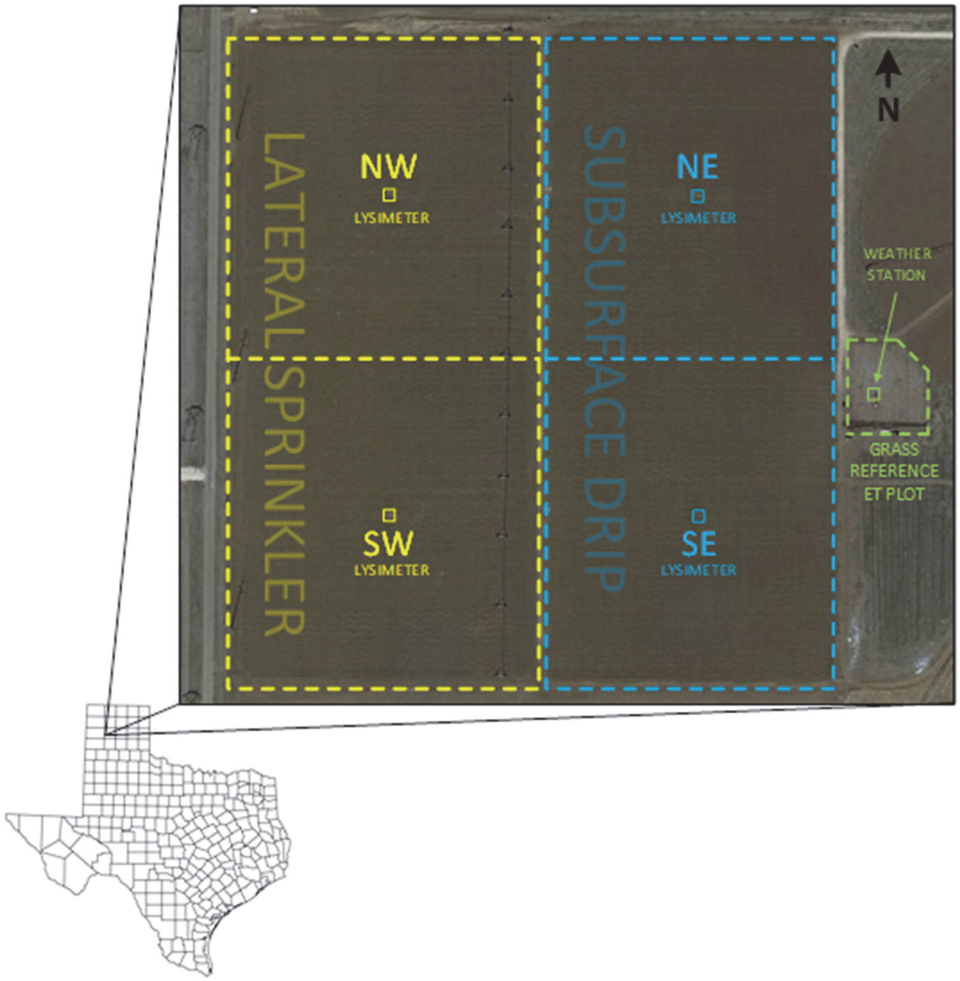

Figure 1. Location and orientation of sprinkler irrigated west (NW, SW) and SDI irrigated east (NE, SE) weighing lysimeter fields at USDA-ARS CPRL near Bushland, Texas.

(LAI) were calculated from destructive field subsamples as the dimensionless ratio of the upper side green leaf area (m^2) to the ground area (m^2) below throughout the growing season. Leaf area values were measured using a digital scanning bed leaf area meter (model LI-3100, LI-COR, Lincoln, Neb.). In 2016, the east fields were planted on DOY 131 and the west fields were planted on the following day (DOY 132), with emergence occurring in both fields on DOY 142. In 2018, the east fields were planted on DOY 143, with emergence occurring on DOY 149. The west fields were planted on DOY 144, with emergence occurring on DOY 151. Twenty sprinkler irrigations were applied to the MESA (SW lysimeter) field in 2016. Twenty-four sprinkler irrigations were applied during the 2018 growing season.

Lysimetric Measurement of Evapotranspiration

Properly designed and managed weighing lysimeters are considered the most accurate method of measuring ET. The efficacy and role of the CPRL large weighing lysimeters in ET and energy and water balance studies are well chronicled (Evett et al., 2016). Quality assurance and quality control (QA/QC) techniques for processing both lysimeter ET data (Marek et al., 2014) and weather data (Evett et al., 2018b) from the CPRL were used in this study. By dividing the lysimeter mass by the relevant surface area (9 m^2) and the density of water (taken as 1,000 kg m^{-3}), the mass equivalent relative storage (mm of water) was calculated. This calculation allowed changes in lysimeter mass to be expressed in terms of water depth, defined as the one-dimensional depth of water (mm) lost or gained per unit of time. The lysimeters had an accuracy of 0.04 mm water depth equivalent or better (Evett et al., 2012). During data processing, lysimeter storage (a five minute avg.) values were plotted for graphical inspection and analysis using a 1-to-5-day window. Plots of lysimeter storage typically exhibit a diurnal sigmoidal shape characterized by a decreased ET rate (flattening of storage plots) during the evening and early morning hours due primarily to decreased temperatures and slower wind speeds. Field operations such as sensor maintenance or taking neutron probe readings require a person to stand on the lysimeter and have a temporary effect on lysimeter storage values. Other events, such as irrigation or precipitation, have a lasting effect on storage. However, most such events can be easily discerned and accounted for to compute daily ET values. For example, a 34.5 mm sprinkler irrigation on a given day of the year (DOY 204) in 2016 was characterized by a

