Opportunities for Improving Water Productivity using Mobile Drip Irrigation

by

Tobias Ebong Oker

B.S., Makerere University, 2005
M.S., IHE Delft, Institute of Water Education, 2010

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Biological and Agricultural Engineering
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Abstract

The Ogallala aquifer has been important to agriculture in the U.S. High Plains for the past six decades. Groundwater from the aquifer helped turn the fertile soils of the region, large parts of which are semi-arid, into some of the most productive agricultural lands in the U.S. and the world. However, this agricultural success has come at a great cost to the aquifer. Today, as a result of drastic aquifer drawdown, well capacities in some regions of the High Plains are no longer sufficient to sustainably irrigate crops. In response to this growing problem, wide ranging efforts towards conservation of the Ogallala aquifer were formulated and implemented. One of these efforts is to further improve irrigation efficiency. Adaptation of microirrigation, an efficient method of irrigation, to center pivots is regarded by some as the next major step towards expanding the usage of microirrigation technology, and along with-it improving the efficiency in center pivot systems. Four studies were conducted as parts of this dissertation with the application of a four-span center pivot, installed at the Kansas State University's Southwest Research and Extension Centre (SWREC) in Garden City, Kansas. The studies assessed the technical performance of Mobile Drip Irrigation (MDI) compared to Low Elevation Spray Application (LESA) and Low Energy Precision Application (LEPA). In the first study, the irrigation uniformity, application efficiency and seasonal irrigation uniformity of MDI were evaluated against those of LEPA and LESA. Two sets of MDIs, one with a dripper flow rate of 3.8 L/h, and another of 7.6 L/h, a LESA spray and LEPA bubbler were utilized. Potential differences in season-long irrigation uniformity between the devices were evaluated by analyzing a periodically acquired vegetative index data from aerial imaging. The results showed that MDI and LEPA were more efficient than LESA as indicated by their significantly higher coefficients of uniformity and higher application efficiencies. The second study evaluated soil water redistribution under MDI against those of LEPA and LESA. The effect of irrigation was found to be mostly limited to the top 60 cm of the soil profile for all the evaluated irrigation application technologies. MDI and LEPA showed the highest horizontal variation in water content, and water redistribution pattern of MDI was similar to LEPA. In the third study, the performance of MDI for corn production, in comparison to LESA and LEPA was conducted by comparing grain yield, water productivity, above ground biomass, leaf area index (LAI), and soil water content. In general, crop biophysical measurements under MDI were not significantly different from those under LEPA and LESA, and any marginal benefits of MDI were likely masked by rainfall. Hence, further evaluation of MDI is recommended under stringent water application conditions. The fourth study assessed MDI dripline spacing and length for different soil types.

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Table of Contents

List of Figures

List of Tables

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Dedication

Dedicated to my wife, Natalie Mukoda Oker, and my daughters, Aliyn and Arielle Oker

Chapter 1 - Introduction

1.1 Background

Water is essential for crop growth. In agriculture, the water that crops need is provided directly as rainfall, and/or indirectly as irrigation water that is harvested from a source and applied to the fields. According to Haddad et al., (2011), as much as 80% of globally cultivated area is rainfed. Most of these areas are in developing countries, where different grains, which are important to their food security, are grown under rainfed conditions (Wani et al. 2009). On the other hand, irrigation, which is the other means by which water can be applied to crops, accounts for 17-20% of cultivated land area, and 40% of global food production (Chartzoulakis & Bertaki, 2015; Elliott et al., 2014; Fereres & Soriano, 2007). Though irrigated agriculture is evidently more productive yield wise, it consumes a lot of water, accounting for 70% of freshwater withdrawals (Chartzoulakis & Bertaki, 2015; Siebert et al., 2010). There is therefore widespread interest exploring ways of making irrigation more water efficient. This is particularly of significant importance presently because of the stress many of the world's water resources are under due to: unsustainable exploitation for economic growth; population pressure; climate change etc. (Elliott et al., 2014; Wada et al., 2011). In the U.S. Midwest, the Ogallala aquifer (a part of the High Plains Aquifer) is one such highly stressed groundwater resource due to years of water withdrawal for agricultural production in the Great Plains region (McGuire, 2017; Steward et al., 2013; Terrell et al., 2002). It has been for several decades, a significant part of the economy of the region and the future economy will continue to be tied to the fate of the Ogallala aquifer. Basso et al., (2013) reported that crops worth over $35 billion are produced annually using water from the High Plains Aquifer.

More the 90% of irrigation in the U.S. High Plains region is done using center pivots (Lamm et al., 2006; Rogers et al., 2008; Scanlon et al., 2012). Patented by Zybach (1952), center pivots have grown to become a popular method of sprinkler irrigation worldwide (Waller & Yitayew, 2016a); especially in developed countries. Center pivots can be fitted with various types of irrigation nozzles. Today many existing options including low energy/pressure spray nozzles, center pivots were originally fitted with overhead impact sprinklers designed for operating pressures of more than 354 kPa (Hanson & Orloff, 1996; King & Kincaid, 1997). Today there is an assortment of low-pressure irrigation nozzle packages for center pivots available and sometimes classified based on mounting location described as: Low Elevation Spray Application (LESA); Mid Elevation Spray Application (MESA); and Low Energy Precision Application (LEPA). Although modern low-pressure nozzles have markedly improved irrigation efficiency in center pivots, in properly employed and managed, it is still thought that there are still some preventable water losses incurred in their utilization. Examples of such water losses are canopy interception and evaporation, wind-drift, soil evaporation and runoff.

Microirrigation is the most efficient method of irrigation (Goyal, 2012; Pathak et al., 2009; Waller & Yitayew, 2016b). Despite this, its adoption for large scale production of closely spaced row crops, like corn, is not widespread. Research has been conducted on Sub surface Drip Irrigation (SDI) (Camp, 1998), one method of implementing microirrigation, and indicates it does significantly improve irrigation efficiency. For example, Lamm and Trooien (2003) reported SDI reduced water use in corn production by 35-55% compared to irrigation methods. The major factors limiting the adoption of SDI are the high installation costs and operation and management challenges (Lamm & Trooien, 2003). Another means through which the versatility of microirrigation might be extended, so that it can be used for closely spaced field crops like corn, is Mobile Drip Irrigation (MDI). Under such a configuration, instead of regular nozzles, drip lines are attached to a center pivot or linear-move system. There have been efforts to develop similar technology in the past (Phene et al., 1981; Phene et al., 1985; Rawlins et al., 1974) but they were beset by technological limitations of the time; many of which have since been addressed. The critical need to improve irrigation efficiency as a means of conserving water has recently revived interest in MDI technology. Considering the widespread use of center pivots for irrigation in the High Plains region, MDI could lead to significant water savings by improving irrigation efficiency; thus, contributing to efforts to conserve the Ogallala aquifer.

This research assessed the technical performance of an MDI system using a 170.6 m long center pivot of four spans, with VRI capability, installed at Kansas State University's Southwest Research-Extension Centre (SWREC) in Garden City, Kansas. Four studies compared MDI to LESA spray and LEPA bubblers. Each span of the pivot was divided into four sections to accommodate a LESA spray, LEPA bubbler and two MDIs of dripper flow rates 3.8 and 7.6 L/h respectively. Description of the technical specifications of the of the MDI center pivot system used in this research is presented in Appendix J, Appendix K and Appendix L. The driplines (DRIPNET PC) used in this research for the MDI were manufactured by Netafim-USA (2018). The technical specifications of both the 3.8 and 7.6 L/h dripper driplines were similar and were: emitter/dripper spacing of 152.4 mm; maximum pressure of 400 kPa; inside diameter of 14.5 mm; wall thickness of 1.1 mm; minimum filtration of 80 mesh.

1.2 Research questions

1. How does the application uniformity and efficiency of MDI compare to that of LESA and LEPA?
2. How does soil water redistribution under MDI compare to that under LESA and LEPA?
3. How does corn yield and water productivity under MDI compare with that under LESA and LEPA?

1.3 Research objectives

1. Evaluation of uniformity and application efficiency of MDI, LESA and LEPA

A study to evaluate the uniformity, application efficiency and season-long irrigation uniformity of MDI against that of LESA and LEPA was conducted at Kansas State University's Southwest Irrigation uniformity was conducted in accordance with the American Society of Agricultural Engineers' standard EP458 (ASAE Standards, 1996; Lamm et al., 1997), for MDI and LEPA, and S436.1 (American Society of Agricultural and Biological Engineers, 2003) for LESA. Soil water content before and after an irrigation event were measured in order to compute application efficiency. Season-long uniformity was assessed through the analysis of vegetative index data periodically collected during each of the growing season. This research objective is discussed in detail in Chapter 3.

2. Evaluation of soil water redistribution under MDI, LESA and LEPA

An experiment to measure soil water content before and after an irrigation an event was conducted at the Southwest Research-Extension Center of Kansas State University located near Garden City. Field measurements of the application rates of the MDI_1 and MDI_2 driplines, LEPA bubbler and LESA sprinklers were conducted under normal operating conditions of the center pivot. Soil water distribution within the soil under each application device was then simulated using a numerical model, HYDRUS (2D/3D) (Šimůnek et al., 2016). Field data was used to calibrate the model. The calibrated model was then used to evaluate soil water distribution under MDI, LESA and LEPA. This research objective is discussed in detail in Chapter 4.

3. Evaluation of corn growth under MDI, LESA and LEPA

A corn crop was grown for two seasons at the experiment fields of the Southwest Research and Extension Center of Kansas State University. Irrigation treatments were administered using a center pivot such that the MDI, LESA and LEPA applied water simultaneously for every event.

Biophysical crop properties that were periodically measured during each season were biomass weight, leaf area index and grain yield. Soil water content was frequently measured during the season and used to compute water productivity. This research objective is discussed in detail in Chapter 5. This study was published in the journal of Agricultural Water Management (Oker et al., 2018).

4. **Determining Mobile Drip Irrigation dripline spacing and length for different soil textural classes using numerical modelling**

Numerical modelling of two-dimensional soil water redistribution in soils of different textural classes for an extended period of time was conducted. Analysis of horizontal water movement was done to ascertain suitable dripline spacing and length. This research objective is discussed in detail in Chapter 6.

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Chapter 2 – Literature Review

2.1 Agriculture: Global perspective, U.S. and Kansas

Agriculture is one of the most common denominators of societies, past and present, and it plays a vital role in the economics and livelihoods of many people around the world today. According to the World Bank (2018a), the sector accounts for 3.5% of the global domestic product (GDP). Presently, there is a wide difference in the contribution of agriculture to national GDPs between highly and least developed countries. In the developed countries, it accounts for 1.3% of GDP, and in least developed ones, 26.3% (World Bank, 2018a). Although agriculture is a very small fraction of the GDPs of highly developed economies, it is important to note that, the overall product output of the sector in such countries is significantly higher than those of many developing countries.

The U.S. economy is the largest in the world (International Monetary Fund, 2018; World Bank, 2018b). Although agriculture accounts for just 1% of the U.S. GDP (OECD, 2011), when the contribution of secondary industries based on the sector is considered, together they account for 5.5% of U.S. GDP (Economic Research Service, 2016). Considering that farm land accounts for 40% of U.S. land use (Nickerson et al., 2012), agriculture is important to the socio-economics and livelihoods of large, mostly rural, areas of the country. Annual crop and livestock produced from U.S. farms are valued at $143 and $153 billion respectively (US EPA, 2015). The main crops grown in the U.S. by acreage are: corn (the U.S. is the largest producer in the world (Heinemann et al., 2014)), soybeans, wheat, cotton, sorghum, rice and hays. (US EPA, 2015).

Agricultural activity in territories that form present day Kansas goes back to pre-European settlement times. For centuries, Native American tribes of the Great Plains of North America practiced rudimentary subsistence farming to supplement food they sourced from hunting and gathering (Weigl Publishing Inc, 2008). The arrival of the first European settlers in the 1800s saw the expansion of agricultural activity. Like their Native American neighbors, farming efforts of the early settlers was focused on production for their subsistence. From such humble beginnings developed what is now a modern and highly productive economic sector of the State. In 2015, the Kansas Department of Agriculture (KDA) reported that farming accounted for 43% of the Gross Regional Product (GRP) of the State, and was the single largest economic sector with a valuation of over $62 billion. Kansas has about 18.6 million hectares of land, of which cropland and pasture occupy approximately 8.5 and 6.5 million hectares respectively (Kansas Department of Agriculture, 2015). According to Ball (2016), the average farm has decreased in recent years in comparison to the period from the 1950s to early. The USDA's latest Census of Agriculture (USDA National Agricultural Statistics Service, 2014) put the number of farms in the State at 61,773. The average number of farms for the last four censuses is 64,299 (USDA National Agricultural Statistics Service, 2014). Forty nine percent of the farms enumerated in the last census were between 50 to 499 acres in size (USDA National Agricultural Statistics Service, 2014). Today agriculture in the Kansas is highly mechanized. A recent agriculture survey put estimates of farm equipment market value at $9.7 billion, which is an increase of 104% from the agriculture survey of 1997 (NASS, 1997). Also, investment in equipment for individual farms rose to $156,740 per farm; an increase of 116% from 1997 figures. This is interesting considering that farm sizes have gotten smaller in the same timeframe (USDA National Agricultural Statistics Service, 2014). Agriculture in Kansas in highly modernized, involving the use of mechanization, fertilizer, herbicides and pesticides; factors which contribute to high productivity whilst minimizing impact on the environment.

According to the Kansas Department of Agriculture (2015), the sector provides employment opportunities for 12% of the working population of Kansas. Over three-quarters (86.4%) of agricultural output is from family-owned farms (Kansas Department of Agriculture, 2015). Ball (2014) reported that, from 1997, the number of women farmers in Kansas started to increase remarkably; a fact which underlines its continued importance as a source of livelihood for many people in the State. The main crops grown in Kansas are wheat, corn, soybeans and sorghum (Kansas Department of Agriculture, 2015; USDA National Agricultural Statistics Service, 2014). Kansas produces more than 46% of the grain sorghum grown in the United States and it ranks first for the crop's production in the country (USDA National Agricultural Statistics Service, 2015a). For wheat and corn, the State ranks second and ninth respectively. Wheat is commonly referred to as Kansas's number one crop. It is the largest crop by acreage and the State has a long history growing it as shown by records of harvested acreage dating back to 1866 (USDA National Agricultural Statistics Service, 2015b). From the last four censuses of agriculture, the mean acreage under wheat production in Kansas has been 3,693,018 hectares. Winter wheat is normally planted in early September and harvested in late June, or early July, of the following year (USDA National Agricultural Statistics Service, 1997). Corn for grain and silage is second most widely grown crop by acreage in Kansas. In terms of area, it represents only about 47% of total wheat acreage; a fact which highlights the acreage dominance of wheat in the State.

Beef cattle ranching is the biggest contributor to the State's agricultural output; providing about $7.8 billion. The beef cattle ranching sector is the main driver for the animal slaughter industry which provides about $9.5 billion to the State. Animal slaughter provides about 15,362 jobs, making it the second highest employment provider. Grain farming contributes about $5.2 billion to Kansas's revenue and is virtually tied for second place in job provision. Generally, direct farming activities, earn about $26 billion and create about 77,528 jobs. Secondary industry (manufacturing, supplies, services etc.) which spinoff agriculture accounts for the rest of Kansas revenue. Beef cattle farming (ranching and feedlots), which provides about 25,112 jobs, is the top employer in the agricultural sector in the State.

Corn is the topic of this dissertation and its production with mobile drip irrigation is discussed in Chapter 5.

2.2 The Ogallala aquifer

The Ogallala aquifer is the largest groundwater resource in the U.S. and the world (Hornbeck & Keskin, 2014; Opie, 2000). The area of the aquifer is estimated to be 450,658 km^2 (Johnson et al., 2011; Maupin & Barber, 2005; Mcguire et al., 2003), and it is spread out across the states of states of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, Wyoming (Chaudhuri & Ale, 2014; Maupin & Barber, 2005). As of the year 2000, it was estimated that the aquifer held 3.6 billion cubic meters of extractable water (Bartos et al., 2014; Mcguire et al., 2003). The saturated thickness of the aquifer ranges from 15 to 366 m (McGuire, 2017). The Ogallala mainly comprises geologic units of the late quaternary and tertiary age which dates it formation between 1.8 to 31 million years ago (Dugan, McGrath, & Zelt, 1994). The 1950s is generally regarded as the start of the period marking large-scale extraction of water from the Ogallala aquifer; mainly for irrigation (Bartos et al., 2014; McGuire, 2017; Rajan et al., 2015). With the aid of irrigation, agricultural production in the High Plains region rapidly expanded over the last six decades. Basso et al., (2013) reported that crops worth $35 billion are produced annually using water from the aquifer. The aquifer accounts for 30% of water used for irrigation in the U.S. (Chaudhuri & Ale, 2014; Maupin & Barber, 2005). Following several years of large-scale pumping, water levels in some areas of the aquifer have significantly reduced. Steward et al., (2013) reported that 30% of the Ogallala has already been pumped. As a result of aquifer drawdown, well capacities in some regions of the High Plains are no longer sufficient to sustainably irrigate crops (Basso et al., 2013).

2.3 Irrigation in the U.S.

Forty percent of world's food is produced on just 20% of arable land using irrigation (Sauer et al., 2010). This underscores the importance of irrigation for meeting global food security. Despite its key role in food production, irrigation is a leading cause of unsustainable exploitation of many water resources; as 70% of the world's freshwater resources goes irrigation (Grafton et al., 2018). As an agricultural practice, irrigation dates back to the earliest records of human history. In the territories that make up part of present-day U.S., Native Americans practiced irrigation in pre-European settlement times (Hess, 1912; Sojka et al., 2002; United States Bureau of the Census, 1904). A well-known case is that of the Hohokam culture, who created the earliest known complex irrigation system in the Sonoran Desert of what is now the present-day U.S. state of Arizona (Earle & Doyel, 2008; Fagan, 2011). Later on, in the 19th and 20th century, irrigation was key to the settlement and development of western U.S. (Stubbs, 2016); which is climatically a semi-arid region (Cotton & Pielke, 2007; Green et al., 2012). The Mormons who settled in the dry Great Basin in 1847 were the first European settlers, in the American west, to establish irrigation systems to cultivate crops for their self-sufficiency (United States Bureau of the Census, 1904). The passing of the Reclamation Act of 1902 by the U.S. Congress was a major governmental initiative which facilitated the establishment of over 100 water programs in the western U.S., from which several irrigation projects were developed (Bureau of Reclamation, 2018). The U.S. Department of Commerce reported that there were 7.8 million acres of land under irrigation in western U.S. in 1900, and this had increased to 18 million acres by 1940 (Gardner, 2002). After the 1940s, this acreage significantly increased following the rapid expansion of irrigation in the Great Plains region, which was made possible by harnessing water from the Ogallala aquifer. Currently, about 55.3 million acres, representing 26% of farmland in the U.S. is irrigated (National Agricultural Statistics Service, 2014). The main water resources harnessed for irrigation in the U.S. are groundwater (55%), off-farm surface-water (35%), and on-farm surface-water (10%) (Stubbs, 2016; USDA, 2014a). Although the area under irrigation has more than doubled from the 1950s to present times, water withdrawals from the area have remained relatively constant over the same period (Kenny et al., 2009). This is attributed to improvements in irrigation efficiency, and advances in other disciplines of agronomy, which together have improved farm productivity. Prior to and at the beginning of the 20th century, irrigation in the U.S., like in many parts of the world, employed the simple method of flooding fields. According to Christian-Smith et al., (2012), as of 1998, flood irrigation was still the most widespread method of irrigation in the U.S., but by 2008 it had dropped to 40% as adoption of sprinkler, drip and microirrigation systems increased. A recent report by Dieter et al., (2018) stated that sprinkler and microirrigation methods accounted for 63% of irrigation in the U.S. The invention of center pivot technology, by Frank Zybach (1952), led to the increased use of sprinkler irrigation. This is because center pivots reduced the labour requirements previously associated with sprinkler irrigation systems (Sherow, 2007); which involved the tedious and strenuous work of moving pipes from one within a field.

Currently 13 states, including Kansas, account for 78.8% of acreage of all irrigated land in the U.S. (Schaible & Aillery, 2017). Of these, the top five leading states are Nebraska, California, Texas, Arkansas, Idaho. Kansas is ranked sixth (Sadler et al., 2003). Cropland and pastures respectively account for 95 and 5% of all irrigated land in the U.S. (USDA, 2014a). The USDA's Economic Research Service reported that in 2012, the main irrigated crops by acreage in the U.S. were: corn (25%), forages (18%), soybean (14%), horticultural produces (8%), cotton (7%), wheat (7%) and rice (5%) (USDA ERS, 2018). With the exception of corn, the fraction of irrigated acreage for each crop varies between the western and eastern states. For example, in 2012 forage accounted for 24.5% of irrigated crop area in 17 western states but only 1.6% in 31 eastern states, and for soybean 7.1 and 29.6% for respectively (USDA ERS, 2018).

2.3.1 Center pivot irrigation

Center pivot have grown over the last seven decades to become a popular and widely preferred method of pressurized irrigation in the U.S. and around the world (Kenny & Juracek, 2013; Lamm & Rogers, 2017; Rogers et al., 2008; Waller & Yitayew, 2016a). Their popularity in the U.S. Midwest has stamped the region's landscape with a unique aerial image of closely stacked green circles. Typically, a center pivot is sized to irrigate a quarter-section sized area (160 acres) (Waller & Yitayew, 2016a). However, often farmers customize center pivots to cover larger or smaller areas. For example, the half-mile center pivot is common (Johnsgard, 1995; Rosenberg, 2007). Unless fitted with an end-gun sprinkler or corner arm extension, a center pivot cannot irrigate areas on the four furthest corners of a field, thus leaving about 21% of a square area unirrigated. The first center pivots were costly to operate due to their high energy consumption because high pressure (380-450 kPa) was required for their drive systems and impact overhead sprinklers (Keller & Bliesner, 1990). Many modern center pivots are fitted with low pressure (40-140 kPa) nozzles (Waller & Yitayew, 2016a) which consume less energy to operate. Generally center pivot nozzles are categorized as either: (1) Low Elevation Spray Application (LESA) or; (2) Low Energy Precision Application (LEPA) (Lyle & Bordovsky, 1981) or; (3) Mid-Elevation Spray Application (MESA). LESA and MESA are unique among low energy irrigation nozzles because they use spray technology. In center pivot systems, LESA nozzles are installed very close to the ground at heights between 0.3-0.6 m, whereas MESA nozzles at 1.5-3 m off the ground (Hanson et al., 2011). Tall crops, such as corn, engulf the LESA nozzles as the crop grows but MESA nozzles are always maintained above the crop canopy (Waller & Yitayew, 2016a). According to Balafoutis et al., (2017), as of 2009, most self-propelled irrigation systems, of which center pivots are, used MESA nozzles. By design, LEPA devices usually installed near to the ground so water is delivered directly the soil surface (Hanson et al., 2011). As such, LEPA avoid the sort of canopy interception and evaporation of LESA and MESA systems. Common LEPA configurations comprise bubblers (Waller & Yitayew, 2016a), socks (Phocaides, 2000) and drop-tubes. With application efficiencies of 95-98% (Lyle & Bordovsky, 1983; Schneider, 2000), LEPA perform better than LESA and MESA which typically have efficiencies of 80-90% (Ondrasek, 2013; Schneider, 2000) and 70-85% respectively (Amosson et al., n.d.; Balafoutis et al., 2017; Rajan et al., 2015).

2.3.2 Drip irrigation

Drip irrigation is the most efficient method of irrigation (Goyal, 2012; Waller & Yitayew, 2016b). This is because it eliminates the common water loss pathways of other irrigation technologies, such as canopy interception and evaporation, wind drift, droplet evaporation and runoff. The transition of drip irrigation from a novelty and economically unfeasible technology in the early 20th century to a technically and commercially viable and successful option, was aided by the increased availability of plastics in the post second world war period. This led to its development in many countries including the U.S. (Ayars et al., 2007; Camp, 1998). Presently, drip irrigation technology is mainly implemented as surface, or subsurface systems. The USDA's (2014b) 2012 Census of Agriculture found that as of the year 2013, 2,583,201 and 766,901 acres were irrigated by surface and subsurface drip, which respectively accounted for 5 and 1% of all irrigated land in the U.S. Between 2008 and 2013, acreage under surface drip grew by 2%, but subsurface irrigation remained at 1%; despite that total irrigated area in the country marginally decreased over the same period. Overall, the indications are that subsurface drip irrigation is growing, albeit slowly. The 1997 Census of Agriculture reported that 385,657 acres were under subsurface drip irrigation, representing 0.6% of irrigated land in the U.S. (Camp et al., 2000). The slow growth of subsurface drip irrigation is because it is an expensive system (Lamm & Rogers, 2017; Lamm & Trooien, 2003). For the most part, drip irrigation is mainly used to grow high value crops such as vegetables and fruits (Lazarova & Bahri, 2004; Waller & Yitayew, 2016b), the rationale being that this agro-economic arrangement yields a faster return on the high investments associated with the technology. However, for decades, there have been concerted efforts to find ways of expanding the use of drip irrigation to grow field crops such as corn and alfalfa (Alam et al., 2007); J.E. Ayars et al., 1999; Lamm & Trooien, 2003); which by comparison to fruit and vegetables production have lower value. The drive to adapt drip irrigation to the production of field crops arises from the need to adapt to water scarcity and conserve water resources through improved irrigation efficiency.

Adapting drip irrigation technology to center pivots is regarded as the next major step towards expanding the usage of the technology and improving efficiency in center pivot systems. Recent research towards this regard, highlighted in studies such as O'Shaughnessy and Colaizzi (2017), Kisekka et al. (2017), Oker et al. (2018), and Olson and Rogers (2008), follows up on earlier works on related technologies for lateral-move irrigation systems such as, Chu (1984), Phene et al. (1981; 1985) and Rawlins et al. (1974). According to Kisekka et al. (2017), improvements in both center pivot and drip irrigation, such as pressure compensated driplines, GPS guided center pivots, circular row planting have renewed interest in the development and promotion of center pivot drip irrigation (or mobile drip irrigation). Unlike in the past, where interest in mobile drip irrigation technologies was mainly confined to researchers, recently there have been private businesses, like Netafim USA (2018), Teeter Irrigation Inc. (2018), T-L Irrigation (2017) that have branded and are marketing mobile drip irrigation technologies. This proactive involvement by the private sector is a major milestone in the decades long quest to combine center pivot and drip irrigation technologies. To producers, mobile drip irrigation is viewed as largely an untested technology. Therefore, there is a need to standardize and thoroughly evaluate modern configurations of the technology in preparation for its promotion. The research presented in this dissertation highlight four of studies which examine some, out of potentially many, questions about mobile drip irrigation.

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Chapter 3 - Evaluation of Dynamic Uniformity and Application Efficiency of Mobile Drip Irrigation

This chapter was submitted to Irrigation Science journal

Abstract

The irrigation uniformity, application efficiency and seasonal irrigation uniformity of Mobile Drip Irrigation (MDI) was compared to Low Elevation Spray Application (LESA) and Low Energy Precision Application (LEPA). A four span center pivot, in which each span was divided into four equal parts to accommodate two sets of MDIs (emitter flow rates 3.8 L/h and 7.6 L/h), LESA and LEPA was utilized. Irrigation uniformity was conducted in accordance with the American Society of Biological & Agricultural Engineers' standard ASAE (1996) EP458, for MDI and LEPA, and ASAE (2003) S436.1 for LESA. Application efficiency of each device was computed as the ratio of depth of water retained in the root zone to that applied. Potential differences in season-long irrigation uniformity between the devices was evaluated by analysis of periodically acquired vegetative index data from aerial imaging from airplane. The coefficient of uniformity (CU), of the 3.8 L/h and 7.6 L/h MDI were 93.8% and 93.7% respectively, 95.1% for LEPA, and 83.8% for LESA. The application efficiencies for the 3.8 L/h and 7.6 L/h MDI, LEPA and LESA were 76.1, 96.8, 98.4 and 51.2% respectively. There were significant differences (p-value = 0.5749) in the amount of water stored in the soil profile between MDI, LESA and LEPA, 72 hours after the irrigation event. For the three irrigation capacities of 6.2, 3.1 and 1.6 mm/d, there were no significant differences in mean seasonal Advanced Difference Vegetative Index (ADVI) between MDI, LESA and LEPA; with p-value = 0.987, 0.999 and 0.999 respectively. A similar observation was made for Normalized Difference Vegetative Index (NDVI), with p-value = 0.998, 0.999 and 0.999, for MDI, LESA and LEPA respectively. Lack of differences in ADVI and NDVI indicates soil water under MDI was comparable to that of LESA and LEPA, which inferentially points to comparable irrigation uniformity and application efficiency across all devices. These results indicate that MDI and LEPA were more efficient than LESA as shown by their significantly higher coefficient of uniformity and higher application. From the study, we deduce that MDI can adapt the high efficiency of traditional drip irrigation to center pivot systems.

Keywords: Mobile Drip Irrigation; LEPA; LESA; uniformity; application efficiency; center pivot

3.1 Introduction

Irrigation systems are designed to ensure that high values of coefficients of uniformity and application efficiency are attained. These two parameters are important determinants of the overall irrigation system efficiency. The irrigation uniformity is a statistical measure of how well applied water is distributed to the field, whereas the application efficiency refers to the amount of water in the root zone that is available to plants compared to the amount delivered to plants (Stewart & Howell, 2003). Ideally, irrigation is applied to fully meet plant transpiration. In practice, the process of evaporation occurs, and evapotranspiration is considered for design purposes. Although, irrigation is sometimes used for other purposes, for example soil leaching (Connellan, 2013; Thokal et al., 2004), fertigation, chemigation and plant cooling (Howell, 2003), the objective of irrigation system design, should be to minimize water losses. However, in practice, some water loss is unavoidable. Broadly, water losses in irrigation can be categorized as either conveyance or in-field losses. In systems, where water is delivered to fields using lined or unlined open canals/channels, the potential conveyance losses can be significantly large, and are thus important aspects of the design. On the other hand, conveyance losses are virtually non-existent in well-designed pressurized irrigation systems. For this reason, discussions pertaining to water losses in such systems are usually concentrated to in-field losses. In the field, irrigation water losses can be through evaporation from the air, soil and canopy evaporation, seepage beyond the crop root zone and runoff. Over the years, irrigation methods have vastly improved, resulting in better irrigation efficiency.

There are primarily three categories of irrigation: flood or surface, sprinkler, and microirrigation or drip. The technical approach of each of these is fundamentally different from the other, and this translates directly to how irrigation uniformity is computed for each method. In flood irrigation, water is introduced into the field under gravity flow. Sprinklers are designed to aerially apply droplets or streamlines of water to all parts of the field. Drip lines and some sprinkler application device options apply water directly to point locations in the field and then water then redistributes to locations to which there was no direct application.

Drip irrigation is presently the most efficient means to apply water to crops (Goyal, 2012; Pathak et al., 2009). Development of drip irrigation technology was facilitated by the availability of plastic after World War 2 (Camp, 1998). There are two variations of the technology: surface and sub-surface. The most common is surface drip irrigation, first developed in Israel (Goldberg & Shmueli, 1970). According to Camp (1998), the earliest known case of subsurface drip irrigation is traced back to the invention of Lee (1920). Due to the need to improve irrigation efficiency, as a move towards sustainable use of water resources, there is wide interest in drip irrigation (Scanlon et al., 2012; Schaible & Aillery, 2017; Steward et al., 2013), and is highlighted by numerous studies to evaluate its performance for the production of crops. For the most part, traditional use of drip irrigation systems has been limited to static installations. This apparent lack of versatility has meant that certain crops, especially those categorized as field-crops, are very difficult, or prohibitively hard/expensive, to produce using drip irrigation. Mobile Drip Irrigation (MDI) has the potential to overcome the technology's static installation limitation. In principle, MDI integrates drip irrigation into linear-move and center pivot system platforms, thus overcoming the aforementioned static limitation. While static drip irrigation systems are a well-developed and widely used technology, alongside others such as sprinkler devices such, as sprays and bubblers, the adaptation of MDI has been by comparison a work in progress beginning with early efforts such as Phene et al., (1981; 1985) and Rawlins et al., (1974). Considering that center pivots have since become a widely used and preferable irrigation method in the U.S. (Kincaid, 2005; Rogers et al., 2008), the adaption of drip irrigation to center pivots has a potential to improve their irrigation efficiency.

The objective of this study was to evaluate event-based and seasonal irrigation uniformity, seasonal irrigation uniformity and application efficiency of MDI compared to that of Low Elevation Spray Application (LESA) and Low Energy Precision Application (LEPA).

3.2 Materials and Methods

3.2.1 Site description and experimental setup

A study to evaluate uniformity, application efficiency and season-long irrigation uniformity of MDI and compared to LESA and LEPA was conducted at the irrigated crop field of the Southwest Research and Extension Center of Kansas State University, near Garden City, Kansas; latitude 32.024°, longitude -100.826°, elevation of 885 m above sea level. The soil at the location is classified as an Ulysses silt loam (Stone et al., 2011). A four span center pivot system (Valley 8000 series made by Valmont Industries, Omaha, NE) was used for the study. The spans one, two, three and four had lengths of were 41.6 m, 41.2 m, 41.2 m and 41.1 m respectively (Figure 3.1). Each span was divided into four equal parts to accommodate two sets of MDI driplines, LESA sprays and LEPA bubblers (hereafter LESA and LEPA respectively). One set of MDIs driplines had an emitter flow rate of 1.05×10^{-3} L/s (or 3.8 L/h), while the rate of the other set was 2.1×10^{-3} L/s (7.6 L/h); hereafter designated MDI_1 and MDI_2 respectively. In each span, the irrigation application devices were spaced 1.52 m apart.

Water to the center pivot was supplied by means of a 74.6 kW three-phase electrical pump (North American Electric Inc, model NAE-VHS-100-4), which was situated about 577 m east from of the center pivot. The pump was set to supply 137.9 kPa of pressure at the well point, which ensured that a required pressure of 89.6 kPa was received at the pivot point. Pressure loss between the pump and center pivot was 48.3 kPa, and this was attributed to friction losses in the pipes and fittings. The pumping flow rate was 0.011 m^3/s. The pump drew water from a well of 71.3 m depth. Static water level in the well was estimated to be 60.0 m. Each LESA and LEPA in the center pivot setup was fitted with a pressure regulator of 41.4 kPa to ensure uniform flow, whereas driplines used for the MDI_1 and MDI_2 were pressure compensated. For all flow measurement experiments, the center pivot was set to travel at a 15% of the maximum speed, which according to its calibration, enabled it to apply 25.4 mm (or 1”) of water to the field. A weather station was instrumented about 224 m northeast of the pivot point. Weather variables that were measured and logged by the station included rainfall depth, temperature (minimum and maximum), wind speed, solar radiation and relative humidity.

In 2016 and 2017, corn was planted in May and harvested in October. Experiments to measure the flow rates of MDI_1, MDI_2, LESA and LEPA were conducted before the corn was planted. Season-long uniformity was also evaluated by the examination of vegetative indices obtained from aerial images.

