ABSTRACT

OWENS, WESLEY AARON. Contrasting Yield, Irrigation Water Use Efficiency, and Economics of Center Pivot and Subsurface Drip Irrigation Systems for Corn Production in the Southeastern Coastal Plain. (Under the direction of Dr. Garry L. Grabow).

The objectives of this study were to 1) evaluate corn grain yield and irrigation water use efficiency differences among three irrigation treatments including grower scheduled center pivot irrigation, grower scheduled subsurface drip irrigation (SDI), and soil-water sensor controlled SDI, 2) perform an economic analysis comparing SDI and center pivot irrigation for corn production in North Carolina, and 3) investigate the extent of lateral movement of irrigation water from the dripline by contrasting the soil-water distributions of grower scheduled SDI and soil-water sensor controlled SDI. The experimental study was conducted at P&S Farms near Rowland, North Carolina. A 9-ha SDI system with a dripline spacing of 1.02-m installed at a depth of 0.25-m was installed in March 2011 adjacent to an existing center pivot system. The 9-ha was separated into two zones: grower scheduled SDI (approximately 6-ha) and soil-water sensor controlled SDI (approximately 3-ha). Corn was planted 15 April 2011 in 0.51-m rows.

Corn grain yield and irrigation water use efficiency was compared for each irrigation treatment. The soil-water sensor controlled SDI had a corn grain yield of 15.69 Mg/ha and was statistically higher than the grower scheduled SDI (12.82 Mg/ha) and the non-irrigated yield (10.73 Mg/ha). The grower scheduled center pivot system produced a corn yield of 13.60 Mg/ha that was not statistically different than the soil-water sensor controlled SDI yield. The irrigation water use efficiency was not statistically different across the treatments.
The economics for SDI and center pivot systems were compared for North Carolina corn production. The economic analysis was based on a square 65-ha field, which is a quarter section. The analysis compared SDI and center pivot systems by varying corn grain yield and sell price, varying the capital cost per hectare of a SDI system and SDI system life, and by varying field size and SDI system life. Higher corn grain yield and corn sell price benefitted SDI systems, due to the fact that SDI systems irrigate a larger portion of the area than the center pivot system. SDI systems that last 15 years would require a capital cost less than $4000 per hectare (approximately $1600/ac) to have an advantage over center pivot systems lasting 20 years. SDI systems that last 10 years are only advantageous over center pivot systems for fields that are 25.6-ha or less.

The lateral movement of irrigation water from the dripline was examined by looking at soil-water content and cumulative soil-water content (to 0.38 m) at three different distances from the dripline: 0.15, 0.30, and 0.51 m. The soil-water content and cumulative soil-water content over time showed that irrigation water reached mid-dripline (0.51 m) for both treatments. Cumulative soil-water content ranges were generally smaller farther away from the dripline.

In North Carolina, SDI systems that can last 15 years or more are especially suitable for corn production in irregularly shaped fields where center pivot systems are not practical. Scheduling irrigation based on manual soil-water content monitoring is recommended for SDI systems. A SDI dripline spacing of 1.02-m (alternate row middle on 0.51-m corn row spacing) is adequate for corn production in loam soils.
Contrasting Yield, Irrigation Water Use Efficiency, and Economics of Center Pivot and Subsurface Drip Irrigation Systems for Corn Production in the Southeastern Coastal Plain

by

Wesley Aaron Owens

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science in Biological and Agricultural Engineering

Raleigh, North Carolina

2013

APPROVED BY:

_______________________________  ________________________________
Dr. Ronnie W. Heiniger              Dr. Rodney L. Huffman

_______________________________
Dr. Garry L. Grabow
Committee Chair
BIOGRAPHY

Wesley Aaron Owens was born in Murphy, North Carolina on December 28, 1986. He is the youngest child of David Owens and Julie Maney. He was raised in Warne, NC, where he helped his father and grandmother, Minnie Owens, on the farm. He spent many hours churning butter on his grandmother’s front porch as a child. He helped his father grow tobacco and raise beef cattle. He and his father would grow a small garden every year and would make sure to set out some hot peppers, such as jalapeno, cayenne, and habanero pepper plants. The bonding time spent on the farm helped him develop an appreciation of agriculture.

He attended school in Hayesville, where he ran cross country and track and field. After graduating from Hayesville High School in 2005, Wesley attended North Carolina State University, where he received his Bachelor of Science in Environmental Science with a concentration in Watershed Hydrology in May of 2010. In August 2011, Wesley enrolled in the Graduate School at North Carolina State University to pursue his Master of Science degree in Biological and Agricultural Engineering under the direction of Dr. Grabow.
I would like to thank everyone that contributed to this project. First and foremost, thank you Dr. Grabow for giving me the opportunity to work on this project and for all of your help and patience along the way. I would also like to thank my other committee members, Dr. Heiniger and Dr. Huffman, for their assistance with this project.

I would like to thank Mr. Bo Stone for letting us conduct the research on P&S Farms. Thank you to Jeremy Roston-Navas, Kenneth “Chip” Campbell, Mitchell Miller, and L.T. Woodlief for all of your work on this project. Also, thank you to all of my fellow graduate students for their help and insight.

Lastly, thank you to my family for all of their prayers, love, and support.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................ vii

LIST OF TABLES ........................................................................................................... ix

Chapter 1: Review of Literature .................................................................................... 1

Introduction ..................................................................................................................... 1

General Description of SDI ............................................................................................ 1

Spacing and Depth ............................................................................................................ 2

SDI Impact on yield and Irrigation Water Use Efficiency .............................................. 4

Corn ................................................................................................................................ 4

Soybean .......................................................................................................................... 7

Economics ......................................................................................................................... 8

Irrigation Control Using Feedback ................................................................................ 9

History and background .................................................................................................. 9

Irrigation Scheduling ....................................................................................................... 10

Automated Irrigation Controls ....................................................................................... 12

REFERENCES ................................................................................................................ 16

Chapter 2: Yield and Irrigation Water Use Efficiency for Subsurface Drip and Center Pivot

Irrigated Corn in the Southeastern Coastal Plain ............................................................. 20
Introduction ........................................................................................................................................ 20

Material and Methods ..................................................................................................................... 23

Site Description and Instrumentation ............................................................................................. 23

Yield Sampling and Statistical Analysis .......................................................................................... 26

Irrigation Water Use Efficiency ...................................................................................................... 27

SDI Economic Comparison with a Center Pivot System ............................................................... 28

Results and Discussion ................................................................................................................... 29

Rainfall and Applied Irrigation ........................................................................................................ 29

Corn Grain Yield ............................................................................................................................ 30

Irrigation Water Use Efficiency ...................................................................................................... 31

Soil Water Distribution ................................................................................................................... 31

Economics ....................................................................................................................................... 32

Summary and Conclusions .............................................................................................................. 35

REFERENCES ................................................................................................................................. 37

TABLES AND FIGURES .................................................................................................................. 41

Chapter 3: Analysis of Soil Water Distribution in Soil-Water Sensor Controlled and Grower Scheduled Subsurface Drip Irrigation .............................................................................................................................. 53

Introduction ....................................................................................................................................... 53

Material and Methods ..................................................................................................................... 57

v
Site Description .................................................................................................................. 57
SDI Installation and Instrumentation .................................................................................. 58
Data Analysis ....................................................................................................................... 60
Results and Discussion ...................................................................................................... 61
Rainfall and Applied Irrigation ......................................................................................... 61
Soil-Water Distribution ...................................................................................................... 62
Summary and Conclusions .................................................................................................. 69
REFERENCES ...................................................................................................................... 71
TABLES AND FIGURES ...................................................................................................... 73
LIST OF FIGURES

Fig. 2.1 Layout of the irrigated field and soil-water sensor locations. ........................................ 46

Fig. 2.2 Yield data samples area from Nahunta very fine sandy loam (the blue (light) boxes) and area from Trebloc loam (the red (dark) boxes). ................................................................. 47

Fig. 2.3 Soil-water content (by volume) for the period 2 May to 26 July: (a). non-irrigated soil-water profile (m/m) and (b). center pivot soil-water profile (m/m). ........................................ 48

Fig. 2.4 Soil-water content (by volume) for the period 2 May to 26 July: (a). SDI zone 1 rep. 2 soil-water profile (m/m) and (b). SDI zone 2 rep. 2 soil-water profile (m/m). ..................... 49