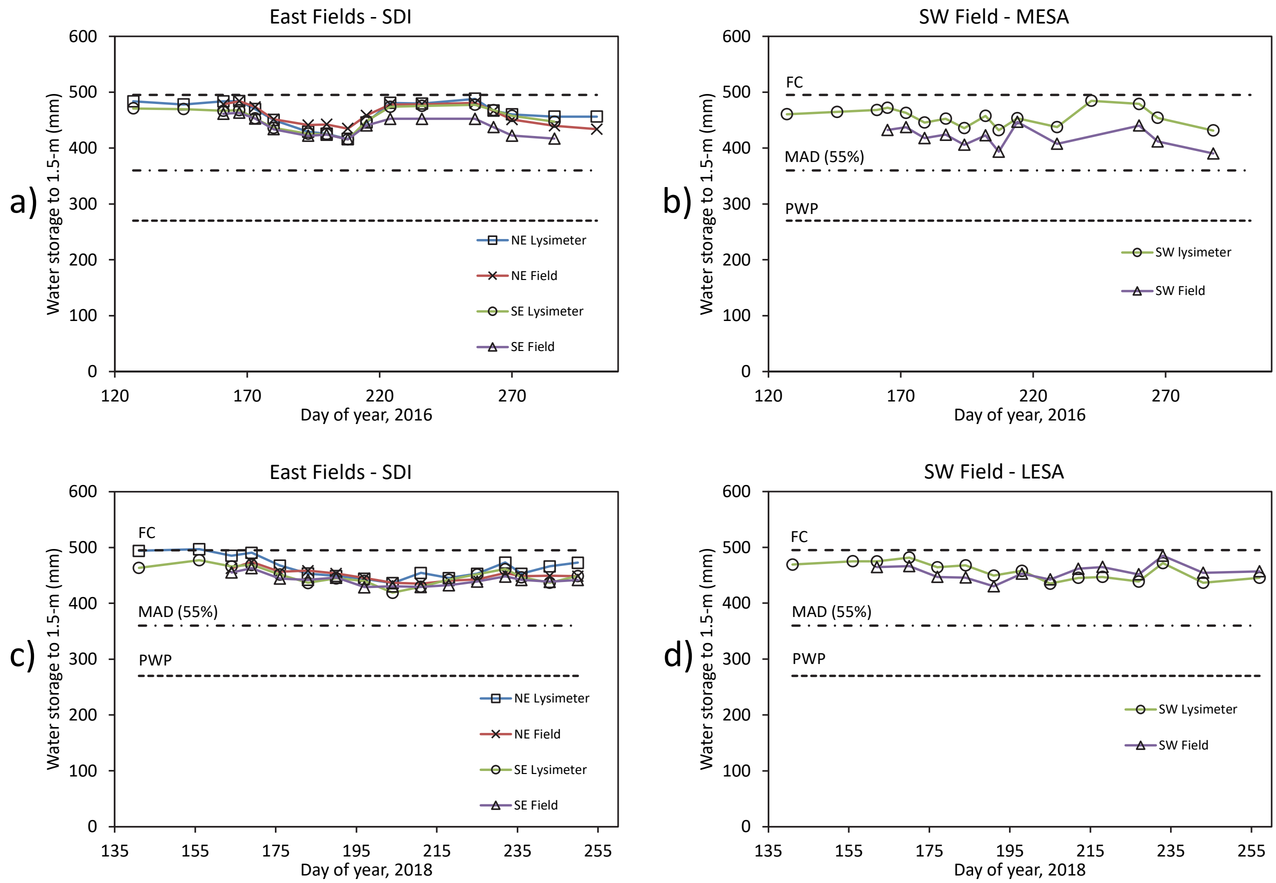

Figure 2. Seasonal volumetric soil water storage values for SDI (a,c) and sprinkler irrigated (b,d) lysimeter fields for 2016 and 2018. Irrigations for both SDI and sprinkler fields were managed to avoid crop water stress, defined as maintaining soil water profile values greater than 55% of management allowed depletion.

distinctive step-like increase in mass (fig. 3a). By offsetting the storage values following the irrigation by subtracting the amount of irrigation, an adjusted storage can be used to estimate the daily ET by subtracting midnight-centered values (fig. 3b). A confounding aspect of this approach is that lysimeter storage is subject to simultaneous ET from the crop canopy and soil surface during the irrigation, potentially reducing the storage gain attributed to the event. However, Tolk et al. (1995) showed that transpiration declined to nearly zero during MESA irrigations at Bushland. Irrigations also typically occurred when soil surface conditions were relatively dry and, therefore, evaporative losses were small. As such, the ET rate was assumed to be zero during irrigation events, and lysimeter storage was adjusted to that of the 5-min period immediately preceding the irrigation for the duration of the event (fig. 3b). The same assumption was made for LESA irrigations in 2018, and it's possible that the lower drop height may have had less of a cooling effect on the canopy and thus resulted in slightly increased transpiration. Although some ET likely occurred during both MESA and LESA irrigations, using this approach provided the most conservative (smallest) estimates of extra ET for sprinkler irrigation as compared to SDI. A 15-term smoothing filter (Savitzky and Golay, 1964) was used to reduce noise in plots of ET rate only, which prevented values from reaching zero during irrigation events (fig. 3c).

Quantifying Evaporative Losses from Sprinkler Irrigation

Lysimeter storage values and ET rate from the sprinkler fields (SW lysimeter) were compared with those from the SDI system (NE and SE lysimeters) for all days when sprinkler irrigation events occurred in 2016 and 2018. To facilitate a graphical presentation in the figures, storage values for the SDI lysimeters were offset to match the starting value of the sprinkler lysimeter on days receiving irrigation. Daily ET values for the SDI lysimeters were averaged and subtracted from the sprinkler daily ET value, and the difference was attributed to extra ET for the sprinkler irrigations. For example, figure 4 illustrates such a comparison of lysimeter storage and ET rate for a 28.2 mm MESA sprinkler irrigation that occurred on DOY 168 in 2016 under incomplete crop canopy conditions, with a plant height of approximately 0.5 meters and a leaf area index (LAI) of ~ 2.0. Visual inspection revealed that storage for all three lysimeters approximated each other well until shortly after the irrigation ended, when MESA (SW) storage decreased markedly compared with SDI lysimeter storage (fig. 4b). The resulting difference in daily ET values was 3.5 mm, representing 12.3% of the effective irrigation amount. The difference in daily ET between the MESA and SDI lysimeters was also reflected in the plot of the ET rate (fig 4c). The relatively large amount of extra ET on DOY 168 is most likely attributable to increased evaporation from bare soil, exacerbated by the