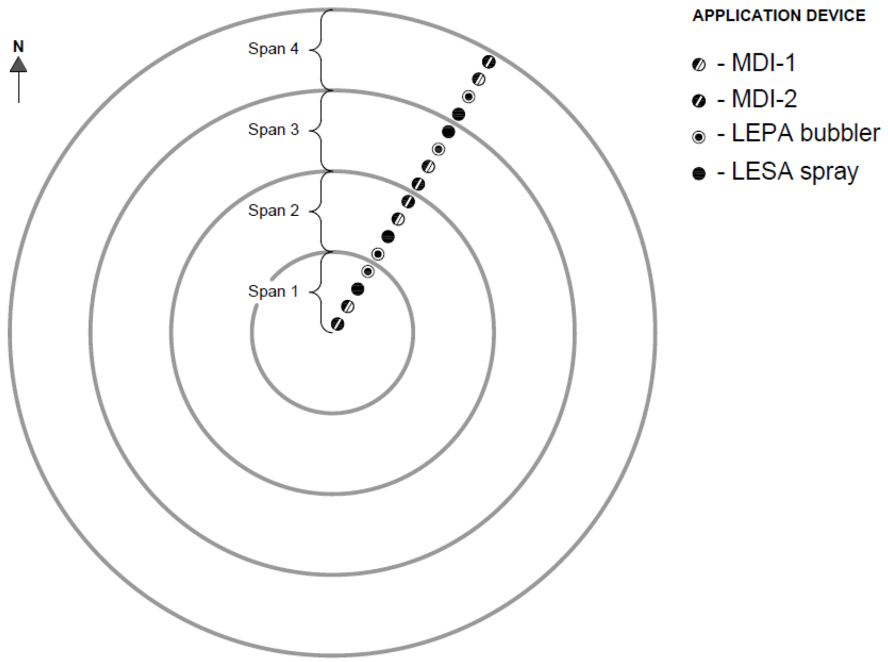

Figure 3.1 Schematic of center pivot at Kansas State University Southwest Research and Extension Center showing arrangement of MDI, LESA spray and LEPA bubbler

3.2.2 Measuring flow uniformity

3.2.2.1 MDI

With the center pivot running, the flow rates of MDI emitters from driplines were measured by holding a 480 mL cylinder and collecting water for 120 s directly under each of 46 MDI_1 and 38 MDI_2 randomly selected emitters in each of the four spans. The emitter flow rate (mL/s) was computed as a measured volume divided by 120 s. To evaluate MDI flow uniformity, the American Society of Biological and Agricultural Engineers' standard for field evaluation of micro-irrigation systems ASAE, EP458 (ASAE Standards, 1996) was used. It is based on the mean, $\bar{q}$, standard deviation, s_q, coefficient of variation, V_{qs}, and statistical uniformity, U_s, of the emitter flow rate (ASAE Standards, 1996; Camp et al., 1997). The mean of emitter flow rate, $\bar{q}$, is computed as:

$$\bar{q} = \frac{1}{n}\sum_{i=1}^{n} q_i \tag{3.1}$$

$$s_q = \sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n} {q_i}^2 - \frac{1}{n}\left(\sum_{i=1}^{n} q_i\right)^2\right]} \tag{3.2}$$

$$V_{qs} = \frac{s_q}{\bar{q}} \tag{3.3}$$

$$U_s = 100(1 - V_{qs}) \tag{3.4}$$

where q_i is the flow of emitter i and n is the number of emitters. The coefficient of uniformity, CU, is computed as (Camp et al., 1997):

$$CU = 20.2 + 0.798U_s \tag{3.5}$$

3.2.2.2 LEPA

Bubblers are classified by the ASABE as a microirrigation systems (American Society of Agricultural Engineers, 2014). Therefore the ASABE standard, EP458, described in section 3.2.2.1, was be used for field evaluation of LEPA uniformity. The flow rates of all the 23 LEPA emitters, in all four spans were measured. With the center pivot running, a 20.9 L bucket was placed directly under each emitter and the time, in seconds, to fill the bucket was recorded (Figure 3.2). Emitter flow rate was calculated as the volume of the bucket divided by the time to fill the bucket. Unlike MDI, where emitter flow rate is constant, LEPA nozzle flow rates increase with increase in distance from the pivot point. This occurs because the irrigated area between two successive nozzles increases with distance from the center of the pivot, therefore the flow rate must increase to ensure uniform water application. A modification of equation (3.1), of the procedure described in section 3.2.2.1, is needed to account for variability in nozzle flow rate. The standardized mean nozzle flow rate was thus calculated as:

$$\bar{q}_s = \frac{1}{n}\sum_{i}^{n}\left(\frac{q_i}{A_i}\right) \quad (3.6)$$

$$A_i = \pi[r_{i+1}^2 - r_i^2] \quad (3.7)$$

where A_i is area between nozzles i and $i + 1$, and r_i is distance from the center of the pivot to nozzle i.

Figure 3.2 Measuring flow rate of a LEPA bubbler while the center pivot moves at Kansas State University's Southwest Research and Extension Center, near Garden City, Kansas

3.2.2.3 LESA

Uniformity evaluation for LESA was done in accordance to the ASABE standard S436.1 (ASABE, 2003). In this method, the center pivot coefficient of uniformity is computed from the modified Heermann and Hein (1968) formula (ASABE, 2003):

$$CU_H = 100\left[1 - \frac{\sum_{i=1}^{n} S_i\left|V_i - \overline{V_p}\right|}{\sum_{i=1}^{n} V_i S_i}\right] \quad (3.8)$$

$$\overline{V_p} = \frac{\sum_{i=1}^{n} V_i S_i}{\sum_{i=1}^{n} S_i} \quad (3.9)$$

where CU_H is Heermann and Hein coefficient of uniformity ; V_i is volume of water collected in gage i; S_i is distance of gage i from the pivot point; $\overline{V_p}$ is weighted average volume of water collected in gages; n is number of irrigation gages; and i is emitter number ($i = 1, 2, 3, \ldots, n$). In each span, irrigation gages were placed at locations where LESA spray nozzles were installed (Figure 3.1). A total of 50 irrigation gages were installed out in a "V" formation (25 on each line) in the southwest section of the center pivot (Figure 3.3). The distance of each gage from the pivot point was measured using a measure tape. Wind speed was measured with handheld anemometer at the start of, and frequently the experiment. Several times during the experiment, the prevailing wind direction was determined, and the anemometer held to face the direction from which the wind was blowing. Average windspeed during the experiment was 3.1 m/s. The volume of water (mL) collected in each gage was measured after completion of the irrigation event.

Figure 3.3 Measuring flow rate of a LESA spray in a center pivot at Kansas State University's Southwest Research and Extension Center, near Garden City, Kansas

3.2.3 Application efficiency of MDI, LEPA and LESA

The application efficiencies, e_a, of MDI, LESA and LEPA were computed with equation (3.10) (Pereira & Trout, 1999):

$$e_a = 100\frac{Z_r}{D} \tag{3.10}$$

where Z_r is average depth of water (mm) in the root zone after irrigation and, D is average depth of applied water (mm). The amount of water reaching the root zone, D, was estimated as the gross applied depth subtracting the losses due to wind drift, free surface evaporation, deep percolation, and runoff. To evaluate application efficiencies of MDI_1, MDI_2, LESA and LESA, two sets of neutron probe access tubes were installed 3 m apart in succession along the travel path of each device in the third span. Each set consisted of five neutron probe access tubes, spaced 0.762 m apart in straight line perpendicular to the travel path of the center pivot. Thus, ten datasets of soil water content readings were collected for each device. Soil water content measurement, taken at 0.31 m intervals up to a depth of 2.44 m, were measured before and after an irrigation event, using a neutron attenuation probe (CPN 503DR Hydroprobe by Campbell Pacific Nuclear International Inc.; http://www.cpn-intl.com/503-elite-hydroprobe/). The experiment was conducted on a bare soil.

At the start of the experiment, each of the application devices was used to apply 25.4 mm of water at the location of the field where their respective neutron probe access tubes were installed. The field was left to freely drain for 48 hours before the second soil water content readings were taken. The change in storage was computed as the difference between soil water content, pre- and post-irrigation; which was interpreted as the depth of water stored in the root zone. Statistical evaluation of soil water storage for MDI_1, MDI_2, LEPA and LESA was conducted using ANOVA statistical tests. Top 0.91 m of the soil profile was considered as the active root zone for the computation of application efficiency, because the effect of irrigation beyond this depth was observed to be negligible for silt-loam soil at the study site.

3.2.4 Analysis of season-long irrigation uniformity through vegetative index

Vegetative index is an indicator from which plant health can be assessed at various growth stages (Candiago et al., 2015; Jackson & Huete, 1991). Since plant physiological development varies with soil water conditions (Klocke et al., 2011; Payero et al., 2006; Veihmeyer & Hendrickson, 1950), extreme non-uniformity in irrigation is correspondingly reflected in differences in vegetative indices. As documented by Lamm (1998), the effect of irrigation non-uniformity can translate to noticeable differences in crop phenology. During the 2016 and 2017 seasons, vegetative index data of two corn varieties (Deklab 64-89 in 2016 and Deklab 62-98 in 2017) planted at seeding rates of 84,016 seeds/ha, was periodically collected by flying an airplane over the area irrigated by center pivot (Figure 3.1). For all irrigation application devices (MDI, LESA and LEPA), vegetative indices of the corn at various growth stages, were analysed for irrigation capacities of 6.2, 3.1 and 1.6 mm/d. In 2016, Advanced Difference Vegetative Index (ADVI) data (Sutton, 2016), by AirScout® ADVI™ Imagery (https://airscout.com/technology/), was collected, whereas the Normalized Difference Vegetative Index (NDVI) data, by Terravion (https://www.terravion.com/) was collected in 2017,. Of the two data types, NDVI is better known and more widely used, thus an extensive body of literature on its application for evaluation of crop biophysical development exists (Jovanovic & Israel, 2012; O'Shaughnessy et al., 2013; Stone et al., 2016). As an example, Nautiyal (2015) used NDVI to assess the performance of smart irrigation systems for turf grass. In contrast, ADVI is a relatively new and recently patented technology. ADVI is generated by capturing light from the visible near-infrared and ultraviolet spectrum and processing the imagery to calculate relative light reflectance between plants in a field (Sutton, 2016).

ADVI data was collected on the following dates of 2016: May 28th, June 10th, June 28th, July 11th, July 18th, July 26th, August 3rd, August 15th and September 2nd. NDVI data was collected on the following dates of 2017: May 4th, May 12th, June 5th, June 19th, July 10th, July 25th, August 2nd, August 14th, August 29th, September 12th, September 27th, October 10th. The georeferenced ADVI and NDVI data were processed and statistically summarized for mean, standard deviation, minimum and maximum, using QGIS version 3.0.2-Girona, (QGIS Development Team, 2018). For each application device, the mean ADVI, or NDVI, for the sequential dates of the season, was arranged as a timeseries. This was done for each device for the irrigation capacities of 6.2, 3.1 and 1.6 mm/d. To compare differences in ADVI and NDVI between MDI_1, MDI_2, LEPA and LESA, analysis of variance (ANOVA) of mean vegetative indices was conducted using PROC GLM in SAS Studio (Littell et al., 2006).

3.3 Results and Discussions

3.3.1 Flow uniformity

3.3.1.1 Uniformity of MDI

The coefficient of uniformity, CU, of MDI_1 and MDI_2 were computed separately because of their different flow rates. Measured mean flow rate, $\bar{q}$, for MDI_1 and MDI_2 were 3.71±0.29 and 7.3±0.58 L/h respectively; which was equivalent to the manufacturer provided values (3.7 L/h for MDI_1 and 7.3 L/h for MDI_2), indicating that the driplines were properly functioning as designed. The coefficient of variation, V_{qs}, was calculated as 0.078 for MDI_1 and 0.08 for MDI_2. Statistical uniformity, U_s, was found at 92.5% for MDI_1 and 92.2% for MDI_2 . The coefficient of uniformity, UC, were 93.8% for MDI_1 and 93.7% for MDI_2.

3.3.1.2 Uniformity of LEPA

As shown in Figure 3.4(a) and Appendix A the measured flow rates of the LEPA nozzles increases as distance from the center of the pivot increases. Therefore, coefficient of uniformity, CU, was computed from the standardized mean nozzle flow rate, $\bar{q}_s$ (Figure 3.4 (b)). For LEPA, the standardized mean nozzle flow rate was 1.25E-07 $m^3/s/m^2$, the coefficient of variation, V_{qs}, was 0.062, the statistical uniformity, U_s, for LEPA was 93.8%, and coefficient of uniformity, CU, was 95.1%.

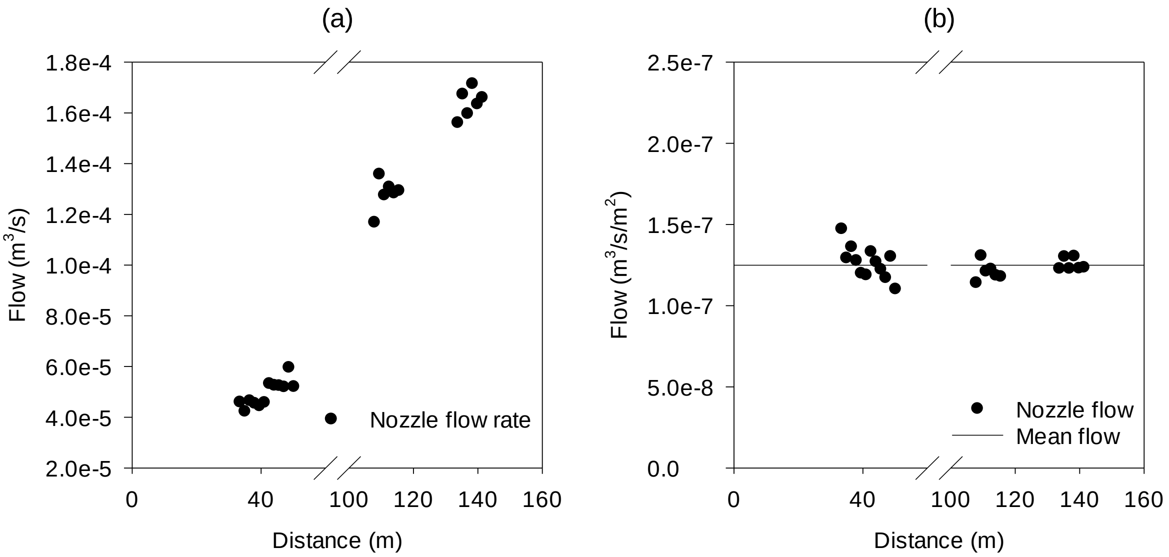

Figure 3.4 (a) Variation of LEPA bubbler flow rate, and (b) standardized flow rate, with distance from the pivot point at the Southwest Research and Extension Center, Kansas State University

3.3.1.3 Uniformity of LESA

In the analysis of LESA uniformity, a distinction was made between nozzle uniformity and application uniformity. Nozzle uniformity was computed by measuring nozzle flow rate (Appendix B), while application uniformity was obtained (Appendix C), using the ASABE standard S436.1. Figure 3.5 below shows the volume of water captured by the irrigation gages versus the distance of the gage from the center pivot during field testing. Figure 3.6(a) shows variation in nozzle flow rate with increasing distance from the center of the pivot, and Figure

3.6(b) shows the standardized flow rate used to compute nozzle uniformity. Since LESA spreads water over a relatively wide area, the amount of water reaching a point on the soil surface at any instance varies. Since water is applied in a form of small droplets, and streams, application uniformity is very susceptible to wind distortion. The coefficient of uniformity, CU_H, for LESA was 83.8%, which was less than that of MDI_1, MDI_2 and LEPA by 8.9%, 8.7% and 11.8%. The statistical uniformity of the LESA nozzles was 80.5%, which is considerably lower than in other applications. Usually, proper design ensures that emitter uniformity is high. The relatively low uniformity of the LESA could partly explain the low coefficient of uniformity observed during field testing. In addition to wind drift, water was lost to soil water evaporation and wind drift.

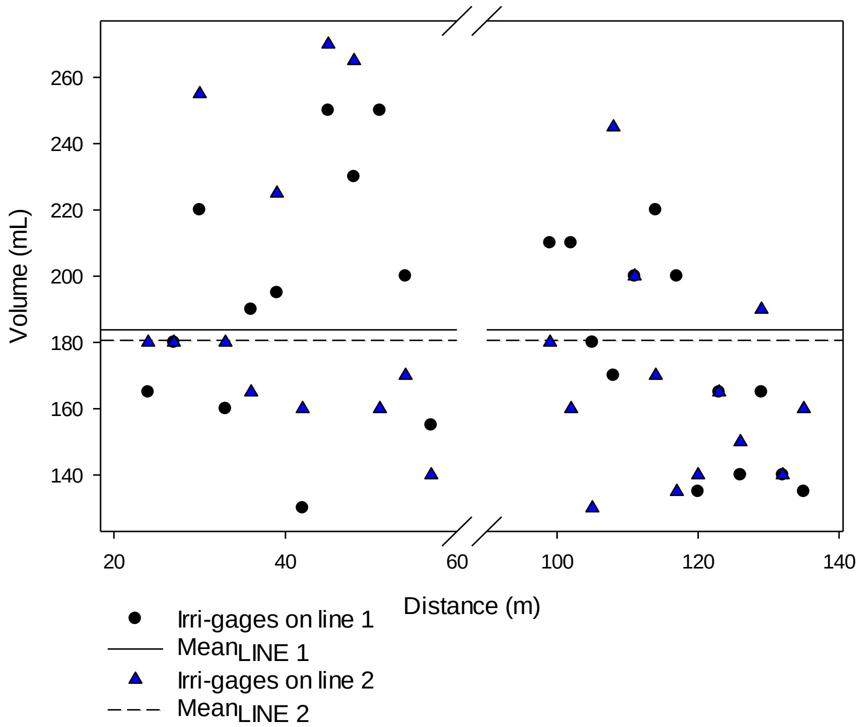

Figure 3.5 Volume of water caught by irrigation gages versus distance from the center of the pivot at the Southwest Research and Extension Center, Kansas State University. There are two lines of irrigation gages arranged in a V-shape as shown in Figure 3.3

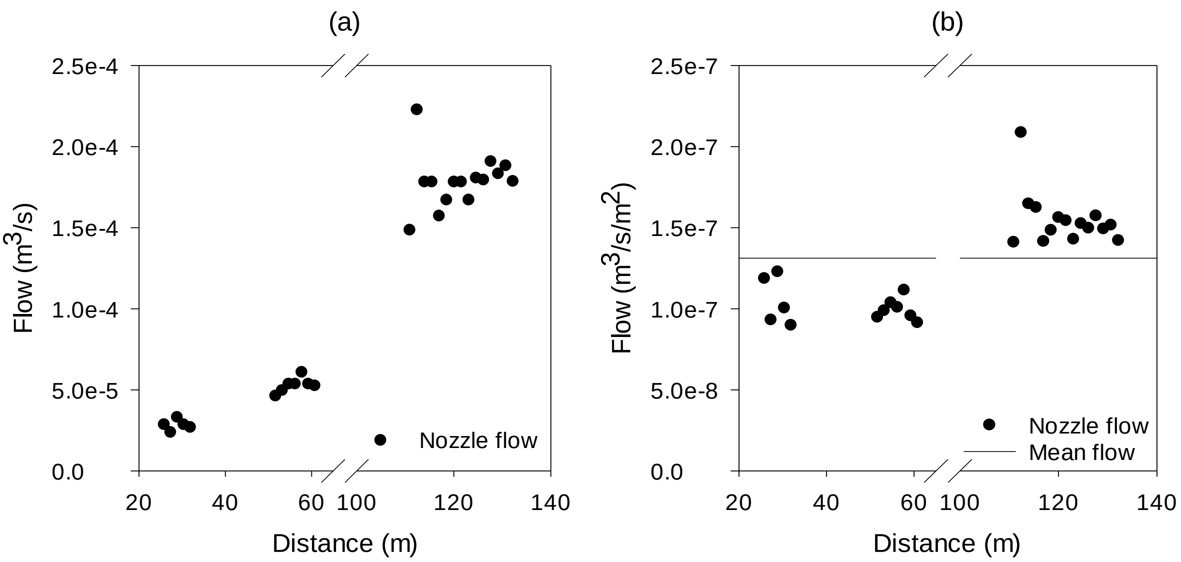

Figure 3.6 (a) Variation of LESA spray nozzle flow rate, and (b) standardized flow rate, with distance from point pivot at the Southwest Research and Extension Center, Kansas State University

Table 3.1 Irrigation performance parameters of MDI, LESA and LEPA for a center pivot the Southwest Research and Extension Center, Kansas State University

	MDI_1	MDI_2	LESA	LEPA
Emitter mean flow, $\bar{q}$, (x 10^{-6} m^3/s)	1.03±0.08	2.03±0.16	-	-
Emitter mean flow/area (x 10^{-7} $m^3/s/m^2$)	-	-	1.30	1.25
Coefficient of variation, V_{qs},	0.078	0.08	0.195	0.062
Statistical uniformity, U_s, (%)	92.2	92.0	80.5	93.8
Coefficient of uniformity (%)	93.8	93.7	83.8	95.1

MDI_1 is Mobile Drip Irrigation (3.8 L/h)
MDI_2 is Mobile Drip Irrigation (7.6 L/h)
LESA is Low Elevation Spray Application
LEPA is Low Energy Precision Application

3.3.2 Application efficiency

The application efficiencies for MDI_1, MDI_2, LEPA and LESA were 76.1, 96.8, 98.4 and 51.2% respectively. This is consistent with the findings in other studies (i.e. Irmak et al., (2011)), that showed that LEPA devices and drip irrigation, from which MDI was devised, were more efficient than LESA sprays or sprinklers. Much lower application efficiency of the LESA, in comparison with MDI or LEPA, can be explained by a higher rate of soil and canopy evaporation associated with it, yielding comparatively lesser fraction of the applied water infiltrated into the soil. The ANOVA test showed that there were significant differences ($p = 0.5749$) in the amount of water stored in the soil profile 72 hours after the irrigation event between MDI, LESA and LEPA. As shown in Figure 3.7, the two MDI_1, MDI_2 and LEPA showed greater variation in soil water storage, than LESA; especially in the top 1.2 m of the profile. This observation was expected because both MDI and LEPA apply water differently from LESA. The former two devices apply water to the soil at locations directly beneath the emitter, whereas the LESA is designed to spread water evenly throughout the soil surface. Therefore, for MDI and LEPA, water has to move, both vertically and horizontally, from the point of direct application to other regions within the soil profile. For this reason, it is expected that points of direct water application will have high water content than those outside of it. For MDI and LEPA, water has to redistribute between two adjacent devices. For LESA, water movement is primarily in the vertical direction; meaning that differences in water content horizontally should be smaller, which is exhibited in Figure 3.1. Means of water storage over the whole 2.4 m depth of the soil profile were: 2.4±5.5 mm for MDI_1; 3.1±9.1 mm for MDI_2; 3.1±6.7 mm for LEPA; and 1.6±4.0 mm for LESA.

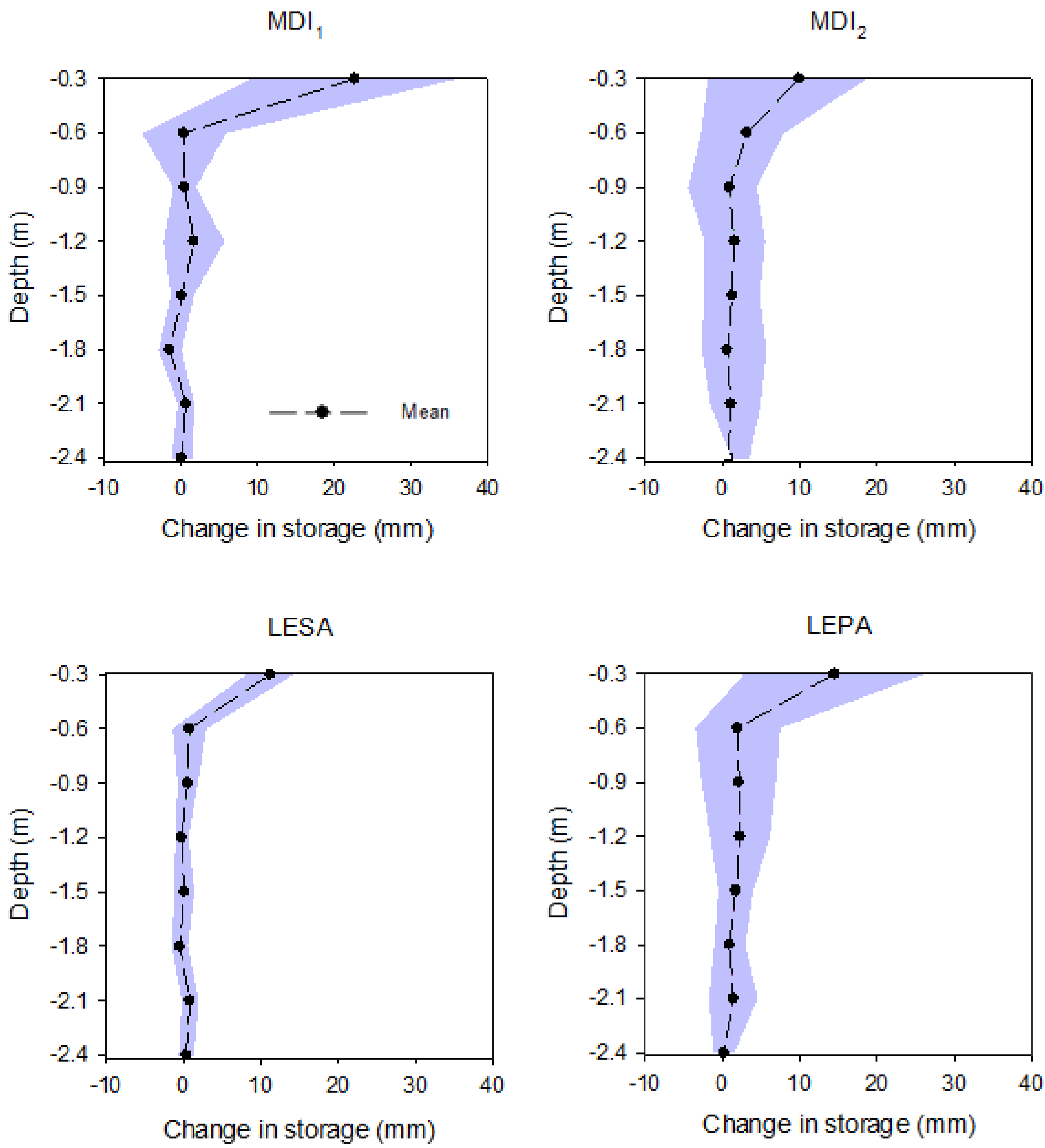

Figure 3.7 Change in soil profile water storage after 72 hours, following irrigation by MDI, LESA and LEPA at the Southwest Research and Extension Center, Garden City, Kansas

3.3.3 NDVI and ADVI

Mean ADVI and NDVI of the corn are shown in Figure 3.8 for 2016 and in Figure 3.9 for 2017. Changes in ADVI and NDVI during the season are show in Appendix D and Appendix E respectively. Seasonal corn NDVI exhibited a concave parabolic profile, which is typical for corn. It increased from very low values at the start of the growth cycle, as the plant established itself and then peaked when the corn was at its most vegetative state. At the latter part of the season, after the crop reached maturity, it gradually dropped. ADVI at the start of the growth cycle was high, and it dropped linearly as the crop established itself. Mid-season, when the crop was at its most vegetative state, the rate of decrease in ADVI was much lower. Towards the end of the crop cycle, the ADVI continued to drop. For the three irrigation capacities, 6.2, 3.1 and 1.6 mm/d, there were no significant differences in mean seasonal ADVI between MDI, LESA and LEPA; with p-value = 0.987, 0.999 and 0.999 respectively. A similar observation was made for NDVI, with p-value = 0.998, 0.999 and 0.999, for MDI, LESA and LEPA respectively. No significant differences found in both ADVI and NDVI indicates that water application by MDI was comparable to that by LESA and LEPA. This implies that the application uniformity of MDI matched that of the LESA and LEPA throughout the crop growth cycle.

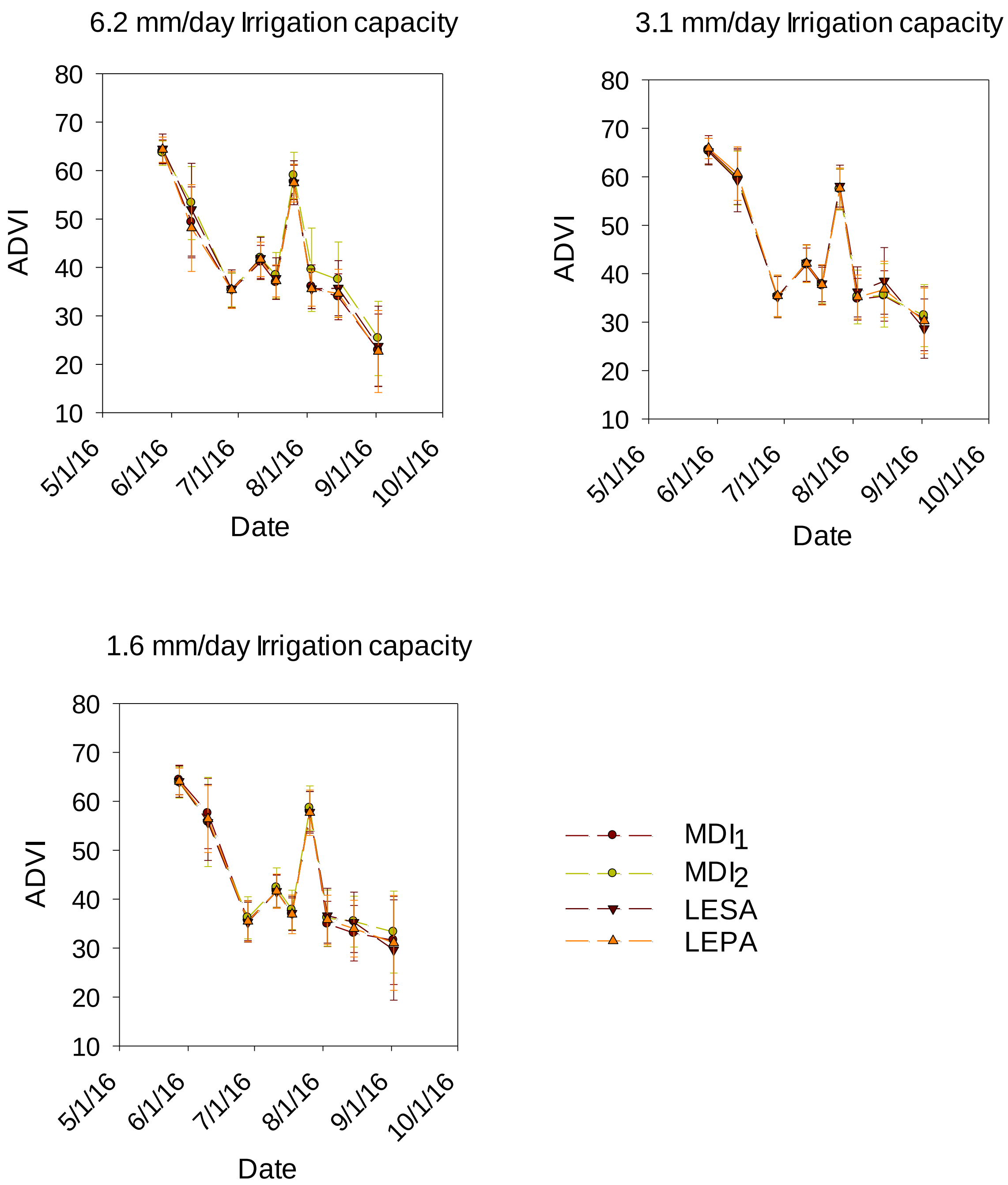

Figure 3.8 ADVI of a corn crop irrigated by MDI, LESA and LEPA, under irrigation capacities of, 6.2, 3.1, and 1.6 mm/d, in 2016, at the Southwest Research and Extension Center, Kansas State University

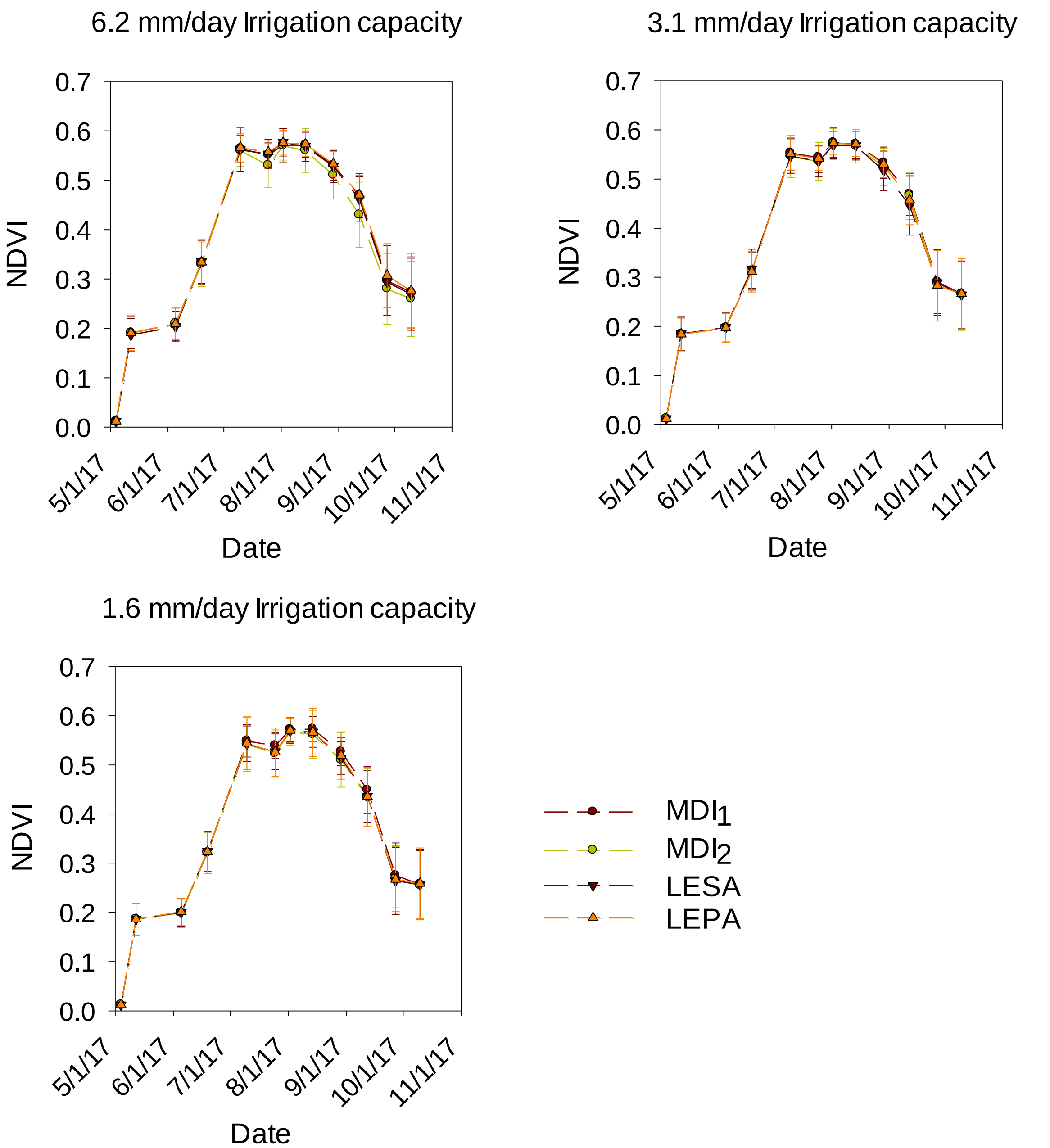

Figure 3.9 NDVI of a corn crop irrigated by MDI, LESA and LEPA, under irrigation capacities of, 6.2, 3.1, and 1.6 mm/d, in 2017, at the Southwest Research and Extension Center, Kansas State University

3.4 Conclusions

This study evaluated the performance of MDI against LESA, a common sprinkler irrigation technology used by area farmers, and LEPA. In general, the standard testing results show that MDI is comparable to LEPA, and that both technologies perform better than LESA. The irrigation performance of MDI matched that of LEPA as indicated by their comparable coefficient of uniformity, statistical uniformity and coefficient of variation. Generally, both MDI and LEPA were found to be more efficient than LESA as shown by their significantly higher coefficient of uniformity and statistical uniformity, in addition to their comparatively lower coefficients of variation. Both MDI and LEPA had higher application efficiency than LESA. These findings are consistent with other findings on the performance of common irrigation application devices in use excluding MDI which is a relatively new technology. This study confirms that the relatively new MDI technology, is capable of beneficially adapting high irrigation efficiency of traditional drip irrigation systems to center pivot systems.

