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Performance of Precision Mobile Drip Irrigation in the Texas High Plains Region

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Abstract: Mobile drip irrigation (MDI) technology adapts driplines to the drop hoses of moving sprinkler systems to apply water as the drip lines are pulled across the field. There is interest in this technology among farmers in the Texas High Plains region to help sustain irrigated agriculture. However, information on the performance of this system and its benefits relative to common sprinkler application technologies in the region are limited. A two-year study was conducted in 2015 and 2016 to compare grain yields, crop water use (ET_c) and water use efficiency (WUE) of corn (*Zea Mays L.*) irrigated with MDI, low elevation spray application (LESA) and low energy precision application (LEPA) methods. Irrigation amounts for each application method were based on weekly neutron probe readings. In both years, grain yield and yield components were similar among application treatment methods. Although WUE was similar for the MDI treatment plots compared with LEPA and LESA during the wet growing season (2015), MDI demonstrated improved WUE during the drier year of 2016. Additional studies using crops with less than full canopy cover at maturity (sorghum and cotton) are needed to document the performance of MDI in the Texas High Plains region.

Keywords: center pivot; corn water productivity; precision irrigation; sprinkler irrigation; surface drip irrigation

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1. Introduction

A mobile drip irrigation (MDI) system adapts drip lines to drop hoses on a moving sprinkler system, applying water directly to the soil surface as the drip lines are pulled across the field. Early forms of traveling trickle irrigation (TTI) technology, now referred to as MDI, were developed in the mid-1970s and mid-1980s [1–3]. The technology was developed with the intent to convert linear move systems to TTI systems and combine the advantages of center pivot sprinklers and subsurface drip irrigation systems. Another TTI technology, LEPA, was developed during the same timeframe [4] to help reduce evaporative losses from moving sprinkler irrigation systems. Double-ended LEPA drag socks are made of canvas, 12 cm wide and 61 cm long, open at both ends, wire-tied to each drop hose and the majority of the canvas drags along the furrow. A more detailed description of the design impetus behind MDI systems is given by Kisekka et al. [5].

Since the inception of MDI, a handful of studies using these systems report yields and WUE relative to conventional moving irrigation systems for grain crops. Olson and Rogers [6] used a dripline system on a center pivot sprinkler in western Kansas and compared yields with LESA, but the dripline emitters clogged and WUE for the two technologies was not explicitly reported. El-Hagarey et al. [7] investigated corn grain yield and WUE between MDI technology and a conventional center pivot using mid-elevation spray application (MESA). They report that yields were similar among technologies, but WUE was significantly greater for MDI, indicating that crop water use was less. Recently, Kisekka et al. [5] compared corn response between MDI and LESA, in western Kansas, and reported no significant differences in yield or WUE, but the study was limited to a wet year and did not compare MDI with LEPA drag socks. In the case of LESA, nozzles are approximately 0.46-m above the ground. Many farmers in the Texas High Plains plant their row crops in circles. Drop hoses designed as LESA or LEPA are located between the crop rows and are referred to as in-canopy drops. Many farmers in the Texas High Plains region use low drift nozzle packages with LESA to limit water loss due to evaporation from high temperatures and wind drift. As the crop matures, the canopy intercepts the spray.

Irrigated agriculture is critical to the economy of the Texas High Plains Region, where the majority of water for cropland production is drawn from the Ogallala Aquifer and exceeds the rate of available recharge [8]. The major crops produced in this area are cotton, corn, sorghum and wheat. Consequently, there is much interest in efficient water application technologies to sustain irrigated agriculture [9]. The inherent design of MDI with its low flow emitters and easy adaptation of driplines onto existing drop hoses of moving irrigation sprinklers may offer farmers the flexibility needed to continue irrigated crop production with very limited water supplies. An important aspect of a MDI system is its ability to operate under low flow conditions. This characteristic is especially important in fields with low well yields. Another attraction is that this region has a large inventory of center pivot sprinklers [10]; and farmers are under continuous pressure to conserve water and increase application efficiencies [11]. However, for farmers who use LESA and LEPA, which already demonstrate high application efficiencies in the Texas High Plains Region [12–14], it is unclear if a MDI system would result in greater benefits. Our objectives in conducting this study were to use a direct method of assessing crop water use (ET_c) to compare yield and grain water use efficiency (WUE) between MDI, LESA and LEPA in the Texas High Plains region and report the potential benefits and disadvantages of the system.

2. Results

2.1. Climate

In 2015, precipitation was above normal for the months of June through October, and totaled 441 mm, which was approximately 60% of ET_c of corn. Average daily ET_o, calculations from ASCE-EWRI [15], was highest in June, and the average maximum and minimum monthly air temperatures were highest in July (Table 1). The majority of precipitation occurred in July, while the corn was in the vegetative stage; however, 25% occurred in October after the crop had reached physiological maturity (Table 2). Harvest was delayed until November when entry into the fields became possible.