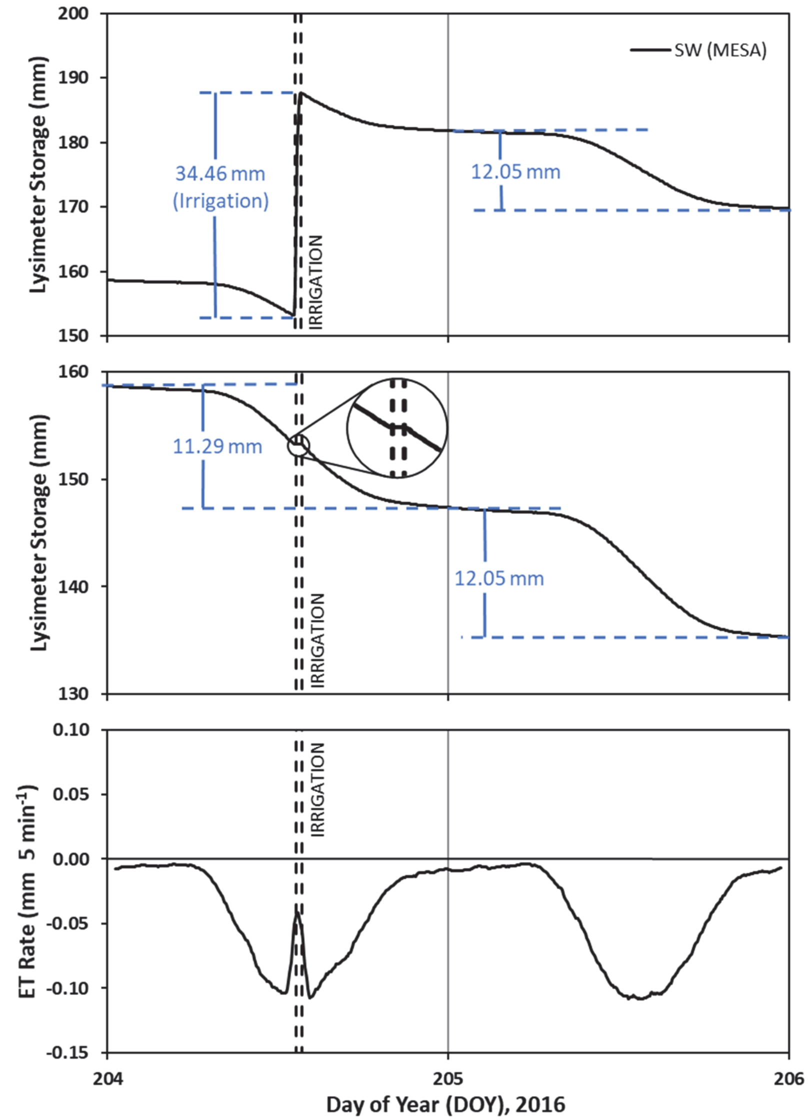

Figure 3. Southwest (MESA) lysimeter storage for DOY 204-205 in 2016. Step-like increase of 34.5 mm was attributed to irrigation event on DOY 204 (a) Daily ET was calculated from midnight-centered values using adjusted storage values obtained by subtracting irrigation amount; ET was assumed to be zero during irrigation (inset) (b) Corresponding ET rates were also calculated using smoothing filter to reduce noise (c).

incomplete canopy condition, plus evaporation from the sparse vegetation wetted by the sprinkler. Differences in ET for the subsequent day (DOY 169) were also considerable, amounting to 2.8 mm of extra ET from MESA compared with SDI lysimeters. This illustrates that extra ET associated with *E* from sprinkler irrigation losses can extend beyond the day of irrigation, although the magnitude of such losses may be mitigated by sprinkler height (MESA vs. LESA), canopy status, and ETos conditions. This study focused primarily on differences in ET for the day of the irrigation but also included the subsequent day unless precipitation or irrigation occurred in the subsequent period. Extending the window beyond two days is often not fruitful due to the occurrence of mass-changing events such as precipitation or subsequent irrigation events. In some cases, rainfall events occurred during the late evening on days when irrigations occurred. ET rates were typically very small during such times (low ET rates) and had a minimal effect on daily ET calculations. As such, values were calculated using evening storage values immediately prior to the late evening rainfall events and are denoted in table 1. On two occasions in 2018 (DOY 214 and 229), small rainfall events occurred just after midnight on days when irrigations occurred. Although these events likely had some effect on daily extra ET calculations, they were considered negligible.

Results and Discussion

2016 (MESA vs. SDI)

Comparisons of extra ET were performed for all irrigation events except for DOY 209, which was omitted due to the occurrence of small rainfall events immediately prior to and following the sprinkler irrigation. Although the additions to lysimeter storage could be adjusted for, the wetting of the soil and plant surfaces in the SDI fields violated the initial conditions present for the other comparisons. In general, extra ET (ET_{MESA} - ET_{SDI}) values from the day of irrigation decreased following emergence (DOY 142)