This study tested the use of vegetative index data, taken at various crop growth stages, as an approach to evaluate the season-long performance of MDI, LEPA and LESA. Though irrigation performance parameters showed that MDI and LEPA were more efficient than LESA, secondary evaluation of season-long irrigation performance through periodic examination of NDVI and ADVI showed that there was no significant difference in vegetative indices of corn irrigated by MDI, LEPA and LESA under deficit irrigation conditions. This suggests that there was no difference in irrigation performance between all tested devices. A plausible explanation for this occurrence is the effect of rainfall received during each of the two seasons; which could have reduced any disparities in the irrigation efficiency between the devices. After corn has established a full canopy, it is highly likely that causes of lower irrigation efficiency in LESA, such as evaporation (both soil and canopy) and wind distortion, were also significantly reduced, hence improving the overall efficiency of LESA.

Acknowledgements

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Chapter 4 - Evaluating soil water redistribution under mobile drip irrigation, low-pressure sprinklers, and bubblers

This chapter was submitted to the Transactions of ASABE journal

Abstract

A study to evaluate soil water redistribution, in a Ulysses silt loam under Mobile drip irrigation (MDI), Low Energy Precision Application (LEPA), and Low Elevation Spray Application (LESA) was conducted in southwest Kansas using a four-span center pivot irrigation system. Each span was divided into equal parts to accommodate two MDI driplines of low (3.7 L/h) and high (7.6 L/h) rates, a LEPA bubbler, and a LESA spray. A numerical model, HYDRUS (2D/3D), was used to simulate water flow within the soil profile for MDI, LESA, and LEPA. Results showed that the effect of irrigation was mostly limited to the top 60 cm of the soil profile for all the evaluated irrigation application technologies. MDI driplines and LEPA showed the highest horizontal variation in water content. Median water contents were 0.250, 0.249, 0.271, and 0.240 cm cm^{-3}, at 30 cm depth, and 0.224, 0.249, 0.220, and 0.210 cm cm^{-3} at 60 cm depth, for the low and high MDI driplines, LEPA and LESA, respectively. Soil water content inter-quartile-range (IQR) at 30 cm depth, for the low and high rate MDI driplines differed from that of the LESA by 97.1% and 94.1%, respectively; indicating a significant difference in profile water redistribution between MDI and LESA. Soil water content IQR at 30 cm, for the low and high rate MDI driplines, varied from that of the LEPA by 0.98% and 0.96%; implying that the MDI matched LEPA bubbler's water redistribution. The results show that MDI water redistribution pattern was similar to LEPA.

Keywords: Mobile drip irrigation; LEPA; LESA; center pivots; water redistribution

4.1 Introduction

The primary role of irrigation is to provide water to crops to replenish plant available water deficits in the root zone. In semi-arid and arid locations with limited irrigation water supply, a deficit irrigation strategies are used (Denef et al., 2008). However, irrigation is not only restricted to areas of extreme water scarcity. Many locations receive the majority of their annual rainfall amounts during cropping seasons but the total amount or distribution of rainfall limits production and rrigation can be used to boost yield and/or cope with dry spells; as described by studies such as Zhang et al., (2006).

Globally, 20% of arable land under irrigated agriculture accounts for 40% of crop production (Sauer et al., 2010). This underscores the importance of irrigation to food production, and the economies of countries where it is widely practiced. This dichotomy in irrigated land area and yield illustrates how irrigation can significantly increases agricultural land productivity. According to Valipour (2015), irrigation controls global crop yield variability, implying that changes in cropped area under irrigation at any one time translates directly to changes in crop production outputs. The broad consensus today is that irrigation has a pivotal role in feeding the world's growing population. This is especially important considering the climatic projections indicate an increase in patterns of unfavourable weather extremes, particularly droughts, which affect rainfed agriculture; hence increasing the need for irrigation (Hanjra & Qureshi, 2010; Lobell et al., 2008).

Important as it is, irrigation in many parts of the world is faced with water shortages, both present and forecasted. For this reason, there is interest in developing and promoting the use of efficient irrigation technologies. It is important to ensure that irrigation water is applied efficiently to minimize water loss (Rajan et al., 2015) and standard engineering design strives towards this objective. Besides, enabling sustainable management of usually finite water resources, efficient water application leads to secondary benefits such as lower operation and management costs, e.g. water pumping and delivery. Water losses in irrigation are normally attributed to evaporation from the soil and canopy interception, runoff, and seepage below the root zone (Agam et al., 2012; Rogers et al., 1997). Mitigation of water losses, such as those mentioned, is one of the key design considerations for modern irrigation devices; especially pressurized systems. However, the efficacy of each device is limited by the method which it delivers water to plants.

Irrigation technologies are broadly divided into the following categories: flood/surface irrigation, sprinkler irrigation, and drip irrigation. Flood irrigation, as the name suggests, involves conveying a large volume of water onto fields, normally levelled to have uniform but slight slopes to allow water to advance across the field. Some flood systems may be nearly flat and let a certain depth of water build up on the soil surface, such as lowland rice irrigated in level paddies or basins. This approach is regarded as the least efficient (Sammis, 1980) of all irrigation technologies and not widely practiced any more in the U.S., except in large delta areas and flood plains, where there is usually a very large water supply. The main pressurized irrigation technologies in use today are sprinkler and drip irrigation (Phocaides, 2000), which are generally more efficient than flood irrigation, which predates them. A major difference between pressurized irrigation systems and flood irrigation is that the former usually does not require precise land levelling, or contouring. The combination of versatility and more efficient water application makes pressurized sprinkler and drip irrigation technology the method of choice for most farmers around the world; especially in countries like the U.S where it is relatively more affordable. Out of all these technologies, drip is regarded as the most efficient irrigation method (Selim et al., 2013; Todd H Skaggs, Trout, & Rothfuss, 2010).

According to Scanlon et al., (2012), center pivot irrigation systems are the method of choice for irrigation in the in High Plains of the U.S. Typically, center pivots are fitted with sprinklers or bubbler nozzles of slightly varied designs. Lamm et al., (2012) and Porter and Marek (2009) categorized sprinkler and bubbler nozzle packages commonly used in center pivots as: (1) Low Energy Precision Application (LEPA), (2) Low Pressure In-canopy (LPIC), (3) Low Elevation Spray Application (LESA), and (4) Mid-Elevation Spray Application (MESA). Prior to the development of low-pressure irrigation devices, center pivots were fitted with impact sprinklers which spread water over large areas (Waller & Yitayew, 2016). Such sprinklers originally operated at high pressures, of 380-450 kPa (Keller & Bliesner, 1990a), which lead to high energy costs. To address this the problem, low pressure sprinklers and sprays were developed. Of the low-pressure devices, LEPA has the lowest operating pressures, in the range of 40-70 kPa (Waller & Yitayew, 2016). A relatively recent addition to center pivot technology is Mobile Drip Irrigation (MDI). Compared to LESA, LEPA, and MESA, MDI can be categorized as an untested irrigation technology that has not been widely used by farmers despite its perceived potential for increasing irrigation efficiency. MDI can be described as the adaptation of drip irrigation technology to center pivot irrigation systems. The central idea is to combine two popular irrigation technologies–center pivot and drip irrigation–to improve irrigation efficiency in center pivots. The idea of retrofitting center pivots with dripline nozzles is relatively old and has been explored by Phene et al., (1981) and Rawlins et al. (1974). Following the development of driplines with pressure-compensating emitters, interest in MDI has been revived. Olson and Rogers (2008) evaluated a variant of mobile drip irrigation against LESA sprinklers for corn production and found that yields under both systems were similar, despite MDI having applied less water to the crops due to emitter clogging. Theoretically, it could be assumed that MDI is more efficient than mainstream LESA, LEPA, LPIC, and MESA technologies. This is because it eliminates, or reduces, some known water losses encountered with other technologies such as canopy interception, runoff, and evaporation of ponded water (Kisekka et al., 2017; O'Shaughnessy and Colaizzi, 2017).

Efficient irrigation is dependent on how effectively water is applied to soil surface, and how it is redistributed within the soil profile; especially in the root zone (Cooley et al., 2007; Satchithanantham et al., 2014). The way water is applied to the soil surface varies with irrigation application devices. In principle, spreading water across all of flat soil surface should enable uniform downward movement and distribution within a homogenous soil profile; barring preferential flow. This is the basic operating principle of flood and sprinkler irrigation methods. In contrast, drip irrigation, is designed to wet only a small area of the soil surface (Dasberg & Or, 1999); leaving some of the soil surface dry. Such concentrated application, at a low flow rate is meant to allow most water to infiltrate into the soil profile without ponding or running off.

Flow rate of the types of emitters found in driplines is calculated by Equation (4.1) (Keller & Bliesner, 1990b):

$$q = K_d H^x \tag{4.1}$$

where q is flow rate (L h^{-1}), K_d is discharge coefficient of the emitter, H is dripline operating pressure head, and x is emitter discharge exponent. The rate at which the emitter flow rate q varies with pressure increases as the emitter discharge exponent x increases. Pressure-compensated drip lines, which are preferred in irrigation practice, have $x \leq 0.1$ (Pereira & Trout, 1999).

Proper drip irrigation design ensures that plants in rows, that are not immediately adjacent to driplines, also have access to the same amount of water as those close to the drip line. For proper functioning of a drip irrigation, it is essential that the water emitted from the driplines redistributes adequately within the soil profile (Selim et al., 2013). The way soil water redistributes, within the soil profile under drip irrigation, is also dependent on dripline spacing and soil type. Several aspects of water redistribution have been widely studied for different irrigation systems (Gärdenäs et al., 2005; Kandelous & Šimůnek, 2010b; Kandelous et al., 2011; Skaggs et al., 2010) but are still not well understood for MDI. Therefore, the objective of this study was to analyze soil water redistribution under the MDI and compare it to that under the LEPA and LESA systems. The Richards equation (Richards 1931; Pachepsky et al. 2003) and the HYDRUS software (Šimůnek et al. 2008) were used for simulating water flow in variably saturated soils under different irrigation technologies.

4.2 Materials and Methods

4.2.1 Site description and experimental setup

An experiment to measure soil water content before and after an irrigation event was conducted between October 28 and 31, 2016 in an experimental field of the Southwest Research-Extension Center of Kansas State University located near Garden City, KS (latitude 32.024°, longitude -100.826°, elevation 885 m above sea level). The soil at the location is classified as an Ulysses silt loam (Stone et al., 2011). The experiment was conducted using a four span center pivot of the following specifications: span one was 41.6 m; spans two and three were 41.2 m; and span four was 41.1 m. The overhang length was 5.5 m. For the experiment, each span of the center pivot was divided into four equal parts to accommodate two MDI driplines, LEPA and LESA. The experiment was set up under the third span of the center pivot as shown in Figure 4.1. Soil water content was measured using a neutron attenuation probe (model CPN 503DR Hydroprobe). For each of the four irrigation application devices under evaluation, water content readings were measured twice; representing two replications of the experiment. To do this, two rows of neutron probe access tubes, as shown in Figure 4.1, were installed for each irrigation device. Each row comprised five neutron probe access tubes spaced 0.38 m apart. This arrangement was implemented for MDI (3.7 L/h and 7.6 L/h); hereafter MDI_1 and MDI_2, LEPA, and LESA nozzle packages. The five access tubes spanned three crop rows (three tubes in crop rows and two tubes in space between the rows). Each access tube facilitated soil water content measurement at intervals of 0.305 m, up to the depth of 2.438 m. The center pivot was programmed to apply 2.54 cm of water over the experiment area. To apply 2.54 cm of water, the center pivot was set to run to at 15.5% of its maximum speed. The experiment was conducted after the corn crop for the 2016 season was harvested. The combine harvester cut the corn such that short corn stubble, about 0.6 m, was left in the plant rows. The corn crop residue was removed from the soil surface carefully to avoid disturbance of the soil surface, leaving the soil surface bare. The soil surface was dry, following an extended period of no wetting, by either rainfall or irrigation. On the morning of October 28, 2016, water was applied to the experiment area shown in Figure 4.1.

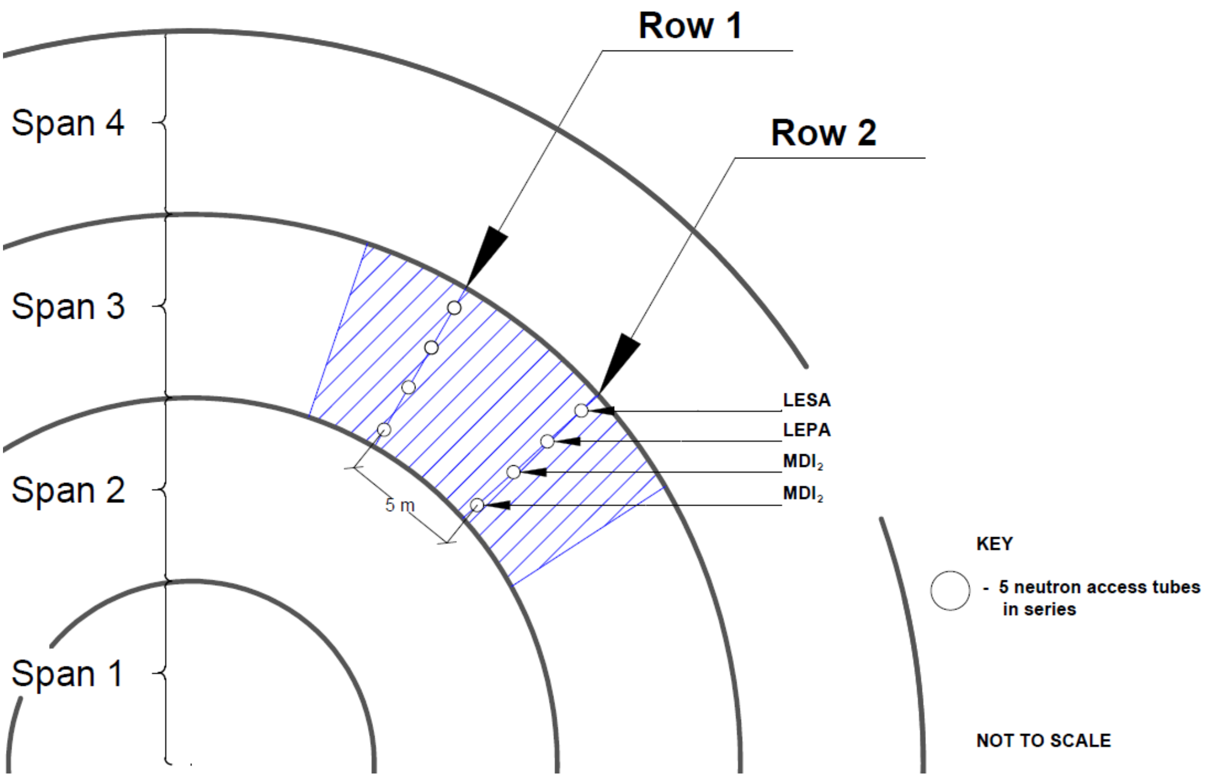
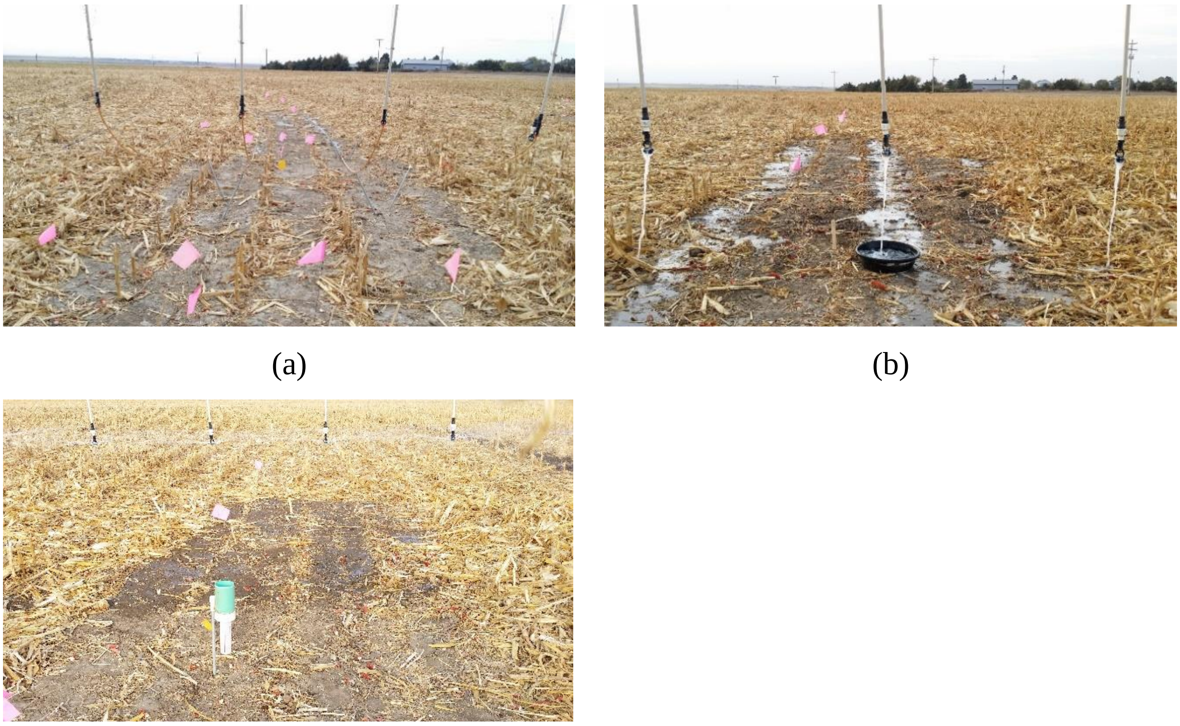


Figure 4.1 North-east section of center pivot irrigation system schematic showing location of experiment and arrangement of irrigation devices



(a) (b)

(c)

Figure 4.2 Measuring irrigation flow rates of MDI (a), LEPA (b) and LESA (c) after the 2016 corn growing season at the Kansas State University Southwest Research-Extension Center near Garden City, KS

4.2.2 Measurement of irrigation device application rate

Each LEPA and LESA nozzle was connected to a 41.4 kPa Senninger pressure regulator and the driplines used for MDI_1 and MDI_2 had pressure compensating drippers. The irrigation pump was set to supply pressure of 137.9 kPa at the well point, which ensured that the required 89.6 kPa was received at the water inlet point of the center pivot.

In Figure 4.3 below, the measured application rates of MDI1, MDI2, LEPA and LESA are graphed against the infiltration rate curve for a silt loam soil. The infiltration characteristic curve for silt loam soil found at the study site was computed using the Horton (1939) infiltration equation (4.2):

$$f = f_c + (f_o - f_c)e^{-kt} \tag{4.2}$$

where f is infiltration capacity; f_o is initial infiltration capacity; f_c is final infiltration capacity, t is time; and k is an empirical constant. For the silt loam soil the values used for f_o, f_c, and k, were 7.62 cm/h, 0.508 cm/h, and 0.069 1/min, respectively (Akan, 1993).

4.2.2.1 Measuring MDI dripline emitter flow rate

A total of 86 emitters (47 of MDI_1 and 39 of MDI_2) were randomly selected from different driplines, from all the fours spans of the center pivot. With the center pivot running, a measuring cylinder bottle (volume 480 mL) was held directly under each of the selected dripline emitters for a period of 120 sec and the amount of water collected (mL) in each gauge was divided by the set time to get the emitter flow rate in (mL/s). The means of the measured emitter flow rates were found to be 3.7±0.29 L/h for the MDI_1 and 7.3±0.58 L/h for the MDI_2 driplines. The measured flow rates were close to the manufacturer's values for both driplines (Netafim USA, 2018). The application rate of the MDI was computed as:

$$d_{MDI} = \frac{q_d \cdot n}{10^4 (cm^2)} \tag{4.3}$$

where d_{MDI} is application rate of MDI; $q_d (cm^3/h)$ is dripper flow rate; n is number of drippers per meter of dripline.

4.2.2.2 Measuring LESA flow rate

Irrigation gauges were placed directly under the path of the LESA sprinklers as shown in Figure 4.2(c). The timer was started when the first water droplets from the sprinkler reached the location of the gauge. After two minutes, the irrigation gauge was quickly removed and replaced with an empty gauge and the timer reset. The amount of water collected in the gauge over the two minutes was recorded. The procedure was repeated with the sprinkler moved towards and away from the gauge. This was continued until no additional water from the sprinkler reached the gauge.

The application rate of the LESA at time, t, was computed as:

$$d_{LESA} = \frac{V_s(cm^3/h)}{A_{can}(cm^2)} \quad (4.4)$$

where d_{LESA} is application rate of LESA; V_s (cm^3/h) is volume of water emitted by LESA spray that is caught in irrigation gage per unit time; $A_{can}(cm^2)$ is cross-section area of irrigation gage.

4.2.2.3 Measuring LEP flow rate

Before a LEPA bubbler reaches a point above a location in its path, water starts reaching the point in the form of a thin sheet flow as shown in Figure 4.2(b). This happens because a bubbler applies water in the form of a turbulent vertical flow, and water is not horizontally projected away from the bubbler, as with sprinklers. When the water exiting the bubbler impacts a horizontal surface (such as soil surface), it flows radially away from the point of impact and causes sheet water flow that can reach areas behind, and in front, of the point of impact along the travel path of the bubbler. This localized surface runoff enables the wetting of the soil surface between two bubblers. In this experiment, the flow rate of the LEPA bubbler was measured by placing a pan directly under the path of the LEPA bubbler. The time it took the LEPA bubbler to completely pass a 21.6 L pan (diameter of 29.2 cm, depth of 35.0 cm) in span 3 was also one minute; during which it travelled 29.2 cm.

. The application rate of the LEPA was computed as:

$$d_{LEPA} = \frac{q_b\ (cm^3/h)}{10^4(cm^2)} \quad (4.5)$$

where d_{LEPA} is application rate of LEPA; q_b (cm^3/h) is LEPA bubbler flow rate. Figure 4.3 shows the calculated infiltration characteristic curve for silt loam soil and the application rates of the irrigation application devices MDI_1, MDI_2, LEPA, and LESA.

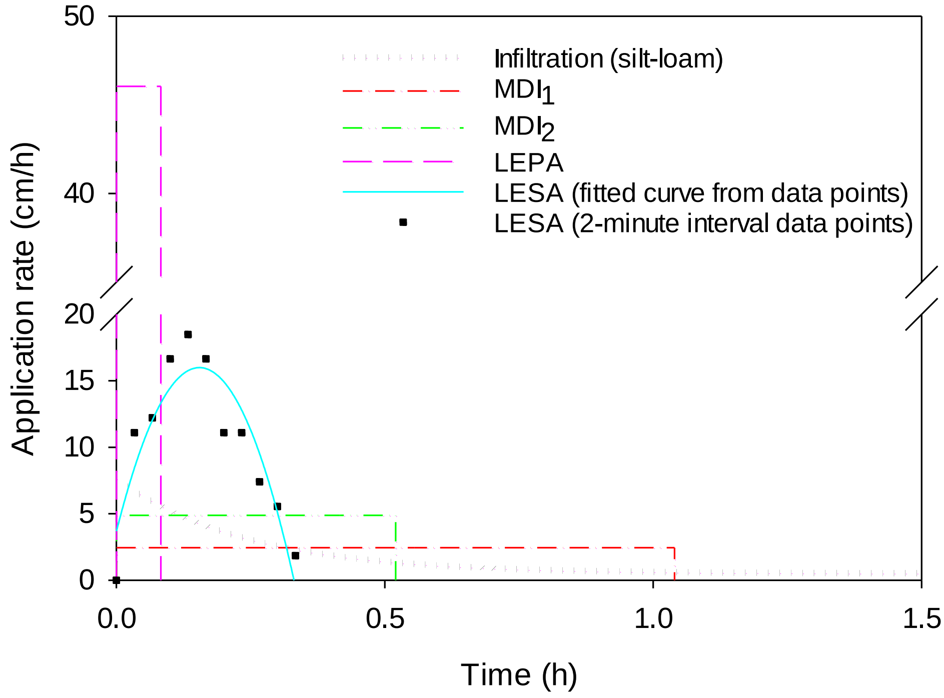


Figure 4.3 Measured application rates for MDI_1, MDI_2, LEPA, and LESA

4.2.3 Two-dimensional soil water flow modelling with HYDRUS

HYDRUS-1D and HYDRUS (2D/3D) are software packages that simulate water, heat, and solute movement in variably saturated porous media (Šimůnek et al., 2016). They are widely used in research and industry for modelling water, heat, and solute transport in the vadose zone. At the core of HYDRUS is the Richards equation, which is solved using finite element methods (Šimůnek et al., 2016). HYDRUS (2D/3D), version 2.05, simulates soil water movement in both two and three dimensions. In this study, the interest was to simulate water redistribution within the soil profile, in a two-dimensional plane between a set of irrigation devices. The 2-D form of the Richards equation solved by HYDRUS (2D/3D) (Li et al., 2015) is expressed as:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \qquad (4.6)$$

where θ is volumetric water content (m^3/m^3); $K(h)$ is unsaturated hydraulic conductivity (m/s); t is time (s); x and z are horizontal and vertical coordinates (directed downwards) (m); and h is the pressure head (m).

4.2.3.1 Soil hydraulic properties

The van Genuchten-Mualem model (van Genuchten, 1980) was used to describe the soil hydraulic properties. The water retention curve, $\theta(h)$ and the hydraulic conductivity function $K(h)$ are presented by the following equations (4.7) and (4.8):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \tag{4.7}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{l/m}\right)^m\right]^2 \tag{4.8}$$

where

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

and

$$m = 1 - \frac{1}{n}$$

In equations 4.7 and 4.8, θ_s and θ_r are saturated and residual water contents, respectively; K_s is saturated hydraulic conductivity; α, m, and n are constants, and l is a parameter for tortuosity. The values of flow parameters for silt loam shown in Table 4.1 were accessed from the soil catalogue and Rosetta software (Schaap et al., 1998) built-in within the HYDRUS (2D/3D) model (Šimůnek et al., 2016).

Table 4.1 Water flow parameters for silt loam soil used in HYDRUS (2D/3D)

Soil type	θ_r	θ_s	α (1/cm)	n	K_s (cm/h)	l
Silt loam (Soil catalogue)	0.067	0.450	0.020	1.410	0.450	0.5
Silt loam (Rosetta)	0.0645	0.439	0.0051	1.663	0.761	0.5
% difference	3.7	2.5	74.5	17.9	69.1	0

4.2.3.2 Model domain setup

Figure 4.4 shows the model domain. The width of the 2-D model domain was based on crop (corn) and emitter (MDI, LESA, and LEPA) spacing with two rows of crops between a pair of irrigation emitters, 76.2 cm and 152.4 cm, respectively. The domain depth was set to match the maximum depth of measurement of soil water content, 243.8 cm. Points marked "X" are calibration points from which water content was measured using a neutron probe.

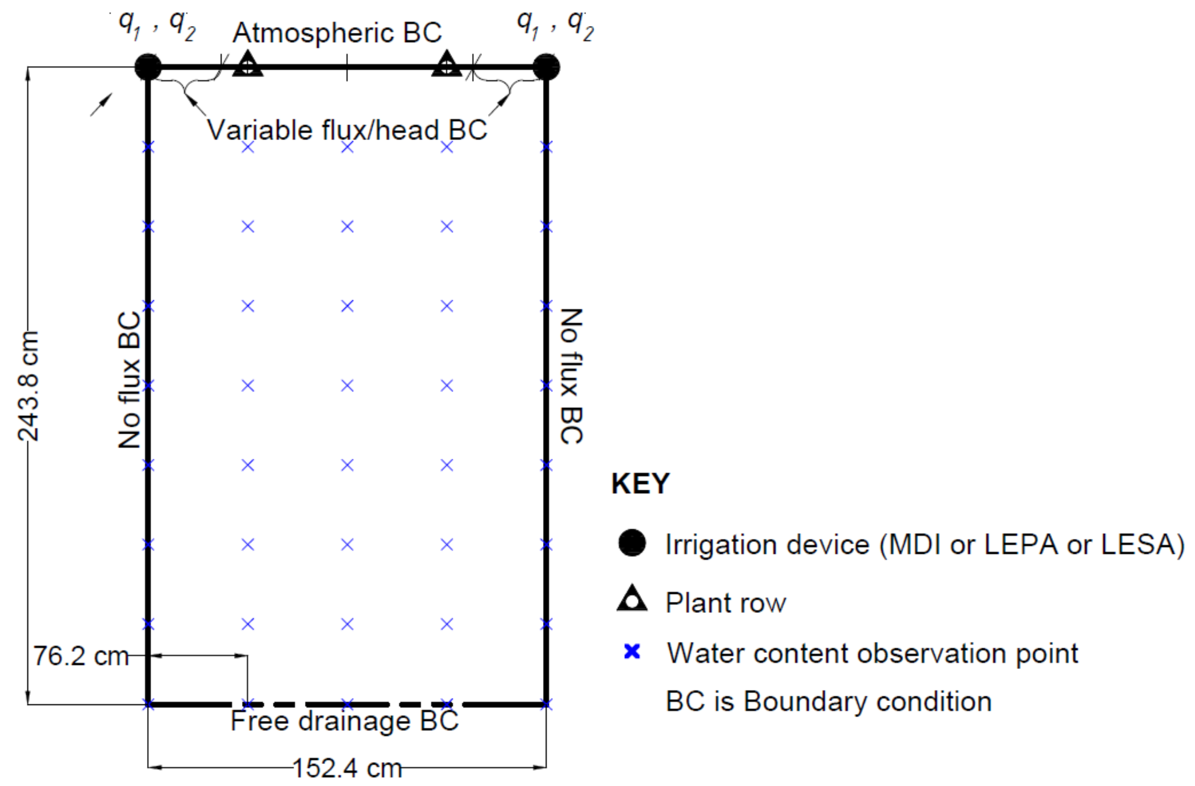


Figure 4.4 HYDRUS (2D/3D) model computational domain

4.2.3.3 Boundary conditions

The boundary conditions of the model domain are described in Figure 4.4. For the four different application devices (MDI_1, MDI_2, LESA, and LEPA), the boundary conditions at the bottom, and right and left sides of the model domain stay the same whereas they vary for the upper boundary. Free-drainage boundary condition was set at the bottom boundary, while no-flux boundary condition was maintained on the right and left sides of the domain. Top boundary represents a soil surface on which the irrigation application devices emit water. The applied flux varies with the emitter type. For surface drip irrigation modelling, HYDRUS (2/3D) uses a computational module available under its "special boundary conditions" menu item (Šejna et al., 2016) with "dynamic wetting" specified at the soil surface. The dynamic wetting area represents the maximum distance from dripline, on which water flows on the surface and before it starts to infiltrate into the soil. However, the main limitation of modelling drip irrigation with "dynamic wetting" in HYDRUS (2D/3D) was inability to model two drip emitters simultaneously, which was essential for simulation the effect of soil water distribution between two emitters. The dripline was implemented as a time-variable flux originating from both corners of the top boundary. Dripline boundary flux, q, (cm/h) in HYDRUS (2D/3D) was calculated as (PC-Progess, 2008);

$$q = Q_t/L \tag{4.9}$$

where Q_t (cm^3/h) is drip tape discharge and L (cm) is drip tape circumference. Drip tape discharge is calculated as (PC-Progess, 2008):

$$Q_t = Q/d \tag{4.10}$$

where Q is dripper discharge (cm^3/h) and d (cm) is distance between drippers on a dripline. The internal diameter and dripper spacing of both driplines were 1.48 cm and 15.5 cm respectively. Using equations (4.9) and (4.10), the boundary fluxes for MDI_1 and MDI_2 were computed as 51.4 and 102.8 cm/h, respectively. Computed boundary fluxes q_1 and q_2 were implemented as time-variable boundary fluxes in HYDRUS (2D/3D) at the top of the model domain as show in Figure 4.4. In this study, LESA was assumed to emit water in the form of raindrops (precipitation) and applied in HYDRUS (2D/3D) as an atmospheric boundary condition. The application rates of the LESA spray, V measured at two-minute time intervals, were converted into flux by computing the depth, d of water captured in the gauge. Depth, d $(\mathrm{cm/s})$, was calculated by dividing the volume of water captured in the can, V (cm^3), by the cross-sectional area, A (cm^2), of the irrigation gauge. The diameter of the irrigation depth measurement gauge used was 10.16 cm. Therefore, its cross-sectional area, A is 81.1 cm^2. The applied flux q_3 was calculated by converting depth, d, to units of cm/h. Table 4.2 below shows the flux for the LESA spray nozzle that were applied to HYDRUS (2D/3D).

Table 4.2 LESA spray nozzle flux calculation

Time (h)	Volume, V (cm^3)	Depth, d x 10^{-3} (cm/s)	Flux, q (cm/h)
0.00	0	0.00	0.00
0.03	30	3.08	11.10
0.07	33	3.39	12.21
0.10	45	4.62	16.64
0.12	50	5.14	18.49
0.17	45	4.62	16.64
0.20	30	3.08	11.10
0.23	20	2.05	7.40
0.27	20	2.05	7.40
0.30	15	1.54	5.55
0.33	5	0.514	1.85

In HYDRUS (2D/3D), a flow from the LEPA nozzle was represented as a time-variable pressure head. Under this condition, flow from the bubbler was assumed to pond on the surface of the soil and then infiltrate into the soil over time. The assumption of ponding is supported by field observations (Figure 4.2(b)). The flow rate of the LEPA bubbler at the measurement point was 0.3601 L/s. This implies that it took the bubbler 70.5 s to apply 2.54 cm of water (equivalent to 25.4 L) on a square meter area. The flow rate of the bubbler thus exceeded the infiltration capacity of the soil of 0.7608 cm/h. A time-variable pressure head of 2.54 cm was applied to the top right and left corners of the HYDRUS (2D/3D) model domain for 3.3 h.

4.2.3.4 Initial conditions

Soil water content, before and after irrigation, was measured on October 28 and 31, 2016, respectively; using a CPN soil moisture neutron probe from locations shown in Figure 4.1. A set of two measurements of soil water content at each depth were taken. The mean of the two measurements, for each layer, was taken as the water content for that layer. Soil water content was measured in eight layers along the depth of the soil profile. The measured soil water content before the irrigation event were input into HYDRUS (2D/3D) as initial soil water content (Table 4.3).

Table 4.3 Initial soil water content used as input in the HYDRUS (2D/3D) model

Depth (m)	MDI_1	MDI_2	LEPA	LESA
0.30	0.222	0.271	0.241	0.275
0.61	0.228	0.245	0.230	0.221
0.91	0.190	0.192	0.169	0.188
1.22	0.196	0.191	0.171	0.200
1.52	0.217	0.217	0.200	0.212
1.83	0.217	0.216	0.211	0.209
2.13	0.214	0.225	0.207	0.204
2.44	0.215	0.229	0.212	0.211

MDI_1 is Mobile Drip Irrigation (3.8 L/h dripper)
MDI_2 is Mobile Drip Irrigation (7.6 L/h dripper)
LEPA is Low Energy Precision Application
LESA is Low Elevation Spray Application

4.2.3.5 Soil evaporation

The experiment was conducted on bare soil, which made it important to account for water loss due to soil evaporation. In HYDRUS (2D/3D) soil evaporation is computed for the atmospheric boundary condition. Reference evaporation, ET_0 data from an onsite weather station, for days between October 28 and 31, 2016 were used. ET_0 values for the days of October 28, 29, 30, and 31 were 0.660, 0.279, 0.737, and 0.42 cm, respectively.