Fig. 2.5 Center pivot advantage over SDI ($/ha) based on corn price and yield, with a negative value meaning SDI advantage over center pivot (Lamm et al., 2012b). .............. 50

Fig. 2.6 Center pivot advantage over SDI ($/ha) based on SDI system cost and SDI system life, with a negative value meaning SDI advantage over center pivot (Lamm et al., 2012b). 51

Fig. 2.7 Center pivot advantage over SDI ($/ha) based on field size and SDI system life, with a negative value meaning SDI advantage over center pivot (Lamm et al., 2012b). .......... 52

Fig. 3.1 Field layout with soil-water sensor and controller locations................................. 79

Fig. 3.2 Layout of the soil-water sensor clusters in the two SDI zones. .............................. 80

Fig. 3.3 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for sensor controlled SDI zone 1 rep. 1.................................................. 81

Fig. 3.4 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for sensor controlled SDI zone 1 rep. 2.................................................. 82
Fig. 3.5 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for “fixed daily” scheduled SDI zone 2 rep. 1 ................................................................. 83

Fig. 3.6 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for “fixed daily” scheduled SDI zone 2 rep. 2 ................................................................. 84

Fig. 3.7 Cumulative soil-water content (mm) for sensor controlled SDI zone 1 rep. 1 to 0.381-m depth ................................................................................................................................. 85

Fig. 3.8 Cumulative soil-water content (mm) for sensor controlled SDI zone 1 rep. 2 to 0.381-m depth ................................................................................................................................. 86

Fig. 3.9 Cumulative soil-water content (mm) for “fixed daily” scheduled SDI zone 2 rep. 1 to 0.381-m depth ................................................................................................................................. 87

Fig. 3.10 Cumulative soil-water content (mm) for “fixed daily” scheduled SDI zone 2 rep. 2 to 0.381-m depth ................................................................................................................................. 88

Fig. 3.11 Cumulative soil-water content (mm) for sensor controlled and “fixed daily” scheduled SDI 0.15-m from the dripline to 0.381-m depth ................................................................. 89
LIST OF TABLES

Table 2.1 Least square means corn yield estimates (Mg/ha). .............................................................. 41

Table 2.2 Difference in corn yield (Mg/ha) between Center Pivot (CP) and SDI zones pooled................................................................. 41

Table 2.3 Least mean squares estimates of the IWUE (kg/m3) by irrigation treatment. ..... 42

Table 2.4 Difference in IWUE (kg/m3) between Center Pivot (CP) and SDI zones pooled. 42

Table 2.5 Cost advantage of CP over SDI ($/ha) varying yield (Mg/ha) and sell price ($/Mg). ................................................................................................................................. 43

Table 2.6 Cost advantage of CP over SDI ($/ha) varying SDI system cost ($/ha) and SDI system life (years) (Lamm et al., 2012b). ................................................................. 44

Table 2.7 Cost advantage of CP over SDI ($/ha) varying field size (resulting in different system costs per ha) and SDI system life (years) (Lamm et al., 2012b)............................... 45

Table 3.1 Statistics of soil-water content (m^3/m^3) by depth (d) and distance (dl) from the dripline for sensor controlled SDI zone 1 replication 1 from 3 May to 25 July. ............... 73

Table 3.2 Statistics of soil-water content (m^3/m^3) by depth (d) and distance (dl) from the dripline for sensor controlled SDI zone 1 replication 2 from 3 May to 25 July. ............... 73

Table 3.3 Statistics of soil-water content (m^3/m^3) by depth (d) and distance (dl) from the dripline for “fixed daily” scheduled SDI zone 2 replication 1 from 3 May to 25 July........ 74

Table 3.4 Statistics of soil-water content (m^3/m^3) by depth (d) and distance (dl) from the dripline for “fixed daily” scheduled SDI zone 2 replication 2 from 3 May to 25 July........ 74
Table 3.5  Cumulative soil-water content (mm) statistics 0.15-m from the dripline .......... 75
Table 3.6  Cumulative soil-water content (mm) statistics 0.30-m from the dripline .......... 75
Table 3.7  Cumulative soil-water content (mm) statistics 0.51-m from the dripline .......... 75
Table 3.8  Summary Statistics for soil-water deficit for Sensor Controlled SDI ............... 76
Table 3.9  Summary Statistics for soil-water deficit for “Fixed Daily” Grower Scheduled
SDI .................................................................................................................................................. 77
Table 3.10 Summary Statistics for soil-water deficit) for Non-Irrigated and Grower
Scheduled Center Pivot .......................................................................................................................... 78
Chapter 1: Review of Literature

Introduction

Subsurface drip irrigation (SDI) use is increasing in North Carolina and across the United States. According to USGS Circular 1344 (Kenny et al. 2009), states in the eastern United States reported increases in the use of all types of irrigation systems with the largest increase in microirrigation. Across the United States microirrigation use increased from 3 percent of total area irrigated in 1995 to nearly 7 percent in 2005 (Kenny et al. 2009). The term microirrigation refers to both SDI and surface drip irrigation (DI). Lamm et al. (2012) found that the use of SDI was increasing at a faster rate than DI, increasing from 163,000-ha in 2003 to 260,000-ha in 2008 based on the latest USDA Farm and Ranch Irrigation Survey (USDA-NASS 2009). During that same period DI use increased from 566,000-ha to 694,000-ha. Kenny et al. (2009) reported that California accounted for 65 percent of microirrigation use in 2005. Lamm et al. (2012) reported that 10 states made up 90 percent of the SDI use in 2009: Arizona, California, Florida, Georgia, Kansas, New Mexico, Oklahoma, Oregon, Texas, and Washington.

General Description of SDI

SDI as defined by ASABE is “application of water below the soil surface through emitters with discharge rates usually less than 8 L h⁻¹” (ASAE 2007). SDI is different than and should not be confused with subirrigation, which involves controlling the water table level to irrigate the root zone. SDI differs from DI in that driplines are buried with the intent.
of being permanently installed. The driplines are connected to the submain by a manifold with valves for each SDI zone. An additional manifold with flushing valves is installed at the distal end of the SDI dripline. In addition, the distal end (flushing) manifold helps to equalize the pressure between driplines and to minimize the effects of a severed dripline by providing positive pressure from both ends of the dripline (Lamm and Camp 2007).

Camp (1998) found that SDI has been used in the USA since as early as 1959 in California and Hawaii. In the early 1960s polyethylene or PVC pipe was used for laterals in which holes or slits were cut, drilled, or punched out of the pipe or discrete emitters were punched into the pipe. By 1970 trial installations on commercial farms had begun that included both commercial and experimental emitters and laterals. An increase in interest in SDI occurred in the early 1980s attributable to lower equipment cost and nutrient management capabilities.

**Spacing and Depth**

Dripline spacing is generally set as one dripline per crop row or driplines in alternate row middles. Areas that are less dependent on irrigation to produce crops could use wider dripline spacings (Lamm et al. 2012).

Research conducted on SDI has examined dripline depths between 0.20- and 0.70-m when using tillage and between 0.10- and 0.40-m when there was no tillage and dripline spacing between 0.25- and 5.0-m (Camp 1998). Lamm and Trooien (2003) compared driplines spaced 1.5-, 2.1-, and 3.0-m installed at a depth approximately 0.40 – 0.45-m apart in a corn field with crop rows at 0.76-m apart in Kansas with deep silt loam soils. Dukes and
Scholberg (2005) evaluated dripline depths of 0.23- and 0.33-m with 0.76-m spacing for sweet corn in a sandy soil in Florida. Evett et al. (2000) studied driplines at a depth of 0.30-m and 1.52-m apart in a clay loam in Texas for corn and soybean production. Grabow et al. (2011) examined driplines that were spaced at 1.52- and 2.29-m at a depth of 0.30-m for corn in piedmont clay soil in North Carolina. Alternate – row spacing (about 1.5-m) of driplines is generally agreed to be adequate for corn and soybean based on 0.75-m spaced crop rows (Camp 1998; Evett et al. 2000; Lamm and Trooien 2003). However, Grabow et al. (2011) found that 2.29-m (under every third row with a corn spacing of 0.76-m) dripline spacing may be more economical than 1.52-m (alternate middle rows) dripline spacing in Piedmont clay soil in North Carolina. Dukes and Scholberg (2005) studied a dripline spacing of 0.76-m, with driplines under each crop row in a well–drained sandy Florida soil for sweet corn production. In general, dripline spacing should be based on soil and crop type rather than simply using a recommended spacing.