In 2016, precipitation from June through October was approximately 50% less than the previous year, with 69% occurring in August when the crop was in the early- to mid-reproductive stages. Seasonal rainfall was only 42% of total ET_c. Atmospheric demand was greatest during June and July, and was markedly reduced in August due to cooler air temperatures and precipitation. No precipitation occurred in October and mean maximum daily air temperatures were unusually high during this month (Table 1).

Table 1. Climatic data for the 2015 and 2016 growing seasons at Bushland, TX, USA.

Month	Rainfall (mm)	Max Air Temperature (°C)	Min Air Temperature (°C)	Max RH (%)	Min RH (%)	Solar Irradiance (MJ m^{-2} d^{-1})	Wind Speed 2-m (m s^{-1})	ET$_o$ (mm d^{-1})
2015 Growing Season								
June	74	30.55	17.01	94.47	37.98	23.79	4.09	6.10
July	227	32.64	24.41	94.81	35.05	23.54	3.29	5.52
August	65	31.66	24.04	90.34	36.53	22.59	2.91	4.91
September	21	30.03	22.43	87.62	32.84	19.35	3.29	5.16
October	128	22.43	15.85	94.95	45.99	12.77	3.03	2.46
2016 Growing Season								
June	35	33.03	17.22	90.22	27.05	26.19	3.86	6.98
July	23	35.96	19.15	82.97	22.68	25.82	3.70	7.54
August	178	31.00	16.99	97.44	36.28	20.67	2.97	4.67
September	21	28.86	14.38	96.37	38.95	19.47	3.30	4.12
October	0	27.15	8.87	81.87	22.86	15.86	4.68	5.57

2.2. Plant Measurements

Maximum plant heights for 2015 were measured at 250 cm and were approximately 50 cm taller as compared with maximum plant heights in 2016. The difference was likely due to the more moderate environmental conditions. However, plant heights among irrigation application treatments were similar within each growing season, and there were no observable differences in crop growth stages among treatment methods during either year. Table 2 summarizes the dates of major growth stages for both years. The rate of the biomass dry-down was distinctly slowed in 2015 due to the late season precipitation.

Table 2. Specific growth stages and dates for corn grown during the 2015 and 2016 growing season in Bushland, TX, USA.

Growth Stage	Dates 2015	Dates 2016
Emergence	29 June (5 DAP)	21 June (5 DAP)
V-4	9 July (15 DAP)	6 July (20 DAP)
V-10	28 July (34 DAP)	22 July (36 DAP)
VT (Tasseling)	11 August (48 DAP)	4 August (39 DAP)
R2 (Blister)	27 August (64 DAP)	24 August (69 DAP)
R4 (Dough)	14 September (82 DAP)	6 September (82 DAP)
R5 (Dent)	27 September (105 DAP)	20 September (96 DAP)
R6 (Physiological Maturity)	17 October (115 DAP)	11 October (117 DAP)

2.3. Soil Water Data and Irrigation

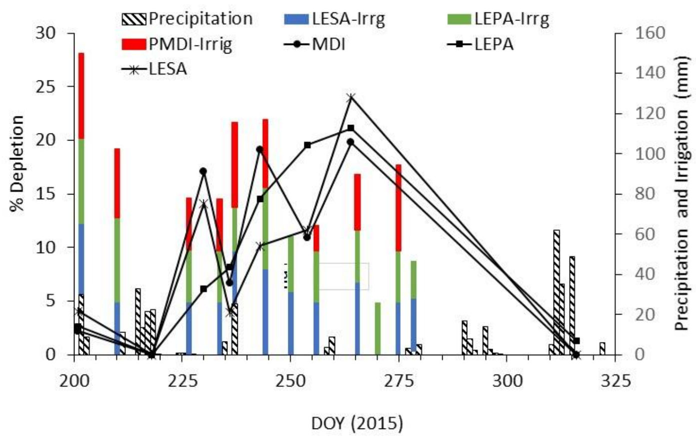
In 2015, no preplant irrigations were applied due to the precipitation received in the spring. Initial soil water content measurements were made on 20 July (26 DAP), after the field was accessible with farm equipment. Mean soil water content levels to the depth of 1.5 m were nearly at field capacity (495 mm), i.e., 488 ± 7 mm (0.3253 ± 0.01 m^3 m^{-3}), 487 ± 6 mm (0.32 ± 0.01 m^3 m^{-3}), and 486 ± 17 mm (0.32 ± 0.03 m^3 m^{-3}) for the MDI, LEPA and LESA irrigation treatment plots, respectively. Cumulative irrigation amounts applied to the MDI treatment plots were similar to the amount applied to the LESA treatment plots and 6% less compared with the amount of water applied to the LEPA treatment plots. Irrigations were terminated on 23 September (91 DAP), after the corn was well into the R5 stage. The total average change in stored soil water (ΔS; initial soil water content level−final soil water content level) to the 2.4 m depth was not significantly different among irrigation application methods, i.e., MDI (−3 mm), LEPA (4 mm) and LESA (−8 mm) (Table 3). Minimal differences were likely the result of the large amount of precipitation received during the growing season. Importantly, NP measurements did not show evidence of deep percolation because θ_v did not increase below 1.5-m depths (data not shown). Each color in the stacked columns in Figure 1 indicates the total irrigation amount (mm) applied onto each type of treatment plot for a given irrigation event. Irrigation amounts for a single event, ranged from 13 mm to 42 mm for each application method depending on weekly neutron probe readings. Throughout the season, the overall soil water depletion was between 0% and 25% among all irrigation treatment methods. The initial soil water depletion levels were low 25 DAP and then again on DOY 215-218. In general, the trend of increasing soil water depletion continued through 100 DAP. Afterwards, the soil profile began to fill again and soil water depletion was reduced to nearly zero on DOY 315.