4.2.4 Statistical evaluation of model

The goodness of the fit between the measured and HYDRUS (2D/3D) simulated soil water content, after irrigation, were evaluated using the root mean square error (RMSE) statistics:

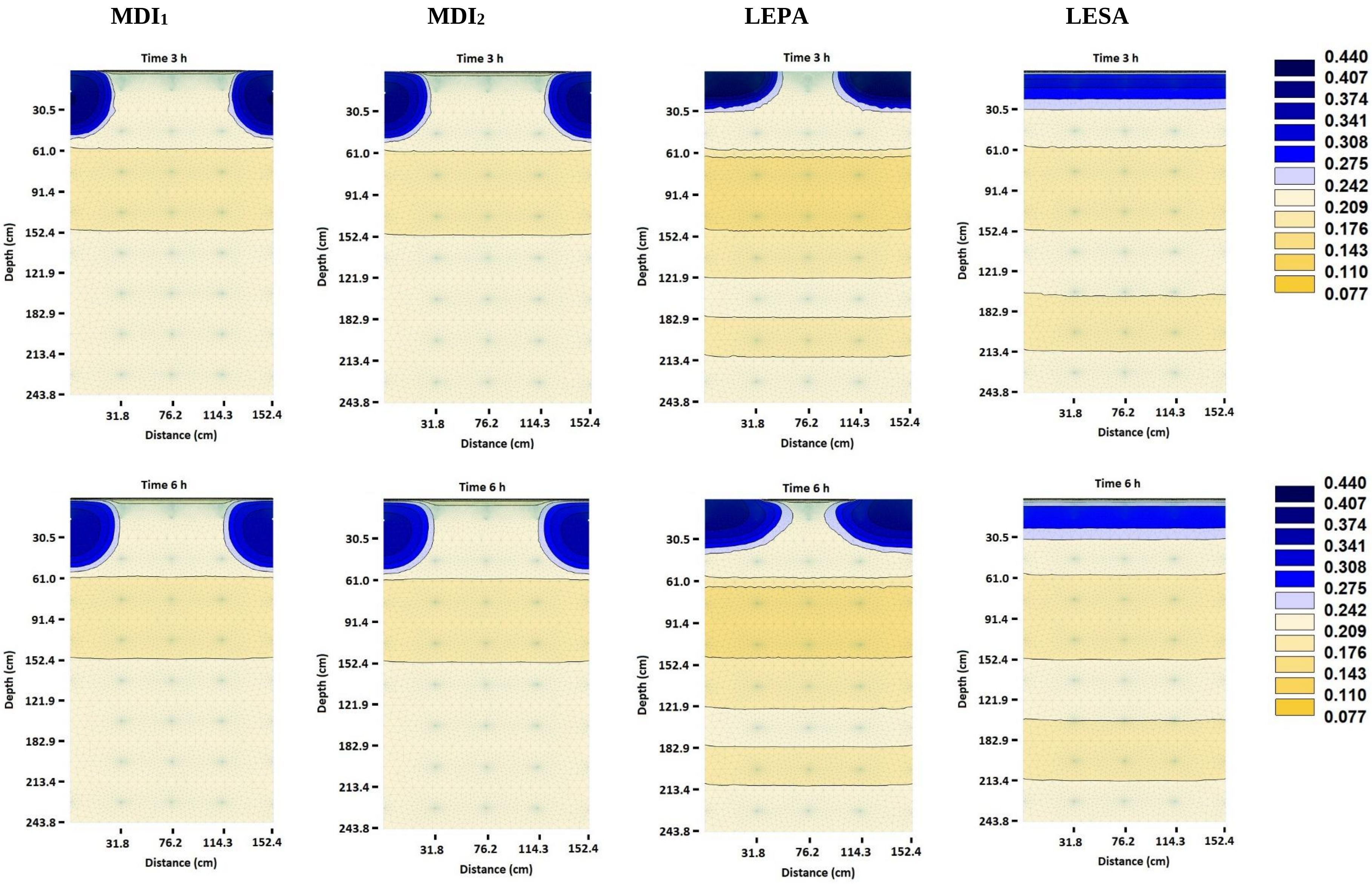
$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\theta_{m_i} - \theta_{s_i})^2} \qquad (4.11)$$

where θ_{m_i} and θ_{s_i} are measured and simulated soil water content, respectively, and n is number of observations. Naglič et al. (2014) and Skaggs et al. (2004) used similar techniques in related works. The HYDRUS (2D/3D) model used in the study had a total of 40 observation points interspersed within its domain as illustrated in Figure 4.4.

4.3 Results and Discussions

4.3.1 Model evaluation

HYDRUS (2D/3D) simulations of water redistribution within the soil profile with time for MDI_1, MDI_2, LEPA, and LESA are shown in Figure 4.5. The graphs show water redistribution patterns after 3, 6, 24, and 72 h for the different irrigation application devices. Comparisons of measured and simulated water content, after 72 h, along the soil profile for MDI_1, MDI_2, LEPA, and LESA are shown in Figure 4.6 with the RMSE statistics for tested irrigation application devices of 0.039 cm cm^{-3} for MDI_1; 0.036 cm cm^{-3} for MDI_2; 0.021 cm cm^{-3} for LEPA; and 0.039 cm cm^{-3} for LESA. These values are comparable to those observed in similar studies. For instance, in drip irrigation numerical modeling studies with HYDRUS, Kandelous and Šimůnek (2010b) reported the RMSE in the range of 0.011 - 0.045 cm cm^{-3}, and Skaggs et al., (2004) reported RMSE in the range of 0.01 - 0.04 cm cm^{-3}. The effect of irrigation is visible in the top 60 cm of the soil profile for all the tested irrigation application devices as shown in Figure 4.5 and Figure 4.6. Beyond this range, there is no pronounced change in water content. The simulations were improved by adjusting soil hydraulic properties away from the default values stipulated for silt loam in the model. In HYDRUS (2D/3D), the soil hydraulic properties in the inbuilt soil catalog and the Rosetta (neural network) predicted values vary for silt loam (Table 4.1). The biggest differences are in saturated hydraulic conductivity (69.1%) and curve parameter α (74.5%). Running the model with default values for silt loam in the HYDRUS (2D/3D) soil catalogue yielded numerical instability when drip irrigation was simulated. Increasing the saturated hydraulic conductivity, k_s, of the soil resolved the drip irrigation modelling problem. The curve parameter, α significantly improved water content values in the top layer of the profile and hence other overall model calibration. The HYDRUS (2D/3D) model was calibrated by adjusting saturated hydraulic conductivity to 0.654 cm hr^{-1} and curve parameter to 0.01628 cm^{-1}.


MDI1
MDI2
LEPA
LESA
Time 3 h
Time 6 h
Depth (cm)
30.5
61.0
91.4
152.4
121.9
182.9
213.4
243.8
Distance (cm)
31.8
76.2
114.3
152.4
0.440
0.407
0.374
0.341
0.308
0.275
0.242
0.209
0.176
0.143
0.110
0.077

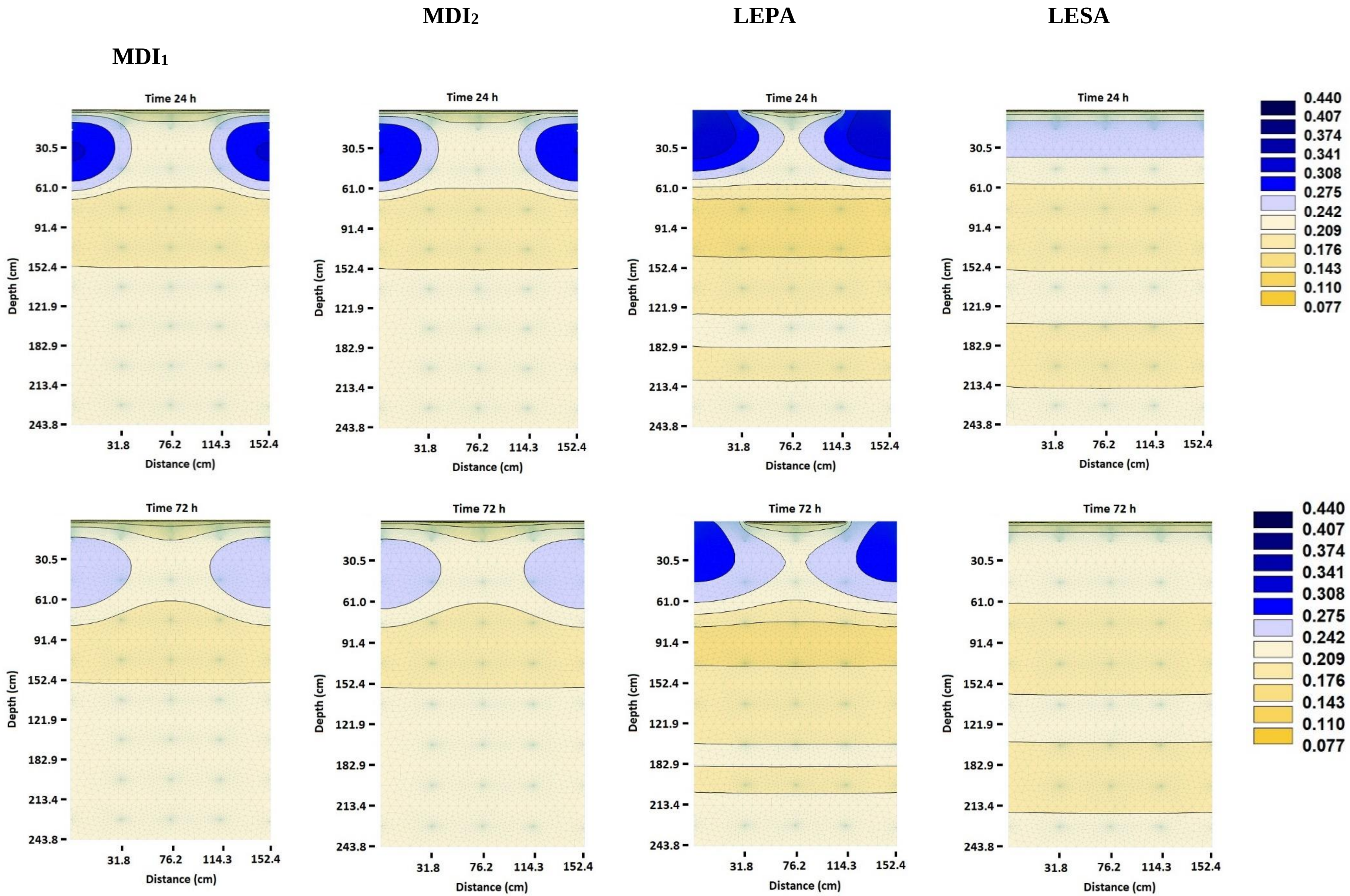
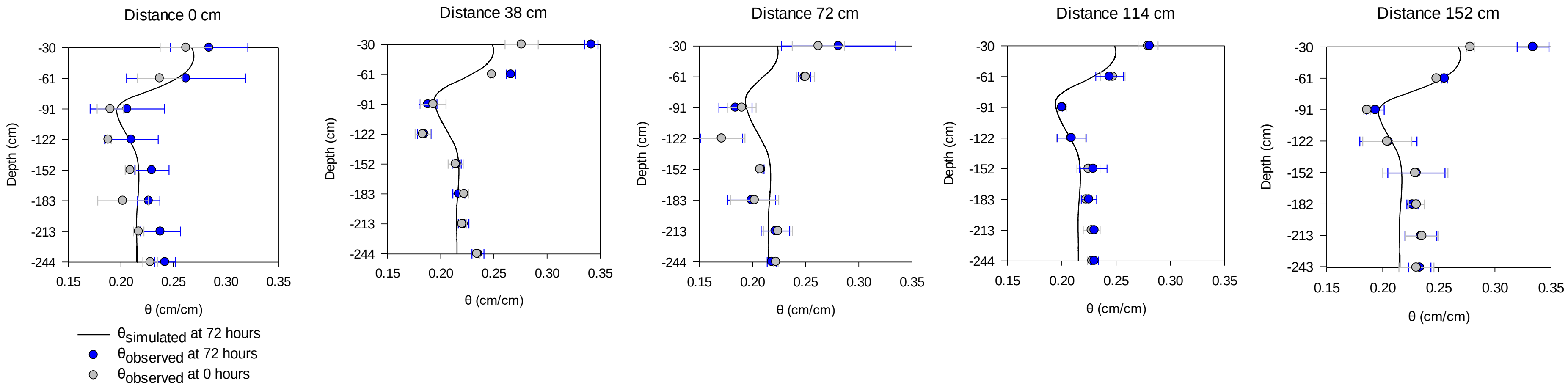
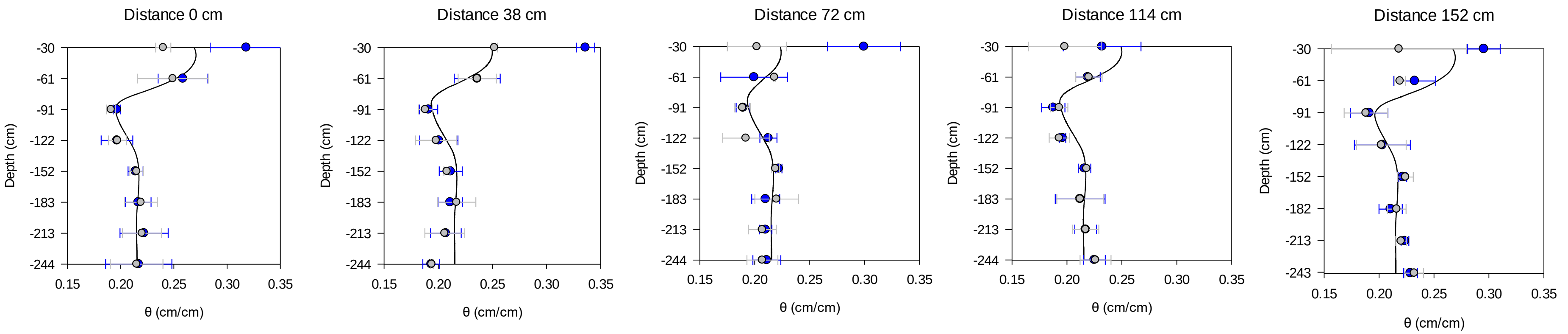


Figure 4.5 Soil water distribution in a silt loam under irrigation with MDI, LEPA and LESA

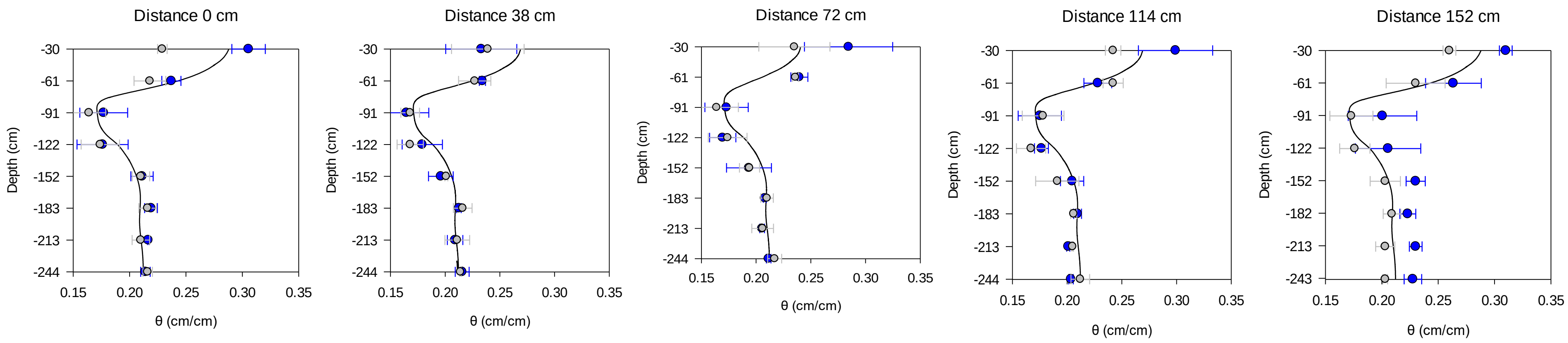
MDI_1


Distance 0 cm
Distance 38 cm
Distance 72 cm
Distance 114 cm
Distance 152 cm
Depth (cm)
-30
-61
-91
-122
-152
-183
-213
-244
0.15 0.20 0.25 0.30 0.35
θ (cm/cm)
θsimulated at 72 hours
θobserved at 72 hours
θobserved at 0 hours

MDI_2


Distance 0 cm
Distance 38 cm
Distance 72 cm
Distance 114 cm
Distance 152 cm
Depth (cm)
-30
-61
-91
-122
-152
-183
-213
-244
0.15 0.20 0.25 0.30 0.35
θ (cm/cm)

LEPA



LESA

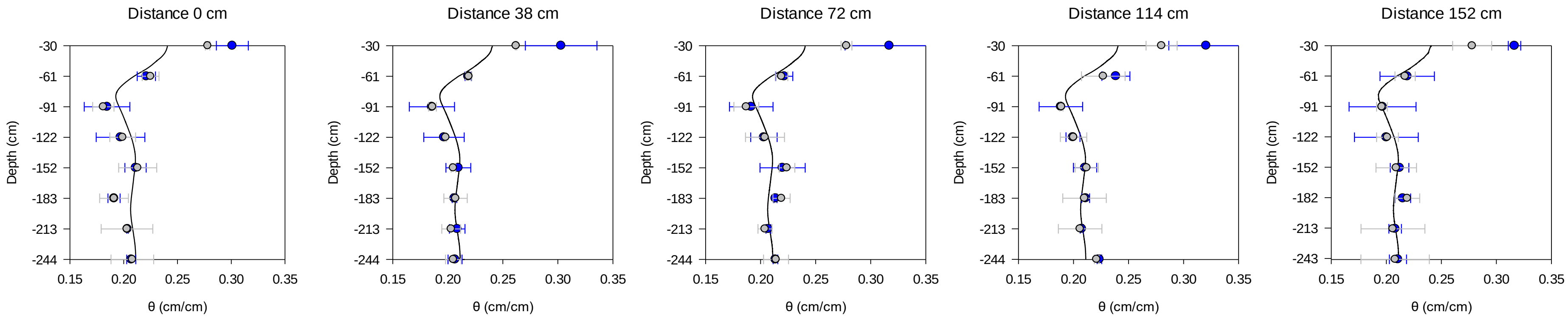


Figure 4.6 Simulated and observed soil profile water content as affected by horizontal distance from left to right

4.3.2 MDI water redistribution

In assessing the post-irrigation soil profile water redistribution, the interest was to measure how effectively water moves from the point of direct application to other secondary points in all directions within the soil profile. This was highlighted in studies by Cooley et al., (2007), Kandelous and Šimůnek, (2010a), and Skaggs et al., (2004). For irrigation devices, such as driplines, which are designed to wet only a small fraction of the soil surface, the measurement of horizontal water movement is important; especially where there is no dripline between two, or more, successive crop rows. Figures 4.7 and 4.8 show variations in soil water content, for the MDI_1, MDI_2, LEPA, and LESA, in the horizontal plane at depths of 30, 60, and 90 cm. LESA shows the smallest variation in soil water content at all depths. This is expected because this method of irrigation is designed to wet the entire soil surface, which allows the horizontal spread of the water front for uniform vertically movement in the profile, assuming homogeneity of the soil. Variation in soil water content in the horizontal plane, in both MDIs and LEPA followed a sinusoidal pattern, with maximums at points of direct application, and lows at the mid-point between the application devices. MDI_1, MDI_2, and LEPA show the highest variation in water content. Median water content at 30 cm depth were 0.250, 0.249, 0.271, and 0.240 cm cm^{-3}, for MDI_1, MDI_2, LEPA, and LESA, respectively (Figure 4.7(a)).

The statistical inter-quartile range (IQR) of soil water content values in horizontal plane (between two emitters) was computed for MDI_1, MDI_2, LEPA, and LESA. Low and high IQR values correspond to low and high variabilities in soil water contents, respectively. The soil water content IQR at 30 cm, for MDI_1 and MDI_2, differed from that of the LESA by 97.1% and 94.1%, respectively; indicating a significant difference in profile water redistribution between MDI and LESA spray. The soil water content IQR at 30 cm, for MDI_1, and MDI_2 varied from that of the LEPA bubbler by 0.98% and 0.96% implying that the MDI matched LEPA bubbler's water redistribution. Though MDI_1, and MDI_2 water redistribution at 30 cm depth was notably different from that of LESA, its median water content was much higher Figure 4.7(a)). This shows that both MDIs enabled greater storage of water within the soil profile in comparison with the LESA spray. The higher soil water content observed under MDI is attributed the reduction in soil evaporation. At 60 cm depth, the median water contents were 0.224, 0.249, 0.220, and 0.210 cm cm^{-3} for MDI_1, MDI_2, LEPA, and LESA, respectively. Soil water content IQR were 0.032, 0.031, 0.026, and 0.000 cm cm^{-3}, respectively, at 60 cm depth. As observed at 30 cm depth, there is high variation in soil water content IQR between, both MDI_1 and MDI_2, and the LESA; 457% and 448%, respectively. The differences in IQR for both MDI_1 and $MDI_{2,}$ from that of the LEPA bubbler was 1.2%. Median water content at 90 cm depth were 0.195, 0.196, 0.171, and 0.197 cm cm^{-3} for MDI_1, MDI_2, LEPA bubbler, and LESA sprayer, respectively. IQR were 0.001, 0.000, 0.000, and 0.000 cm cm^{-3}, respectively Figure 4.7(b)). As shown by the much narrow IQRs, variations in water content at 90 cm, for all the four irrigations application technologies, were small. This is because the effect of irrigation did not have a significant effect on soil water content at 90 cm 72 h after water was applied. As shown in Figure 4.8 (a) and (b), the lowest water content for MDI and LEPA bubbler were at the mid-point between the irrigation devices. As expected the highest water contents were below the points of water application. Differences between the highest and lowest soil water contents for MDI_1, MDI_2, and LEPA bubbler were 0.044, 0.043, and 0.048 cm cm^{-3} at 30 cm depth, and 0.043, 0.043, and 0.037 cm cm^{-3} at 60 cm depth. At 90 cm depth, differences were negligible.

Though implementation of surface irrigation, in HYDRUS (2D/3D) as subsurface dripline, as described by Skaggs (2004) is a reasonable workaround, a more realistic representation of surface drip irrigation would be possible if the "dynamic wetting" option of the software could be adapted such that it can be implemented at more than a single point.

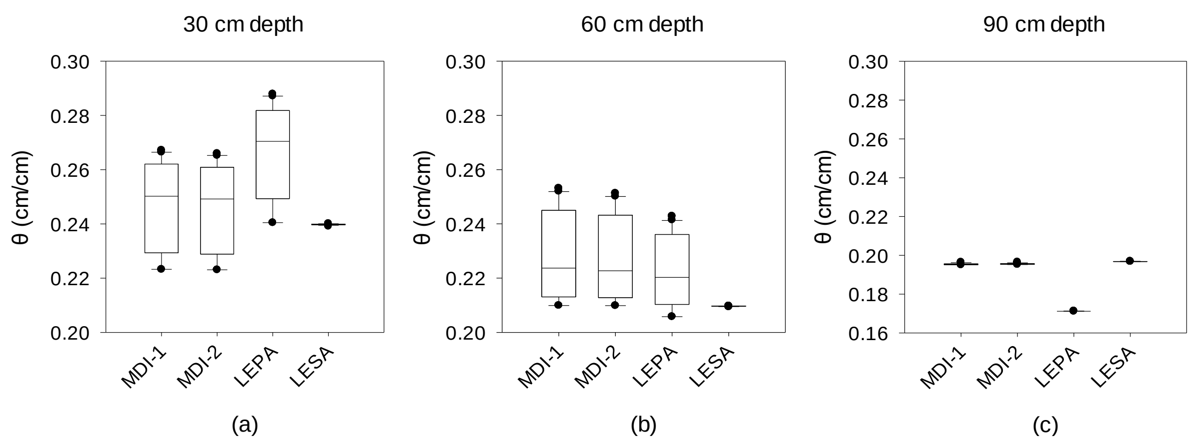


Figure 4.7 Variation in water content in horizontal direction at, (a) 30, (b) 60 and (c) 90 cm, after 72 h

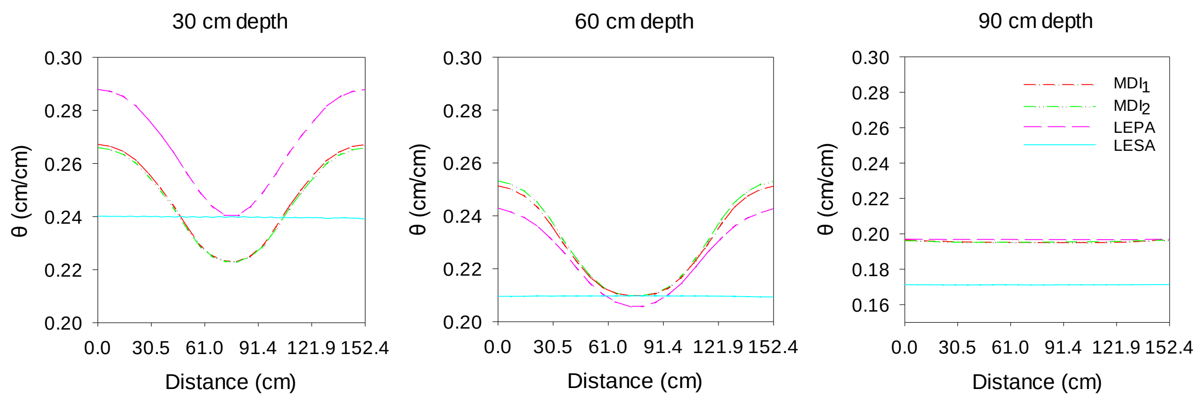


Figure 4.8 Water content along horizontal profile between two irrigation application devices after 72 h

4.3.3 Analysis of runoff potential

One of the problems of center pivots fitted with conventional or spray application devices is high runoff potential, especially in the outer spans of the center pivot (Kincaid, 2005). Runoff potential increases with distance from the pivot point of the center pivot. Besides leading to runoff, King and Bjornberg (2011) also reported that high application rates in center pivots led to soil erosion. Reducing the flow rate of the irrigation device, as reported by King and Bjornberg (2011), reduces the runoff risk. However, reducing flow rate implies reducing the travel time of the center pivot, which often is practically challenging to producers, due to the need to maintain a set irrigation schedule for all of the irrigated area. MDI has the potential to address runoff problems in center pivots because of its low application rate. In this experiment, analysis for runoff reduction shows that both MDI_1 and MDI_2 had 48% less runoff potential compared with LEPA, and a 19% less when compared with LESA. Figure 4.9 shows how application rates for MDI, LEPA, and LESA increase with center pivot radius. For the center pivot used for this study, under LEPA, runoff potential increases by 30.5%, from span 1 to span 4. For LESA, runoff potential increases by 56.9%, from span 1 to span 4. For both MDI_1 and MDI_2, there is a less than 1% increase in runoff potential from span 1 to span 4. The increase in dripline length with increase in distance from the pivot point ensures that sufficient water is applied while maintaining a low application rate.

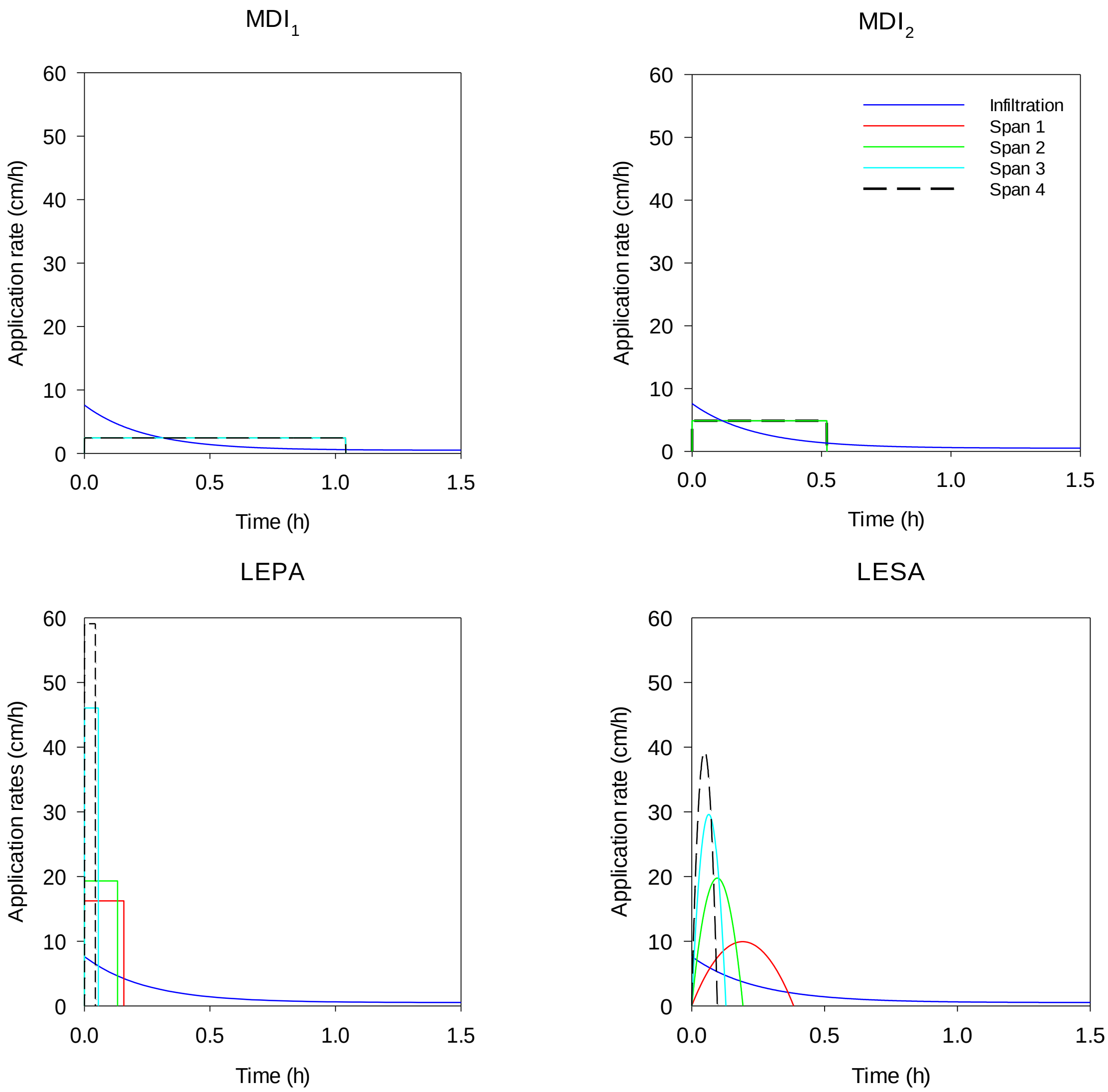


Figure 4.9 Application rates of MDI, LEPA, and LESA systems compared with the infiltration rate of a silt loam soil

4.3.4 MDI plant available water and root zone wetting

For silt loam soils, the plant-available-water (PAW) upper and lower soil water content limits are 0.3 and 0.15 $cm^3\ cm^{-3}$ respectively (O'Green, 2013). The available water is thus 0.15 $cm^3\ cm^{-3}$. Effective irrigation in such soils should ensure that water content should meet the upper limit of PAW. The modeling experiment, described in this study, was designed according to an irrigation schedule stipulating a water application depth of 2.54 cm every four days. This represented the "full irrigation" scenario to match corn evapotranspiration at the study site. Four days post irrigation, vertical water movement was limited to less than 90 cm depth, as illustrated by both HYDRUS model results and the measured water content data.

The rooting depth of corn usually ranges from 0.8 to 1.7 m (Pereira & Allen, 1999). Under the irrigation conditions previously described, the active zone of the corn crop would mostly be limited to the top 60 cm of the soil profile. Plant available water at 30 cm depth for both MDI_1 and MDI_2 ranged from 0.073 to 0.12 at the edges and center of the HYDRUS (2D/3D) model domain, respectively. At a depth of 60 cm, PAW for MDI_1 ranged from 0.10 to 0.06 from the edge to center, and that of MDI_2 ranged from 0.12 to 0.07, respectively. Considering maximum PAW of silt loam soil, which is 0.15, it is reasonable to state that both MDIs were able to meet irrigation design requirements. It is apparent that under MDI, PAW follows a sinusoidal pattern with peaks and troughs at the points directly below and farthest from the driplines, respectively. The magnitude of variation in water content between two adjacent MDIs is dependent on both soil hydraulic properties and driplines spacing.

4.4 Conclusions

The aim of this study was to evaluate the application efficacy of MDI and compare it against LEPA and LESA, two mainstream irrigation application systems. With the aid of numerical modelling, the analysis of how applied water redistributes within the soil profile with a special focus on MDI was conducted. The results of the study indicate that the MDI can effectively apply water and meet PAW across the soil profile. This conclusion supports the results by Kisekka et al., (2017). Although variability in water content, in the horizontal plane, under MDI was several magnitudes higher than that under LESA spray, the soil profile was still sufficiently wetted. Soil water content under MDI was higher than that of the LESA at 30, 60, 90 cm, which shows that the former was more efficient in storing water in soil profile. This is because MDI, like conventional drip irrigation, reduces soil evaporation as has been reported in numerous related studies. It also reduces runoff risk because of the low water application rates.

The results of this study were developed for a silt loam soil which was found at the study location near Garden City in southwest Kansas. To broaden the understanding of MDI performance, it would be beneficial to expand the study to different soil types. In this experiment, it was assumed that the driplines remained centered between rows as the center pivot moved. However, under the actual field conditions, the driplines are rarely position perfectly between the rows as the center pivot moves. Dripline movement is an even bigger problem if the crop rows are not circular. This leads to non-uniform water application as the pivot moves, an action which in turn undermines proper water redistribution within the soil profile. For this reason, it is important to assess MDI performance under conditions where driplines are not properly aligned between crop rows. The problem of dripline misalignment in center pivots could, however, be solved by a precise planting in circular rows with the aid of GPS guided tractors. This study answered an important question about the technical viability of MDI, specifically, if water application uniformity under MDI was comparable to commonly used LESA and LEPA technologies? The findings of this study conclude that MDI can reasonably apply water uniformly to fields, and that MDI water redistribution is comparable that to that of LEPA, a commonly used device. The illustration that MDI significantly reduces runoff risk in center pivots will help make the technology an attractive option to areas more prone to runoff and soil erosion.

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Chapter 5 – Evaluation of corn production under Mobile Drip Irrigation

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Abstract

Declining water levels in the Ogallala aquifer of the U.S. High Plains necessitate more efficient irrigation technology to help sustain agricultural production. A study to evaluate the performance of Mobile Drip Irrigation (MDI) for corn production, in comparison to common center pivot nozzles (Low Elevation Spray Application (LESA) and Low Energy Precision Application (LEPA)) was conducted. A center pivot was retrofitted with MDI, LEPA and LESA. Irrigation capacities of 6.3, 3.1, and 1.6 mm/d were considered. Grain yield, water productivity, above ground biomass, leaf area index (LAI), and soil water content was compared. Differences in grain yield between irrigation application devices were not significant ($p = 0.085$), but there were differences between irrigation capacities was significant ($p < 0.0001$), at 5% significance level. There were no significant differences in monthly biomass yield between the application devices but there were significant differences in biomass yield between irrigation capacities. There were no significant differences in LAI between both the application devices and irrigation capacities. There were no significant differences in water productivity between the application technologies ($p = 0.2352$), at 5% significance level, however, differences between irrigation capacities were significant ($p = 0.050$). Generally, crop

[1] Oker, T. E., Kisekka, I., Sheshukov, A. Y., Aguilar, J., Rogers, D. H. (2018). Evaluation of maize production under mobile drip irrigation. Agricultural Water Management, 210, 11–21. https://doi.org/10.1016/J.AGWAT.2018.07.047

biophysical measurements under MDI were not significantly different from those under LEPA and LESA. Any marginal benefits of MDI were likely masked by rainfall, thus further evaluation of MDI is recommended under conditions of less applied water than LEPA or LESA accompanied by low rainfall. The other benefits of MDI were found in reduction of wheel-track rutting and ease of carrying out fertigation.