Dripline installation depth is dependent on crop rooting depth, soil type, and tillage practices. Lamm and Trooien (2003) studied depths of approximately 0.40-0.45-m for well-drained silt loam soils under ridge-till for corn production in Kansas. Dukes and Scholberg (2005) found that 0.23-m dripline depth produced higher yields than 0.33-m depth for a well-drained sandy soil in Florida for sweet corn production. Ayars et al. (1999) evaluated SDI systems in California installed at about 0.45-m depth for tomato, cantaloupe, and sweet corn production. A dripline depth of 0.30-m was evaluated for corn and soybean production by

**SDI Impact on yield and Irrigation Water Use Efficiency**

**Corn**

Several researchers have studied the suitability of SDI for corn production by comparing it with other irrigation systems. The studies have been conducted in North Carolina, South Carolina, Georgia, Florida, and Kansas.

Camp et al. (1989) compared subsurface in-row (SSIR) irrigation with surface in-row (SIR) and surface alternate middle (SAM) irrigation techniques in a loamy sand near Florence, SC. They studied continuous and pulsed irrigation. The pulse mode applied 2-mm over 40 minutes followed by 40 minutes of no irrigation until the entire amount was applied for the SAM technique. The other treatments (SSIR and SIR) had 20 minute pulses. The yield was not statistically different for any irrigation technique or pulse mode in 1985. In 1986, the yields were statistically higher for SSIR and SIR than the SAM treatment for both continuous and pulsed modes. In 1987, the yields were not statistically different for the continuous mode across the three treatments. For the pulsed mode the SIR had a statistically higher yield than the SAM treatment, but was not statistically different than the SSIR. The SSIR yield was not statistically different than the SIR or SAM treatments (Camp et al. 1989).

SDI was compared with a linear move sprinkler system and a non-irrigated treatment in sandy soils in Florida (Dukes and Scholberg 2005). These soils consist of over 97% sand
and have field capacities between 5 and 7.5% soil-water by volume. They studied SDI installed at 0.23 and 0.33 meter depths using time scheduled and sensor scheduled irrigation for both depths for a total of four treatments. In the first year of the study three of the four SDI treatment yields were not statistically different than the linear move sprinkler system, and the 0.33 meter depth SDI with sensor scheduled irrigation treatment had a statistically lower yield. In the second year of the study, the 0.23 meter depth SDI with sensor controlled irrigation treatment yield was not statistically different than the linear move system, but the other three SDI treatments had statistically lower yields than the linear move system. The non-irrigated treatment produced no marketable yield for either year. Irrigation water use efficiency (IWUE) was also compared. In the first year of the study the IWUE for three of the SDI treatments was not statistically different than the IWUE of the linear move system, and the 0.33 meter depth SDI with sensor scheduled irrigation treatment had a statistically lower IWUE. In the second year of the study the linear move IWUE was not statistically different than any of the four SDI treatments.

Stone et al. (2008) compared SDI in a loamy sand with surface drip irrigation and rain-fed (non-irrigated) treatments near Florence, SC. The SDI and surface drip irrigation systems were both evaluated at 1- and 2-m dripline spacing. Pulsed SDI was compared with continuous (one pulse) SDI. The three pulse treatments consisted of: one pulse where irrigation was applied in one continuous application, two pulses where irrigation was applied in two equal applications 12 hours apart, and three pulses where irrigation was applied in three equal applications each 8 hours apart. Total irrigation was the same across the three
pulse treatments and no significant differences in the corn yield between any of the treatments and no significant differences in pooled pulse corn yield between and continuous (one pulse) SDI.

Lamm et al. (2010) compared SDI with simulated low energy precision application (LEPA) sprinkler irrigation for 12 years in northwest Kansas. Using a higher irrigation capacity (25 mm/4 days for LEPA or 6.4 mm daily for SDI) resulted in higher corn grain yields for SDI in 8 out of the 12 years. Using a lower irrigation capacity (25mm/8days for LEPA or 3.3 mm daily for SDI) resulted in each system type having 6 years of higher corn grain yield than the other system. Overall, there were no appreciable differences when averaged over the entire period.

Sorenson and Lamb (2010) compared shallow subsurface drip irrigation (S$^3$DI) with non-irrigated corn in a fine sandy clay loam soil in Georgia. Driplines were 1.83-m apart (alternate row middles) and on average 0.03-m below the soil surface. An average yield was calculated for the S$^3$DI corn and compared with an average non-irrigated yield. S$^3$DI produced statistically higher corn yield than non-irrigated corn all 3 years of the study.

Subsurface drip irrigation at 1.52- and 2.29-m dripline spacings was compared with overhead sprinkler irrigation and non-irrigated treatments in a clay loam soil in the Piedmont of North Carolina (Grabow et al. 2011). All three irrigated treatments produced statistically higher corn yield than the non-irrigated treatment. When averaged over the 4 years in the study there was no significant difference in corn yield between the three irrigated treatments
and the overhead sprinkler irrigation treatment had a statistically higher IWUE than the two SDI treatments.

Generally, these studies found that SDI produced statistically higher corn yield than non-irrigated treatments, with the one exception being Stone et al. (2008) that found SDI produced corn yields that generally were not statistically different than other irrigation treatments. The other irrigation treatments included surface drip, linear move sprinkler, LEPA sprinkler, and overhead sprinkler irrigation. Corn IWUE for SDI was not statistically different than the other irrigation system treatments.

**Soybean**

Few studies have compared SDI with other irrigation methods for soybean production. However, irrigation has been found to increase soybean yield. Camp et al. (1999) found that SDI increased soybean yield over non-irrigated by 17 and 105% in a two year experiment.

Colaizzi et al. (2010) compared center pivot and non-irrigated methods with SDI for soybean production in a clay loam soil in Texas. They used mid elevation spray applicators (MESA), low elevation spray applicators (LESA), and low energy precision applicator (LEPA) for 3 center pivot irrigation methods. The soybean yield for the SDI system was statistically higher than the LESA and LEPA center pivot methods and the non-irrigated yield, but yield from the MESA method was not statistically different than the SDI yield. They found that the soybean IWUE for the SDI system was statistically higher than the three center pivot methods.
Soybean yield under SDI with dripline spacings at 1.52- and 2.29-m was compared with soybean yield from overhead sprinkler irrigation and a non-irrigated treatment in a clay loam soil in the North Carolina Piedmont (Grabow et al. 2011). Yield means were calculated over 2002 – 2004 for early soybeans and 2002 – 2005 for late soybeans. There was no statistical difference in the yields for non-irrigated, the two SDI dripline spacings, and overhead sprinkler irrigated soybeans for both early and late plantings. There was also no statistical difference in soybean IWUE among the irrigated treatments.

SDI produced soybean yields that were competitive with center pivot methods in a clay loam soil in Texas. However, results from the Piedmont of North Carolina suggest that SDI may not improve soybean yields over overhead irrigation or even rainfed for soybeans that are a relatively drought tolerant crop. More research is needed to determine the effect of SDI on soybean yield over a range of rainfall patterns in regions that typically rely on rainfall for soybean production.

Economics

Multiple-year SDI systems that can be amortized over many years are normally required for economic feasibility in the production of lesser-valued commodity crops (Lamm et al 2010). Lamm et al. (2010) state that SDI has a higher investment cost than other irrigation systems, but as field size decreases SDI can be competitive with these systems. This is due to SDI costs remaining relatively constant on a per hectare basis, whereas costs for center pivot systems increase as field size decreases (O’Brien et al. 1998). Lamm et al. (2010) also state that small irregularly shaped fields may be ideal for SDI systems. Bosch et
al. (1992) found that for a 75 acre field SDI was more profitable than towable and fixed center pivot systems, but the towable center-pivot system was most profitable for 150 and 300 acres fields under a corn – soybean rotation. O’Brien et al (1998) found that in the U.S. Great Plains region a life span of 15 years for SDI is required to be competitive with center pivot systems for corn fields that are less than 65 hectares. Lamm and Trooien (2003) had similar findings and stated that at a field size of 50-ha SDI must have a lifespan of at least 10 – 15 years to be economically competitive with center pivot systems that generally last 20 years.