In 2016, the earliest neutron scatter measurements from all plots (13 DAP) indicated that the average soil water content in the 1.5 m profile were near FC, i.e., 483 ± 17 mm (0.32 ± 0.03 m^3 m^{-3}), 495 ± 5 mm (0.33 ± 0.01 m^3 m^{-3}) and 491 ± 2 mm (0.33 ± 0.004 m^3 m^{-3}) for the MDI, LEPA and LESA irrigation treatment plots, respectively. Total water applied to the MDI treatment plots was approximately 11% and 12% less as compared with LESA and LEPA treatment plots, respectively. It was assumed that the additional water applied by LESA was lost to evaporation or wind drift, while some water applied by LEPA was lost to evaporation and runoff. Irrigations were terminated after 99 DAP; the crop had reached the R5 stage. The average change in soil water content in the soil profile (depth to 2.4 m) during the growing season was significantly less for the MDI treatment plots as compared with the LESA and LEPA treatment plots (Table 3). Irrigation savings with the MDI system in Bushland were on the lower end of water savings reported by Derbala [16] for a center pivot MDI system irrigating potatoes as compared with a conventional center pivot with impact sprinklers. For this study, comparisons were made with MDI and application methods used by farmers in the region (LESA and LEPA); thereby lesser savings in watering amounts were expected than those reported by Derbala.

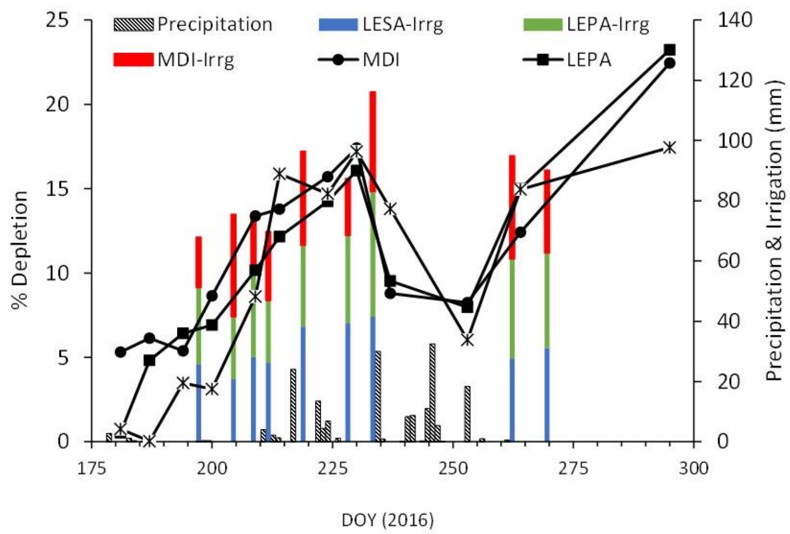
Table 3. Mean cumulative irrigation amounts and change in stored soil water (to the depth of 2.4 m) for each of the irrigation application treatments for 2015 and 2016. Mean values followed by the same letters are not significantly different for $p < 0.05$.

Application Method	Irrigation (mm)		Change in Stored Soil Water (mm)	
	2015	2016	2015	2016
LESA	291	352	−8a	34b
LEPA	312	357	4a	58a
MDI	294	314	−3a	20c

Patterns of mean soil water depletion for the MDI treatment plots were most similar to LESA throughout the 2015 irrigation season (Figure 1a). Despite similar irrigation timing and amounts, high levels of depletion occurred for LEPA treatment plots from 65 DAP to 90 DAP. This may have been caused by soil evaporative losses or runoff from unmaintained tillage basins, which could have limited ponding and reduced the infiltration of water in the vertical direction. The soil water depletion pattern in 2016 was most similar between MDI and LEPA treatment plots (Figure 1b).



(**a**)



(**b**)

Figure 1. Average percent soil water depletion in the top 1.5 m depth (calculated using Equation 2) of treatment plots for mobile drip irrigation (MDI), low energy precision application (LEPA) and low elevation spray application (LESA) methods during: (**a**) the 2015 and (**b**) 2016 growing seasons.