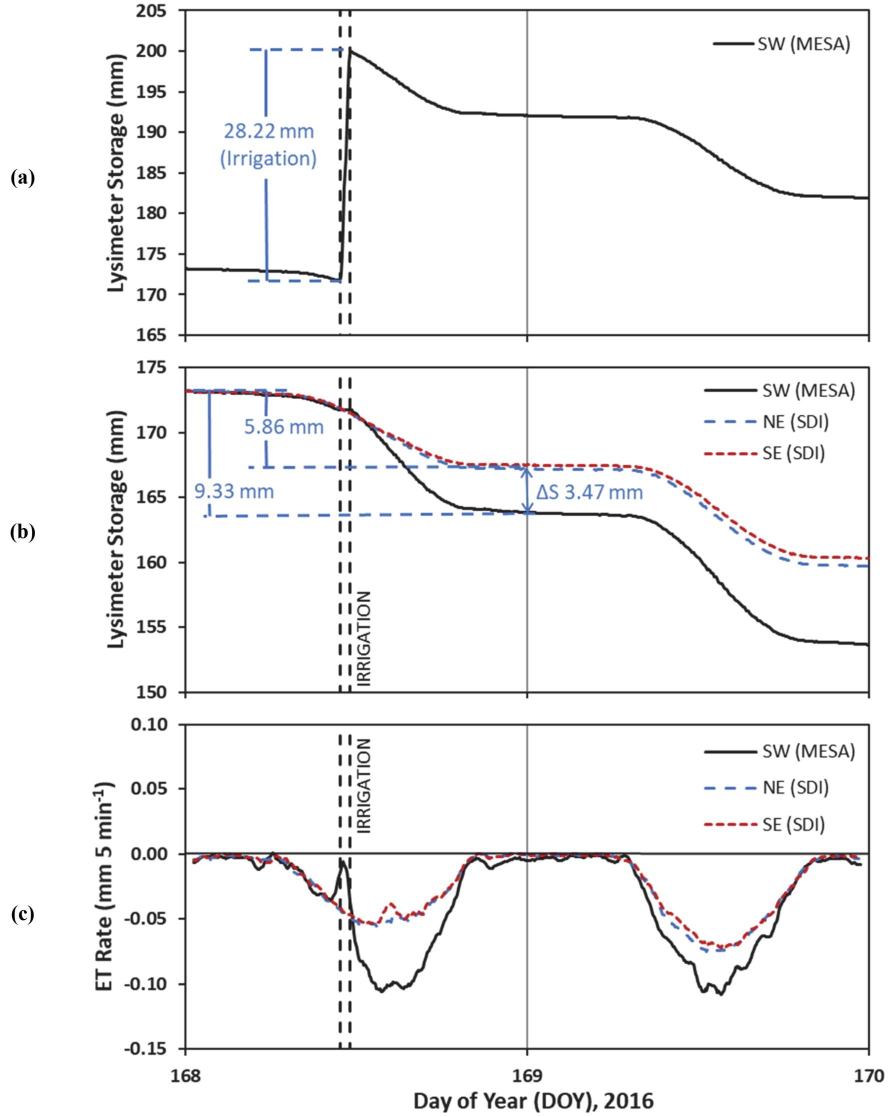

Figure 4. An irrigation event of (a) 28.2 mm on DOY 168 resulted in (b) 3.5 mm of Extra ET on DOY 168 (calculated as difference between daily ET from SW and SDI lysimeters) and (b) 2.8 mm of extra ET on DOY 169. The difference in ET was reflected in marked increases in (c) ET rate after irrigation occurred).

throughout the growing season in 2016 (table 1, fig. 5a). The first irrigation after planting (DOY 137) resulted in only 2.0 mm of extra ET. Although the irrigation occurred over bare soil conditions, evaporative demand on DOY 137 was relatively small, with a daily ETos of 1.9 mm (fig. 5b). The first irrigation after emergence on DOY 148 resulted in the greatest daily extra ET of 4.9 mm, with daily ETos conditions of more than three times those of DOY 137 (6.2 mm). In general, extra ET decreased as crop height and LAI values increased from emergence until reaching their approximate maximums around DOY 200 (fig. 5b). Daily extra ET was consistently smaller for irrigations under full canopy conditions (DOY 200 – harvest) than for incomplete canopy conditions (planting – DOY 199). Average extra ET values in 2016 for incomplete and full canopy conditions were 2.1 mm and 0.6 mm, respectively (table 1). The average daily extra ET was 1.4 mm with all extra ET values following DOY 200 ≤ 1.3 mm. Targeted irrigation depths varied throughout the season but were typically between 19 and 32 mm. Lysimeter-derived irrigation depths approximated targeted values in most cases, although small variations did occur due to inconsistencies in the travel time of the lateral-move system when passing over the lysimeters. Extra ET values were compared to lysimeter-derived irrigation depths to determine the percent losses of each irrigation. MESA irrigation losses in 2016 averaged 5.4% of irrigations over the entire growing season, with the largest loss of 26.8% occurring on DOY 148 (table 1). In general, losses decreased with crop development, with average values of 7.9% and 1.9% for incomplete and full canopy conditions, respectively. The 2016 growing season was characterized by typical ETos conditions during the early and mid-season with smaller evaporative demand later in the season.

2018 (LESA vs. SDI)

The first irrigation in 2018 was relatively large (~51 mm) and applied almost two weeks prior to planting (DOY 130-131) as a pre-watering event on both the east and west fields

Table 1. Irrigation depths and extra ET values for day of irrigation for MESA (2016) and LESA (2018).

2016

		Lysimeter ET						
		MESA	SDI					
DOY	Irr Depth[a] (mm)	SW (mm)	NE (mm)	SE (mm)	East Avg (mm)	Extra ET (mm)	xET % of irr	xET % of ETos
137	18.2	3.2	1.2	1.2	1.2	2.0	11.1	52.1
148	18.2	6.1	1.4	1.1	1.2	4.9	26.8	79.1
161	29.1	6.3	3.0	2.4	2.7	3.6	12.5	40.3
168	28.2	9.3	6.0	5.7	5.8	3.5	12.4	38.4
173	32.7	8.0	5.8	5.7	5.7	2.2	6.9	27.3
179	35.6	6.6	6.3	5.7	6.0	0.7	1.8	10.4
183	40.3	7.2	7.3	7.0	7.1	0.1	0.3	1.70
187	35.3	11.0	9.3	9.0	9.1	1.9	5.4	21.5
190	35.5	6.6	5.3	5.2	5.3	1.4	3.8	22.0
194	31.0	9.8	9.1	9.0	9.1	0.8	2.4	9.2
196	51.0	9.0	7.3	7.6	7.4	1.5[b]	3.0	19.9
200	25.6	10.7	9.6	9.2	9.4	1.3	5.2	14.9
204	34.5	11.3	10.7	10.1	10.4	0.9	2.6	9.8
207	26.0	7.0	6.4	6.3	6.4	0.7	2.5	10.5
209	25.1	-	-	-	-	-	-	-
211	27.0	6.3	5.9	5.8	5.8	0.5[b]	1.8	7.3
214	30.5	8.6	8.7	8.0	8.3	0.2	0.6	2.4
224	22.2	6.7	7.1	6.5	6.8	-0.1[b]	0.0	0.0
230	46.4	7.8	7.3	7.1	7.2	0.7	1.4	10.5
232	24.2	4.6	4.4	4.2	4.3	0.3[b]	1.1	4.9
average (season)						1.4	5.4	20.1
average (part canopy)						2.2	7.9	29.3
average (full canopy)						0.6	1.9	7.5