Colaizzi et al. (2010) found that SDI produced the largest gross returns, averaged over four seasons, for cotton when compared with 3 center pivot treatments in a clay loam soil in Texas. Sorensen and Lamb (2010) found that the total net revenue for a corn, cotton, and peanut rotation was statistically higher than non-irrigated total net revenue. Grabow et al. (2011) suggested that a 2.29-m dripline spacing (every third row) may be more economical than a 1.52-m (alternate row middles) for corn production in a clay soil in the Piedmont of North Carolina. They also concluded that SDI was not an economical option for producing soybeans only in North Carolina based on low to negative irrigation water use efficiencies.

**Irrigation Control Using Feedback**

**History and background**

Irrigation control must be based upon an understanding of plant–soil–water relations. Soil is made up of air, solids, and water. Porosity refers to the amount of void (pore) space that is present in the soil and represents the percent of the soil that is filled with water and air.
When the soil-water content exceeds the porosity the result is runoff or deep percolation. At saturation the pore space is completely filled with water. After allowing the soil to drain for 1-2 days, “field capacity” is reached. “Field capacity” is the amount of water that the soil can hold against gravity. When irrigating, it is best to never exceed field capacity to maximize irrigation water use efficiency. The lower level of soil-water content at which a plant can extract water is termed the “permanent wilting point”. At a soil-water content at or below the “permanent wilting point” plants can no longer extract water from the soil resulting in plant death. The difference in soil-water content between field capacity and permanent wilting point is termed “plant available water”. As the soil-water content decreases toward the “permanent wilting point” the water grows increasingly difficult for the plant to extract. Therefore, a “management allowable depletion” (MAD) level above the wilting point should be set to minimize plant water stress. The difference between field capacity and MAD is known as readily available water (RAW) (Allen et al. 1998) and to limit plant water stress and maximize yield the soil water content should be maintained above MAD. Researchers have used several different methods to maintain soil-water content between MAD and field capacity.

**Irrigation Scheduling**

Several strategies have been used for irrigation scheduling such as, fixed timing and varied depth of application, fixed depth and varied timing, fixed depth and fixed timing, methods to achieve scheduling include using a soil-water balance, sensors, crop growth models, and crop water stress indices. Soil water content is an important component of soil-
water balance and has been measured using several instruments including neutron probes, time domain reflectometry (TDR), and also through gravimetric methods (Camp 1998).

Camp et al. (1988) studied three irrigation scheduling treatments for corn in a study conducted from 1979 to 1981. The three treatments were tensiometer, screen-covered evaporation pan, and a computer based water balance. They scheduling treatments for soybeans included tensiometer, screen-covered evaporation pan, and 70% screen-covered evaporation pan, which was replaced with a computer based water balance in the third year of the study. They found that the mean yields over the three year span were not statistically different amongst the treatments for both corn grain yields and soybean seed yields.

Caldwell et al. (1994) studied subsurface drip irrigation of corn using several irrigation frequencies replenishing the cumulative soil-water depletion every 1, 3, 5, and 7 days. They also evaluated irrigation initiation at cumulative soil water depletion of 12.7, 25.4, 38.1, and 50.8 mm. They found that yields were not statistically different for any of the 8 treatments. Treatments with longer periods between irrigation events had higher irrigation water use efficiencies and lower amounts of drainage.

Stone et al. (2008) evaluated subsurface drip irrigation in corn under varying dripline spacing and irrigation cycling. They used a 1 and 2 meter dripline spacing to apply 1, 2, or 3 pulses per irrigation. The 2 pulse treatment applied equal amounts of irrigation 12 hours apart and the 3 pulse treatment applied equal amounts 8 hours apart. Irrigation was scheduled weekly using estimated crop water requirements. Irrigation was applied twice weekly, each application represented half of the crop water requirement for that week. If rainfall occurred
before the irrigation application, then the irrigation depth was calculated by subtracting the amount of rainfall from the total weekly crop water requirements. In the first year, they found that there was no statistical difference in yield between any of the spacing and pulse treatment combinations. In the second year, the 1 and 2 pulse treatments with dripline spacing of one meter resulted in statistically higher yields than the 1 and 2 pulse treatments for the lateral spacing of two meters.

Colaizzi et al. (2010) used irrigation treatments of 0, 25, 50, 75, and 100% of crop ET for soybeans. Crop ET was measured using a neutron probe. They found that irrigating to 100% of ET had a statistically higher yield than the other treatments. Irrigated water use efficiency was not statistically different for any of the irrigated treatments.

**Automated Irrigation Controls**

Irrigation scheduling (manual control) is the basis for automatic irrigation control. Automated irrigation is based on feedback from sensors that monitor soil, crop, or environmental conditions. In an open-loop irrigation system feedback is analyzed and then irrigation is initiated manually. As opposed to “open loop” systems in which irrigation is initiated manually, “closed-loop” systems analyze feedback from sensors, raingages, etc. and initiate irrigation automatically.

Evett et al. (2000) controlled irrigation using a canopy temperature-time threshold method for corn and soybean using automatic SDI. They used threshold temperatures of 28°C and 27°C for corn and soybeans, respectively. They also studied irrigating 2°C above the threshold temperature. They used threshold times of 160 and 240 minutes for both 28°C
and 30°C temperature thresholds for corn and 171 and 256 minutes for both 27°C and 29°C temperature thresholds for soybean. The threshold times that they used were determined in a previous study and represent the daily mean time duration during the irrigation season that well-watered crops of each species were above the threshold temperatures. They also evaluated manual irrigation using weekly irrigations to replenish the soil moisture content (measured using a neutron probe) to field capacity (100%). They also study two other weekly irrigated treatments that applied 33 and 67% of the full amount. They found that for corn the canopy temperature – time threshold method produced excellent yields for both years that corn was planted with yields greater than those using the manual method for the first year. For soybean they found that the yields were not statistically different amongst the treatments in the first year except for the manual 33% treatment which was statistically lower than all but the 67% manual irrigation treatment. In the second year, yields from the 29°C – 256 minute, 67%, and 33% treatments were statistically lower than the other treatments.

Dukes and Scholberg (2005) studied SDI for sweet corn using two scheduling methods with drip tapes at 0.23- and 0.33-m below the surface in sandy soils in Florida. The first method was sensor-controlled irrigation that initiated and terminated irrigation based on soil-water content measured by TDR probes installed 0.05-m above dripline. This automatic method used a programmed low soil-water threshold to open the solenoid valve and a high soil-water threshold to close the solenoid valve. The other method used a daily irrigation schedule. In both years, the yield for the sensor-controlled irrigation at 23 cm below the surface was statistically higher than the daily irrigation at the same depth and the sensor-
controlled at 33 cm below the surface. In the first year, the yield for the sensor-controlled irrigation at 23 cm below the surface was not statistically different than the daily time scheduled irrigation at 33 cm below the surface. In the second year, the yield for the sensor-controlled irrigation at 23 cm below the surface was statistically higher than the time scheduled irrigation at 33 cm below the surface.

Stone et al. (2010) tested irrigation using 0, 75, and 150% of an irrigation base rate (IBR) to determine application. The maximum irrigation depth was set at 13 mm and represented 150% IBR, and an irrigation depth of 6.5 mm was used for 75% IBR. The IBR was estimated using soil water potential values (measured with tensiometers at a depth of 0.30m) for 75% and 150% IBR and interpolating between the two treatments. They found that for the first year the 150% IBR was statistically higher than the 0 and 75% treatments. In the next two years, the 75 and 150% IBR was statistically higher than the 0% treatment, but were not statistically different from one another for corn grain yield in loamy sand near Florence, SC.