2.4. Plant Height and Density, Grain Yield, ETc and WUE

In 2015, plant height, dry grain yield, kernel mass, kernels per ear and harvest index (HI, grain yield/above ground biomass) were similar for the three application methods (Table 4). Plant density in all plots was determined to be 8.3 plants m^{-2}. Location significantly affected grain yield, with greater yields harvested in Span 5 as compared with Span 1(data not shown). Seasonal ET_c was significantly greater for LEPA treatment plots as compared with LESA, yet, ET_c in MDI was not significantly different compared with LEPA or LESA. Span, application method and their interaction had a significant effect on ET_c.

Water use efficiencies were similar for MDI compared with LESA treatment plots and MDI compared with LEPA treatment plots. However, WUE for LEPA was significantly less compared with LESA treatment plots. The significantly smaller value for LEPA may have been caused by soil evaporative losses or runoff. In slowly permeable soils, runoff is common for LEPA even with basin tillage and relatively flat slopes in the direction of the basins [17]. The interaction of Span X Application method did not have a significant effect on WUE. Crop response to corn in Bushland was similar for corn grown near Garden City, KS, by Kisekka et al. [5] under MDI. In the one-year study (2015), they also reported no significant difference in grain yields (1.56 kg $m^{-2}$and 1.60 kg m^{-2}) and WUE (2.06 kg m^{-3} and 2.17 kg m^{-3}) compared with LESA. Planting rates were similar in both locations, and precipitation amounts received during the growing season in Garden City were also greater than average for this location. Yield and WUE values were higher in Garden City compared with Bushland, most likely due to the mid-season hybrid used in Garden City, DKC 61–89 GENVT2P, Monsanto Company, with a comparative relative maturity (CRM) of 111 days.

In 2016, plant density was 8.1 plants m^{-2}, similar to the previous year. Plant height, grain yield, kernel mass, kernels per ear and HI were again similar among application methods. However, ET_c was significantly different among all application methods, and was significantly greater for LEPA treatment plots and significantly smaller for MDI treatment plots. The interaction of Span and Application method in the LEPA and MDI treatment plots had a significant effect on ET_c. Compared with LESA and LEPA treatment plots, WUE was significantly greater for the MDI treatment plots. The interaction of Span by Application method was significant for ET_c and WUE in the LEPA and MDI treatment plots.

Table 4. Mean measurements (n = 6) of soil water content and crop response for the 2015 and 2016 growing season for corn hybrid, P9697AM, in Bushland, TX, USA. Grain yield is presented on a dry basis. In each category, mean values followed by the same letters are not significantly different for $p < 0.05$.

Application Method	Plant Height (cm)	Grain Yield (kg m^{-2})	ET_c (mm)	WUE (kg m^{-3})	Kernel Weight (mg)	Kernels ear^{-1}	HI
2015 Growing Season							
LESA	261a	0.989a	675b	1.47a	265a	451a	0.54a
LEPA	256a	0.926a	710a	1.30b	258a	448a	0.55a
MDI	258a	0.962a	685b	1.40ab	263a	451a	0.56a
Span	NS †	*	*	NS	NS	NS	NS
Application method	NS	NS	*	*	NS	NS	NS
Span × Application method	NS	NS	*	NS	NS	NS	NS
2016 Growing Season							
LESA	195a	1.05a	622b	1.69b	276a	545a	0.55a
LEPA	203a	1.08a	651a	1.67b	276a	541a	0.57a
MDI	204a	1.04a	552c	1.90a	277a	535a	0.56a
Span		NS	NS	NS	NS	NS	NS
Application method	NS	NS	**	*	NS	NS	NS
Span × Application method	NS	NS	**	*	NS	NS	NS

† NS = not significant; * significant at the $p < 0.05$; ** significant at the $p < 0.01$.

3. Discussion

Application methods for moving sprinkler irrigation systems play an important role in improving crop water productivity, which is especially important in areas where water is limited. Although seasonal ET_c was significantly greater for LEPA, yields were similar among treatments. An increase in ET_c in LEPA plots was due in part to larger amounts of irrigation (Table 3). However, there was not a corresponding increase in grain yield for these treatment plots. This could be due to soil evaporative losses for LEPA, similar to those reported by Bordovsky and Lyle [18] while using LEPA drag socks. It was also assumed that some water was lost to runoff. Runoff using LEPA was also reported by Schneider and Howell [17], where treatment plots under full irrigation, i.e., meeting 100% ET_c, demonstrated measured amounts of runoff, approximately 22% of water applied. Figure 1 indicates that soil water depletion levels in the top 1.5-m for LEPA plots in 2015 were greatest compared with LESA and MDI after DOY 240 (65 DAP) through DOY 260 (95 DAP). The higher level of depletion occurred despite irrigations applied on the same days and in similar amounts to LESA and MDI.