Keywords: Mobile Drip Irrigation; LEPA; LESA; Center pivot; Irrigation; Ogallala

5.1 Introduction

Corn is one of the major crops cultivated in the U.S. Midwest, and it is among the five main crops grown in Kansas (Kansas Department of Agriculture, 2016a). The state of Kansas is among the top ten producers of corn for grain in the U.S. contributing 4% of the total national production (USDA National Agricultural Statistics Service, 2015). In addition to grain production, Kansas grows some corn for silage. Between 2011 and 2015, the average value of corn exported annually from Kansas was $339.92 million (Kansas Department of Agriculture, 2016b), making it the fifth largest agricultural export. The land area under corn production in Kansas has increased over the years indicating an upward trend into the future. Between 2006 and 2016, the average acreage under corn production was 1,738,125 ha (Kansas Department of Agriculture, 2016b). The crop is grown in all geographic regions of Kansas, but the southwest and northwest regions of the state are the two largest production areas by land area. These areas are also in the western region of Kansas, which receives the lowest amounts of rainfall averaging 440 mm annually (Goodin et al., 2004; Rahmani et al., 2013). Corn is the most irrigated crop in Kansas according to (Kenny & Juracek, 2013) and requires from 500 to 800 mm of rainwater to meet full crop evapotranspiration demands (Rogers et al., 2015). To meet the water demand in western Kansas, additional 13.6 to 81.8% of crop water need to be supplied through irrigation. According to Kenny and Juracek (2013), the mean irrigation application rate for corn in Kansas is 381 mm/year with an upward trend in the acreage from 1992 to 2011. In 1992, corn contributed to 43% of irrigated acreage followed by increase to 56% in 2000 and 58% in 2011 (Kenny & Juracek, 2013). Although corn production in Kansas has steadily increased over the years, the amount of water in the Ogallala aquifer, which is a main source of groundwater used for irrigation, declined (McGuire, 2017; Steward et al., 2013; Wada et al., 2010). This reduction in groundwater levels has led to diminished well pumping capacities (Steward et al., 2013) and affected farming decisions and management practices. Improved irrigation efficiency is the water management strategy that can extend the usable life of the Ogallala aquifer as well as better cope with water scarcity.

More than 90% of irrigation in Kansas (Rogers et al., 2008) is done using center pivots that are typically fitted with Low Elevation Spray Application (LESA) nozzles (Lamm et al., 2006). LESA is one of two spray nozzle categories. The other is Mid Elevation Spray Application (MESA) which is better suited for fields with high elevation changes. Although not common in Kansas, Low Energy Precision Application (LEPA) nozzles are widely used in many regions of the Southern High Plains, like Texas (O'Shaughnessy et al., 1999). The earliest iteration of LEPA devices were developed in Texas by Lyle and Bordovsky (1983) and the primary design objective was to develop devices which could operate at low pressures to save energy and water (Lamm et al., 2006). A LEPA application device could refer to either a sock that is dragged on the ground, or a bubbler fitted a slight distance off the ground (Schneider & Howell, 1999). For this study, a LEPA bubbler was selected. The application efficiencies these technologies are in the ranges of 70-80% for LESA (Irmak et at., 2011; Rajan et al., 2015), 80-95% for LEPA (Irmak et al., 2011; Waller & Yitayew, 2016) and 85% for MESA (Peters et al., 2016).

Though they are relatively efficient irrigation technologies, there are some water loss pathways which they cannot prevent, like canopy interception and evaporation, soil water evaporation, wind drift and runoff. Mobile Drip Irrigation (MDI), in theory, has potential to eliminate the aforementioned water loses, hence improve irrigation efficiency of center pivot systems. In MDI, water is applied directly to soil surface instead of aerial broadcasting in LEPA and LESA. MDI is the combination of drip irrigation, presently the most efficient irrigation method (Goyal, 2012; Pathak et al., 2009), and center pivot systems. Instead of typical spray nozzles, the center pivot is fitted with drip lines that are dragged along the soil surface as the center pivot rotates during irrigation event. The MDI concept has been tried in the past using various configurations that were dependent on the prevailing technologies of the time (Phene et al., 1981; Phene et al., 1985), but its development and adoption was beset by technological challenges. With technological advancements in irrigation, such as improvement in water filtration and pressure compensating emitters (Kisekka et al., 2017), the interest in MDI was revived and, furthermore, bolstered by the need for more efficient irrigation technologies that are better adapted to water scarcity and increase water conservation. The objective of this study was to evaluate corn production under MDI as compared to LEPA and LESA, two common irrigation application devices used by farmers in the Ogallala area of Kansas. This is an effort to benchmark modern MDI against other well-known and widely-used irrigation technologies.

5.2 Materials and Methods

5.2.1 Field description

A two-year field experiment on biophysical properties of corn impacted by different irrigation technologies (MDI, LEPA and LESA) was conducted at the Kansas State University's

Southwest Research and Extension Center near Garden City, Kansas (32.024° lat., -100.826° long., 885 m above sea level). The experimental field was in Ulysses silt loam soil (Stone et al., 2011) and under four-span center pivot with Variable Rate Irrigation (VRI) capability. The center pivot had the following specifications: span one 41.6 m; spans two and three of 41.2 m; span four of 41.1 m; and 5.5 m overhang (Figure 5.1). The experiment was set up on the eastern half of the center pivot as a 3x4 split-plot randomized complete block design, with two factors (irrigation capacity and irrigation application device) and three replications (Figure 5.1). Span 1 not considered for data collection. Therefore, there were 12 treatments in each block, with a total of 36 treatments for the whole experiment. A treatment was made up of an irrigation device and an irrigation capacity. Each span was divided into four equal parts that accommodated two MDIs with dripper flow rates of 3.8 L/h and 7.6 L/h (hereafter, MDI_1 and MDI_2, respectively), LEPA bubbler, and LESA spray nozzle. The applied three irrigation capacities were 6.2, 3.1, and 1.6 mm/d that related to full, 1/2, and 1/4 corn evapotranspiration (ET) demands, respectively, for the studied site. A matrix of the irrigation treatment combinations is shown in Table 5.1.

Table 5.1 Irrigation treatment combinations for a Mobile Drip Irrigation Study conducted in corn at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas from 2016 to 2017.

	MDI_1	MDI_2	LEPA	LESA
6.2 mm/d	T1	T2	T3	T4
3.1 mm/d	T5	T6	T7	T8
1.6 mm/d	T9	T10	T11	T12

MDI_1 is dripline of flow rate 3.8 L/h
MDI_2 is dripline of flow rate 7.6 L/h
LESA is Low Elevation Spray Application
LEPA is Low Energy Precision Application

5.2.2 Agronomic Management

For both years, a no-till planter was used to plant the corn, in fields covered with stubble from previous seasons. The corn varieties of Deklab 64-89 in 2016 and Deklab 62-98 in 2017 were planted at a seeding rate of 84,016 seeds/ha.

In the 2016, the corn was planted on May 6th and emerged on May 23rd, while in 2017, it was planted on May 8th and emerged on May 22nd. Fertilizer was applied in three stages: (1) nitrogen in form of urea (N-P-K; 46-0-0) applied at rate of 336.3 kg/ha before planting; (2) phosphorus (N-P-K; 11-52-0) applied at a rate of 112.1 kg/ha and; (3) nitrogen, phosphorus and potassium fertilizer combination (N-P-K; 10-34-0), applied in liquid form at a rate of 93.5 L/ha at the time of planting. For both 2016 and 2017, the following herbicides were applied to corn-stubble covered field before planting: (1) Starene Ultra (fluroxypyr) at a rate of 0.95 L/ha; (2) Lumax EZ (S-metolachlor, atrazine, mesotrione) at a rate of 7.0 L/ha and; (3) Sharpen (saflufenacil) at a rate of 0.15 L/ha. In 2016, Roundup Max (glyphosate) was also applied at a rate of 2.3 L/ha before planting in addition to the mentioned herbicides. In 2017, Rifle (dicamba) at a rate of 1.2 L/ha, Balance Flexx (isoxaflutole) at a rate of 0.11 L/ha, and Cornbelt atrazine 90DF (atrazine) at a rate of 1.12 kg/ha were also parts of the herbicide treatment before planting. Furthermore, Prowl H2O (pendamethalin) at rate of 3.5 L/ha and Roundup Max (glyphosate) at rate of 2.3 L/ha were applied after corn emergence in 2017. A pesticide, Zeal SC (etoxazonle), was aerial-sprayed at a rate of 0.29 L/ha on 9 August 2017 as an extra treatment against spider mite infestation.

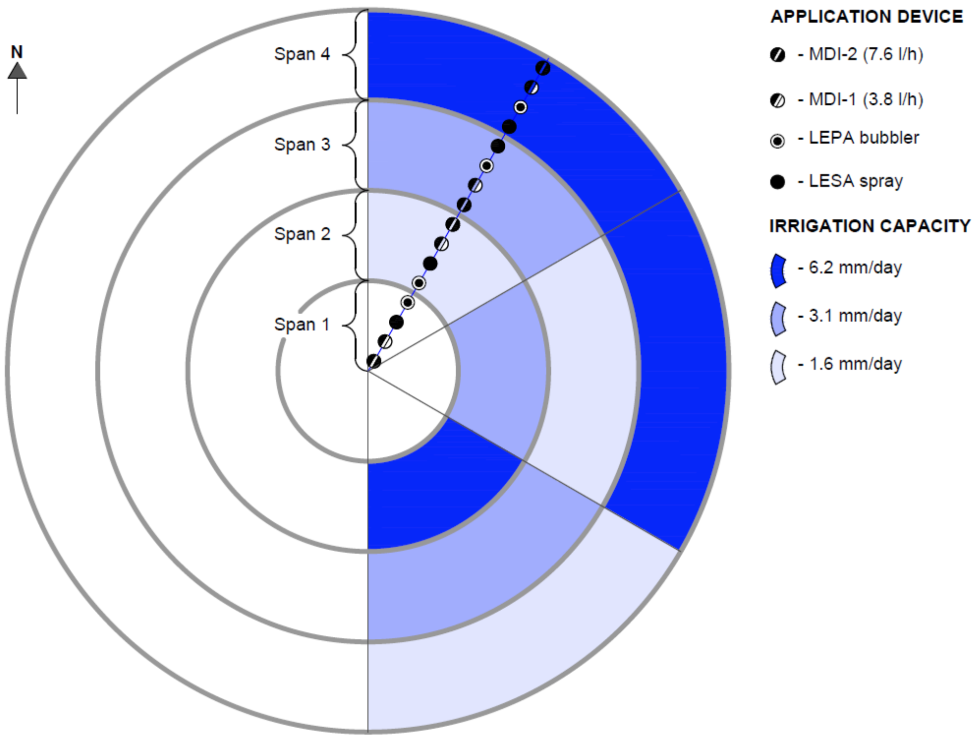

Figure 5.1 Center pivot schematic showing experimental setup and irrigation treatment (i.e., devices and irrigation capacities) corn at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas from 2016 to 2017.

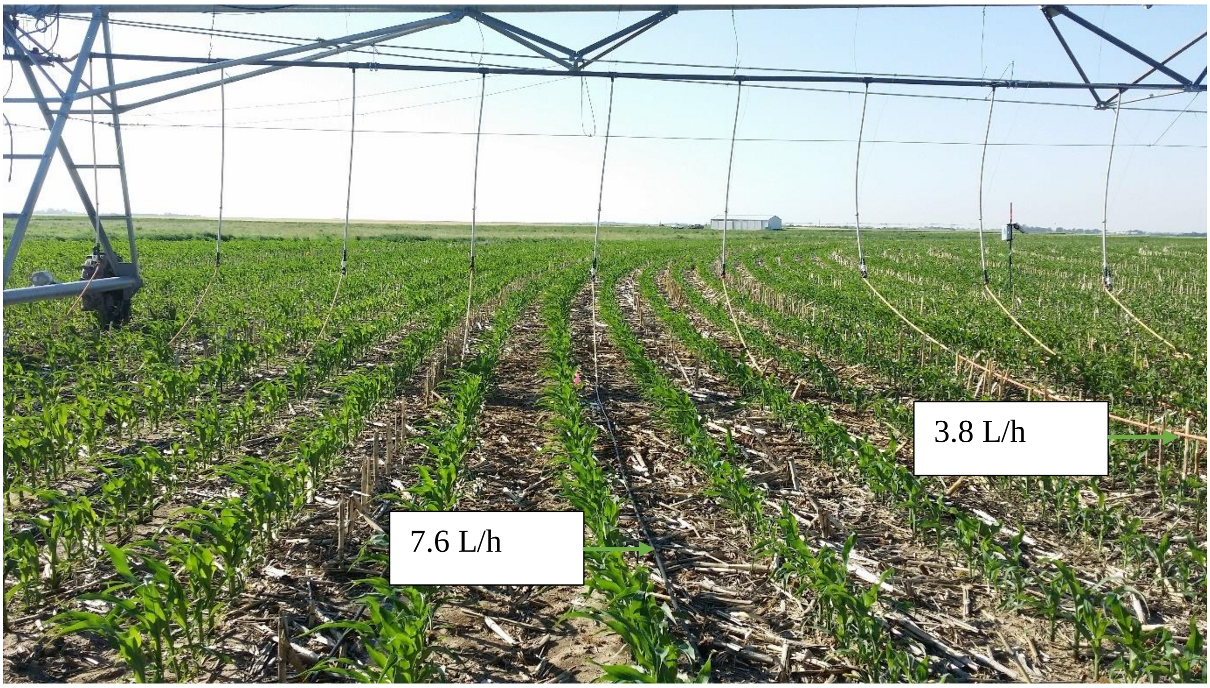

Figure 5.2 Center pivot span showing irrigation of corn using MDI of 3.8 and 7.6 L/h flowrates, at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas.

5.2.3 Irrigation management

After planting, 12.7 mm of water was applied to all treatments to aid germination uniformity. Thereafter, irrigation schedules were determined by frequently computing the water balance using soil water content, rainfall, and reference evapotranspiration data. During each irrigation event, 25.4 mm of water was applied to all studied plots and considered to complement water application by rainfall during the season. The irrigation capacities of 6.2, 3.1, and 1.6 mm/d were derived from well capacities of 37.9, 18.9 and 9.5 L/s, respectively. The irrigation capacity of 6.2 mm/d was designed to ensure meeting full seasonal ET requirement for corn. Thus, the irrigation capacities of 3.1 and 1.6 mm/d met 50% and 25% of seasonal ET, respectively. In the 2016 season, the amounts of water applied were 215.9, 114.3, and 88.9 mm for respective irrigation capacities of 6.2, 3.1, and 1.6 mm/d, while in 2017 they were 266.7, 139.7, and 88.9 mm/d, respectively.

Table 5.2 Dates of irrigation application events for 2016 for irrigation capacities 6.2, 3.1 and 1.6 mm/d at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas from 2016 to 2017.

	Depth of water applied		
Date	**IC_1**	**IC_2**	**IC_3**
10-May-16	12.7	12.7	12.7
25-May-16	25.4	25.4	25.4
8-Jun-16	25.4		
11-Jun-16		25.4	25.4
22-Jun-16	25.4		
29-Jul-16	25.4		
20-Aug-16	25.4	25.4	
26-Aug-16	25.4		
29-Aug-16	25.4	25.4	25.4
9-Sep-16	25.4		
Total	**215.9**	**114.3**	**88.9**

IC_1, IC_2, and IC_3, are irrigation capacities of 6.2, 3.1 and 1.6 mm/d

Table 5.3 Dates of irrigation events for 2017 for irrigation capacities 6.2, 3.1 and 1.6 mm/d at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas from 2016 to 2017.

Date	**Depth of water applied**		
	IC_1	**IC_2**	**IC_3**
10-May-17	12.7	12.7	12.7
25-May-17	25.4	25.4	25.4
17-Jun-17	25.4		
23-Jun-17	25.4		
30-Jun-17	25.4		
7-Jul-17	25.4		
25-Jul-17	25.4	25.4	25.4
6-Aug-17	25.4	25.4	
15-Aug-17	25.4	25.4	
25-Aug-17	25.4	25.4	25.4
14-Sep-17	25.4		
Total	**266.7**	**139.7**	**88.9**

IC_1, IC_2, and IC_3, are irrigation capacities of 6.2, 3.1 and 1.6 mm/d

5.2.4 Soil water content

Soil water content was measured weekly, unless hindered by excessive rainfall events, using a neutron attenuation probe (CPN 503DR Hydroprobe by Campbell Pacific Nuclear International Inc.; http://www.cpn-intl.com/503-elite-hydroprobe/). In each treatment sub-plot, neutron probe access tubes were installed for measuring volumetric soil water content at 0.3 m intervals up to a depth of 2.4 m. Each neutron probe access tube was installed between two plants in a selected row.

5.2.5 Biophysical properties

Biomass measurements were taken monthly. For each treatment, five plants in a healthy row were randomly selected and cut at the base. They were then ground into fine pulp using a motorized forage chopper. The samples of pulp were inserted into paper bags and dried at 60°C in a forced-convection electrical oven until no significant changes in sample weights taken between successive dates were detected. The weights of dry sample were recorded, and biomass yield, Y_b (kg/ha), was calculated as:

$$Y_b = \frac{W_b \cdot m}{n} \tag{5.1}$$

where W_b is sample weight (kg), m is the number of plants per hectare (ha^{-1}), and n is the number of plants harvested. Leaf area index was periodically measured using a ceptometer (AccuPAR LP-80, METER Group, Pullman, WA (METER GROUP Inc, 2017)). The grain was determined to be harvest-ready upon the attainment of black-layer (Daynard & Duncan, 1969). To determine grain yield, corn cobs were hand-harvested from 12.2 m long sections of randomly selected crop rows. The above ground dry matter-based grain yield, Y_d (kg ha^{-1}), was calculated using equation (5.2):

$$Y_d = \frac{W_s \cdot MC}{A} \tag{5.2}$$

where W_s is sample weight (kg), A is harvest area (ha), and MC is moisture content of a sample (%). The grain yield, Y (kg ha^{-1}), adjusted to 15.5% moisture content was calculated as:

$$Y = Y_d \cdot MC_{15.5} \tag{5.3}$$

where $MC_{15.5}$ is 15.5% moisture content.

5.2.6 Water productivity

Water productivity is the ratio of yield to water used for crop growth (Cai & Rosegrant, 2003; Zwart & Bastiaanssen, 2004). Assuming that runoff and deep drainage were negligible, the grain water productivity, WP_{grain} (kg ha^{-1} mm^{-1}), was computed as:

$$WP_{grain} = \frac{Y}{ET} \quad (5.4)$$

$$ET = R + I + \Delta S \quad (5.5)$$

where Y is grain yield (kg ha^{-1}), ET is crop evapotranspiration (mm), R is rainfall (mm), and I is irrigation (mm). The change in water storage, ΔS, is the difference between the first water content, taken immediately after planting, and the last water content, taken when grain maturity was reached.

5.2.7 Data analysis

A generalized linear mixed model was used to assess for differences in grain yield, biomass, weight, LAI, and water productivity among the treatments (Littell et al., 2006). The *GLIMMIX* procedure in SAS software was used for data analysis (Schabenberger, 2005). A 5% significance level was used to conduct statistical tests.

5.3 Results and Discussions

5.3.1 Rainfall

Total rainfall received at the experiment site for a growing season (April to October) were 475.5 and 440.8 mm for 2016 and 2017, respectively. These amounts are considered above normal seasonal rainfall totals for the Kansas State University Southwest Research Extension Center, and within the range of the yearly rainfall for western Kansas (Goodin et al., 2004; Rahmani et al., 2013).

Although the seasonal rainfall totals in 2016 and 2017 were close, their monthly distribution was different (Figure 5.3). The bulk of the rainfall in 2016 was constricted to the months of

April, May, June, July and August, with September and October receiving little or no rainfall. Between April and July, year 2016 received 179.3 mm more rainfall than the corresponding period in 2017. For this reason, fewer irrigation events were carried out in 2016 between April and July in comparison to 2017.

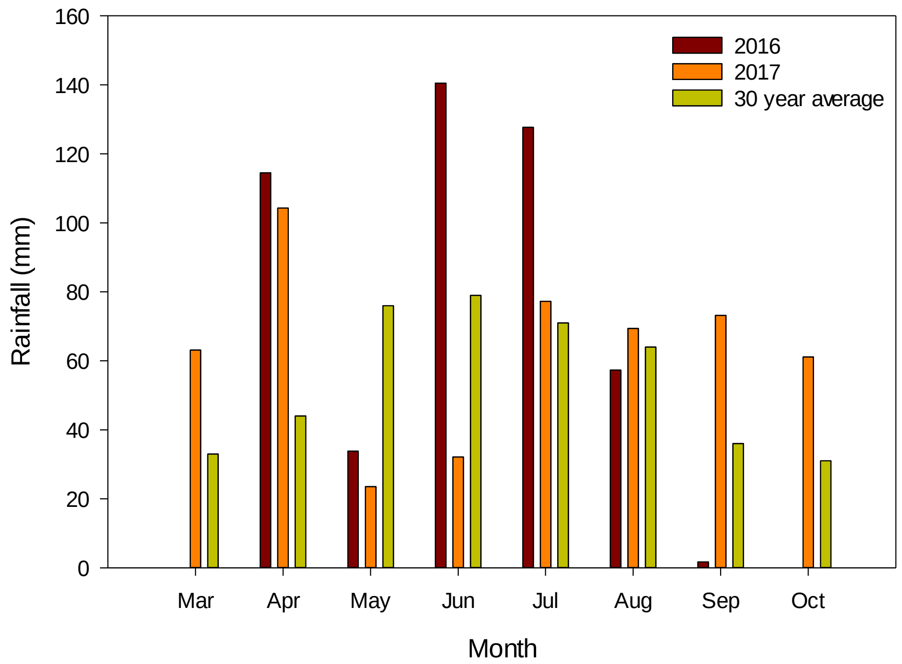

Figure 5.3 Monthly rainfall received at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas from 2016 to 2017.

5.3.2 Soil water content

Change in soil water storage, between the start and end of the cropping season, was used to

Change in soil water storage between the start and end of the cropping season was used to compare the differences in water application between the irrigation application devices. A similar approach was used by Benjamin et al. (2015) for comparison of the change in soil moisture storage under full and deficit irrigation scenarios. The results of the statistical analysis presented in Table 5.4 showed that the change in soil water storage among MDI, LEPA, and

LESA was not significantly different ($p = 0.1990$), while the change in storage between the rates of 6.2, 3.1 and 1.6 mm/d was significant as indicated by $p < 0.0001$ at 5% significance level. The highest and lowest changes in storage were for 1.6 and 6.2 mm/d treatments, respectively.

Soil profile water contents for 2016 and 2017 seasons are shown in Figures 5.4 and 5.5. Water content at the start of the 2017 season was significantly higher than in 2016. This is attributed to 63.1 mm of rainfall received in March 2017, whereas there was no rainfall in the same period in 2016. In 2017, generally for all treatments, the top layers in the soil profile had higher water content in comparison to 2016. This is attributed to a thick mulch of corn stover from the 2016 season. Higher soil water contents seen in September and October of 2017 were attributed to the 73.2 and 61.1 mm of rainfall received in those months respectively, in contrast to 1.7 and 0 mm received in the same period in 2016. Figures 5.4 and 5.5 indicate that MDI had larger zones of high water content than LESA and LEPA; even although the change in seasonal soil water storage was not statistically different for all the application technologies. Towards the end of the 2016 season, the largest soil water depletion was under the 6.2 mm/d irrigation capacity and at a depth range between 0.9 and 1.5 m for all irrigation devices. The depletion depths were greater for the 3.2 and 1.6 mm/d irrigation capacities, which indicated that the plants were drawing water from deeper depths. Similar depletion pattern was apparent for 2017 with the higher water content in the soil profile than in 2016.

Table 5.4 Change in soil water content between start and end of growing season at the Kansas State University Southwest Research and Extension Center near Garden City, Kansas from 2016 to 2017.

	Change in soil water storage (mm)	
	2016	**2017**
	6.2 mm/d	
MDI_1	-76.7±72.3	-8.5±48.8
MDI_2	-42.1±41.4	-2.1±59.9
LEPA	-80.2±27.0	-42.5±18.9
LESA	-61.0±58.1	-5.4±9.0
	3.1 mm/d	
MDI_1	-124.2±16.1	-44.5±30.4
MDI_2	-92.5±35.4	-50.0±9.1
LEPA	-114.2±14.0	-59.5±14.2
LESA	-58.9±33.8	-47.2±15.7
	1.6 mm/d	
MDI_1	-107.8±36.2	-102.9±19.8
MDI_2	-157.6±36.2	-124.5±39.6
LEPA	-119.5±6.4	-97.7±39.4
LESA	-114.0±51.9	-87.3±66.9

MDI_1 is dripline of flow rate 3.8 L/h
MDI_2 is dripline of flow rate 7.6 L/h
LESA is Low Elevation Spray Application
LEPA is Low Energy Precision Application

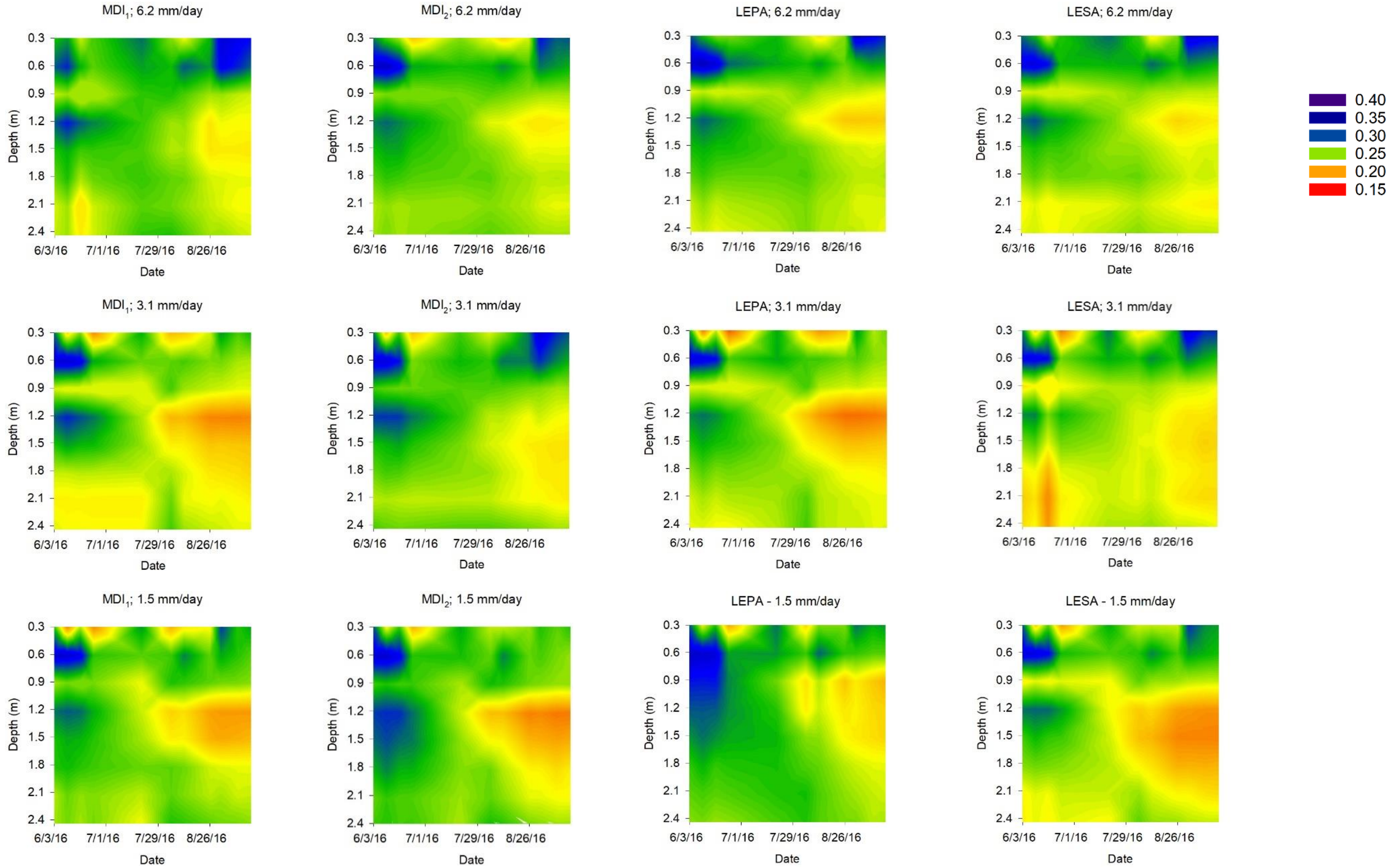

Figure 5.4 Soil water content changes under MDI, LEPA and LESA for the 2016 season

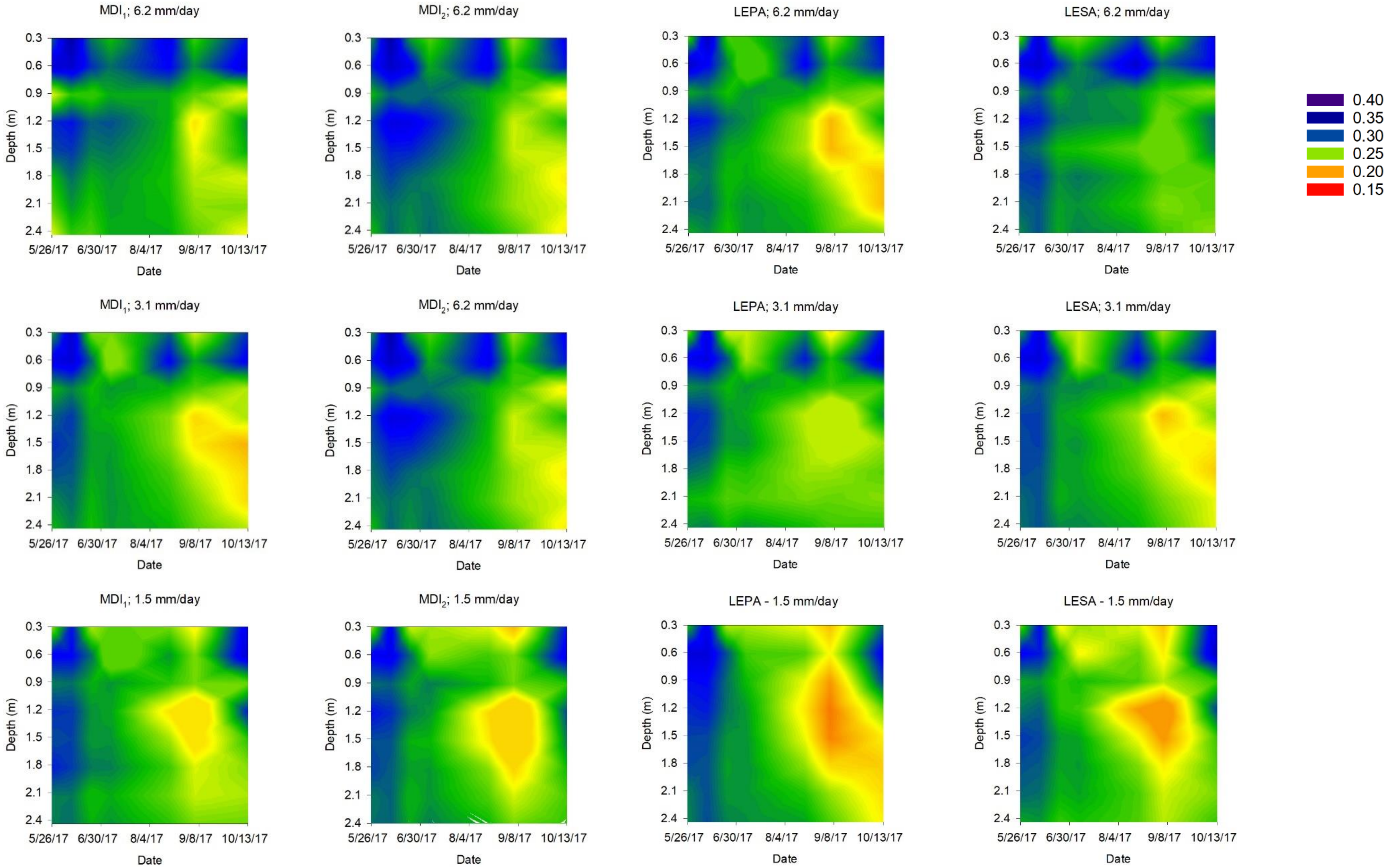

Figure 5.5 Soil water content changes under MDI, LEPA and LESA for the 2017 season

5.3.3 Grain yield, seed weight, biomass yield and LAI

The differences in grain yields[2] for 2016 and 2017 shown in Figure 5.6 for four irrigation application devices (MDI_1, MDI_2, LEPA, LESA) were not significant ($p = 0.085$) at 5% significance level. This finding is similar to observations reported by Kisekka et al. (2017) and O'Shaughnessy and Colaizzi (2017) who found no differences in grain yield between MDI and LESA. However, significant differences were found between the three irrigation capacities ($p < 0.0001$) at 5% significance level.

Table 5.5 shows the mean weights of the 500-seed-count[3] for each treatment. Although no significant differences ($p = 0.2134$, at 5% significance level) in the weights of seeds were found between the irrigation application devices, the differences between the three irrigation capacities were found significant ($p = 0.0148$). The interaction effects between application device and irrigation capacity did not have a significant effect on seed weight ($p= 0.5073$).

As anticipated, grain yield for all devices generally decreased when irrigation capacity decreased; 6.2 and 1.6 mm/d irrigation capacities caused the highest and lowest grain yields, respectively. The interaction effects between irrigation application devices and irrigation capacity were not significant ($p = 0.228$) at 5% significant level, which implies a general impact of irrigation capacity on grain yield regardless of the type of application device used. Based on five years (2005-09) of data by Klocke et al. (2011), the yields of corn grown in western Kansas and irrigated at 100%, 50%, and 25% capacities were 12,000, 9,000 and 6,000 kg/ha, respectively. These values represent yield differences of 25% and 50% in yield between the full, half and quarter irrigations. Klocke et al., (2007) also reported corn yields of 12,000 and

[2] Appendix F

[3] Appendix G

11,000 kg/ha for 100% and 50% irrigation for west central Nebraska region, indicating a marginal difference in yields between full and half irrigation. In this study, the difference in mean grain yield between 6.2 mm/d, and 3.1 and 1.6 mm/d irrigation capacities were small at 5.4% and 11.4%, respectively. Though irrigation capacity is known to be a significant determinant of grain yield, the slight differences observed between three irrigation capacities can be attributed to the effect of above normal growing season rainfall at critical growth stages, which reduced the impact of water stress in under-irrigated areas.

Monthly increases in biomass yield[4] plotted alongside in-season irrigation events for different treatments are shown in Figure 5.7. Similar to grain yield, there was no significant difference in monthly biomass yields between irrigation application devices for all months (Table 5.6). Except for the first month, there was significant difference in biomass yield between the 6.2, 3.1, 1.6 mm/d irrigation capacities. The interaction effects between irrigation application devices and irrigation capacity were found not significant (Table 5.6). Biomass yields in 2016 were generally lower than those in 2017, confirming the results of other studies on yearly corn biomass variation (Benjamin et al., 2015; Djaman et al., 2013; Ning et al., 2012).