2018

		Lysimeter ET						
		MESA	SDI					
DOY	Irr Depth[a] (mm)	SW (mm)	NE (mm)	SE (mm)	East Avg (mm)	Extra ET (mm)	xET % of irr	xET % of ETos
131	58.3	-	-	-	-	-	-	-
145	13.6	-	-	-	-	-	-	-
151	19.2	3.1	1.4	1.3	1.3	1.8	9.1	20.6
159	30.6	6.3	2.1	2.2	2.1	4.2[b]	13.6	37.5
165	33.0	6.9	3.3	3.2	3.3	3.6	10.9	33.1
172	24.6	6.2	4.9	4.2	4.5	1.7	6.8	24.7
178	26.7	10.2	8.2	7.1	7.7	2.6	9.7	22.9
180	25.0	9.6	7.0	6.3	6.6	3.0	12.0	25.0
186	36.1	6.5	6.8	6.5	6.6	-0.2	0.0	-
191	28.9	8.2	7.3	7.2	7.2	0.9	3.2	21.1
193	34.1	6.5	5.8	5.4	5.6	0.9	2.6	12.3
198	28.1	10.2	9.7	9.3	9.5	0.7	2.4	8.8
200	24.5	12.7	11.2	10.9	11.0	1.7	6.9	18.9
205	34.0	6.0	5.7	5.8	5.7	0.3	0.9	4.8
208	13.4	4.0	3.7	3.6	3.6	0.3	2.5	7.0
212	26.6	5.7	5.6	5.7	5.6	0.0	0.1	0.3
214	12.4	7.8	7.1	7.2	7.2	0.7[c]	5.2	9.4
219	21.6	8.2	8.1	7.9	8.0	0.2	1.0	2.7
227	24.6	6.2	6.0	6.1	6.1	0.1	0.5	2.0
229	23.4	5.8	5.7	5.6	5.7	0.1[c]	0.4	1.6
236	27.2	8.3	7.5	7.1	7.3	1.1	3.9	14.2
239	11.9	9.7	7.9	7.2	7.6	2.1	17.7	22.8
243	33.0	7.9	7.7	6.9	7.3	0.6	1.9	6.7
247	18.9	5.2	4.7	4.2	4.5	0.7[b]	3.9	12.8
average (season)						1.2	5.2	13.5
average (part canopy)						1.9	7.0	19.4
average (full canopy)						0.6	3.5	7.7

[a] Values presented for irrigation depth are quantified using lysimeter storage values. Depths may vary from targeted irrigation depths due to variations in sprinkler travel time across the lysimeter.

[b] Extra ET was calculated using lysimeter storage values immediately preceding a small, late evening rainfall event

[c] Extra ET was calculated using lysimeter storage values immediately following a small, early morning rainfall event just after midnight

to remedy low soil profile water conditions stemming from a dry winter season. Light irrigation of ~13 mm was applied one day after planting on DOY 145 to facilitate germination. However, on that day, erroneous data from the east lysimeters prevented comparison of extra ET. Like for most MESA comparisons in 2016, extra ET values (ET_{LESA} - ET_{SDI}) in 2018 generally decreased from planting through harvest (fig. 6). Also similar was early irrigation at germination (DOY 151) that resulted in a relatively small extra ET value (1.8 mm). However, the 8.5 mm daily ETos value was much greater than the relatively small corresponding value in 2016. The decreased extra ET may be explained in part by greater infiltration due to the surface cracking of the Pullman following a light irrigation on DOY 145, resulting in less surface water available for evaporation. Extra ET values decreased with increasing LAI and crop height under incomplete canopy conditions (planting - DOY 203). Although LAI and crop height values didn't reach maximum values until DOY 239 and DOY 221, respectively, extra ET values were consistently smaller following DOY 204. As such, full canopy conditions were defined as DOY 204 – harvest. Somewhat surprising is that elevated extra ET values were observed in the late season under full canopy conditions. In contrast to 2016, the 2018 growing season was characterized by larger ETos conditions later in the season, particularly during DOY 235-242, which coincided with elevated extra ET values for irrigations on DOY 236, 239, and 243. These findings suggest that considerable evaporation from soil and plant surfaces can occur under high ETos conditions even when protected by full canopy cover and irrigated with LESA. The seasonal average extra ET for LESA in 2018 was 1.2 mm. The average extra ET during incomplete canopy conditions in 2018 was 1.9 mm, with a maximum value of 4.2 mm. The average extra ET for full canopy conditions was 0.6 mm, with a maximum value of 2.1 mm. Irrigation losses for LESA in 2018 averaged 5.2% of irrigation depth over the entire season (table 1). However, that value was influenced by the greatest loss value of 17.7% attributed to a small lysimeter-derived irrigation amount of ~12 mm on DOY 239, which far exceeded other late-season values. Distinct discrepancies between targeted and lysimeter-derived irrigation depths were observed for DOY 208, 214, and 239 in 2018, resulting in decreased values for the latter. A 5.2% loss value was associated with a ~12 mm irrigation amount on DOY 214. The larger loss values were likely attributable to the relatively small irrigation amounts because the extra ET values on both days weren't disproportionately large. However, a ~13 mm irrigation on DOY 208 yielded a loss value of only 2.5%, associated with a relatively low ETos value of 4.8 mm. The largest irrigation loss during incomplete canopy conditions in 2018 was 13.6%, occurring on DOY 159. Average loss values of 7.0% and 3.5% were observed for incomplete and full canopy conditions, respectively.

A comparison for DOY 200 in 2018 under full canopy conditions (crop height of ~2.7 m and LAI of 5.5) is presented in figure 7. Similar to figure 4, storage for all

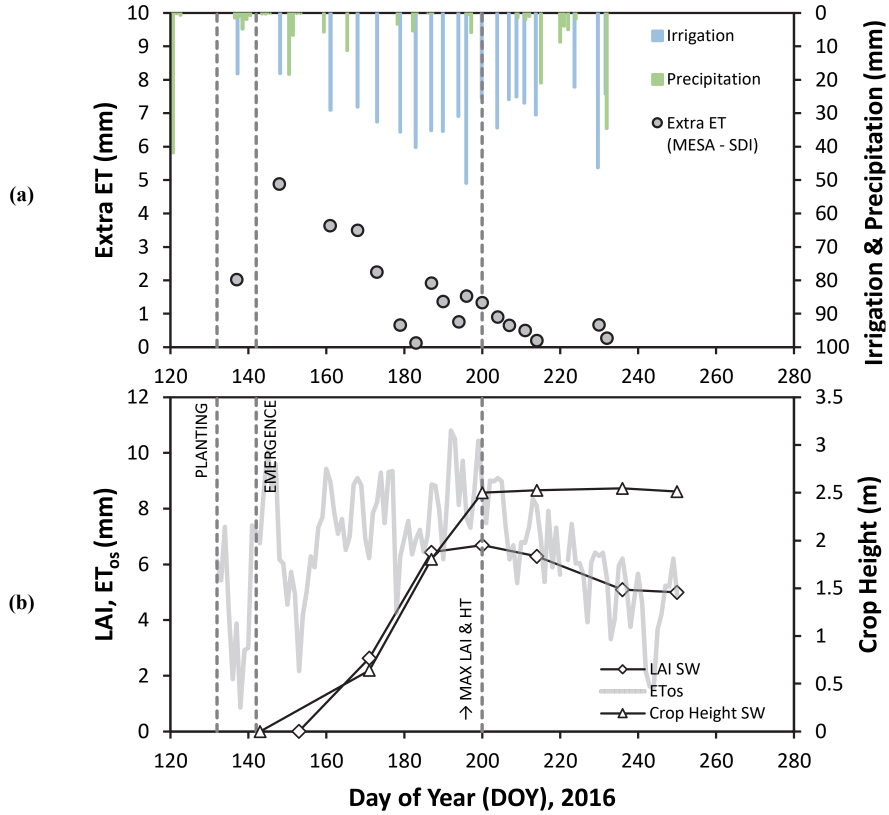

Figure 5. Daily (a) extra ET (ET_{LESA} - ET_{SDI}) for irrigations in 2016. Incomplete (planting - DOY 203) and full (DOY 204 – harvest) canopy conditions were determined by (b) maximum leaf area index (LAI) and (b) plant height values.