The small change in soil water content in MDI plots could be attributed to uniform redistribution of water in the soil profile. Kisekka et al. [5] reported that water redistribution in the soil profile under MDI occurred in both the horizontal and vertical directions. In both years, near DOY 265 (approximately 100 DAP) soil water depletion was lowest for MDI treatment plots, indicating that more water was present in the soil profile when the crop reached maturity.

In 2016, WUE was significantly greater for MDI plots due to the average smaller ET_c values for MDI plots. In fact, grain yields were not significantly different. The average ET_c values were smaller due in part to a lesser amount of cumulative applied irrigations for MDI plots (Table 3), suggesting that more water was partitioned to transpiration than evaporation using the MDI application method for this season. The amount of soil surface wetted by the MDI method was less than LEPA and LESA. This is observable in images in Figures 3 and 4. Similar observations concerning the wetting pattern of the soil surface was reported by Kisekka et al. [5].

Area productivity in the Texas High Plains region is due mainly to irrigated agriculture, which contributes approximately $6.6 billion (US dollars) in industry output and $2.1 billion in value added to the region's economy [19]. Sustaining irrigated agriculture in this area is critical to sustaining the surrounding economy. This study indicates that crop WUE for MDI systems is similar compared with LESA and LEPA for corn production. However, there are benefits and disadvantages to using a MDI system in this region.

Benefits of the MDI system that were observed relative to the LESA and LEPA application methods are that deep ruts within the wheel tracks were avoided where driplines were adjacent to drive trains. This observation was also reported by Swanson et al. [20] and Kisekka et al. [5]. During the 2016 growing season, the dripline remained in the furrows between the crop rows. Since LEPA drag socks also applied water only in the furrows, LESA (with nozzles approximately 0.46-m above the ground) was the only application method where irrigation water was intercepted by the canopy because of its radial spray patterns (see the Materials and Methods section). The instantaneous application rate of LEPA could result in runoff, while the use of MDI driplines in these same locations is less likely to result in runoff.

In the case of low capacity wells for center pivot fields (those that pump less than 28.1 l per min per ha or 3 gpm/acre), farmers may be able to continue with irrigated crop production if the sprinkler is outfitted with a MDI system. The cost to convert a center pivot equipped with LESA to a MDI system is approximately $600 to $700 ha^{-1} USD, or one quarter of the cost to install a subsurface drip irrigation system, which can easily cost upward of $2,500 ha^{-1} [21,22].

The disadvantages that were observed in the field included the dripline "riding" onto the crop in the 2015 season, which damaged leaves, but did not affect corn ears. Olson and Rogers [6] and Kisekka et al. [5] also reported this problem. To prevent tangling the MDI driplines with the crop when changing the direction of pivot travel, the pivot was moved into fallow ground for a distance that was at least the length of the inner driplines. In 2016, clogging (from algae in the reservoir) occurred at the filters in the MDI drops early in the irrigation season. No clogging was observed at the emitters. The filters were removed and irrigation continued throughout the season through the driplines. The lines were flushed after each irrigation event, with no clogging observed at the emitters throughout the season.

During both irrigation seasons, the dripline was damaged by wildlife and required repair. The dripline assembly was removed for the winter and stored indoors to prevent further damage from wildlife. The upfront cost to convert a typical center pivot sprinkler from LESA to MDI in the Texas High Plains is approximately 2.5 times the amount to convert the system from LESA to LEPA.

4. Materials and Methods

4.1. Field and Crop Characteristics

The study area was composed of 18 plots at the Conservation and Production Research Laboratory (CPRL) in Bushland, TX, USA (35°11′ N, 102°6′ W, 1170 m above mean sea level). The field soil was a Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (USDA-NRCS, 2011). Water content for field capacity (0.33 m^3 m^{-3}) and wilting point (0.19 m^3 m^{-3}) [23] were assumed uniform across the center-pivot field. The field sloped from the northwest to the southeast corner; the slope was <0.25% in 460 m. The climate is semi-arid with an average annual precipitation of 470 mm [24]. Plots were arranged in a randomized block design, with blocks being Span 1 and Span 5.

Corn (*Zea Mays* L.) hybrid, P9697AM, drought tolerant hybrid, (96 days to maturity as reported by Pioneer® Optimum® AQUAmax™) was planted on 23 June 2015, under a six-span variable rate irrigation (VRI) center pivot system [25] after a previous corn crop was lost to a hail event on 14 June. This portion of the field was fallowed the previous year. A second hailstorm occurred 15 DAP when the crop was around V4 stage. The crop sustained moderate damage to the outer leaves, but was able to recover in a few weeks. The same hybrid was planted on 16 June 2016 on the southeast half of the field, previously fallowed in 2015. For both seasons, the planting rate was 79,000 seeds ha^{-1} and nitrogen and phosphorous were applied uniformly to all treatment plots based on soil samples tested by a commercial laboratory to achieve a yield goal of 1.6 kg m^{-2}.