Statistical analyses of monthly LAI[5] for 2016 and 2017 shown in Figure 5.8 were conducted separately because the monthly readings for either year were not taken on (or close to) the same dates. Table 5.7 and Table 5.8 show the least square means of LAI for 2016 and 2017. The results for 2016 show that there were generally no significant differences in LAI between both the application devices as well as irrigation capacities. In contrast 2017, while no significant differences in LAI were found between application devices, there were differences between

[4] Appendix H

[5] Appendix I

irrigation capacities. LAI for month one was not significantly different between either application devices or irrigation capacities. The interactive effects between the application devices and the irrigation capacities were also not significantly different.

The absence of significant differences found for plant growth parameters (grain yield, biomass yield, and LAI) between MDI, LEPA and LESA indicates that all devices delivered similar amounts of water to the crops. According to Yin and McClure (2013), biomass growth can be a good indicator of the health of a corn crop from early to mid-stages of its growth. Since other crop management factors (nutrients, weed, pests control) were the same for all irrigation treatments, the lack of significant difference in biomass yields between MDI, LESA, and LEPA indicates that all devices applied the same amount of water to the corn. A strong relationship exists between crop yields and ET (Saseendran et al., 2014), and reported for corn in several studies (Çakir (2004) and Djaman et al., (2013))

This study postulated that MDI would apply water more efficiently in comparison to LEPA and LESA, however, the results did not indicate any significant yield advantage of MDI over both LEPA and LESA. Kisekka et al. (2017) reported that soil evaporation under MDI was lower than that under LESA by 35%, indicating that MDI did apply water more efficiently which is consistent with drip irrigation in general. The reason why greater differences in the measured biophysical benefits were absent in this study can be attributed to the effect of rainfall received over 2016 and 2017 seasons.

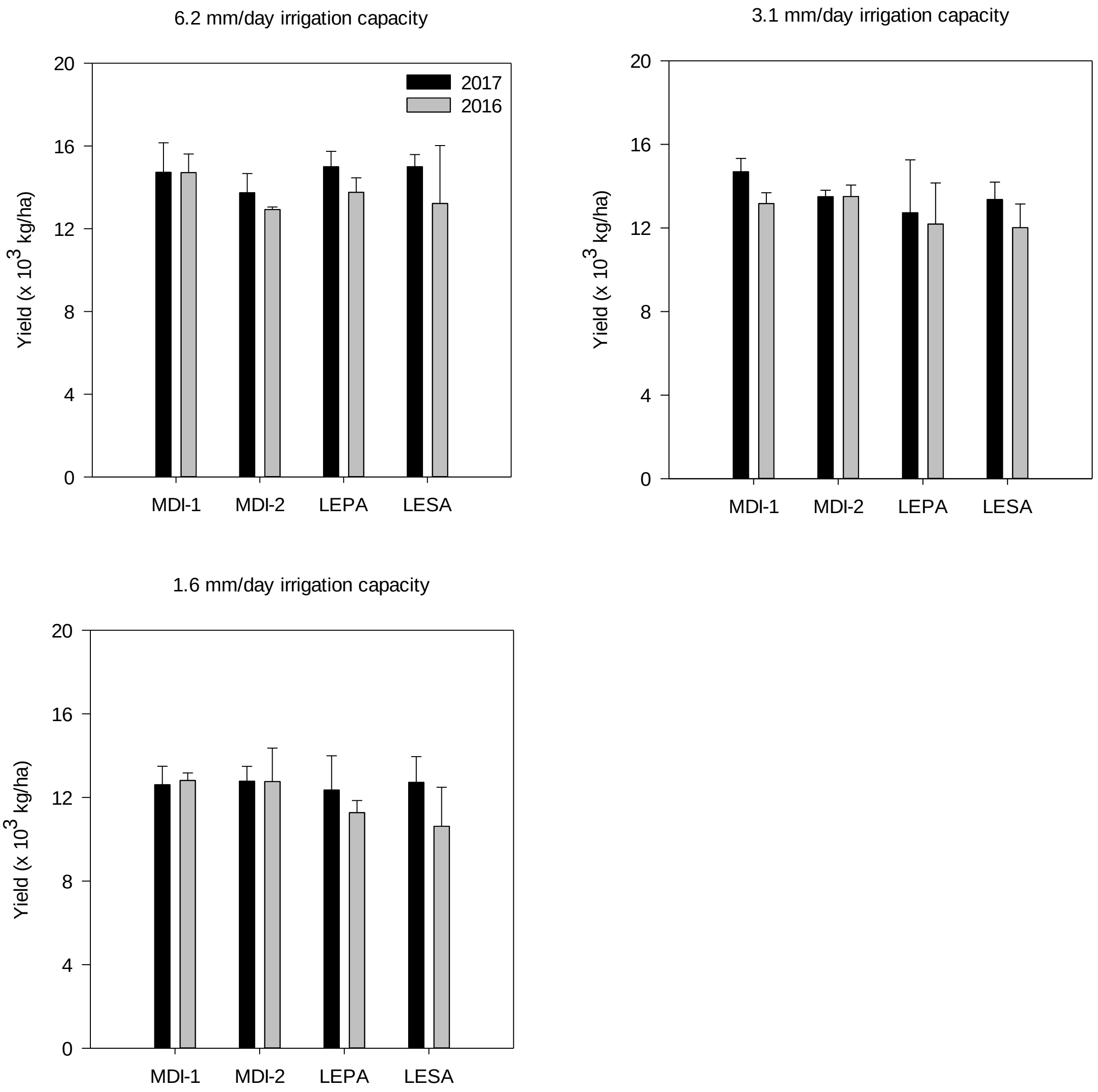

Figure 5.6 Grain yield under MDI, LEPA and LESA

Table 5.5 Weight of 500-seed-count for MDI, LEPA and LEAs for 6.2, 3.1, 1.6 mm/d irrigation capacities

Device	Mean 500-seed-weight (g)		
	6.2 mm/d	3.1 mm/d	1.6 mm/d
MDI$_1$	174.8±22.8	167.4±31.9	168.6±29.6
MDI$_2$	170.2±27.8	172.0±30.3	168.9±28.7
LEPA	171.7±29.3	164.8±30.0	165.3±31.1
LESA	171.7±29.0	166.0±37.8	159.2±36.8

Table 5.6 Least squares means of monthly biomass yield of corn for irrigation capacities of 6.2, 3.1 and 1.6 mm/d

	Biomass yield (kg/ha)			
	Month 1	Month 2	Month 3	Month 4
	6.2 mm/d			
MDI$_1$	1,111.5^{a,b}	14,033^{e,d}	17,137^{k}	25,058^{l}
MDI$_2$	1275.2^{a}	13,962^{e}	17,939^{h,i,j,k}	23,441^{m,n,l}
LEPA	833.7^{c}	18,206^{d}	19,958^{h,i}	25,435^{l}
LESA	1,006.4^{a,b,c}	15,670^{d}	20,117^{h}	24,021^{m,l}
	3.1 mm/d			
MDI$_1$	1,072.3^{a,b,c}	14,191^{e,f,g}	17,591 ^{i,j,k}	21,144^{o,n}
MDI$_2$	1,115.9^{a,b}	14,347^{e,f}	18,760 ^{h,i,j}	21,734^{m,o,n}
LEPA	985.9^{b,c}	14,597^{e,f}	17,661^{i,j,k}	21,114^{o,n}
LESA	1,158.9^{a,b}	12,388^{e,f,g}	17,845^{h,i,j,k}	21,342^{m,o,n}
	1.6 mm/d			
MDI$_1$	1,016.2^{a,b,c}	11,541^{e,f,g}	17,487^{j,k}	21,483^{m,o,n}
MDI$_2$	1,124.6^{a,b}	12,035^{e,f,g}	16,275^{k}	19,995^{o}
LEPA	1,036.1^{a,b,c}	12,399^{e,f,g}	15812^{k}	21,526^{m,o,n}
LESA	1,075.9^{a,b,c}	13,390^{e,f,g}	17,197 ^{j,k}	20,444^{o}
Application method	NS	NS	NS	NS
Irrigation capacity	NS	*	*	*
Interaction	NS	NS	NS	NS

NS – Not significant at 5% level; * - Significant ($p < 0.05$); Biomass yields with similar letters are not significantly different

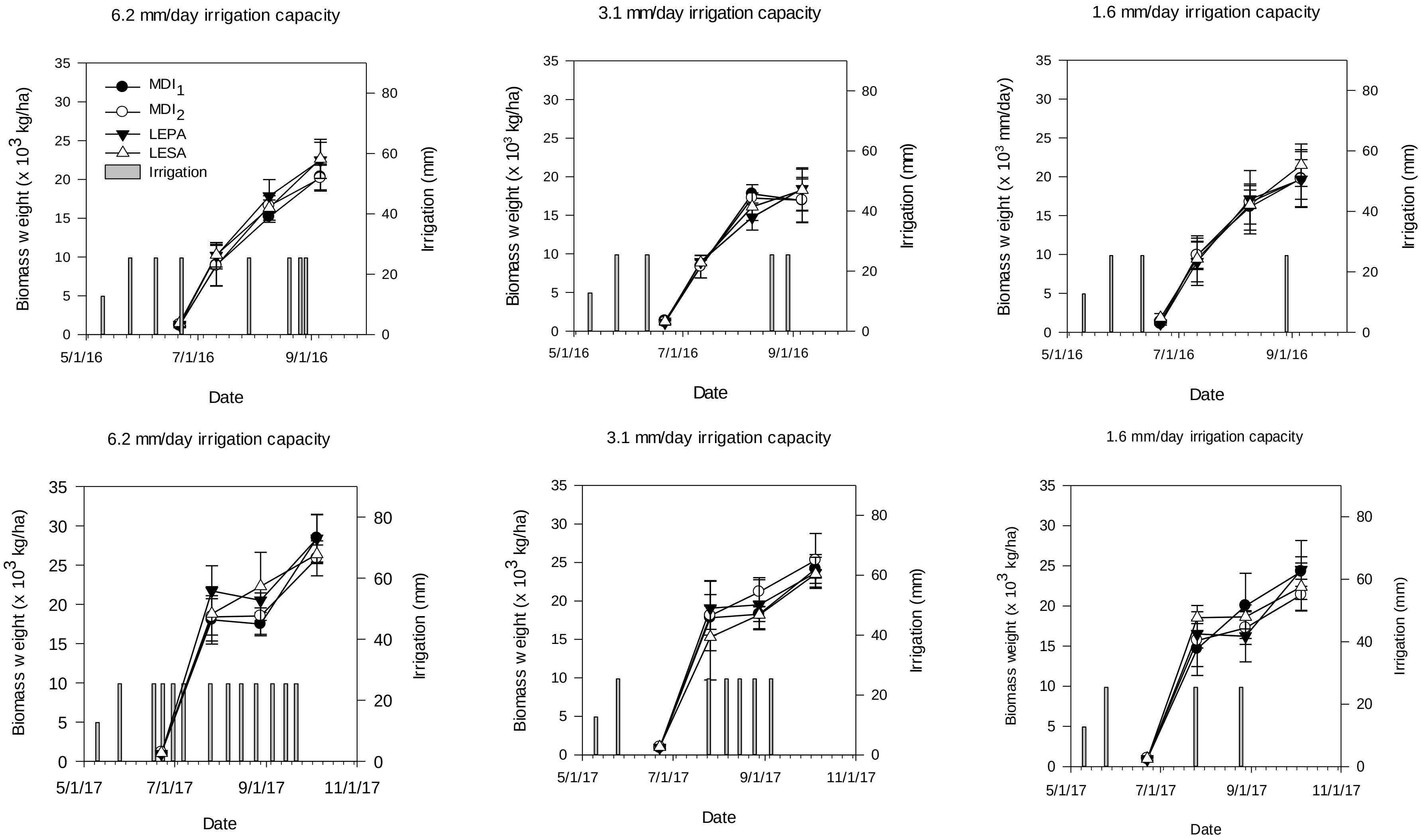

Figure 5.7 Monthly Biomass yields MDI₁, MDI₂, LEPA and LESA for irrigation capacities 6.2, 3.1 and 1.6 mm/d

Table 5.7 Least squares means of monthly leaf area index of corn for irrigation capacities of 6.2, 3.1 and 1.6 mm/d for 2016

	2016 LAI		
	Month 1	Month 2	Month 3
	6.2 mm/d		
MDI_1	3.96^{a}	$5.47^{b,c}$	$3.11^{e,f}$
MDI_2	2.47^{a}	2.45^{d}	1.24^{h}
LEPA	3.02^{a}	$5.19^{b,c,d}$	$2.56^{e,f,g}$
LESA	3.86^{a}	$4.0^{b,c,d}$	$2.21^{f,g}$
	3.1 mm/d		
MDI_1	3.26^{a}	5.69^{b}	$2.11^{e,f}$
MDI_2	3.18^{a}	$3.95^{c,d}$	$2.8^{e,f,g}$
LEPA	2.68^{a}	5.78^{b}	3.53^{e}
LESA	2.69^{a}	$5.17^{b,c}$	$1.79^{h,g}$
	1.6 mm/d		
MDI_1	3.82^{a}	$5.12^{b,c}$	2.34^{f}
MDI_2	3.59^{a}	$4.75^{b,c}$	$2.6^{e,f,g}$
LEPA	3.04^{a}	$4.23^{b,c,d}$	$2.64^{e,f,g}$
LESA	3.42^{a}	$5.09^{b,c}$	$2.25^{f,g}$
Application method	NS	*	NS
Irrigation capacity	NS	NS	NS
Interaction	NS	NS	*

NS – Not significant at 5% level; * - Significant ($p < 0.05$); Biomass yields with similar letters are not significantly different

Table 5.8 Least squares means of monthly leaf area index of corn for irrigation capacities of 6.2, 3.1 and 1.6 mm/d for 2017

	Biomass yield (kg/ha)			
	Month 1	Month 2	Month 3	Month 4
	6.2 mm/d			
MDI_1	$0.617^{a,b}$	$2.08^{c,d,e}$	$3.24^{f,g,h}$	3.81^{i}
MDI_2	$0.513^{a,b}$	$1.97^{d,e}$	$3.24^{f,g,h}$	$3.67^{i,j,k}$
LEPA	$0.507^{a,b}$	$2.43^{c,d}$	3.54^{f}	3.90^{i}
LESA	$0.590^{a,b}$	$2.29^{c,d,e}$	$3.40^{f,g}$	3.84^{i}
	3.1 mm/d			
MDI_1	$0.643^{a,b}$	2.66^{c}	$2.90^{f,g,h}$	3.76^{i}
MDI_2	$0.613^{a,b}$	$1.90^{d,e}$	$3.33^{f,g}$	$3.58^{i,j,k}$
LEPA	$0.650^{a,b}$	$2.42^{c,d}$	$3.15^{f,g,h}$	$3.77^{i,j}$
LESA	0.773^{a}	$2.25^{c,d,e}$	$2.99^{f,g,h}$	$3.56^{i,j,k}$
	1.6 mm/d			
MDI_1	0.470^{b}	1.76^{e}	2.50^{h}	$3.40^{i,j,k}$
MDI_2	$0.673^{a,b}$	$1.99^{d,e}$	$2.74^{g,h}$	$3.50^{i,j,k}$
LEPA	$0.493^{a,b}$	$2.11^{c,d,e}$	$2.76^{g,h}$	3.14^{k}
LESA	$0.643^{a,b}$	1.70^{e}	$3.13^{f,g,h}$	$3.21^{j,k}$
Application method	NS	NS	NS	NS
Irrigation capacity	NS	*	*	*
Interaction	NS	NS	NS	NS

NS – Not significant at 5% level; * - Significant ($p < 0.05$); Biomass yields with similar letters are not significantly different

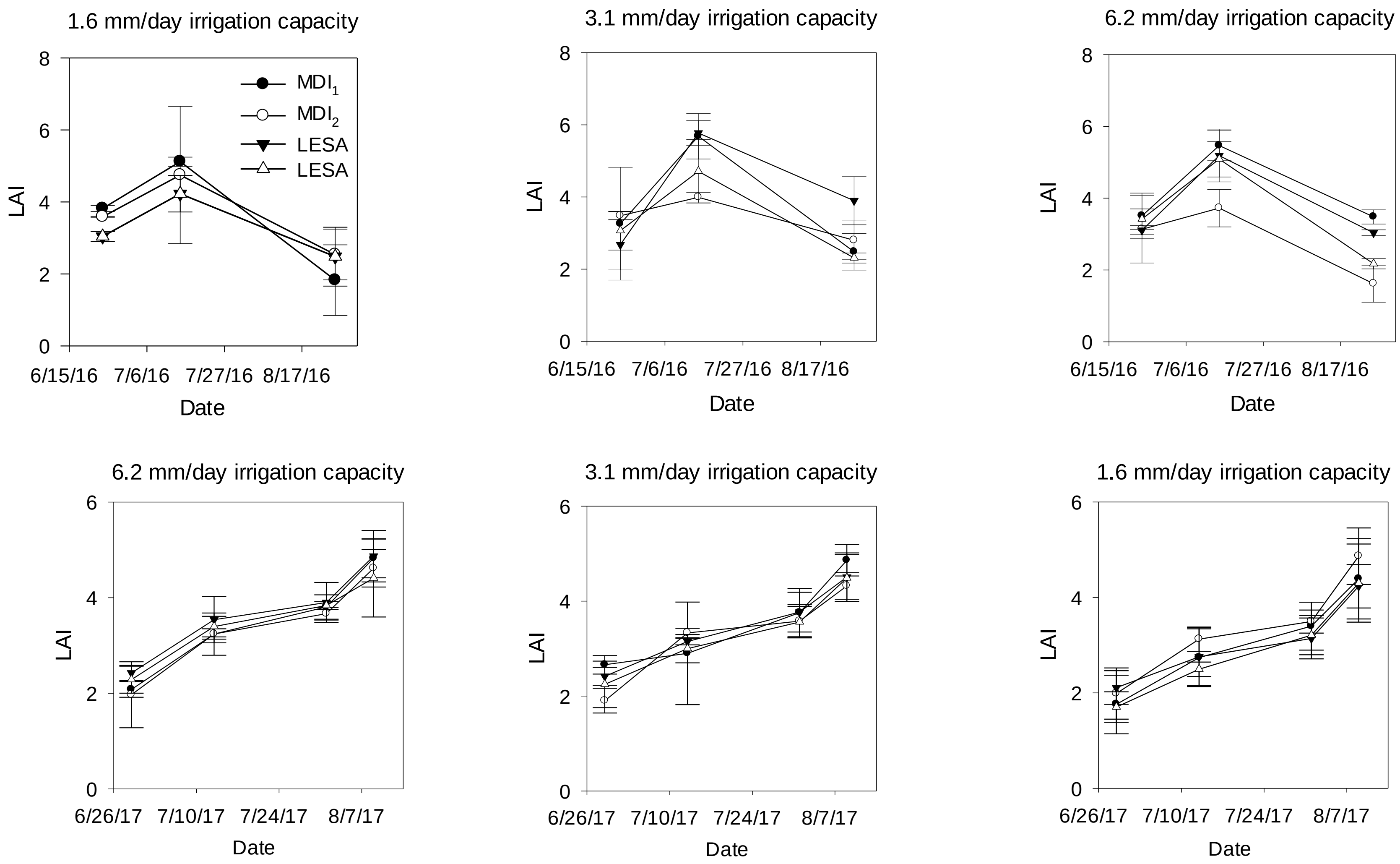

Figure 5.8 Monthly LAI growth under irrigation by MDI, LEPA and LESA for 2016 and 2017

5.3.4 Water productivity

Water productivity for 2016 and 2017 seasons under MDI, LEPA and LESA with 6.2, 3.1, and 1.6 mm/d irrigation capacities is shown in Figure 5.9. There were no significant differences in water productivity between the application devices ($p = 0.2352$) at 5% significance level, however, the differences between irrigation capacities were found significant ($p = 0.050$). The interaction effects were not significant with $p = 0.7469$ at 5% significant level. These observations were consistent with similar statistical analyses for grain yield. The analysis of seasonal ET for the two cropping seasons showed that there was no significant difference in ET between MDI, LEPA and LESA with $p = 0.2352$ for 2016 and $p = 0.6805$ for 2017, while significant differences were found between the 6.2, 3.1, 1.6 mm/d irrigation capacities with $p = 0.0014$ and $p < 0.0001$ for 2016 and 2017 respectively. Any differences in the biophysical properties in this study were expected to have resulted from the differences in ET, which in turn arose from the differences in soil water storage. The fact that no differences in ET were found between the irrigation application devices is consistent with the absence of significant differences between measured biophysical properties under different devices.

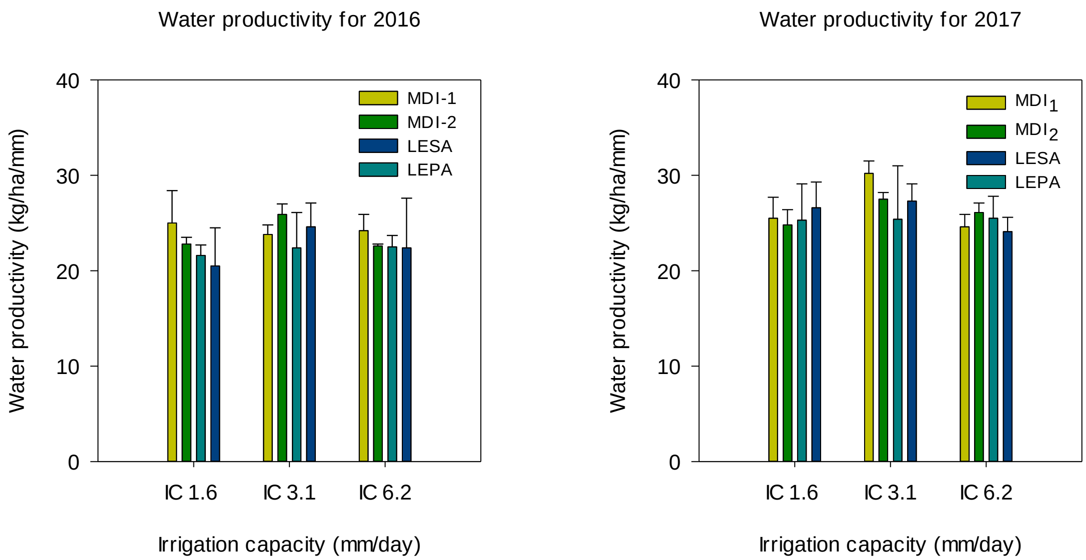

Figure 5.9 Water productivities for MDI, LEPA and LESA for irrigation capacities 6.2, 3.1 and 1.6 mm/d for 2016 and 2017

5.3.5 Other study observations

Wheel-tracking rutting is a common problem in center pivot irrigation systems fitted with LESA, LEPA (used without furrows) and MESA nozzles. This is because such nozzles tend to spread water over wide areas on the soil surface (including wheel paths) and have high application rates. During the study, frequent visual inspection for wheel-track rutting showed that the depths of wheel ruts in areas under MDI were much less than those in locations under LESA and LEPA. This reduced wheel-track rutting highlights another advantage of MDI. Though fertigation was not done in the study, it is important to note that MDI would also make the process relatively easier to implement because, it is designed to apply water directly to the soil surface, which prevents foliage-burn.

5.4 Conclusions and Recommendations

The results of this study showed that no significant differences were detected in grain yield, above ground biomass, water productivity, and LAI between MDI and LEPA and LESA. It also showed that there were no major differences in soil water transitions during the season. From these facts, we concluded that MDI did not perform nor better or worse than either LEPA or LESA. However, since the main advantage of MDI was to reduce water losses as compared to sprinkler-type devices like LESA and LEPA, it was anticipated to observe benefits of MDI by measuring of biophysical properties and soil water content. Above normal rainfall received during each of the two studied growing seasons highly likely led to relatively uniform soil water distribution throughout the fields, negating any marginal increases in soil water content due to MDI efficiency and resulting in statistically insignificant measurements of the changes in biophysical properties.

Considering that variation of rainfall during two seasons did affect the results of this study and altered the anticipated conclusions, it is recommended additional research to compare MDI to LEPA and/or LESA be continued under the following two conditions: (1) MDI applying lesser water than LEPA and LESA during each irrigation event, and (2) MDI evaluated against LEPA and LESA during years with very little rainfall. Evaluating MDI under conditions in which it applies less water in comparison to LEPA and LESA is based on the idea that since MDI minimizes water loss, biophysical measurements of crops under MDI, applying fraction of water under LEPA and LESA, will still be comparable. This way of evaluating MDI against LEPA and LESA will isolate any effects of rainfall. It could also help better understand the rainfall thresholds for which MDI makes a difference in comparison to other technologies.

Acknowledgements

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Chapter 6 – Determining Mobile Drip Irrigation dripline spacing and length for different soil textural classes using numerical modelling

Abstract

A Mobile Drip Irrigation (MDI) system does not apply water across the soil surface as other common irrigation technologies. It consists of a water drip line dragging along the surface between rows of crop. It is thus important to ensure that dripline spacing is sufficient to ensure irrigation uniformity. Using a numerical modelling software HYDRUS (2D/3D), two-dimensional soil water redistribution over a 30-day period, for sandy, sandy loam, silt loam and clay loam was analyzed. Irrigation was applied to each soil every five days. The results show that change in horizontal soil water content beyond a distance of 76.2 cm is minimal for all the other soils, with the exception of clay loam. At 15.2 and 30.5 cm depth, loam and silt loam had the highest percentage change, from initial conditions, in soil water content. At 60 cm depth and below, percentage change in soil water content for loam and silt loam was low. A tool was developed in Microsoft Excel to compute recommended dripline lengths for MDI dripline lengths for 3.8 and 7.6 L/h drippers and spacings of 76.2 and 154.2 cm. A strong linear relationship exists between the recommended dripline length and the distance from the center of the pivot.

Keywords: Mobile Drip Irrigation; HYDRUS; Center pivot

6.1 Introduction

According to Steward et al., (2013), the High Plains aquifer, an important water resource for agriculture in the U.S. Midwest, is already 30% depleted and another 39% of its capacity will be lost in the next 50 years if current withdrawal trends continue. Furthermore Scanlon et al., (2012) project that at current water withdrawal rates, 35% of the southern High Plains will not be able to support irrigation in 30 years' time. In response to these challenges, a broad range of water conservation efforts are presently being continually assessed and promoted by relevant stakeholders and policy makers. Of interest, among the set of solutions, are ways to improve irrigation efficiency and water productivity. The adaptation of the highly efficient drip irrigation technology to center pivots, or Mobile Drip Irrigation (MDI) may be one of the ways to improve irrigation productivity and through widespread use of center pivots in the High Plains region. Though the idea of equipping center pivots or lateral move systems is not new (Chu, 1984; Phene et al., 1981; Phene et al., 1985), until recently the technology had not reached a status where it was viewed a market-ready. MDI relatively new by comparison to other irrigation technologies like Low Elevation Spray Application (LESA), Low Energy Precision Application (LEPA) and Mid-elevation Spray Application (MESA). Recent developments in center pivot and drip technologies, coupled with the pressing need for more efficient irrigation and accompanying incentives, have heightened interests in the technology, such that private sector companies are actively involved. However, since MDI is relatively new, the technology needs to be rigorously assessed and standardized for the benefit of farmers and dealers. Because MDI does not apply water across the soil surface as do many common irrigation technologies, ensuring dripline spacing is vital in order to prevent irrigation non-uniformity. This study analyses horizontal soil water redistribution under MDI in different soil textural classes in order to ascertain suitable dripline spacings and lengths.

6.2 Methodology

A numerical model, HYDRUS 2D/3D (Šejna et al., 2016) was used to model water redistribution under an MDI, with a dripper flow rate of 3.8 L/h, for the following textural classes: sand, sandy loam, loam, silt loam and clay loam. Basing on the horizontal water redistribution patterns for each soil, recommendations on dripline spacings were made. To assess MDI dripline spacing and length, a center pivot sized for a quarter-section (65 ha) of land, which typically has eight spans and a total length of 402 m, was considered. This is the most common center pivot of the region. A crop row spacing of 72.6 m, which is used for corn in Kansas, was assumed. Four MDI dripline spacings, each a multiple of crop row spacing, were selected for evaluation were set: 76.2, 152.4, 228.6, 304.8 cm. The simulations were based on an irrigation schedule in which 25.4 mm of water is applied every 4 days.

6.2.1 Soil water redistribution modelling using HYDRUS (2D/3D)

HYDRUS (2D/3D) is a software package that simulates water, heat, and solute movement in variably saturated porous media (Šimůnek et al., 2016). The software solves the Richards equation using finite element methods (Šimůnek et al., 2016). For this modelling experiment, HYDRUS (2D/3D), version 2.05, was used to simulate soil water movement, under MDI, in a two-dimensional plane i.e. vertically and horizontally. The 2-D form of the Richards equation solved by HYDRUS (2D/3D) (Li et al., 2015) is expressed as:

$$\frac{\partial\theta(h)}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \tag{6.1}$$

where θ is volumetric water content (m^3/m^3); $K(h)$ is unsaturated hydraulic conductivity (m/s); t is time (s); x and z are horizontal and vertical coordinates (directed downwards) (m); and h is the pressure head (m).

6.2.1.1 Soil hydraulic properties

The van Genuchten-Mualem model (van Genuchten, 1980) was used to describe the soil hydraulic properties. The water retention curve, $\theta(h)$ and the hydraulic conductivity function $K(h)$ are presented by the following equations (6.2) and (4.8)6.3):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \tag{6.4}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{l/m}\right)^m\right]^2 \tag{6.5}$$

where

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

and

$$m = 1 - \frac{1}{n}$$

where, θ_s and θ_r are saturated and residual water contents, respectively; K_s is saturated hydraulic conductivity; α, m, and n are constants, and l is a parameter for tortuosity. HYDRUS (2D/3D) soil hydraulic parameters for sand, sandy loam, loam, silt loam and clay loam are shown in Table 6.1 (Šimůnek et al., 2016).

Table 6.1 Water flow parameters for soil types in HYDRUS (2D/3D)

Soil type	θ_r	θ_s	α (1/cm)	n	K_s (cm/h)	l
Sand	0.045	0.43	0.145	2.68	712.8	0.5
Sandy loam	0.065	0.41	0.075	1.89	106.1	0.5
Loam	0.078	0.43	0.036	1.56	24.96	0.5
Silty loam	0.067	0.45	0.02	1.41	10.8	0.5
Clay loam	0.095	0.41	0.019	1.31	6.24	0.5

6.2.1.2 Model domain setup

Figure 6.1 shows the HYDRUS (2D/3D) model domain. The width of the 2-D model domain is 152.4 cm, which is the mid-point of four crop rows, and the length is 304.8 cm, which is the depth of root zone. Since two-dimensional soil water modelling in HYDRUS (2D/3D) is symmetrical, often only half of the horizontal distance of the modelling domain in considered.

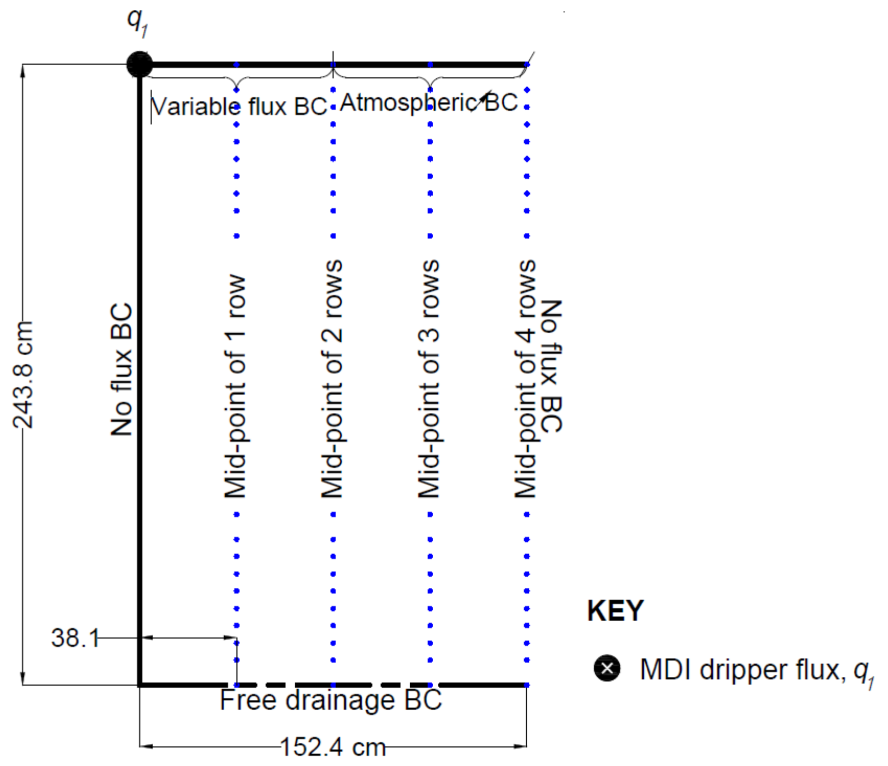

Figure 6.1 HYDRUS (2D/3D) model computational domain

6.2.1.3 Boundary conditions

The boundary conditions of the model domain are illustrated in Figure 6.1. No-flux boundary conditions were implemented on the right and left sides of the domain. A free-drainage boundary condition was set at the bottom boundary. At the top of the model domain, which represents the soil surface onto which irrigation water is applied, two boundary conditions were implemented as shown in Figure 6.1. The left and right halves of the top of the model domain had variable flux and atmospheric boundary conditions respectively. For surface drip irrigation modelling, HYDRUS (2/3D) uses a computational module available under its "special boundary conditions" (Šejna et al., 2016; Šimůnek et al., 2016) with a "dynamic wetting" zone specified at the soil surface. The dynamic wetting area represents the maximum distance from dripline, on which water flows on the surface and before it starts to infiltrate into the soil. The

MDI was implemented as a time-variable flux, q, at the top left corner of the domain. Dripline boundary flux, q, (cm/h) in HYDRUS (2D/3D) was calculated as;

$$q = Q_d \cdot 10^3 \tag{6.6}$$

where Q_d (cm^3/h) is dripper flow rate, which was 3.785 L/h. Therefore, the flux, q, of the dripper was 3,785 cm^3/h. The flux application time, t, (h) was calculated as (Gärdenäs et al., 2005):

$$t = \frac{S_d \cdot S_l \cdot d}{Q_d} \tag{6.7}$$

where S_d is dripper spacing (15.5 cm), S_l is dripline/MDI spacing, S_d, d (cm) is irrigation depth (2.54 cm). Thus, the application time, t, (h) was computed for the largest dripline spacing (290.4 cm) was 3.02 h. Application time for largest dripline spacing was selected because it encompasses any that is less than it i.e. dripline spacings of 76.2, 152.4, 228.6 cm have application times of 0.76, 1.51 and 2.27 h respectively. Choosing the longest application time, enables the simulation for all dripline spacings in a single HYDRUS (2D/3D) run.

6.2.1.4 Initial conditions

For each soil type, an irrigation event, in which 2.54 cm of water is applied, was implemented every five days for 30 days in HYDRUS (2D/3D); making it a total of five irrigation events for each simulation. The soil surface, represented by the top of the HYDRUS (2D/3D) model domain, was assumed to be bare so as to simulate MDI water application under conditions of maximum evaporation. A mean evaporation rate of 0.62 cm/day was considered for the simulation period. This was the mean reference evaporation for the growing season (May 1st to October 1st) for 2017 and 2018 for Garden City.