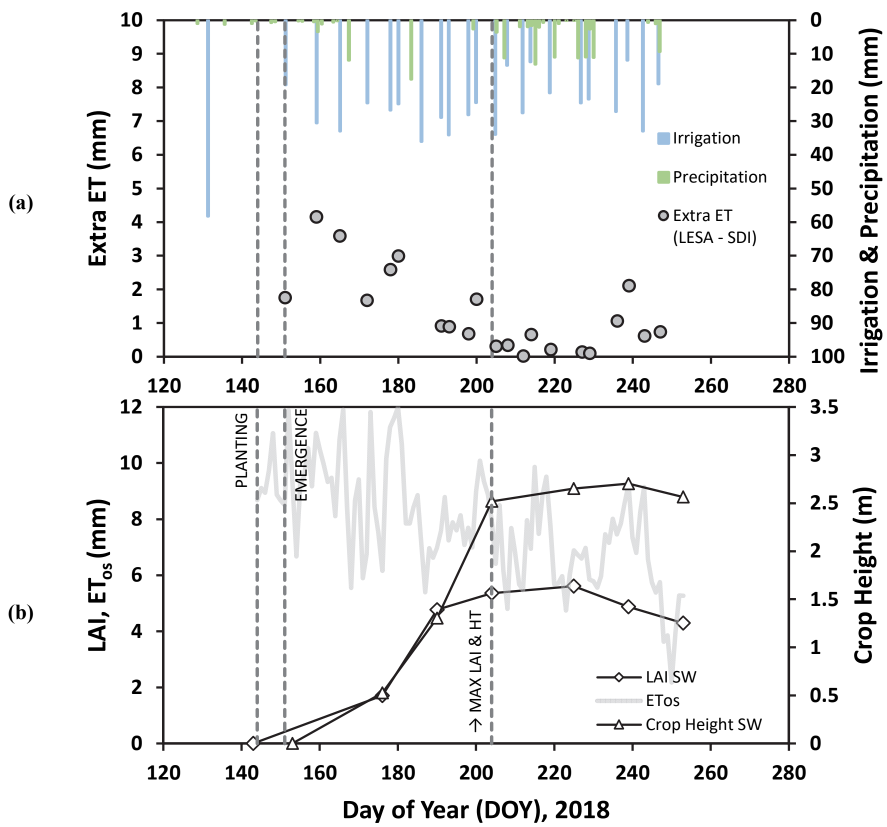

Figure 6. Daily (a) extra ET (ET_{LESA} - ET_{SDI}) for irrigations in 2018. Incomplete (planting - DOY 203) and full (DOY 204 – harvest) canopy conditions were determined by (b) maximum leaf area index (LAI) and b) plant height values.

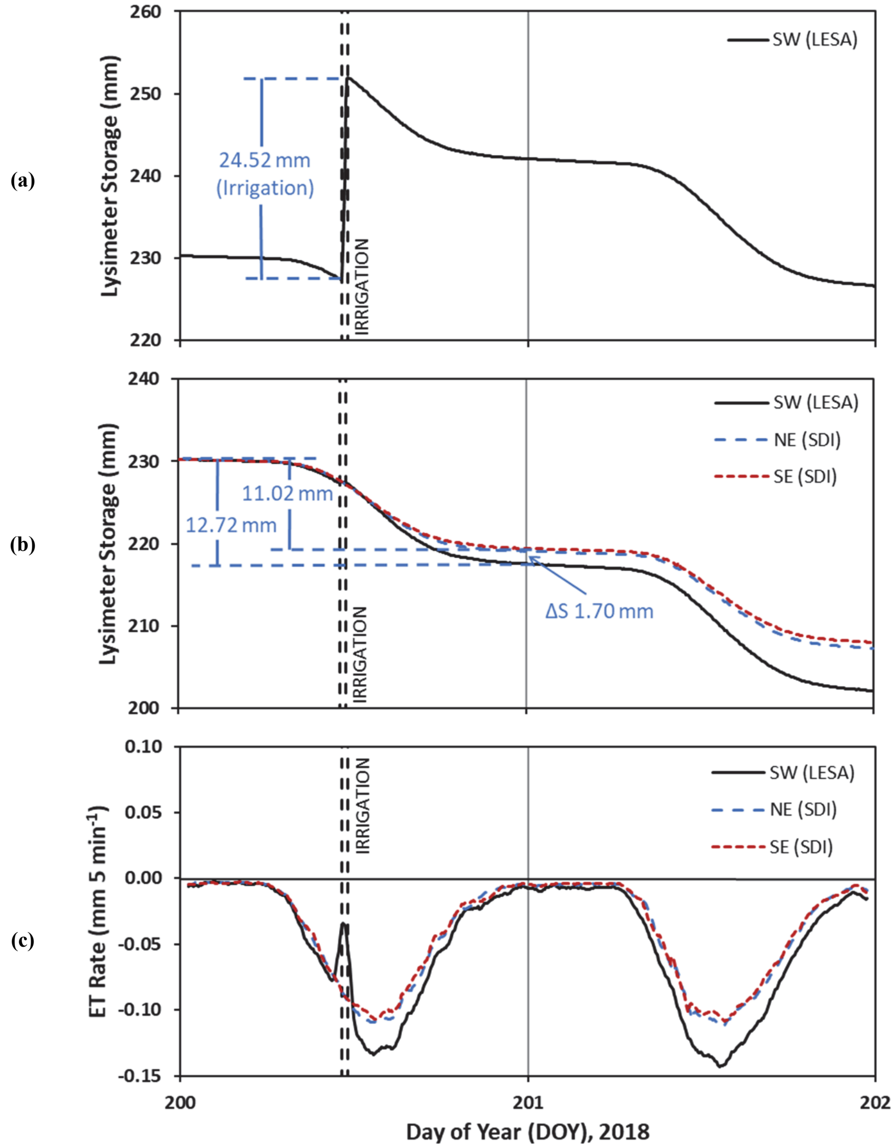

Figure 7. An irrigation event of (a) 24.5 mm on DOY 200 resulted in b) 1.7 mm of Extra ET on DOY 200 (calculated as difference between daily ET from SW and SDI lysimeters) and (b) 3.8 mm of extra ET on DOY 201. The difference in ET was reflected in marked increases in (c) ET rate after irrigation occurred.