4.2. Agronomic and Farm Practices

Agronomic practices were similar to commercial farm practices in the region (Table 5). Corn was planted in a circular pattern in rows spaced 0.76 m apart and furrows were basin tilled following V4 stage to control run on and runoff of irrigation water and precipitation, as described in Schneider and Howell [17]. Plant height and width measurements were taken periodically from three plants in each plot. On 12 November 2012, 143 DAP, and on 24 October 2016, 130 DAP, grain and biomass yields were hand-harvested from four adjacent rows in each plot in close proximity to the neutron access tube (Table 5). The areas harvested were 10 m^2 (3-m × 3.35-m) and 1 m^2 (0.76-m × 1.32-m) to assess grain yields and aboveground biomass, respectively. Plot sizes varied from 652 m^2 to 1139 m^2 in Span 1 and from 1550 m^2 to 1664 m^2 in Span 5.Ears and biomass were dried in an oven at 60 °C and grain yield was presented as a dry basis. The ears were weighed and shelled by a small belt thresher and kernel mass and kernels per ear were determined from three 500-kernel subsamples. Crop water use efficiency (WUE) was determined as the ratio of economic yield (grain) to total seasonal crop water use (Yield/ET_c). Harvest index (HI) was calculated as the ratio of grain yield to aboveground biomass as assessed from the biomass samples.

Table 5. Agronomic practices for the 2015 and 2016 growing seasons.

Agronomic Practices	2015	2016
Bed Preparation	20 April (DOY 110)	28 April (DOY 119)
Planting	23 June (DOY 175)	16 June (DOY 168)
Harvest	12 November (DOY 317)	24 October (DOY 298)
Fertilizer		
Application Rate (preplant)	224.5 kg N ha^{-1}; 56.1 kg P ha^{-1}	224.5 kg N ha^{-1}; 56.1 kg P ha^{-1}
Date	10 April (DOY 100)	8 April (DOY 99)
Herbicides		
Application Rate (preplant)	3.51 l ha^{-1} of Bicep Lite II Magnum- pre-emergent	1.61 l ha^{-1} of Glyphosate and 5.61 l ha^{-1} of Atrazine w/s-metolachlor
Date	18 May (DOY 138)	7 June (DOY 159)
Pesticides		

Application Rate (preplant)	0.44 l ha^{-1} of Tundra EC	None applied
Date	7 August (44 DAP)	

4.3. Experimental Design and Application Methods

Application method treatments (MDI, LEPA and LESA) were arranged in a randomized block design [26] with Spans 1 and 5 serving as blocks (Figures 2a,b). The white circles represent neutron access tubes that were located in the center of each plot. Because farmers who are interested in this MDI technology are choosing to outfit their entire sprinkler system with dripline, it was decided that dripline would be placed in Spans 1 and 5 to provide a comparison of crop response per location, and to provide an assessment of the manageability of dripline for a range of lengths between 7-m and 24-m. Fixed plate spray sprinklers with low drift nozzles (Senninger Irrigation Inc., Clermont, Fla.) were used for LESA (Figure 3a), with nozzle height approximately 0.46 m above the ground. The LEPA drag socks were adapted to drops in Spans 1 and 5 and dragged in the furrows (Quest & Sons, Lubbock, TX, USA) (Figure 3b). Drop hoses for both types of application methods were spaced 1.52 m apart (i.e., in alternate furrows).