Grabow et al. (2011) used soil moisture sensors to control irrigation frequency for SDI for corn and soybean in the Piedmont of North Carolina with clay soils. Nests of sensors were installed at depths of 0.15, 0.30, 0.45 meters. Sensor nests were installed at distances of 0.15, 0.38, and 0.76 meters from the dripline for the every other row (1.52 m) dripline spacing and 0.15, 0.38, 0.76, and 1.14 meters from the dripline for the every third row (2.28 m) dripline spacing. Irrigation was scheduled based on a threshold soil-water level and a rainfall threshold of less than 13 mm over the past 24 hours. The irrigation depth applied
when the soil-water and rainfall conditions were met varied between 5 and 13 mm and was based on crop type and growth stage. This was compared with non-irrigated plots and sprinkler irrigated plots that were scheduled based on manually read soil moisture sensors and attempting to apply a similar amount of irrigation as the SDI treatments on a weekly basis. For corn, the yield for the SDI and sprinkler treatments were statistically higher than a non-irrigated treatment, but were not statistically different from one another. The irrigated water use efficiency was statistically higher for the sprinkler irrigated than either SDI treatments (1.52 and 2.28 meter dripline spacings). For soybean, the yield was not statistically different for SDI, sprinkler, and non-irrigated. Soybean IWUE was not statistically different for SDI and sprinkler treatments.

**Objectives**

The primary objectives of this study were to:

1) Evaluate corn grain yield and irrigation water use efficiency differences among three irrigation treatments including: grower scheduled center pivot irrigation, grower scheduled SDI, and soil-water sensor controlled SDI

2) Perform an economic analysis comparing SDI and center pivot irrigation for corn production in North Carolina

3) Investigate the extent of lateral movement of irrigation water from the dripline by contrasting soil-water distributions of grower scheduled SDI and soil-water sensor controlled SDI
REFERENCES


Chapter 2: Yield and Irrigation Water Use Efficiency for Subsurface Drip and Center Pivot Irrigated Corn in the Southeastern Coastal Plain

Introduction

Subsurface drip irrigation (SDI) is a relatively new technology. In the late 1950s and early 1960s SDI was used in California and Hawaii using PVC pipe as dripline laterals (Camp 1998). In the 1980s, SDI use began to increase because of lower material costs and its nutrient management (fertigation) capabilities. The USGS reported that the use of microirrigation (of which SDI is a sub-category) increased from 3 percent to 7 percent of the total area irrigated from 1995 to 2005 (Kenny et al. 2009). According to the USDA-NASS Farm and Ranch Irrigation Survey (USDA-NASS 2009) SDI use in the United States increased by 59% from 163,000-ha irrigated in 2003 to 260,000-ha in 2008. At the same time, other microirrigation practices such as surface drip (DI) and low-flow micro sprinkler irrigation increased at slower rates of 23 and 20% respectively. In North Carolina, SDI accounts for about 2% of the total area that is irrigated (USDA-NASS 2009). These values for SDI in North Carolina are likely too high due a misunderstanding of the definition of SDI.

SDI is defined as “application of water below the soil surface through emitters with discharge rates usually less than 8 L h\(^{-1}\)” (ASAE 2007). SDI should not be confused with subirrigation, which involves controlling the level of the water table to irrigate the root zone. SDI also differs from DI in that it is buried below the soil surface with the intent of being permanently installed.
Several studies have been conducted comparing SDI to other irrigation types and non-irrigated (rainfed) treatments. Camp et al. (1989) examined SDI, surface drip in-row irrigation, and surface drip alternate middle irrigation in loamy sand in South Carolina for corn production. The SDI yield was not statistically different than the two surface irrigation treatments. Dukes and Scholberg (2005) evaluated SDI, linear move sprinkler irrigation, and a non-irrigated treatment for sweet corn production in a Florida sand soil. They discovered that sensor controlled SDI with driplines installed 0.23 meters below the surface produced yields and irrigation water use efficiencies (IWUE) that were statistically higher than time scheduled SDI at 0.23 and 0.33 meters below the surface, sensor controlled SDI at 0.33 meters below the surface, and non-irrigated treatments. Stone et al. (2008) compared SDI with surface drip irrigation and non-irrigated treatments for corn production in loamy sand in South Carolina. They found that there was no statistical difference in corn yield between SDI and surface drip irrigation treatments. Sorensen and Lamb (2010) compared SDI with a non-irrigated treatment for corn production in fine sandy clay loam in Georgia. They concluded that SDI produced statistically higher yields than non-irrigated treatments for all years of a three year study. Lamm et al. (2010) explored SDI and low energy precision application (LEPA) center pivot sprinkler irrigation for corn production in Kansas. The SDI treatments on average produced yields that were similar to the LEPA sprinkler irrigation treatments in a twelve year study. Grabow et al. (2011) looked at SDI, overhead sprinkler irrigation, and a non-irrigated treatment for corn production in the Piedmont of North Carolina in a clay loam. The SDI and overhead sprinkler irrigation yields were not statistically different. These
studies show that SDI can be competitive with other irrigation techniques for corn production in various regions and soil types.

Using SDI for commodity crops is a relatively new practice (Lamm et al. 2010). SDI systems are ideal for smaller (<50 hectares) irregularly shaped fields (Lamm et al. 2010). Bosch et al. (1992) found that SDI in a corn-soybean rotation was more profitable for fields that were 30 hectares or less and that for fields greater than 60 hectares center pivot was more profitable. O’Brien et al. (1998) found that SDI could be competitive with center pivot systems for fields that were less than 65 hectares when the SDI system lasted at least 15 years. Lamm and Trooien (2003) found that for a 50 hectare field a SDI system would need to last 10 – 15 years to be economically competitive with center pivots that generally last 20 years.

The objective of this study was to compare SDI with center pivot irrigation and a non-irrigated treatment in North Carolina from data collected in 2011. Two different irrigation scheduling techniques were used with SDI: one a grower determined schedule that was basically a fixed daily schedule, and the second a sensor controlled irrigation schedule. The center pivot was also scheduled by the grower. Corn yields and irrigation water use efficiency (IWUE) for each of the treatments are compared, and an economic comparison of SDI and center pivot systems using typical North Carolina inputs is presented.
Material and Methods

Site Description and Instrumentation

The fields for this study are located in the Coastal Plain near Rowland, North Carolina. For this study, four treatments were implemented: non-irrigated (control), center pivot irrigated, SDI irrigated (grower scheduled), and SDI irrigated (soil-water controlled). The dominant soil types are Nahunta very fine sandy loam (fine-silty, siliceous, and thermic Aeric Paleaquults), Aycock very fine sandy loam (fine-silty, siliceous, and thermic Typic Paleudults), and Trebloc loam (fine-silty, siliceous, and thermic Typic Paleaquults) (USDA Web Soil Survey 2013). A 9 hectare subsurface drip irrigation (SDI) system was installed in March of 2011 adjacent to an existing center pivot system (Fig. 2.1). The irrigated field is under a no-till corn – winter wheat – soybean rotation. Corn was planted on 15 April 2011 in rows 0.51-m apart and a planting density of about 94,000 seeds per ha (38,000/ac) for the irrigated field and about 79,000 seeds per ha (32,000/ac) for the non-irrigated field.