6.2.2 Evaluation of horizontal water redistribution

Soil water redistribution on day 30 of the HYDRUS (2D/3D) simulation was examined. This was done by taking horizontal profiles of the simulated soil water content at depths of 15.2, 30.5, 61.0 and 91.4 cm from the surface for the soil types considered in the study and plotted to find the distance of travel of the water front.

6.2.3 Sizing MDI dripline length

Microsoft Excel was used to develop the tool for calculating dripline length basing on spacing recommendations from HYDRUS (2D/3D) simulation. The following were the steps used to compute dripline length:

1. Distance, d_i (m) of the i^{th} dripline from center of the center pivot was calculated as:

$$d_i = S_c \cdot i \qquad (6.8)$$

   where S_c (m) crop spacing (m) and i = 1, 2, 3, …

2. Area, A_i (m^2) between driplines i and $i+1$ was calculated as:

$$A_i = \pi \cdot (d_{i+1}^2 - d_i^2) \qquad (6.9)$$

3. Volume, V_i (m^3) of water required to irrigation area A_i (m^2) was computed as:

$$V_i = A_i \cdot D \qquad (6.10)$$

   where D(m) is the irrigation application depth which was set at 2.54 cm (or 1 inch).

4. Flow rate, Q_i (m^3/h) required to supply volume, V_i (m^3) of water in center pivot revolution time, T (h) was as:

$$Q_i = V_i \cdot T \qquad (6.11)$$

   where T is (Washington State University Extension, 2018):

$$T = \frac{\left(\frac{452.6 \cdot A}{Q}\right)}{Eff} \qquad (6.12)$$

where A (acres) is total center pivot area, Q (gpm) flow rate at pivot, and Eff is irrigation efficiency, assumed to be 0.95% for MDI.

5. Therefore, length, L_i (m) of the i^{th} dripline rate was calculated as:

$$L_i = {}^{Q_i}/_{Q_t} \tag{6.13}$$

where Q_t (cm^3/h/m) is dripline flow rate per meter, calculated as:

$$Q_t = \frac{Q_d \cdot 100}{S_d} \tag{6.14}$$

where Q_d (cm^3/h) is dripper flow rate (3.785 L/h), and S_d is dripper spacing (15.5 cm)

6.3 Results and Discussions

6.3.1 Horizontal soil water content

Figure 6.2 show the simulated horizontal soil water content with distance from the MDI dripper for sandy, sandy loam, loam, clay loam, and silt loam soils. With the exception of clay loam, change in horizontal soil water content beyond a distance of 76.2 cm (2 rows) is minimal for all the other soils evaluated (Figure 6.3). This implies that for the tested soil types the maximum recommended dripline spacing is two rows, or 152.4 cm. Mean horizontal water content at depths of 15.2, 30.5, 61 and 91 cm after 30 days was computed and used to calculate the percent change, from initial conditions, in water content for all the soils considered. A higher percentage change at a depth implies greater horizontal soil water distribution of the irrigation water applied through the MDI dripline, and vice-versa. Table 6.2 shows the means of simulated and percentage change in soil water content after 30 days, of sandy, sandy loam, loam, clay loam and silt loam soils at depths of 15.2, 30.5, 61 and 91 cm. At 15.2 and 30.5 cm depth, loam and silt loam had the highest percentage change, from initial conditions, in soil water content. At 60 cm depth and below, percentage change in soil water content for loam and silt loam was low. This is because much of the applied irrigation water remained entrained in the upper layers of their profiles. Although the percentage change in horizontal soil water content for clay loam was comparatively lower than those of loam and silt loam, its soil water content was higher was higher at all depths. Clay loam also had the largest horizontal water redistribution (Figure 6.3).

Table 6.2 Simulated soil water content for at depths of 15.2, 30.5, 61 and 91 for sandy, sandy loam, loam, clay loam and silt loam soils after 30 days

	Soil depth (cm)							
	15.2		30.5		61		91	
	Soil water content ($cm^3\ cm^{-3}$) and percent change[6] (%)							
Sand	0.062	(24)	0.064	(28)	0.072	(43)	0.075	(49)
Sandy loam	0.135	(35)	0.138	(38)	0.142	(42)	0.127	(27)
Loam	0.199	(53)	0.191	(47)	0.160	(23)	0.130	(0)
Clay loam	0.290	(21)	0.285	(19)	0.253	(5)	0.240	(0)
Silt loam	0.240	(50)	0.224	(40)	0.165	(3)	0.160	(0)

[6] In brackets

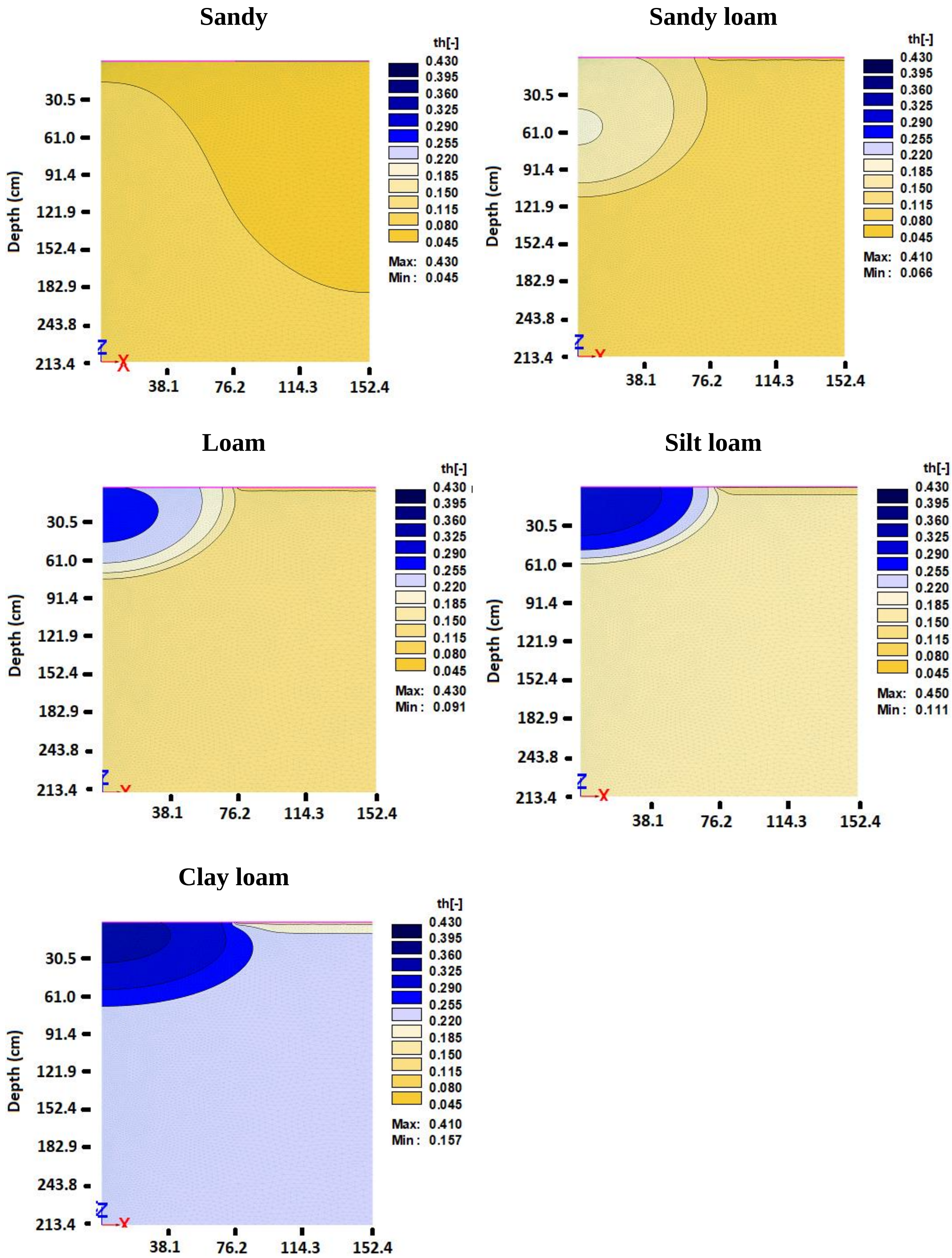

Figure 6.2 Simulated soil water content of sandy, sandy loam, loam, silt loam and clay loam 30 days after five irrigation events

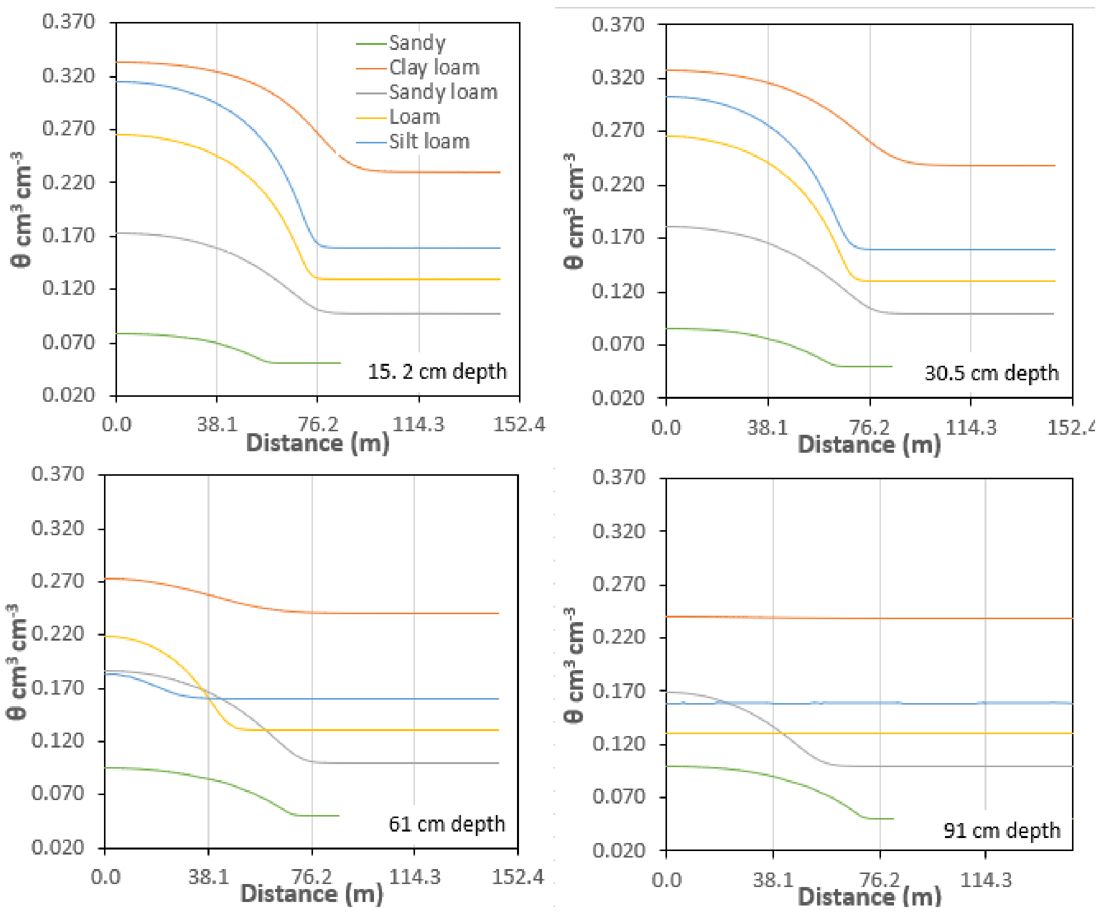

Figure 6.3 Horizontal soil water content for different soil types at depths of 15.2, 30.5, 61 and 91 cm

6.3.2 MDI dripline length

The tool developed in Microsoft Excel was used to generate recommended dripline lengths for 3.8 and 7.6 L/h drippers and spacings of 76.2 and 154.2 cm, for all the soils evaluated. It was observed that strong linear relationships exist between the recommended dripline length and the distance from the center of the pivot as shown in Figure 6.4. The linear equations shown in in Figure 6.4 can thus be used to quickly calculate the dripline length for MDI using drippers of 3.8 and 7.6 L/h flow rates. The dripper flow rate and spacing configuration for the shortest driplines is to use the 7.2 L/h dripper at a spacing of 76.2 cm (Figure 6.4(c)). For soils with better horizontal soil water redistribution such as loam, silt loam and clay loam, driplines with dripper flow rates of 7.8 L/h and a spacing of 152.4 cm is an option to consider in order to reduce drag on the center pivot by reducing the total drip line length (Figure 6.4(d)). For tall crops like corn, a scenario shown in Figure 6.4(b), could be problematic to work with due to enhanced likelihood of the very dripline climbing the crop canopy. Secondly, from an operation and maintenance perspective, very long driplines would be cumbersome to work with. For these two reasons, the MDI scenario presented in Figure 6.4(b), is not recommend for the standard quarter-section center pivot.

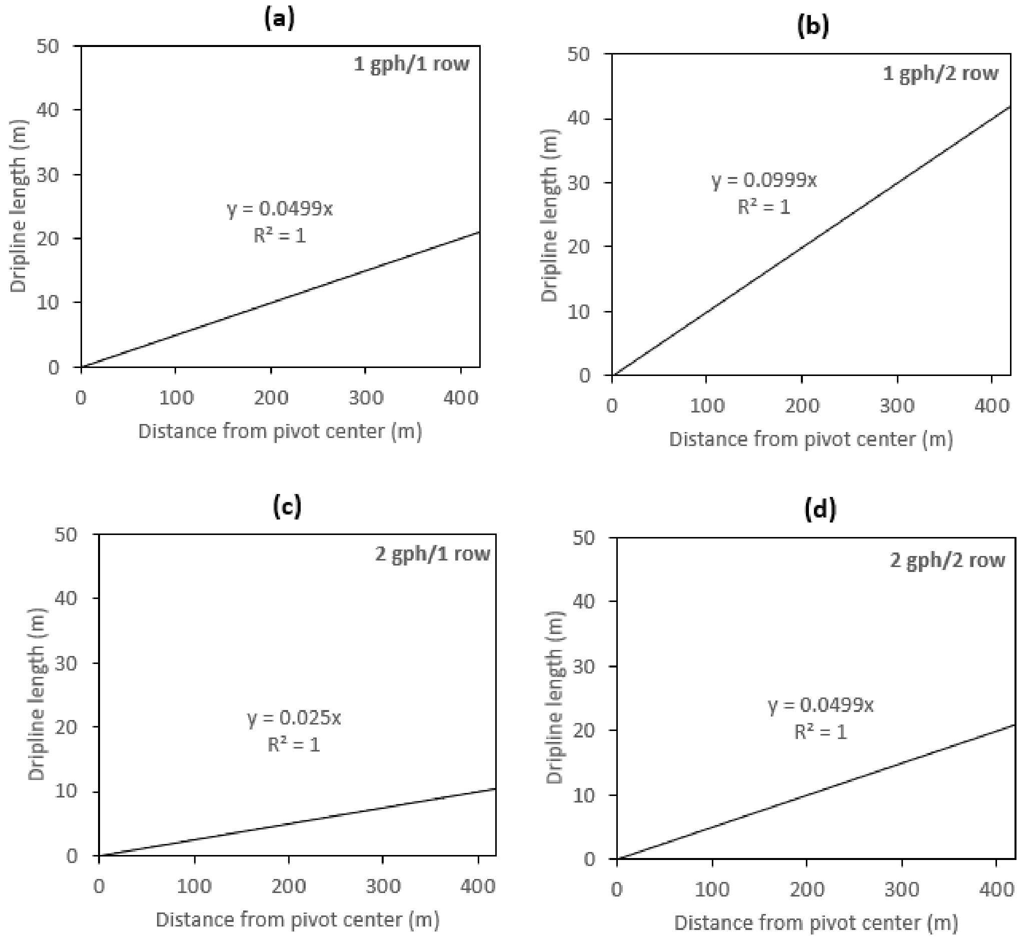

Figure 6.4 Variation of dripline length with distance from the center of pivot for sandy, sandy loam, loam, silt loam and clay loam, for 3.8 and 7.6 L/h drippers, and spacings of 76.2 and 154.2 cm

6.4 Conclusions

The recommended maximum spacing for MDI driplines for loam, silt-loam and clay loam is 152.4 cm. Distances beyond this increase the likelihood of non-uniform irrigation in many soil types. Dripline length show a strong linear relationship with distance from the center of the pivot.

Acknowledgements

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Chapter 7 – Summary, Conclusions and Recommendations

Summary and Conclusions

Further improvement of irrigation efficiency is one of the technological interventions being promoted in order to contribute to efforts to conserve the Ogallala aquifer (Colaizzi,et al., 2009; Rajan et al., 2015). Over the past several years as drip and center pivot technologies advanced, there have been continuous research efforts to adapt the two into a technically viable irrigation package that farmers can easily use (Chu, 1984; Kisekka et al., 2017; O'Shaughnessy & Colaizzi, 2017; Olson & Rogers, 2007; Phene et al., 1981; Phene et al., 1985). Judging from recent involvement of private companies, indications are that the technology has reached a point where it is viewed as a market-ready. This research evaluated the technical performance of a Mobile Drip Irrigation (MDI) system against Low Elevation Spray Application (LESA) and Low Energy Precision Application (LEPA) technologies, focusing on: (1) Uniformity and application efficiency; (2) Soil water redistribution; (3) Corn production and; (4) MDI design (spacing and length) for different soil types. The researched was carried at Kansas State University's Southwest Research and Extension Center, in Garden City, Kansas, where a four-span center pivot specially fitted with MDI, LESA and LEPA irrigation devices, was installed in 2015.

In general, both MDI and LEPA were found to be more efficient than LESA as shown by their significantly higher coefficients of uniformity and statistical uniformity, in addition to their comparatively lower coefficients of variation. The irrigation performance of MDI matched that of LEPA as indicated by their comparable coefficient of uniformity (CU), (93.8% and 93.7% for 3.8 L/h and 7.6 L/h MDI respectively and 95.1% for LEPA), statistical uniformity and coefficient of variation. The application efficiencies for the 3.8 L/h and 7.6 L/h MDI, LEPA and LESA were 76.1, 96.8, 98.4 and 51.2% respectively; showing that MDI and LEPA had higher application efficiency than LESA. Comparison of season-long irrigation uniformity between the irrigation devices, through vegetative index analysis, showed that there was no significant difference in vegetative indices of corn, inferentially implying that was no difference in irrigation uniformity between all tested devices. However, this observation is attributed to effect of rainfall received during the seasons; which could have evened out any disparities in the irrigation uniformity between the devices.

Through numerical modelling using HYDRUS (2D/3D) software, analysis of soil water redistribution in a Ulysses silt loam, under irrigation by a 3.8 L/h and 7.6 L/h MDI, LEPA and LESA was conducted. Results showed that the effect of irrigation was mostly limited to the top 60 cm of the soil profile for all the evaluated irrigation application technologies. As expected, MDI driplines and LEPA showed the highest horizontal variation in water content. Soil water content inter-quartile-range (IQR) at 30 cm, for the low and high rate MDI driplines, varied from that of the LEPA by 0.98% and 0.96%; implying that the MDI matched LEPA bubbler's water redistribution. Soil water content inter-quartile-range (IQR) at 30 cm depth, for the 3.8 L/h and 7.6 L/h MDI differed from that of the LESA by 97.1% and 94.1%, respectively; indicating a significant difference in profile water redistribution between MDI and LESA. Although variability in water content, in the horizontal plane, under MDI was several magnitudes higher than that under LESA spray, the soil profile was still sufficiently wetted. Soil water content under MDI was higher than that of the LESA at 30, 60, 90 cm, which shows that the former was more efficient in storing water in soil profile.

To evaluate MDI in an actual crop production setting, an experiment to evaluate its performance or corn production, in comparison to LESA and LEPA was conducted in 2016 and 2017. Three irrigation capacities were assumed: 6.3, 3.1, and 1.6 mm/d. The results study showed that no significant differences were detected in grain yield, above ground biomass, water productivity, and LAI between MDI and LEPA and LESA. Above normal rainfall received during each of the two studied growing seasons likely led to relatively uniform soil moisture distribution throughout the fields, and any marginal increases in soil water content due to MDI efficiency were negated, thus resulting in statistically insignificant measurements of the changes in crop biophysical properties.

Using a numerical modelling software HYDRUS (2D/3D), two-dimensional soil water redistribution over a 30-day period, for sandy, sandy loam, silt loam and clay loam was analyzed. Irrigation was applied to each soil every five days. The results show that change in horizontal soil water content beyond a distance of 76.2 cm is minimal for all the other soils, with the exception of clay loam. At 15.2 and 30.5 cm depth, loam and silt loam had the highest percentage change, from initial conditions, in soil water content. At 60 cm depth and below, percentage change in soil water content for loam and silt loam was low. A tool was developed in Microsoft Excel to compute recommended dripline lengths for MDI dripline lengths for 3.8 and 7.6 L/h drippers and spacings of 76.2 and 154.2 cm. A strong linear relationship exists between the recommended dripline length and the distance from the center of the pivot.

Recommendations

- Further field evaluation of MDI under more stringent irrigation conditions is needed so as to isolate the effect of rainfall on measured crop biophysical properties.
- Guided by recommendations on dripline spacing and lengths from this research, field evaluation of MDI should be conducted so as to validate and standardize the technology for different soil textural classes.

- For tall crops like corn, there is a need to conduct field experiments to determine the thresholds of maximum dripline lengths in order to reduce severe “corn canopy riding”.

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List of Appendices

Appendix A Change in LEPA nozzle flow rate with increase in distance from center of pivot

Nozzle #	Radius (m)	Flow rate (m^3/s)	Area between circles (m^2)	Standardized flow rate ($m^3/s/m^2$)
1	33.44	4.5989E-05	312	1.4729E-07
2	34.96	4.22727E-05	327	1.29371E-07
3	36.48	0.0000465	341	1.36252E-07
4	38	4.54891E-05	356	1.2785E-07
5	39.52	4.44268E-05	370	1.19967E-07
6	41.04	4.57877E-05	385	1.18977E-07
7	42.56	5.32443E-05	399	1.33321E-07
8	44.08	5.25754E-05	414	1.27027E-07
9	45.6	5.24436E-05	428	1.22413E-07
10	47.12	5.19231E-05	443	1.17225E-07
11	48.64	5.96154E-05	457	1.30318E-07
12	50.16	5.20522E-05	472	1.10284E-07
13	107.92	0.000116899	1024	1.14178E-07
14	109.44	0.000135877	1038	1.30857E-07
15	110.96	0.000127591	1053	1.21183E-07
16	112.48	0.000130781	1067	1.22523E-07
17	114	0.000128374	1082	1.18653E-07
18	115.52	0.000129374	1096	1.17994E-07
19	133.76	0.000156157	1271	1.22888E-07
20	135.28	0.0001674	1285	1.30248E-07
21	136.8	0.000159733	1300	1.22894E-07
22	138.32	0.000171516	1314	1.30501E-07
23	139.84	0.000163477	1329	1.23025E-07
24	141.36	0.000166071	1343	1.23626E-07

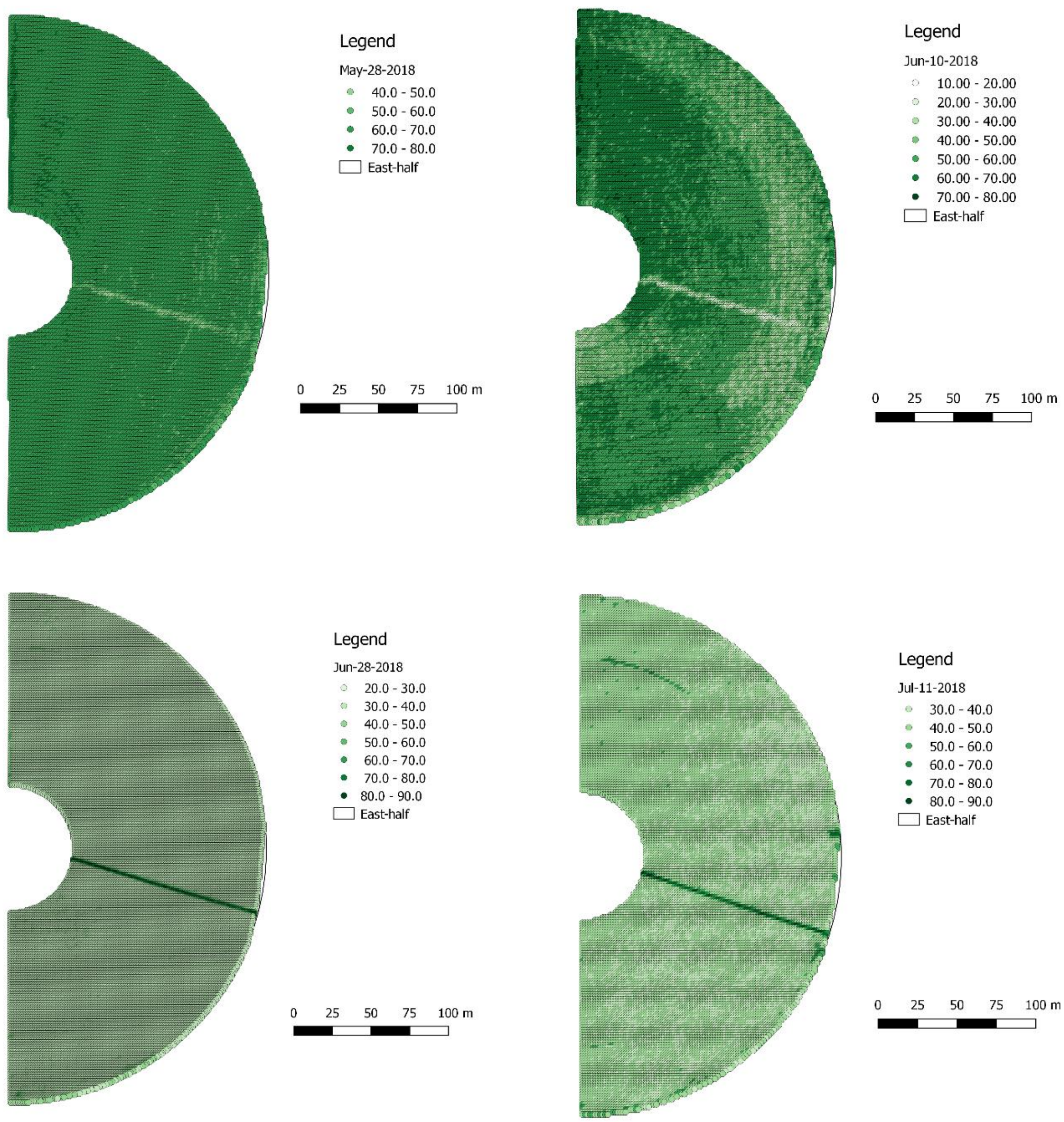
Appendix B Change in LESA nozzle flow rate with increase in distance from center of pivot

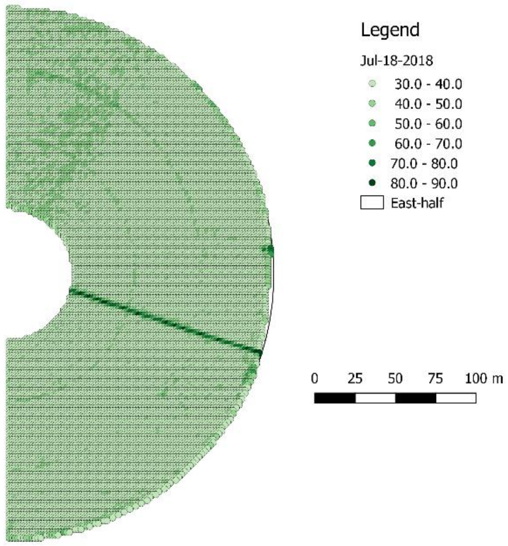
Nozzle #	Distance (m)	Flow (m^3/s)	Area between circles	Standardized flow rate (m^3/m^2)
1	25.84	2.84E-05	240	1.18649E-07
2	27.36	2.37E-05	254	9.30592E-08
3	28.88	3.3E-05	269	1.22806E-07
4	30.4	2.84E-05	283	1.00395E-07
5	31.92	2.67E-05	298	8.97681E-08
6	51.68	4.61E-05	487	9.47116E-08
7	53.2	4.95E-05	501	9.87786E-08
8	54.72	5.35E-05	516	1.03676E-07
9	56.24	5.35E-05	530	1.00835E-07
10	57.76	6.07E-05	545	1.1153E-07
11	59.28	5.35E-05	559	9.55972E-08
12	60.8	5.24E-05	574	9.135E-08
13	110.96	0.000148	1053	1.41015E-07
14	112.48	0.000223	1067	2.08645E-07
15	114	0.000178	1082	1.64675E-07
16	115.52	0.000178	1096	1.62494E-07
17	117.04	0.000157	1111	1.41503E-07
18	118.56	0.000167	1125	1.48407E-07
19	120.08	0.000178	1140	1.56284E-07
20	121.6	0.000178	1155	1.54318E-07
21	123.12	0.000167	1169	1.42876E-07
22	124.64	0.000181	1184	1.52566E-07
23	126.16	0.000179	1198	1.49705E-07
24	127.68	0.000191	1213	1.57308E-07
25	129.2	0.000183	1227	1.49267E-07
26	130.72	0.000188	1242	1.51573E-07
27	132.24	0.000179	1256	1.42114E-07

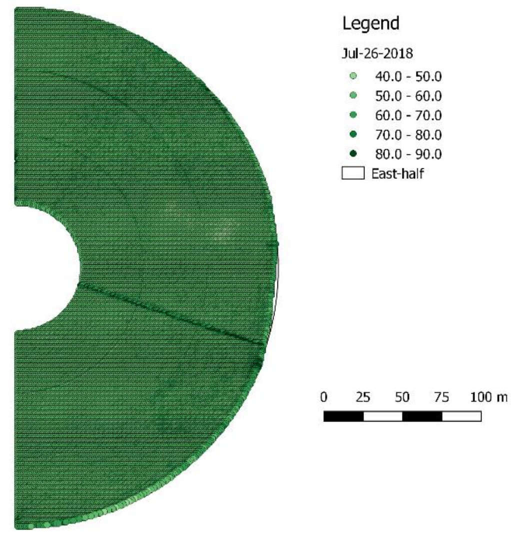
Appendix C Calculation of LESA coefficient of uniformity

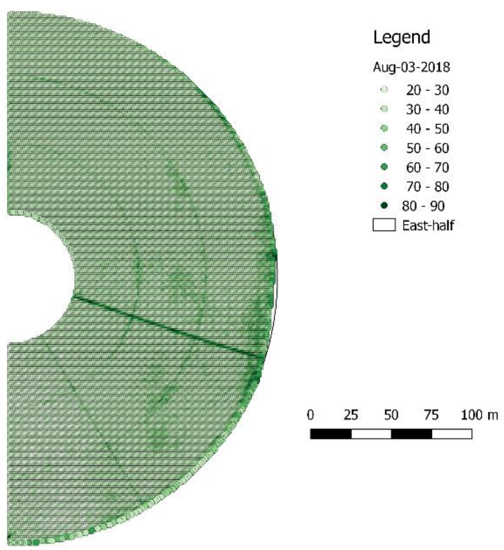
Span #	Can #	Distance, S (m)	Vol (ml)	V_iS_i	S_i*(V_i - V_p)	Can #	Vol (ml)	V_iS_i	S_i*(V_i - V_p)
				Left				Right	
1	6	24	165	3960	316	57	180	4320	175
	7	27	180	4860	50	58	180	4860	197
	8	30	220	6600	1255	59	255	7650	2469
	9	33	160	5280	599	60	180	5940	241
	10	36	190	6840	426	61	165	5940	277
2	11	39	195	7605	657	62	225	8775	2040
	12	42	130	5460	2022	63	160	6720	533
	13	45	250	11250	3233	64	270	12150	4379
	14	48	230	11040	2489	65	265	12720	4430
	15	51	250	12750	3664	66	160	8160	648
	16	54	200	10800	1180	67	170	9180	146
	17	57	155	8835	1320	68	140	7980	1864
3	31	99	210	20790	3153	82	180	17820	723
	32	102	210	21420	3248	83	160	16320	1295
	33	105	180	18900	194	84	130	13650	4483
	34	108	170	18360	881	85	245	26460	7809
	35	111	200	22200	2425	86	200	22200	3031
	36	114	220	25080	4770	87	170	19380	308
	37	117	200	23400	2556	88	135	15795	4411
4	38	120	135	16200	5178	89	140	16800	3924
	39	123	165	20295	1618	90	165	20295	947
	40	126	140	17640	4807	91	150	18900	2860
	41	129	165	21285	1697	92	190	24510	2232
	42	132	140	18480	5036	93	140	18480	4316
	43	135	135	18225	5826	94	160	21600	1714

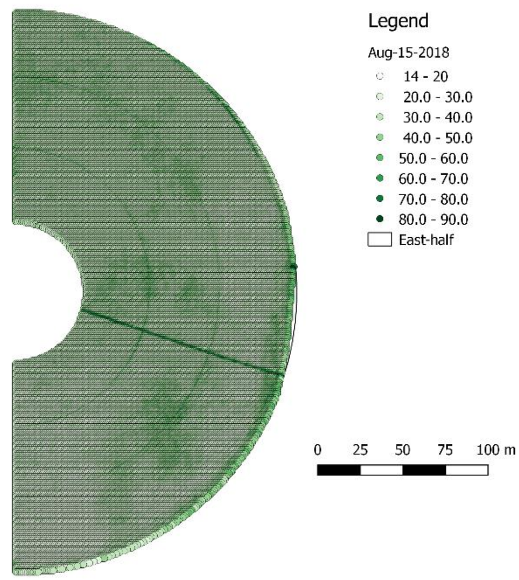
Appendix D ADVI for 2016 of corn irrigated with MDI, LESA and LEPA on a center pivot at the southwest research and extension center of Kansas State University, near Garden City Kansas

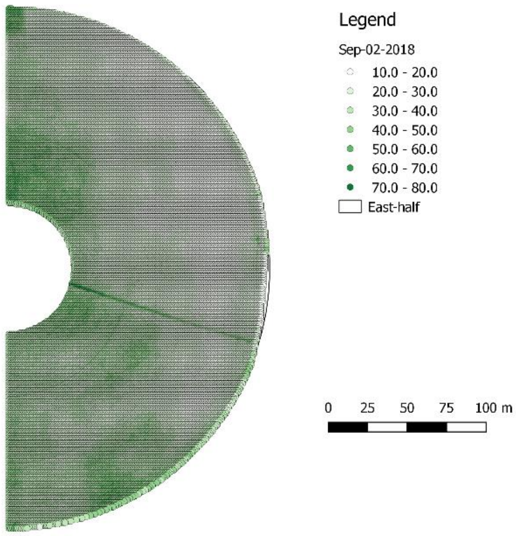



Legend
Jul-18-2018
30.0 - 40.0
40.0 - 50.0
50.0 - 60.0
60.0 - 70.0
70.0 - 80.0
80.0 - 90.0
East-half
0 25 50 75 100 m