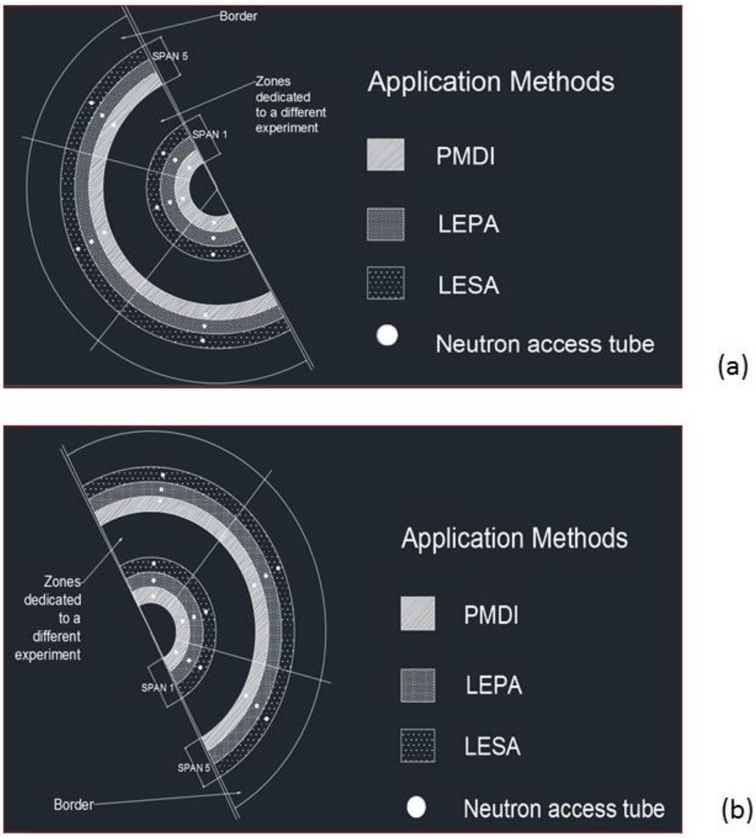


Figure 2. Plot plan showing randomized block design layout to compare MDI with LEPA and LESA in spans 1 and 5: (**a**) 2015 growing season; and (**b**) 2016 growing season in Bushland, TX, USA.

Design details of the MDI system must ensure that movement of driplines towards the crop rows is limited as the pivot pipeline moves across the field to prevent the driplines from climbing onto the crop. The MDI driplines were a trademarked product, Dragonline™ (Ulysses, KS, USA) (Disclaimer: Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.), with integrated pressure-compensated emitters spaced 15.24 cm apart and installed on the VRI center pivot system. The driplines provided a flow capacity of 0.41 L min^{-1} per m^{-1}. The first strip of MDI plots was located 38 m from the pivot point (Span 1); and the second strip of plots was located 180 m from the pivot point in Span 5 (Figure 4). To reduce the length of driplines in Span 5, additional drops were plumbed in-between the existing drops for the MDI treatment, locating a dripline in each furrow between crop rows. The additional drops allowed the length of the driplines to be reduced by 50% (from a maximum length of 23.6-m to 11.8-m). Plots for each application method were replicated three times in each span.

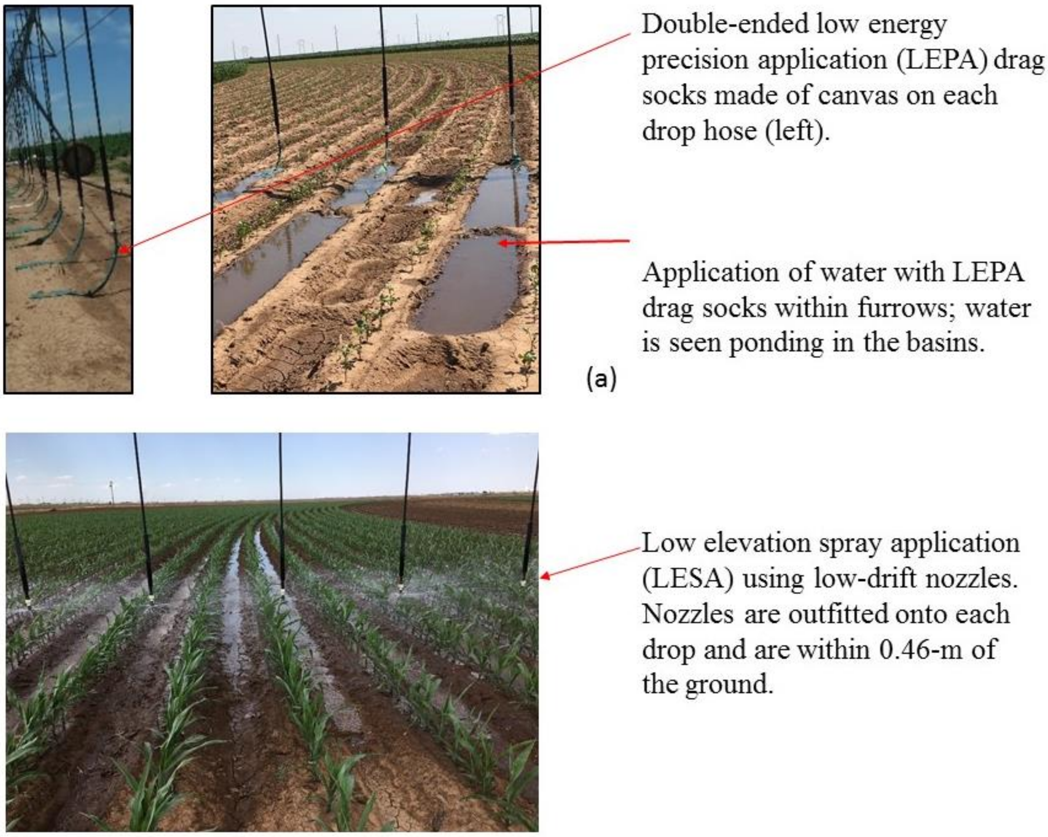


Figure 3. Application methods commonly used on center pivot systems in the Texas High Plains region (**a**) low energy precision application (LEPA); and (**b**) low elevation spray application (LESA).