For the SDI system, Netafim 13 mil 16 mm diameter Typhoon drip tape (Netafim USA Fresno, CA) with 0.91 liter per hour emitters spaced at 0.60-m was installed at a 1.02-m dripline spacing 0.25-m below the soil surface. The 9-ha irrigated by SDI are split into two zones, with zone 1 (approximately 3-ha) using Echo EC-5 (Decagon Devices, Inc. Pullman, WA) soil-water sensors and a tipping bucket (0.2 mm per tip) rain gage (Davis Instruments Vernon Hills, IL) both logged by a CR10X data controller/logger (Campbell Scientific Inc. Logan, Utah) to provide feedback for automated irrigation control and zone 2 (approximately 6-ha) using a grower determined schedule that was set to irrigate daily, referred to as a “fixed
daily” schedule. Soil-water sensors were installed in all four treatments and were set to log water content at 10 minute intervals (Fig. 2.1). The soil-water controlled SDI (zone 1) and “fixed daily” scheduled SDI (zone 2) each had two replications of soil-water sensors. A soil-water sensor replication consisted of soil-water sensors installed at 0.15- and 0.30-m depths 0.15-, 0.30-, 0.51-m from the dripline – two replications totaling 12 soil-water sensors in each zone. The 12 soil-water sensors in zone 1 (SDI sensor controlled SDI) provided feedback for automated irrigation control. The irrigation program required a minimum of 8 “working” soil-water sensors (2/3 of the 12 total) to compute the 4 hour moving average. If there were not at least 8 “working” sensors then the program reported -100 for the 4 hour moving average soil-water content which implied that there was an insufficient amount of data to compute average soil-water content. A cellular modem was installed at the logger/controller to allow remote monitoring of control status and to help immediately identify problems. A Netafim NMC Junior irrigation controller (Netafim USA Fresno, CA), located 0.4 km away on the opposite side of the field, was programmed to irrigate both zones daily, but an internal logger program overrode irrigation if the soil-water exceeded a user-set water content threshold based on a 4 hour moving average and when the precipitation was less than 13 mm over the past 24 hours. Both of these criteria had to be met for irrigation to proceed. The soil-water threshold was determined based on an assumed field capacity of 30%, soil-water by volume, for a Trebloc soil. The threshold was initially set at 22% soil-water by volume, but was later intentionally increased to 23% soil-water by volume to ensure that the system was working properly. When the soil-water content or precipitation was above the threshold the internal logger program would not enable the irrigation program in
the Netafim controller. The algorithm in the Campbell logger made a daily decision (yes/no) based on soil-water content and precipitation readings at 5:50 AM EDT. If both rainfall and soil-water thresholds were met two irrigation cycles of 2:15 duration each occurred in SDI zone 1 beginning at 6:00 AM and 9:45 AM EDT. Irrigation in SDI zone 2 was accomplished daily in two irrigation cycles of 1:30 duration each at 8:15 AM and noon daily, unless overridden by the grower. The two SDI zones are adjacent to a half-circle (wiper) center pivot system that irrigates between 35 – 40 hectares and is also on a “fixed daily” schedule (Fig. 2.1). The center pivot field had three blocks of soil-water monitoring locations each consisting of two replications. A replication consisted of two soil-water sensors installed at 0.15- and 0.30-m depths. The replications were approximately 4-m apart for each block. These sensors were attached to a Hobo micro station data logger (Onset Computer Corporation Bourne, MA) that was placed in a valve box. Desiccant was placed in each of the Hobo micro station data loggers and then they were wrapped in plastic in an effort to prevent water entry and logger damage. The center pivot soil-water sensors were installed mid-span on each of the last three towers of the center pivot boom. There were two blocks of soil-water sensors in the non-irrigated field with each block consisting of two replications installed in the same manner as the center pivot soil-water sensors. The non-irrigated fields’ soil-water sensors were installed in the northeast corner of the non-irrigated field. The CR10X and Hobo micro stations were set up to log soil-water content every 10 minutes. The sensors for the SDI and center pivot treatments were installed in Trebloc loam and the sensors for the non-irrigated field were installed in Aycock very fine sandy loam and Exum very fine sandy loam. A Watchdog Weather Station (Spectrum Technologies, Inc. Plainfield,
IL) was installed at the central headquarters of the farm, located midway between the SDI/Center Pivot irrigated field and the non-irrigated field. This weather station was used to estimate reference ET and as a backup to the rain gage in the irrigated field and to monitor precipitation for the non-irrigated field. The non-irrigated (control) field was located approximately 1 km northeast of the irrigated field.

**Yield Sampling and Statistical Analysis**

Corn grain yield was obtained from a yield monitor on-board the combine. Information was collected every 1 – 2 meters while harvesting and attributes such as width and length from which the sample was collected, grain flow rate, grain moisture content, and yield adjusted to standard moisture content (15.0%, Saraswat and Ehsani 2002) were recorded to a database. Sampling points were then projected onto an aerial map obtained from the ESRI data server using ArcGIS (ESRI Redlands, CA). In order to sub-sample by soil type, a soil map was obtained from the Web Soil Survey (USDA 2012) and overlain onto the yield map. A polygon layer of the irrigation treatments was created based on the center pivot boom seen in an aerial image and the SDI design plans. Using the soil layer and irrigation treatments polygons it was determined that two dominant soil types existed in each treatment: Nahunta (very fine sandy loam) and Trebloc (loam). Composited samples from the yield map were taken using an 18 meter by 18 meter square polygon that was placed over yield sample points as seen in Fig. 2.2. This area captures three harvested header widths representing between 29 and 39 sample points from the yield monitor. The number of yield sample points varied due to a non-constant harvesting speed resulting in varying distances.
between yield sample points. Three polygons were created for each soil type and irrigation treatment combination for a total of 24 composite samples representing 800 yield samples. The yield layer was clipped to include only the data points within the sample polygons. The data was then exported from ArcGIS to an Excel Spreadsheet (Microsoft Redmond, WA) and the points assigned additional attributes for soil type and treatment. A “control” factor was added within irrigation treatment to indicate the presence or absence of sensor-controlled irrigation with sensor-controlled SDI (zone 1) receiving a “1” and the other irrigation treatments a “0”. The data was then imported into SAS (SAS, Inc. Cary, NC) and the individual yield map sample points composited by irrigation-soil type combination using PROC MEANS. A mixed effect model was constructed in PROC MIXED with irrigation treatment nested within control modeled as fixed effects and soil type modeled as a random effect. An LSMeans statement was used to test for means separation of the fixed effects for each of the four treatments.

**Irrigation Water Use Efficiency**

Irrigation water use efficiency (IWUE) was calculated as:

\[
IWUE = \frac{Y_{irr} - Y_{NI}}{Y_{irr}} \times 100
\]  

(2.1)

where,

\[\text{IWUE} = \text{irrigation water use efficiency (kg/m}^3\text{)}\]

\[Y_{irr} = \text{irrigated yield (Mg/ha)}\]
\( Y_{NI} = \) non-irrigated yield (Mg/ha)

\( \text{Irr} = \) irrigation applied (mm)

The IWUE for each irrigation treatment and soil type was calculated using the mean non-irrigated corn grain yield. A mixed effect model identical to the model used to explain corn grain yield was used to model IWUE. Mean IWUEs were determined for each of the 3 irrigated treatment using the LSMeans statement and tested for means separation at the alpha = 0.05 level. The LSMeans for yield and IWUE were then compared using the “pdiff” option in the LSMeans statement. The two SDI treatments were also evaluated as a single treatment to compare center pivot with SDI, regardless of control type, using an estimate statement.

**SDI Economic Comparison with a Center Pivot System**

An economic analysis comparing SDI to center pivot irrigated corn was performed using an Excel-based spreadsheet developed by Lamm et al. (2012a and 2012b). The spreadsheet takes into account irrigation coverage, initial system cost, economic life, interest rate for system investment, annual insurance cost, and variable production costs from Kansas studies. The variable costs that are taken into consideration include seed, fertilizers, labor, insecticides, herbicides, crop insurance, drying, maintenance and repairs, fuel and oil cost. For this study, these variable cost values were adjusted to values reflective of North Carolina agricultural practices based on a Bullen et al. (2011) report. The SDI and center pivot economic analysis spreadsheet presents net annualized returns per hectare in 3 ways, each way with two varying factors: SDI system life and field size, SDI cost per hectare and SDI system life, and corn yield and corn sell price. The values for these three tables, by default,
include a wide range of values and therefore would encompass most any system installed in
North Carolina. The corn sell price was extended to $322.53/Mg ($8.20/bu) to allow for
increases in corn sell price based on a current sell price of $275.33/Mg ($7.00/bu), which was
initially the highest corn sell price in the table. Also, the net return for dryland cropped area
for the center pivot system was changed from the current dryland crop cash rent estimate for
Northwest Kansas to a North Carolina value based on non-irrigated corn yields.

**Results and Discussion**

**Rainfall and Applied Irrigation**

The irrigated field received 247 mm of rainfall and the non-irrigated field received
301 mm from 15 April (plant) to 22 July (last irrigation). The 30 year average rainfall (1981 –
2010) from 1 May to 31 July for this area is 326 mm (NOAA 2012). There were 22
irrigation events totaling 127 mm for SDI zone 1 and 26 irrigation events totaling 82.6 mm
for SDI zone 2. Zone 1 called for irrigation 38 times between 5 June and 23 July and zone 2
was scheduled to irrigate 50 times in 50 days. Zone 1 failed to irrigate on some occasions that
irrigation was called for due to either the grower turning the system off following rainfall
events or a bad fiber optic receiver at the Campbell Scientific logger. If irrigation had
commenced at the time it was called for in zone 1, then the system could have called for
irrigation fewer than 38 times due to raised soil-water contents from irrigation events. For
zone 2 the 24 missed irrigation events were due to the system being turned off by the grower
following rainfall events and this also applied to the center pivot system. The center pivot
system did not have a flow meter installed for 2011. Therefore, the amount of irrigation applied for the center pivot system was estimated using runtime.