lysimeters matched well until shortly after the irrigation ended. However, the divergence of LESA (SW lysimeter) storage from SDI lysimeter storage was considerably less than for DOY 168 in 2016 (fig, 4), resulting in a daily ET difference of only 1.7 mm, representing 7.0% of the 24.5 mm irrigation (figs. 7a and 7b). This suggests that the full canopy conditions mitigated the magnitude of extra ET for sprinkler irrigation. However, extra ET was more than double the next day, at 3.8 mm, indicating that *E* losses from sprinkler irrigation can extend beyond the day of irrigation even in full canopy conditions.

MESA vs LESA

Seasonal average extra ET values for MESA in 2016 were 15.4% greater than those for LESA in 2018 at 1.4 mm and 1.2 mm, respectively (table 1). Average extra ET during incomplete canopy conditions was 2.1 mm and 1.9 mm for MESA and LESA, respectively, representing an increase of 8.5%. Extra ET values were 0.6 mm for both LESA and MESA under full canopy conditions. This finding suggests that the difference in spray drop height had little effect on evaporative losses for fully developed corn. All extra ET values were positive except for one day each year. Extra ET ($ET_{MESA} - ET_{SDI}$) on DOY 224 in 2016 was essentially zero (-0.05 mm), with the SE lysimeter accounting for the negative value. An extra ET ($ET_{LESA} - ET_{SDI}$) value of -0.18 mm was calculated for DOY 191 in 2018 with comparisons to both east lysimeters resulting in negative values. No unique circumstances surrounding either day were observed, and lysimeter storage plots for all three lysimeters approximated one another. The negative differences may be in part due to the assumption of zero ET during irrigation, as small amounts of ET may have occurred during irrigation. For comparison, extra ET for all events was recalculated using daily storage values in which the ET rate during irrigation was interpolated as the average of rates immediately preceding and following the irrigation. Results showed a 35% increase (0.5 mm) in average seasonal extra daily ET for MESA and a 26% increase for LESA (0.3 mm). However, as previously argued, assuming zero ET during irrigation is likely much more representative of actual ET conditions during irrigation. Extra ET from available comparisons for MESA on the day of irrigation in 2016 totaled 27.0 mm, accounting for 4.6% of the corresponding 591 mm of irrigation. Over 83% (22.6 mm) of extra ET occurred under incomplete canopy conditions, with only 4.4 mm under full canopy conditions. Extra ET for comparisons of LESA in 2018 also totaled 27.0 mm, but with 6.3 mm occurring under full canopy conditions, likely due to greater late-season ETos conditions. Evaporative losses for irrigations were slightly larger overall for MESA (5.4%) than LESA (5.2%). Loss values of 7.9% and 7.0% were observed for incomplete canopy conditions for MESA and LESA, respectively. Average loss values for LESA (3.5%) under full canopy conditions were greater than those for MESA (1.9%) due to a large late-season value in 2018. Irrigation depths typically ranged from 19 to 36 mm in both years, requiring approximately 10 to 14 hours of sprinkler run time to traverse the fields. This resulted in the irrigations occurring over the lysimeters during the noon to early afternoon hours. Therefore, the comparisons of losses between SDI and sprinkler irrigation might be considered conservative, or somewhat of a "worst case scenario," as irrigation occurred during a typically warmer period of the day and thus were subjected to greater evaporative demand. However, while additional ET was observed for the sprinkler irrigations during incomplete canopy conditions, with divergence beginning immediately following the irrigation event (fig. 4), figure 7 clearly shows that divergence between SDI and LESA did not begin until several hours after the end of the irrigation event. This further supports the mitigation of evaporative losses from sprinkler irrigation under full canopy conditions in corn

The interannual variation illustrated by the seasonal differences in ETos for 2016 and 2018 can bias comparisons of extra ET values for MESA and LESA. Therefore, extra ET values were also computed as a percentage of both ETos and irrigation depth to further analyze irrigation losses for MESA and LESA (fig. 8). A comparison of extra ET values expressed as a percentage of ETos indicated that average losses from MESA in 2016 were 20.1%, while losses from LESA in 2018 were less at 13.5%. The greater value for MESA was likely skewed by the large early season value (79.1%) observed for DOY 148; as the average values for full canopy conditions were much closer at 7.7% and 7.5% for MESA and LESA, respectively (fig. 8a). Corresponding values for incomplete canopy conditions were 29.3% of ETos for MESA and 19.4% for LESA. Figure 8a shows that, while losses from early season irrigations can be large and variable, extra ET values from MESA and LESA applications are comparable overall and trended well throughout the growing season. These findings further support the notion that reduced losses associated with LESA systems are limited to the relatively short vegetative growth stages in corn.

A similar comparison of extra ET expressed as a percentage of irrigation depth illustrated a similar trend for MESA and LESA. Overall, results showed that irrigation depth had little influence on differences between losses, with average values of 5.3 and 5.2 mm for MESA and LESA, respectively (fig. 8b). Marek et al. (2021) also showed similar seasonal crop water productivity values for corn grown using less frequent, larger irrigations and more frequent, smaller irrigations. Extra ET values as a percentage of depth for