The MDI system was configured for a high stature crop (corn), but could also be used to irrigate a low-stature crop such as cotton. System design can vary among distributors of the product and from field to field. An 80-mesh filter was incorporated into each MDI drop and checked periodically for debris. Individual filters were used on each drop hose dedicated to MDI, but in the case of a total conversion to MDI, a single inline filtration system would be installed at the inlet pipe of the sprinkler system. Inline flow meters (Model 36M201T, Netafim, Fresno, CA, USA) were installed in one drop in each of the MDI sprinkler banks. The experiment was repeated in the 2016 growing season after several measures were made to stabilize the dripline system and curtail its ability to "climb" onto the crop. Finally, the existing dripline in Span 5 was replaced with dripline that delivered double the capacity, 830 mL min^{-1} m^{-1}, which reduced the length of each dripline by half (Figure 4a,b). Flows were measured at each MDI sprinkler bank prior to the start of the irrigation season using inline flow meter measurements and timed catchments.

Figure 4. Precision mobile drip irrigation (MDI) system: (**a**) shown on span 1 to the left; and (**b**) zoomed-in view of one MDI drop showing sprinkler hardware, filter and dripline dragging between.

4.4. Irrigation Method

A neutron access tube was located in the center of each plot and soil water was measured weekly from 0.1 m to 2.3 m in 0.2-m increments using a field-calibrated neutron probe (NP) (model 503DR1.5, Instrotek, Campbell Pacific Nuclear, Concord, CA, USA). The calibration included three distinct soil layers (Ap, Bt, and BTca) using methods described by Evett et al. [27]. Briefly, calibrations were obtained at wet (field capacity) and dry (near wilting point) locations, and included four independent gravimetric soil water measurements for each NP measurement depth. The calibration resulted in root mean square error <0.01 $m^3\ m^{-3}$. A depth control stand [28] was used during the calibrations, field measurements, and standard counts to ensure reproducibility of depth measurements relative to the soil surface. The irrigation amount applied to each treatment was based on the average replenishment of soil water depletion to field capacity for the three plots of each application method in each block.

Soil water measurements were also used in a soil water balance equation to calculate seasonal water use, ET_c:

$$ET_c = P + I - R + F - \Delta S \quad (1)$$

where P is precipitation, I is irrigation, R is the sum of run-on and run-off (which was assumed to be zero in these fields due to minimal slope and basin tillage practices), F is flux across the lower boundary of the control volume (includes deep percolation and capillary flux, assumed zero due to irrigation scheduling based on soil water profile measurements and a groundwater table >100 m below the surface), and ΔS is the change in soil water stored in the 1.5-m profile (i.e., measured by NP). The first NP reading was DOY 201 (20 July) in 2015, when the crop was in the V7 stage; severe weather hampered earlier entrance into the fields. While in 2016, the first NP reading was on DOY 181 (29 June) when the crop was in V2 stage. The final NP readings were on DOY 317 (13 November) in 2015 and DOY 299 (25 October). For both years, seasonal ET_c was calculated using the product of crop coefficient [29] and reference ET_o ($ET_c = ET_o \times K_c$) from the day after planting (DAP) through the day before the first NP reading, and then summed with ET_c calculated from Equation (1) from the first NP readings until the last NP reading at harvest.

Percent soil water depletion was calculated as:

$$\%Depletion = \frac{\theta_{fc} - \theta_v}{\theta_{fc} - \theta_{pwp}} x100 \quad (2)$$

where θ_{fc}, θ_v, and θ_{pwp} are volumetric soil water contents at field capacity, measured by NP, and permanent wilting point, respectively (m^3 m^{-3}).

4.5. Statistical Procedures

Treatment values of grain yield, ET_c, WUE, kernel mass, kernels per ear, and HI were the mean of six samples. Irrigation application method was treated as a fixed effect and location (Span1 vs. Span 5) was treated as a random effect. These effects and their interaction were analyzed using SAS Proc Mixed Models (SAS Institute, Inc., Cary, NC, USA) and the least significant difference test. Differences were considered to be significant at the $p < 0.05$ level. Grain yields and ET_c were significantly affected by year, therefore statistical comparisons of responses were made for individual seasons.

5. Conclusions

The results of this study suggest that in a wet year (2015), the MDI application method performs in a manner similar to LESA and LEPA with no significant differences in grain yield, grain yield components or WUE. However, in a drier year (2016), it was demonstrated that the MDI application method can result in higher WUE by applying less water while producing similar grain yields. The conversion of a MDI system from LESA or LEPA can alleviate some farm management issues, however, the upfront costs of such a system must be taken into consideration, as well as the increase in system maintenance throughout the irrigation season. It is possible that MDI systems will become the appropriate niche technology for farms with low well capacities. However, more research is needed during seasons with less than average rainfall and for other crops grown in the Texas High Plains region, particularly those having partial canopy cover at maturity (sorghum and cotton), to investigate improvements in crop water productivity and to establish long-term cost benefits of a MDI system.

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