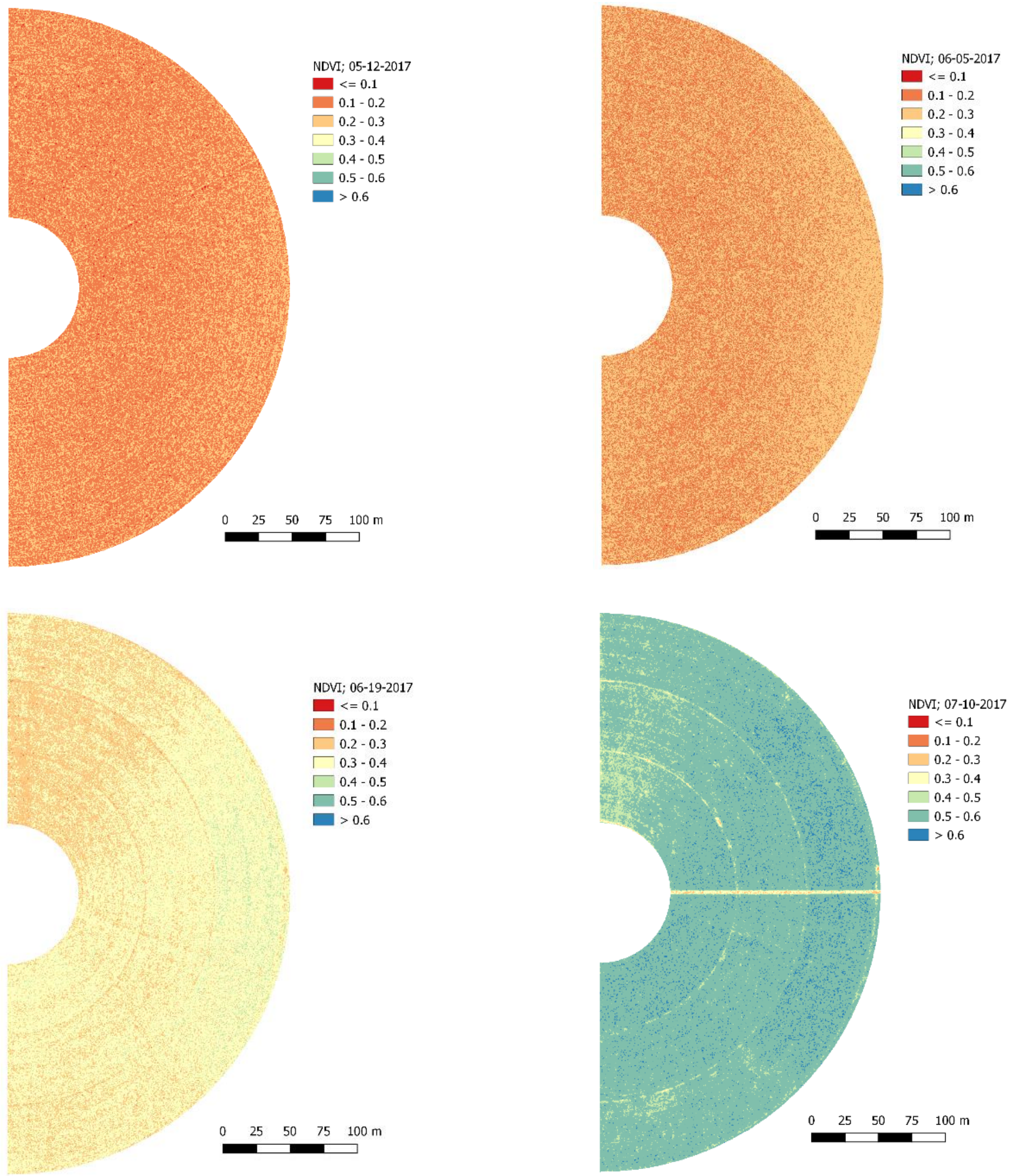

Legend
Jul-26-2018
40.0 - 50.0
50.0 - 60.0
60.0 - 70.0
70.0 - 80.0
80.0 - 90.0
East-half
0 25 50 75 100 m

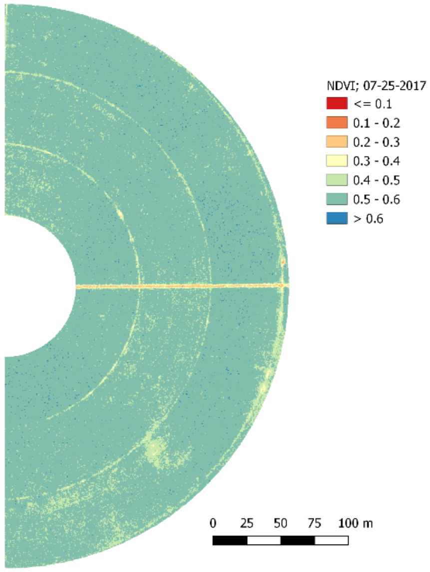

Legend
Aug-03-2018
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
East-half
0 25 50 75 100 m

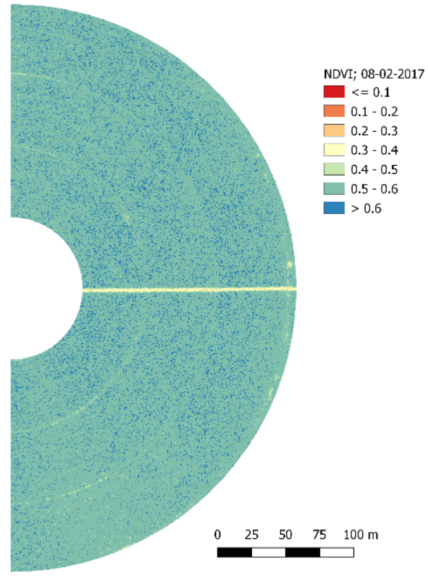

Legend
Aug-15-2018
14 - 20
20.0 - 30.0
30.0 - 40.0
40.0 - 50.0
50.0 - 60.0
60.0 - 70.0
70.0 - 80.0
80.0 - 90.0
East-half
0 25 50 75 100 m

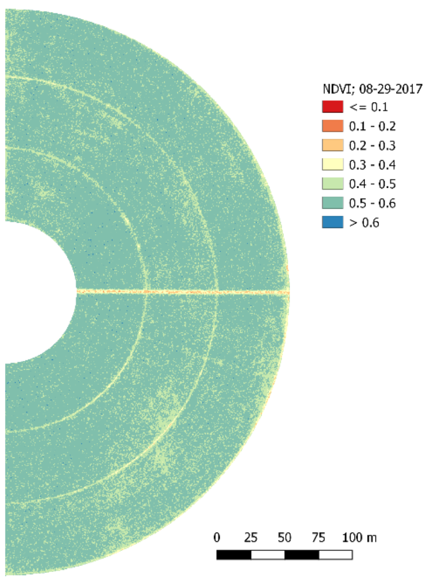

Legend
Sep-02-2018
10.0 - 20.0
20.0 - 30.0
30.0 - 40.0
40.0 - 50.0
50.0 - 60.0
60.0 - 70.0
70.0 - 80.0
East-half
0 25 50 75 100 m

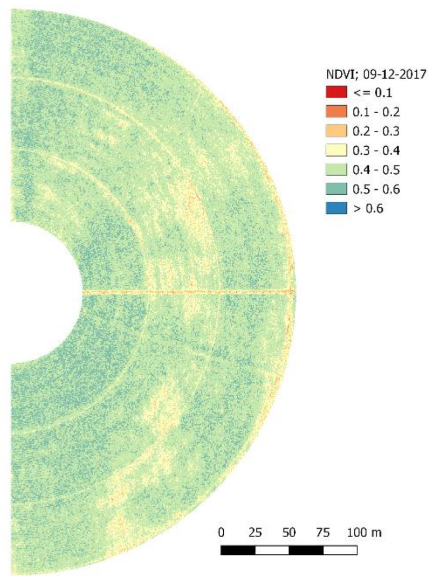
Appendix E NDVI for 2016 of corn irrigated with MDI, LESA and LEPA on a center pivot at the southwest research and extension center of Kansas State University, near Garden City Kansas

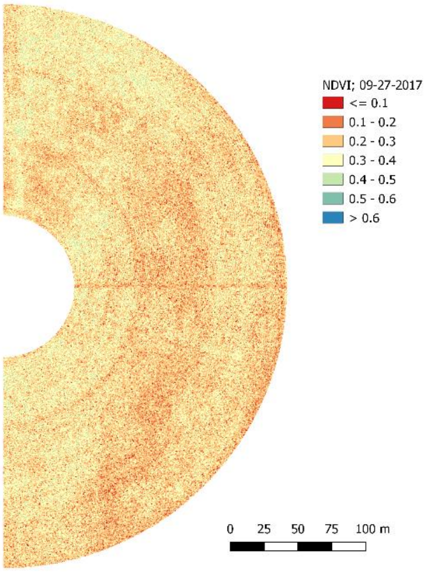


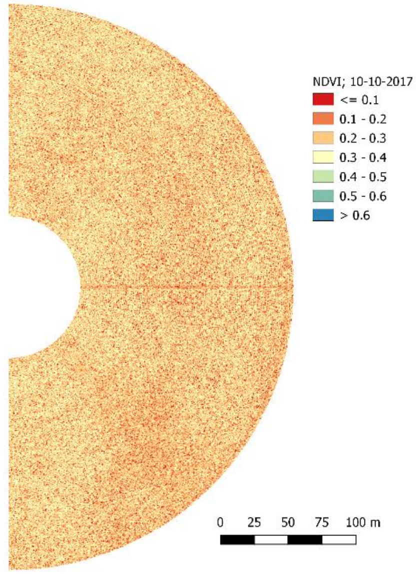

NDVI; 07-25-2017
<= 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
> 0.6
0 25 50 75 100 m


NDVI; 08-02-2017
<= 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
> 0.6
0 25 50 75 100 m


NDVI; 08-29-2017
<= 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
> 0.6
0 25 50 75 100 m


NDVI; 09-12-2017
<= 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
> 0.6
0 25 50 75 100 m


NDVI; 09-27-2017
<= 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
> 0.6
0 25 50 75 100 m


NDVI; 10-10-2017
<= 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
> 0.6
0 25 50 75 100 m

Appendix F Corn grain yield for 2016 and 2017 from experiment conducted at Kansas State University's Southwest Research Extension Center, Garden City, KS, to evaluate irrigation by MDI, LESA and LEPA

2017

Replication 1

Sample	Device	Sample weight (g)	MC (%)	Wt. of MC sample (g)	No. of plants	No. of ears	% dry matter	Yield (kg/ha)	$Yield_{15.5\%\ MC}$ (kg/ha)
1411	MDI (2 gph)	12,905	12.8	59.6	68	63	0.872	12,113	14,335
1412	MDI (1 gph)	14,579	13.1	59.6	81	76	0.869	13,637	16,138
1421	LEPA	13,183	14.9	59.2	74	68	0.851	12,076	14,291
1422	LESA	13,235	12.6	59.0	74	74	0.874	12,451	14,735
1321	LESA	11,675	14.9	59.6	75	73	0.851	10,694	12,656
1322	LEPA	13,449	14.1	60.3	75	73	0.859	12,435	14,716
1311	MDI (1 gph)	13,524	12.3	58.9	73	71	0.877	12,767	15,109
1312	MDI (2 gph)	12,643	14.5	60.3	72	72	0.855	11,635	13,769
1211	MDI (2 gph)	12,028	11.3	59.4	84	79	0.887	11,484	13,590
1212	MDI (1 gph)	11,266	12.3	59.1	70	70	0.877	10,635	12,586
1221	LESA	12,612	12.1	59.3	71	71	0.879	11,933	14,122
1222	LEPA	10,152	11.4	59.6	72	67	0.886	9,682	11,458

Replication 2

Sample	Device	Sample weight (g)	MC (%)	Wt. of MC sample (g)	No. of plants	No. of ears	% dry matter	Yield (kg/ha)	$Yield_{15.5\%\ MC}$ (kg/ha)
2411	MDI (2 gph)	11,429	12.9	60.4	62	56	0.871	10,715	12,681
2412	MDI (1 gph)	13,639	15.0	61.0	76	78	0.850	12,478	14,767
2421	LEPA	13,520	13.1	61.1	73	61	0.869	12,646	14,966
2422	LESA	13,104	12.5	60.3	74	74	0.875	12,342	14,606
2321	LESA	10,520	11.8	60.1	74	67	0.882	9,987	11,819
2322	LEPA	12,928	13.5	59.4	77	82	0.865	12,037	14,245
2311	MDI (1 gph)	11,971	11.5	60.1	66	59	0.885	11,404	13,495
2312	MDI (2 gph)	11,158	12.6	59.5	76	73	0.874	10,497	12,423
2211	MDI (2 gph)	12,442	14.4	59.8	72	68	0.856	11,464	13,567
2212	MDI (1 gph)	13,616	13.5	59.6	68	68	0.865	12,678	15,003

2221	LESA	12,886	13.0	59.4	58	64	0.870	12,067	14,280
2222	LEPA	12,292	13.2	59.5	63	68	0.868	11,484	13,591

Replication 3

Sample	Device	Sample weight (g)	MC (%)	Wt. of MC sample (g)	No. of plants	No. of ears	% dry matter	Yield (kg/ha)	$Yield_{15.5\%\ MC}$ (kg/ha)
3411	MDI (2 gph)	10,973	11.9	60.1	53	48	0.881	10,405	12,314
3412	MDI (1 gph)	10,604	13.2	59.1	77	74	0.868	9,907	11,725
3421	LEPA	12,075	12.7	59.5	70	68	0.873	11,346	13,428
3422	LESA	11,268	14.9	58.8	76	76	0.851	10,321	12,214
3321	LESA	11,839	12.8	60.0	71	70	0.872	11,112	13,150
3322	LEPA	10,395	11.7	60.4	74	59	0.883	9,880	11,692
3311	MDI (1 gph)	12,579	12.9	60.3	71	71	0.871	11,794	13,957
3312	MDI (2 gph)	11,715	11.9	60.1	77	65	0.881	11,109	13,147
3211	MDI (2 gph)	12,816	12.9	59.6	75	62	0.871	12,016	14,220
3212	MDI (1 gph)	12,277	15.1	60.2	67	69	0.849	11,220	13,278
3221	LESA	14,078	12.6	58.9	68	50	0.874	13,244	15,673
3222	LEPA	14,123	12.4	60.6	73	68	0.876	13,316	15,759

2016

Replication 1

Sample	Device	Sample weight (g)	MC (%)	Wt. of MC sample (g)	No. of plants	No. of ears	% dry matter	Yield (kg/ha)	$Yield_{15.5\%\ MC}$ (kg/ha)
1411	MDI (2 gph)	11,099	9.2	59.6	68	63	0.908	10,848	12,838
1412	MDI (1 gph)	12,654	9.6	59.6	81	76	0.904	12,313	14,572
1421	LEPA	11,821	9.3	59.2	74	68	0.907	11,541	13,658
1422	LESA	11,119	9.0	59.0	74	74	0.910	10,891	12,889
1321	LESA	9,690	9.2	59.6	75	73	0.908	9,471	11,208
1322	LEPA	11,723	9.5	60.3	75	73	0.905	11,420	13,515
1311	MDI (1 gph)	11,157	8.8	58.9	73	71	0.912	10,952	12,962
1312	MDI (2 gph)	12,240	9.4	60.3	72	72	0.906	11,937	14,126
1211	MDI (2 gph)	11,210	9.2	59.4	84	79	0.908	10,956	12,966
1212	MDI (1 gph)	11,183	9.4	59.1	70	70	0.906	10,906	12,906

1221	LESA	10,752	9.0	59.3	71	71	0.910	10,532	12,464
1222	LEPA	10,308	9.4	59.6	72	67	0.906	10,052	11,896
1121	LEPA	11,668	9.3	59.7	73	72	0.907	11,391	13,481
1122	LESA	11,297	9.5	59.8	86	77	0.905	11,005	13,023
1111	MDI (1 gph)	12,114	9.4	59.2	72	77	0.906	11,814	13,981
1112	MDI (2 gph)	10,311	9.4	59.6	70	69	0.906	10,055	11,900

Replication 2

Sample	Device	Sample weight (g)	MC (%)	Wt. of MC sample (g)	No. of plants	No. of ears	% dry matter	Yield (kg/ha)	Yield$_{15.5\%\ MC}$ (kg/ha)
2411	MDI (2 gph)	9,405	9.0	60.4	62	56	0.910	9,212	10,902
2412	MDI (1 gph)	13,676	10.0	61.0	76	78	0.900	13,249	15,679
2421	LEPA	11,430	9.9	61.1	73	61	0.901	11,085	13,119
2422	LESA	14,047	9.6	60.3	74	74	0.904	13,669	16,176
2321	LESA	9,239	9.4	60.1	74	67	0.906	9,010	10,663
2322	LEPA	9,629	9.0	59.4	77	82	0.910	9,432	11,162
2311	MDI (1 gph)	10,733	9.2	60.1	66	59	0.908	10,490	12,414
2312	MDI (2 gph)	12,296	9.1	59.5	76	73	0.909	12,031	14,238
2211	MDI (2 gph)	11,564	9.5	59.8	72	68	0.905	11,265	13,331
2212	MDI (1 gph)	11,103	9.6	59.6	68	68	0.904	10,804	12,786
2221	LESA	9,974	9.3	59.4	58	64	0.907	9,737	11,524
2222	LEPA	11,344	9.2	59.5	63	68	0.908	11,087	13,121
2121	LEPA	9,759	8.9	58.9	71	75	0.911	9,570	11,325
2122	LESA	10,271	9.6	59.6	83	72	0.904	9,994	11,828
2111	MDI (1 gph)	10,826	9.3	59.2	64	64	0.907	10,569	12,508
2112	MDI (2 gph)	11,596	9.4	58.9	74	73	0.906	11,309	13,383

Replication 3

Sample	Device	Sample weight (g)	MC (%)	Wt. of MC sample (g)	No. of plants	No. of ears	% dry matter	Yield (kg/ha)	Yield$_{15.5\%\ MC}$ (kg/ha)
3411	MDI (2 gph)	9,607	9.6	60.1	53	48	0.904	9,348	11,063
3412	MDI (1 gph)	11,390	9.6	59.1	77	74	0.904	11,083	13,116
3421	LEPA	10,959	8.8	59.5	70	68	0.912	10,758	12,731

3422	LESA	7,529	9.0	58.8	76	76	0.910	7,375	8,728
3321	LESA	11,545	9.5	60.0	71	70	0.905	11,246	13,309
3322	LEPA	10,123	8.9	60.4	74	59	0.911	9,927	11,747
3311	MDI (1 gph)	11,963	9.7	60.3	71	71	0.903	11,628	13,761
3312	MDI (2 gph)	11,294	9.1	60.1	77	65	0.909	11,050	13,078
3211	MDI (2 gph)	11,280	9.4	59.6	75	62	0.906	11,000	13,018
3212	MDI (1 gph)	12,053	9.5	60.2	67	69	0.905	11,741	13,895
3221	LESA	9,171	9.2	58.9	68	50	0.908	8,963	10,608
3222	LEPA	12,615	9.7	60.6	73	68	0.903	12,262	14,511
3121	LEPA	9,828	9.6	59.2	64	54	0.904	9,563	11,317
3122	LESA	12,765	9.2	59.2	70	70	0.908	12,476	14,765
3111	MDI (1 gph)	9,641	9.6	59.3	74	70	0.904	9,381	11,102
3112	MDI (2 gph)	10,471	9.2	60.1	65	65	0.908	10,234	12,111

Appendix G 500 seed weight of corn for 2016 and 2017 from experiment conducted at Kansas State University's Southwest Research Extension Center, Garden City, KS, to evaluate irrigation by MDI, LESA and LEPA

		2017		2016	
Sample		Wet weight (g)	Dry weight (g)	Wet weight (g)	Dry weight (w)
1411	MDI (2 gph)	209.5	197.0	156.5	147.2
1412	MDI (1 gph)	210.6	198.2	161.0	150.7
1421	LEPA	206.1	196.9	147.7	138.5
1422	LESA	211.8	201.1	143.0	134.4
1321	LESA	205.8	194.3	131.3	123.4
1322	LEPA	210.2	197.7	148.6	139.5
1311	MDI (1 gph)	202.3	190.2	143.0	134.7
1312	MDI (2 gph)	214.1	202.0	147.0	139.0
1211	MDI (2 gph)	202.6	191.4	141.6	133.1
1212	MDI (1 gph)	205.2	194.3	146.7	137.3
1221	LESA	196.3	185.7	146.3	137.6
1222	LEPA	207.5	195.8	141.1	130.2
2411	MDI (2 gph)	202.6	191.7	158.8	150.3
2412	MDI (1 gph)	200.3	190.9	165.0	155.1
2421	LEPA	207.9	198.0	174.9	164.4
2422	LESA	200.0	189.9	170.4	160.1
2321	LESA	202.1	191.5	144.0	135.3
2322	LEPA	198.3	188.1	139.5	131.1
2311	MDI (1 gph)	203.1	191.7	168.4	158.4
2312	MDI (2 gph)	207.1	196.9	153.4	144.5
2211	MDI (2 gph)	207.5	195.7	160.8	150.8
2212	MDI (1 gph)	210.4	198.3	155.1	145.2
2221	LESA	214.8	202.6	142.6	134.0
2222	LEPA	208.0	197.1	150.2	141.0
3411	MDI (2 gph)	205.0	194.9	162.4	152.7
3412	MDI (1 gph)	208.9	197.2	141.6	132.8
3421	LEPA	204.9	194.1	161.1	152.7
3422	LESA	209.6	196.9	115.5	108.4
3321	LESA	213.8	203.4	147.0	138.1
3322	LEPA	MS	MS	157.4	148.5
3311	MDI (1 gph)	211.5	199.9	144.3	135.8
3312	MDI (2 gph)	212.1	200.4	153.5	144.2
3211	MDI (2 gph)	209.6	197.1	146.8	137.9
3212	MDI (1 gph)	208.5	197.2	166.8	156.6
3221	LESA	210.7	199.8	154.3	145.1
3222	LEPA	206.5	195.7	145.6	136.7

Appendix H Seasonal biomass weights of corn for 2016 and 2017 from experiment conducted at Kansas State University's Southwest Research Extension Center, Garden City, KS, to evaluate irrigation by MDI, LESA and LEPA

		6/22/17	7/26/17	8/28/17	10/5/17	6/21/16	7/11/16	8/9/16	9/6/16
Sample		Gross[7] sample weight (g)				Gross[8] sample weight (g)			
1411	MDI (2 gph)	157.6	1223.3	993.4	1647.5	284.0	655.9	1088.5	1140.5
1412	MDI (1 gph)	143.6	1319.5	1101.0	1753.9	232.8	662.5	999.5	1149.7
1421	LEPA	124.7	1157.8	1292.0	1928.8	198.7	690.6	1210.5	1408.3
1422	LESA	160.7	1272.2	1337.9	1613.3	286.5	697.6	1111.6	1419.7
1321	LESA	168.7	618.6	1010.9	1470.9	290.4	592.9	1101.0	989.8
1322	LEPA	154.7	977.1	1008.1	1597.3	250.0	598.9	1011.0	997.8
1311	MDI (1 gph)	139.8	1069.2	1142.6	1584.5	308.1	635.8	1157.4	1125.2
1312	MDI (2 gph)	130.7	996.0	1192.8	1763.8	241.5	642.2	1062.8	1134.3
1211	MDI (2 gph)	132.4	783.4	982.5	1392.8	236.2	553.3	962.1	1293.0
1212	MDI (1 gph)	143.9	802.1	1520.1	1609.2	211.5	558.9	883.5	1303.4
1221	LESA	139.2	1172.6	1107.6	1505.0	265.5	399.2	986.7	1294.2
1222	LEPA	128.5	1109.4	1003.5	1280.2	222.2	403.2	906.1	1304.6
2411	MDI (2 gph)	181.4	987.0	1240.0	1684.9	205.9	397.3	1015.8	1333.3
2412	MDI (1 gph)	141.3	955.4	1175.4	1557.7	246.1	401.3	932.8	1344.1
2421	LEPA	164.5	1539.6	1315.0	1569.3	327.5	618.8	1012.4	1363.8
2422	LESA	153.6	1304.6	1653.1	1695.1	308.1	625.1	929.7	1374.8
2321	LESA	159.7	1186.2	1262.6	1178.3	171.0	752.9	1197.5	1035.5
2322	LEPA	143.8	1077.5	1212.7	1529.4	198.8	760.5	1099.6	1043.9
2311	MDI (1 gph)	154.5	1064.2	1104.0	1391.0	215.3	751.9	929.8	975.9
2312	MDI (2 gph)	139.5	894.8	1036.3	1387.5	296.5	759.5	853.8	983.8
2211	MDI (2 gph)	143.4	946.8	1325.6	1555.5	208.0	529.2	1118.5	859.3
2212	MDI (1 gph)	125.2	1213.5	1081.1	1367.3	303.7	534.5	1027.1	866.2
2221	LESA	135.7	1278.3	1185.4	1465.0	243.1	582.5	1032.8	1109.2
2222	LEPA	148.9	1394.5	1390.9	1392.5	169.7	588.4	948.4	1118.1
3411	MDI (2 gph)	168.8	1278.1	1214.0	1190.8	298.6	599.2	1317.4	1385.9
3412	MDI (1 gph)	125.4	907.7	1101.6	1488.2	249.7	605.3	1209.7	1397.1
3421	LEPA	145.3	915.0	833.7	1714.6	248.1	605.6	1115.7	1317.7
3422	LESA	129.4	1103.9	1110.7	1463.3	355.4	611.7	1024.5	1328.3
3321	LESA	139.6	985.8	1206.4	1414.2	230.1	555.1	891.2	1311.1
3322	LEPA	120.3	1185.3	1238.1	1386.0	271.7	560.7	818.4	1321.7
3311	MDI (1 gph)	142.9	1052.1	1194.6	1515.6	203.2	464.7	1138.0	1175.7

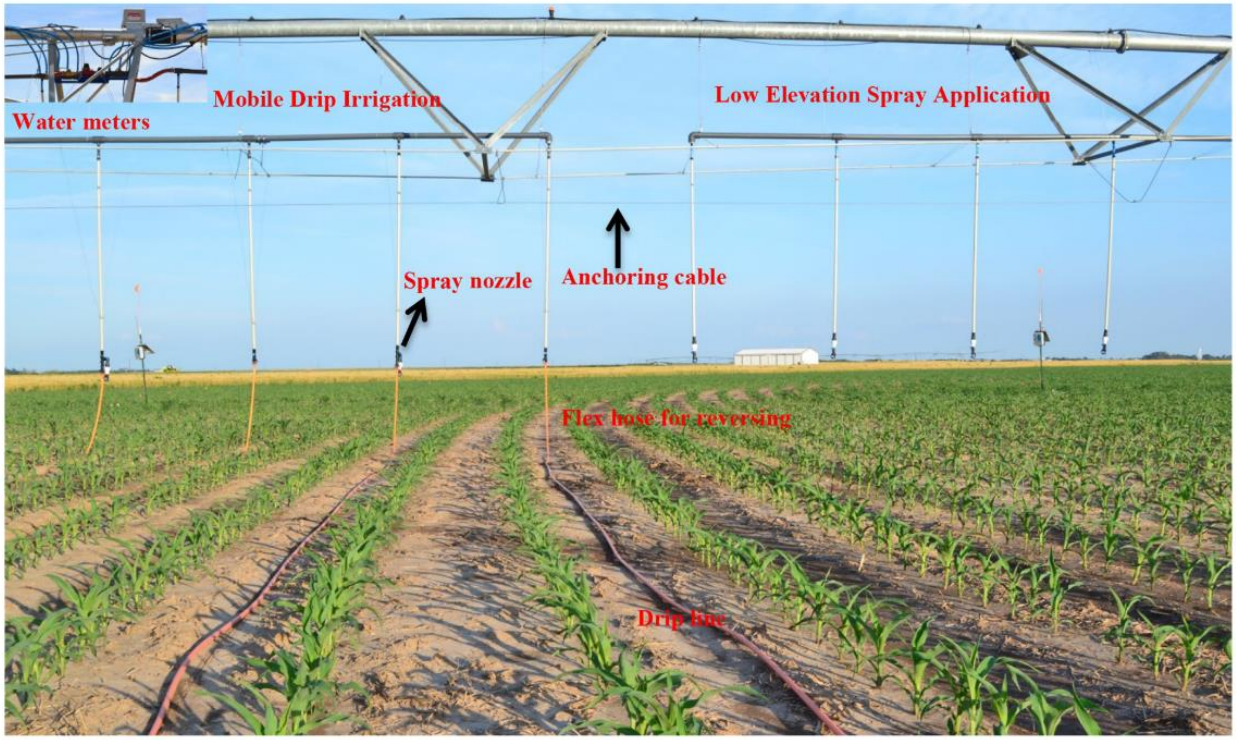
[7] Mean bag weight was 51.1 g

[8] Mean bag weight was 49.5 g

3312	MDI (2 gph)	164.6	1439.2	1414.0	1349.5	262.2	469.4	1045.0	1185.2
3211	MDI (2 gph)	146.8	1228.9	1227.6	1438.5	301.5	679.6	1005.7	1273.9
3212	MDI (1 gph)	163.5	1097.7	998.4	1918.5	250.1	686.5	923.5	1284.2
3221	LESA	141.6	931.9	1142.2	1554.3	297.3	810.0	1058.9	1141.0
3222	LEPA	136.8	1331.7	1207.4	1721.9	280.2	818.2	972.4	1150.2

Appendix I Seasonal leaf area index (LAI) of corn for 2016 and 2017 from experiment conducted at Kansas State University's Southwest Research Extension Center, Garden City, KS, to evaluate irrigation by MDI, LESA and LEPA

Sample	Device	6/24/16	7/15/16	8/24/16	6/15/17	6/29/17	7/13/17	8/1/17	8/9/17
1411	MDI (2 gph)				0.36	1.80	2.73	3.82	4.22
1412	MDI (1 gph)				0.26	2.03	3.12	4.10	5.21
1421	LEPA				0.97	2.25	3.70	4.14	5.03
1422	LESA				0.46	2.57	3.51	3.92	3.68
1321	LESA		4.76		0.35	2.73	3.04	3.87	4.03
1322	LEPA	1.91	5.53		0.23	2.20	3.08	4.25	4.56
1311	MDI (1 gph)	1.82	5.24		0.24	2.67	3.50	4.19	5.21
1312	MDI (2 gph)	3.56	4.09	2.20	0.33	1.63	3.30	3.77	4.32
1211	MDI (2 gph)	3.58	6.10		0.36	1.37	2.95	3.40	4.67
1212	MDI (1 gph)	3.76	5.21	1.13	0.16	1.27	2.48	3.44	4.87
1221	LESA	4.17	5.56	1.53	0.28	1.48	2.43	3.10	4.82
1222	LEPA	2.94	3.87	1.90	0.27	1.73	2.44	2.66	4.07
2411	MDI (2 gph)	2.47	2.45	1.98	1.13	2.73	3.48	3.59	5.00
2412	MDI (1 gph)	3.96	5.77	3.62	1.17	1.95	3.30	3.63	4.87
2421	LEPA	3.02	5.71	2.98	0.97	2.47	3.93	4.15	5.31
2422	LESA	3.86	4.00	2.68	0.73	2.28	3.53	3.76	5.29
2321	LESA	2.95	4.62	2.81	0.65	2.07	2.67	3.67	4.73
2322	LEPA	3.14	4.59	3.06	1.08	2.43	3.46	3.47	4.75
2311	MDI (1 gph)	3.88	5.03	3.22	1.02	2.45	3.43	3.88	4.89
2312	MDI (2 gph)	3.60	3.40	3.04	0.44	2.37	3.42	3.77	5.53
2211	MDI (2 gph)	2.69	5.57	3.22	0.66	1.93	3.25	3.80	4.60
2212	MDI (1 gph)	4.70	6.13	2.12	0.77	2.85	1.65	3.20	4.83
2221	LESA	3.45	3.81	2.21	0.48	1.75	3.22	3.60	5.01
2222	LEPA	2.84	6.02	3.43	0.60	2.50	3.15	3.50	4.99
3411	MDI (2 gph)				1.19	2.22	3.01	3.32	4.40
3412	MDI (1 gph)				1.16	1.55	2.31	2.88	3.42
3421	LEPA		4.67		1.05	2.18	2.38	3.30	3.89
3422	LESA	3.14	5.09	2.41	0.95	1.56	2.39	2.87	3.36
3321	LESA			2.48	1.27	2.26	2.71	3.21	4.42
3322	LEPA	3.29		4.37	1.40	2.55	3.22	3.56	3.97
3311	MDI (1 gph)			2.84	1.40	2.46	3.55	3.89	4.55
3312	MDI (2 gph)	3.40		2.99	1.40	2.15	3.44	3.18	4.04
3211	MDI (2 gph)			1.25	1.40	1.38	3.51	3.59	4.63
3212	MDI (1 gph)		5.17	3.34	1.40	2.27	3.31	3.69	4.40
3221	LESA				1.40	2.01	3.15	3.83	4.27
3222	LEPA		4.36		1.40	2.56	3.00	3.42	4.27



Appendix J Section of center pivot fitted with MDI at the Kansas State University Southwest Research and Extension Center, near Garden City, Kansas (Kisekka et al., 2017)

Appendix K Number of MDI driplines and LEPA and LESA nozzles for center pivot installed at the Kanas State University Southwest Research abd Extension Center near Garden City, Kansas

	Number of driplines/nozzles			
Span	MDI_1	MDI_2	LEPA bubbler	LESA spray
1	5	5	6	5
2	7	7	6	7
3	6	5	6	7
4	7	7	6	8

MDI_1 dripper flow was 3.8 L/h
MDI_2 dripper flow was 7.6 L/h

Appendix L Hydraulic characteristics of mobile drip irrigation system installed at the Kansas State University Southwest Research and Extension Center (SWREC) near Garden City Kansas (Kisekka et al., 2017)

Span	Outlet #	Distance to pivot point (m)	Flow (m^3/h)	Pressure (kPa)	MDI_1 length (m)	MDI_2 length (m)
1	1	10.7	0.05	123.4		1.0
	2	12.2	0.06	123.0		1.2
	3	13.7	0.07	124.1		1.3
	4	15.2	0.07	123.8		1.5
	5	16.8	0.08	123.6		1.6
	6	18.3	0.09	123.4	3.4	
	7	19.8	0.09	123.2	3.7	
	8	21.3	0.1	123.1	4.0	
	9	22.9	0.11	123.1	4.3	
	10	24.4	0.12	123.2	4.6	
2	35	62.5	0.3	120.7	11.9	
	36	64.0	0.3	120.6	12.2	
	37	65.5	0.31	120.6	12.5	
	38	67.1	0.32	120.6	12.8	
	39	68.6	0.33	120.7	13.1	
	40	70.1	0.33	119.4	13.4	
	41	71.6	0.34	119.7	13.7	
	42	73.2	0.35	120.0		7.0
	43	74.7	0.35	120.3		7.1
	44	76.2	0.36	119.2		7.3
	45	77.7	0.37	119.7		7.4
	46	79.3	0.38	118.7		7.6
	47	80.8	0.38	119.2		7.7
3	48	82.3	0.39	119.1		7.9
	49	83.8	0.4	118.9		8.0
	50	85.3	0.41	118.4		8.1
	51	86.9	0.41	119.1		8.3
	52	88.4	0.42	118.3		8.4
	53	89.9	0.43	117.8		8.6
	54	91.4	0.43	118.6		8.7
	55	93.0	0.44	118.0	17.7	
	56	94.5	0.45	117.5	18.0	
	57	96.0	0.46	118.5	18.3	
	58	97.5	0.46	118.1	18.6	
	59	99.1	0.47	117.8	18.9	
	60	100.6	0.48	117.5	19.2	
	61	102.1	0.49	117.3	19.5	
4	89	144.8	0.69	112.9	27.7	

90	146.3	0.7	112.7	28.0	
91	147.8	0.7	112.7	28.4	
92	149.4	0.71	112.7	28.7	
93	150.9	0.72	112.7	29.0	
94	152.4	0.72	111.4	29.3	
95	153.9	0.73	111.6	29.6	
96	155.5	0.74	111.8		14.7
97	157.0	0.75	112.0		14.8
98	158.5	0.75	110.9		15.0
99	160.0	0.76	111.6		15.1
100	161.5	0.77	110.6		15.3
101	163.1	0.78	111.0		15.4
102	164.6	0.78	110.6		15.6

MDI_1 dripper flow was 3.8 L/h
MDI_2 dripper flow was 7.6 L/h