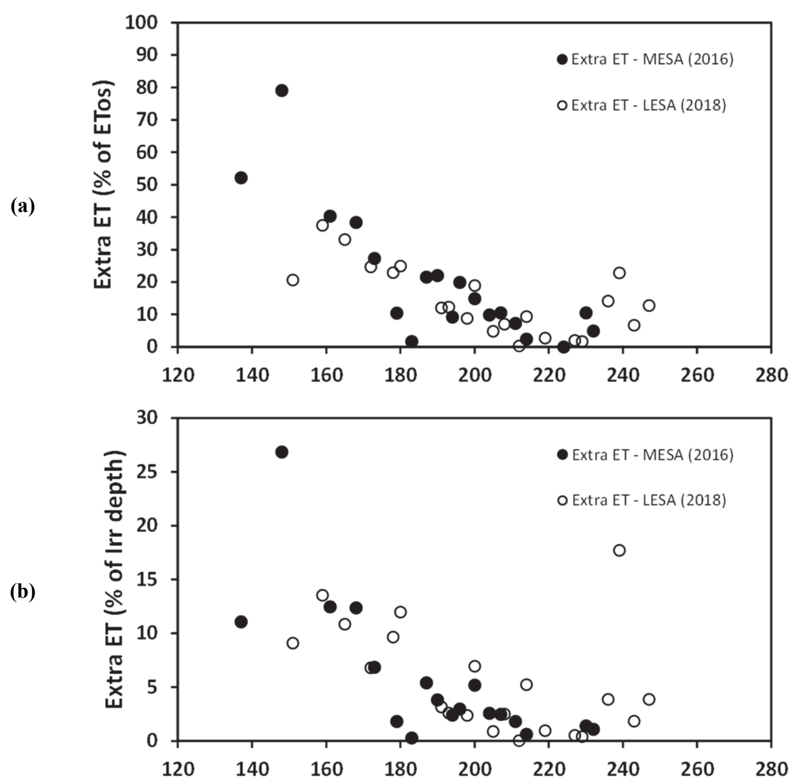

Figure 8. Extra ET expressed as a percentage of (a) ETos and (b) depth of irrigation for MESA in 2016 and LESA in 2018.

incomplete canopy conditions were 7.9% and 7.0% for MESA and LESA, respectively, with corresponding values of 1.9% and 3.5% for full canopy conditions. Notably large values were observed for both MESA and LESA, with a value of 26.8% on DOY 148 in 2016 and 17.7% on DOY 239 in 2018 (fig. 8b). DOY 148 in 2016 was characterized by moderate daily ETos of 6.3 mm but also near bare soil conditions as plants had only recently emerged. Conversely, DOY 239 in 2018 was characterized by full canopy conditions but also relatively high daily ETos at 9.2 mm. These findings demonstrate how AE may be affected by various conditions of canopy density and height, vegetative growth stage, atmospheric demand for water, and sprinkler height.

MESA vs. LESA – Day Following Irrigation

In nearly all cases, the lysimeter storage data revealed considerable extra $ET_{(SPRINKLER-SDI)}$ for days following irrigation events, including the examples presented in figures 4 and 7. Although the previous analyses focused on losses restricted only to the day of irrigation, it's important to recognize that losses associated with sprinkler irrigations may not be fully realized until multiple days following the application. However, it's rarely possible to fully quantify such losses in field experiments, as rainfall or subsequent irrigations work to obfuscate lysimeter storage data. Even so, it's worthwhile to characterize losses by quantifying extra ET for subsequent days following irrigation events whenever possible. Extra ET and the percentage of ETos were calculated for thirteen days in 2016 (MESA) and eleven days in 2018 (LESA) (table 2.). Although the available data were limited, the average values for both extra ET and the percentage of ETos for the day after irrigation were greater than those of the previous day. Average daily extra $ET_{(MESA-SDI)}$ was 51.7% greater at 2.2 mm, while $ET_{(LESA-SDI)}$ was 125.0% greater at 2.7 mm. Summing of extra ET values for both days yielded average values more than double those for the day of irrigation only, at 3.9 and 4.3 mm for MESA and LESA, respectively. Not surprisingly, values of extra ET as a percentage of irrigation depth were also more than double those for the day of irrigation only, with the greatest values of 39.5% for MESA and 28.0% for LESA. Average seasonal corn water use for the SDI fields was 15% and 16% less than the sprinkler-irrigated fields in 2016 and 2018, respectively.

Table 2. Extra ET values and percentage of ETos for day following irrigation.

2016 - MESA				2018 – LESA			
DOY	ETos (mm)	Extra ET (mm)	xET % of ETos	DOY	ETos	Extra ET (mm)	xET % of ETos
149	6.0	2.3	38.3	166	11.9	5.4	45.4
162	9.0	3.3	36.7	173	11.8	5.2	44.1
169	8.9	2.8	31.5	179	11.7	2.7	23.1
174	9.3	3.4	36.6	181	10.7	3.7	34.6
180	6.9	2.9	42.0	187	5.4	0.4	7.4
184	7.2	1.4	19.4	192	8.8	3.0	34.1
188	8.8	2.8	31.8	194	7.9	1.5	19.0
191	8.3	1.7	20.5	201	10.1	3.8	37.6
195	9.8	2.2	22.4	206	8.5	1.6	18.8
201	8.9	1.5	16.9	237	7.8	1.6	20.5
205	9.0	1.8	20.0	240	7.4	1.1	14.9
208	6.7	1.4	20.9				
231	6.4	1.2	18.8				
avg. (season)		2.2	27.4	avg. (season)		2.7	27.2
avg. (part canopy)		2.5	31.0	avg. (part canopy)		3.4	31.4
avg. (full canopy)		1.5	19.1	avg. (full canopy)		1.9	22.2

Conclusions

Seasonal extra ET for LESA and MESA irrigation methods were not much different, although LESA losses were slightly smaller overall. Under full canopy conditions, the average extra ET values for MESA and LESA were similar, most likely due to canopy shading and plant height exceeding drop heights in both systems. Results also demonstrated that torrid climatic conditions could result in considerable extra ET for sprinkler (MESA or LESA) irrigation compared with SDI, even under full canopy conditions. Overall, extra ET during incomplete canopy conditions was somewhat mitigated by the relatively short period of vegetative development and decreased temporal density of irrigations under bare soil conditions stemming from relatively low plant water requirements during early development. Even so, evaporative losses during incomplete canopy conditions accounted for most seasonal losses associated with sprinkler irrigation. Findings in this study suggest that although LESA appears to mitigate evaporative losses marginally more in corn than MESA on the day of irrigation, considerably more evaporative losses occurred for both methods during the subsequent day, with slightly increased losses for LESA, resulting in little difference between overall losses over the two days. This may in part be explained by the temporary cooling effect of the irrigation inside the canopy on the day of irrigation, which is diminished by the second day. Greater differences between evaporative losses for MESA and LESA are likely to be observed for crops having shorter stature or lower leaf density such as cotton. Knowledge of these findings provides useful information for both producers and water managers when considering irrigation management and water planning strategies.

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