**Corn Grain Yield**

Irrigation control was analyzed as a fixed effect and was not statistically significant to the corn grain yield model. The soil type was modeled as both a fixed and a random effect, and was found to not have a statistically significant effect ($\alpha=0.05$) on corn grain yield. The corn grain yield was greatest for the sensor controlled SDI treatment at 15.69 megagrams per hectare (Mg/ha) (Table 2.1). The lowest yield was for the non-irrigated treatment at 10.73 Mg/ha. The sensor controlled SDI had statistically higher yield than both the fixed daily scheduled SDI and the non-irrigated treatments (Table 2.1). The combined SDI corn grain yield was not statistically different from the center pivot corn grain yield (Table 2.2).

The non-irrigated field received 33 mm more rainfall than the irrigated field from 1 May to 31 July. This led to relatively high yields for the non-irrigated treatment and could explain why there was no statistical difference between the fixed daily scheduled SDI and the non-irrigated treatment. The sensor controlled SDI applied more irrigation than the fixed daily scheduled SDI, which likely led to the sensor controlled treatment having a statistically higher yield. Yields from the center pivot treatment were not statistically different than yields from either SDI treatment. The center pivot treatment was estimated to apply the most irrigation using runtime.
Irrigation Water Use Efficiency

The irrigation water use efficiency (IWUE) was computed using equation 2.1. Applied irrigation was 177.8 mm for the center pivot (estimated using runtime), 127 mm for the sensor controlled SDI, and 83 mm for the fixed daily scheduled SDI. The IWUE was highest for the sensor controlled SDI at 4.50 kilograms per cubic meter (kg/m$^3$) (Table 2.3). However, the IWUEs were not statistically different ($\alpha=0.05$) between the three irrigated treatments (Tables 2.3). At $\alpha=0.10$, the sensor controlled SDI IWUE was statistically greater than the center pivot IWUE. Combined SDI IWUE was not statistically different than the center pivot IWUE (Table 2.4). The relatively high yield from the non-irrigated field led to lower IWUE and could have caused these values to not be statistically different due to increased relative variability.

Soil Water Distribution

Time series graphs of soil-water were developed for all four treatments. In the non-irrigated field (Fig. 2.3), the soil-water content at 0.15-m depth was below 20% by volume at times during the V6 (6 collars), V12 (12 collars), VT (tassel), and R1 (silking) growth stages for corn (growth stage was approximated using 50/86 growing degree day method) (Lee 2011). During this time, the non-irrigated corn suffered from plant water stress causing that treatment to have a lower corn yield. The center pivot soil-water showed heavy extraction resulting in two substantial declines in soil-water between 22 May and 6 June at 0.15-m depth for both replications. The soil-water content at 0.30-m was generally higher than at 0.15-m and this could be attributed to a shallow rooting zone early in the season. The SDI
plots also show declines in soil moisture content in late May and into early June. Subsequently the soil-water content was better maintained for the soil-water controlled SDI. The fixed daily scheduled SDI plot shows smaller responses to irrigation than the sensor controlled SDI because of less irrigation depth per event. The plots from the three irrigated treatments contrasted to the non-irrigated plots show that irrigation is critical in minimizing plant water stress in periods receiving less than normal rainfall.

**Economics**

The economic analysis comparing SDI with center pivot irrigation systems using the spreadsheet and accompanying paper produced by Lamm et al. (2012a and 2012b) was modified to represent values found in North Carolina. This analysis was based on a 65 hectare field, which is a square quarter section, on which an SDI system can irrigate 63 hectares (with 2-ha being used for field roads and access areas) and the center pivot can irrigate 51 hectares (with 12-ha being available for non-irrigated crop area and 2-ha beingused for field roads and access areas). In the first analysis, the capital cost per hectare was fixed at $1419.64 ($574.52/ac) for the center pivot system and $3230.11 ($1307.21/ac) for the SDI system. These values were the suggested values from the worksheet (total cost was $71,815 for center pivot and $202,617 for SDI) and were based on implementing a new system on a field where there was an existing well and pump. The variable cost per hectare for the center pivot system was $1157.37 and $1130.95 for the SDI system. Variable production cost takes into account seed, fertilizer, herbicide and insecticide, crop consulting, crop insurance, drying, machinery expenses, irrigation labor, pumping, irrigation
maintenance and repair, and ½ year interest at an annual rate of 6.25%, from Bullen et al. (2011), on variable costs. The lower variable cost for the SDI system can be attributed to using 25% less water than a center pivot system for irrigation based on findings by Lamm and Trooien (2003). Irrigation amounts were set to 254 mm (10 in.) and 190.5 mm (7.5 in.) for the center pivot and SDI systems, respectively. System life was estimated at 20 years for a center pivot and 10 years for SDI and corn yield and corn sell price was varied. The chosen SDI system life reflects conservative estimates for SDI of 10 years by Bosch et al. (1992) and Lamm and Trooien (2003) and that for center pivots of 20 years is based on estimates by Lamm and Trooien (2003) and Lamm et al. (2012a). The interest rate for system investment was set at an annual rate of 6.25% and the annual property insurance rate at 1.6% of the total system cost for center pivot and 0.6% of the total system cost for SDI. The net return of the non-irrigated crops (12-ha of center pivot field) was set to $554.90 per hectare ($221.96/ac) based on average non-irrigated corn grain yield of approximately 6.4 Mg/ha (100 bu/ac) for North Carolina (USDA-NASS 2013) and the default corn sell price of $226.16/Mg ($5.75/bu). Table 2.5 and Fig. 2.4 present SDI or center pivot advantage in $/hectare (positive values represent center pivot advantage) by corn yield per hectare and corn price per megagram (Mg). Higher corn grain yield and higher corn grain sell prices are beneficial to SDI due to the fact that it irrigates a larger portion of the 65 hectare field evaluated.

Another way of comparing SDI with center pivot systems is by varying the capital cost per hectare and the system life for SDI. The parameters from the previous comparison were used with the following exceptions: corn grain yield was set to 14 Mg/ha (220 bu/ac)
for both systems, the corn selling price was $226.16 per Mg ($5.75/bu), and the SDI capital cost and system life varies. Table 2.6 and Fig. 2.5 presents center pivot or SDI advantage in $/ha (positive values represent center pivot advantage) with varying capital cost per hectare and economic life for SDI. The SDI system must have an economic (system) life of 10 years or greater to have an advantage over center pivot, using these specified values. A system that lasts 15 years would require a capital cost $4000 per hectare ($1600/ac) or less to be advantageous over center pivot. If an SDI system lasts 30 years, then the capital costs for the system could be as high as $5750 per hectare ($2300/ac) and still be advantageous over center pivot.

A third way of comparing SDI and center pivot systems is to vary field size and SDI’s economic (system) life. The same parameters as the previous comparison were used with the exception being field size for both the center pivot and SDI vary. The spreadsheet suggested values were used for field size and system cost per hectare for both center pivot and SDI systems. Table 2.7 and Fig. 2.6 show center pivot or SDI advantage with varying field size and SDI economic life. SDI is advantageous for fields that are 25.6-ha and less when the system lasts 10 years or more. When the SDI system lasts 15 years or more it is advantageous for field sizes up to 65-ha.

This economic analysis shows that the ability to cover a higher percentage of the field area with lower variable costs (lower energy costs for pumping associated with SDI using 25% less water than sprinkler systems) helps SDI to have an economic advantage over center pivot systems when the system lasts 15 years or longer. However, due to SDI systems higher
capital costs, systems that last only 10 years must produce high yields coupled with high sell prices or be installed on a field 25.6-ha or less to be advantageous over center pivot systems. SDI systems that last 5 years or less are not competitive with center pivot systems regardless of field size, SDI capital cost, or corn grain yield/sell price based on the given parameters.

**Summary and Conclusions**

In this study, the sensor controlled yield was found to be statistically higher than the grower scheduled SDI and non-irrigated treatment, but was not statistically different than the fixed daily scheduled center pivot system at an alpha level of 0.05. The sensor controlled SDI treatment IWUE was not statistically different ($\alpha=0.05$) than those for the grower scheduled center pivot or SDI treatments. The SDI treatments produced yields that were comparable to the center pivot treatment. Therefore, SDI can be competitive, from an agronomic standpoint, with center pivot systems in North Carolina. Sensor controlled SDI performed better than the fixed daily scheduled SDI and therefore it would be recommended that soil-water content be monitored for scheduling irrigation for SDI systems in North Carolina. Manual soil-water content monitoring for irrigation scheduling is recommended rather than automated irrigation due to controlled irrigation’s complexity and the inability to buy these systems preconfigured.

The economic comparison showed that SDI can be economically competitive with center pivot systems when the life of the system is at least 15 years. The SDI system is more economical for corn production when it produces a yield of 14.0 Mg/ha (220 bushels/acre) or more and the corn cash price is $243.86 per Mg ($6.20/bushel) or greater, using the
parameters from the first economic comparison. These prices and yields are currently attainable for North Carolina agriculture. Overall, SDI systems that can last at least 15 years are practical for North Carolina, especially in irregularly shaped fields not conducive to installation of center pivots.
REFERENCES


TABLES AND FIGURES

Table 2.1 Least square means corn yield estimates (Mg/ha). CP stands for center pivot, NI stands for non-irrigated, SDI1 is sensor controlled SDI, and SDI2 is grower scheduled SDI. Estimates with similar letters were not statistically different ($\alpha = 0.05$).

| Effect          | Treat | Control | Estimate | Standard Error | DF | t Value | Pr > |t| |
|-----------------|-------|---------|----------|----------------|----|---------|-------|
| Treat(Control)  | CP    | 0       | 13.50 ab | 1.11           | 19 | 12.19   | <.0001|
| Treat(Control)  | NI    | 0       | 10.73 c  | 0.84           | 19 | 12.78   | <.0001|
| Treat(Control)  | SDI1  | 1       | 15.69 a  | 0.94           | 19 | 16.73   | <.0001|

Table 2.2 Difference in corn yield (Mg/ha) between Center Pivot (CP) and SDI zones pooled.

| Label     | Estimate | Standard Error | DF | t Value | Pr > |t| |
|-----------|----------|----------------|----|---------|-------|
| CP vs. SDI| -0.75    | 1.18           | 19 | -0.64   | 0.53  |
Table 2.3 Least mean squares estimates of the IWUE (kg/m\text{3}) by irrigation treatment. CP stands for center pivot, NI stands for non-irrigated, SDI1 is sensor controlled SDI, and SDI2 is grower scheduled SDI. Estimates with similar letters are not statistically different ($\alpha = 0.05$).

| Least Squares Means | Effect          | Treat   | Control | Estimate | Standard Error | DF  | t Value | Pr > |t| |
|---------------------|----------------|---------|---------|----------|----------------|-----|---------|-------|---|
|                     | Treat(Control) | CP      | 0       | 1.98 a   | 1.97           | 12  | 1.01    | 0.33  |
|                     | Treat(Control) | SDI2    | 0       | 3.45 a   | 1.86           | 12  | 1.85    | 0.09  |
|                     | Treat(Control) | SDI1    | 1       | 4.50 a   | 1.86           | 12  | 2.42    | 0.03  |

Table 2.4 Difference in IWUE (kg/m\text{3}) between Center Pivot (CP) and SDI zones pooled.

| Estimates           | Label            | Estimate | Standard Error | DF  | t Value | Pr > |t| |
|---------------------|------------------|----------|----------------|-----|---------|-------|---|
|                     | (CP-SDI)         | -1.99    | 1.28           | 12  | -1.55   | 0.15  |

42
Table 2.5 Cost advantage of CP over SDI ($/ha) varying yield (Mg/ha) and sell price ($/Mg). The values in blue (light) represent an economic advantage for center pivot systems and the red (dark) represents an economic advantage for SDI. This table was based on Kansas State center pivot and SDI economic comparison spreadsheet (Lamm et al., 2012b) with adaptations for North Carolina values.

<table>
<thead>
<tr>
<th>Mg/ha</th>
<th>Corn Yield</th>
<th>Corn Cash Price $/Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$180.93</td>
</tr>
<tr>
<td>10.2</td>
<td>$271.16</td>
<td>$241.51</td>
</tr>
<tr>
<td>10.8</td>
<td>$249.85</td>
<td>$218.34</td>
</tr>
<tr>
<td>11.4</td>
<td>$228.53</td>
<td>$195.18</td>
</tr>
<tr>
<td>12.1</td>
<td>$207.22</td>
<td>$172.01</td>
</tr>
<tr>
<td>12.7</td>
<td>$185.91</td>
<td>$148.84</td>
</tr>
<tr>
<td>13.3</td>
<td>$164.60</td>
<td>$125.68</td>
</tr>
<tr>
<td>14.0</td>
<td>$143.29</td>
<td>$102.51</td>
</tr>
<tr>
<td>14.6</td>
<td>$121.97</td>
<td>$79.35</td>
</tr>
<tr>
<td>15.3</td>
<td>$100.66</td>
<td>$56.18</td>
</tr>
<tr>
<td>15.9</td>
<td>$79.35</td>
<td>$33.02</td>
</tr>
<tr>
<td>16.5</td>
<td>$58.04</td>
<td>$9.85</td>
</tr>
<tr>
<td>17.2</td>
<td>$36.72</td>
<td>-$13.31</td>
</tr>
</tbody>
</table>
Table 2.6 Cost advantage of CP over SDI ($/ha) varying SDI system cost ($/ha) and SDI system life (years) (Lamm et al., 2012b). The values in blue (light) represent an economic advantage for center pivot systems and the red (dark) represents an economic advantage for SDI.

<table>
<thead>
<tr>
<th>SDI Cost $/ha</th>
<th>SDI system life, years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>2500</td>
<td>$166.44</td>
</tr>
<tr>
<td>2750</td>
<td>$223.90</td>
</tr>
<tr>
<td>3000</td>
<td>$281.36</td>
</tr>
<tr>
<td>3250</td>
<td>$338.82</td>
</tr>
<tr>
<td>3500</td>
<td>$396.28</td>
</tr>
<tr>
<td>3750</td>
<td>$453.74</td>
</tr>
<tr>
<td>4000</td>
<td>$511.20</td>
</tr>
<tr>
<td>4250</td>
<td>$568.66</td>
</tr>
<tr>
<td>4500</td>
<td>$626.12</td>
</tr>
<tr>
<td>4750</td>
<td>$683.58</td>
</tr>
<tr>
<td>5000</td>
<td>$741.03</td>
</tr>
<tr>
<td>5250</td>
<td>$798.49</td>
</tr>
<tr>
<td>5500</td>
<td>$855.95</td>
</tr>
<tr>
<td>5750</td>
<td>$913.41</td>
</tr>
<tr>
<td>6000</td>
<td>$970.87</td>
</tr>
<tr>
<td>6250</td>
<td>$1,028.33</td>
</tr>
</tbody>
</table>
Table 2.7 Cost advantage of CP over SDI ($/ha) varying field size (resulting in different system costs per ha) and SDI system life (years) (Lamm et al., 2012b). The values in blue (light) represent an economic advantage for center pivot systems and the red (dark) represents an economic advantage for SDI.

<table>
<thead>
<tr>
<th>Field Size</th>
<th>64</th>
<th>50.8</th>
<th>38</th>
<th>25.6</th>
<th>12.8</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP Size</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP Cost</td>
<td>$1,436.30</td>
<td>$1,675.30</td>
<td>$2,022.02</td>
<td>$2,634.46</td>
<td>$4,309.76</td>
<td>$2,805.27</td>
</tr>
<tr>
<td>CP Dry</td>
<td>12</td>
<td>9.6</td>
<td>7.2</td>
<td>4.8</td>
<td>2.4</td>
<td>5.6</td>
</tr>
<tr>
<td>SDI Size</td>
<td>62</td>
<td>49.6</td>
<td>37.2</td>
<td>24.8</td>
<td>12.4</td>
<td>31.2</td>
</tr>
<tr>
<td>SDI Cost</td>
<td>$3,268.02</td>
<td>$3,340.73</td>
<td>$3,419.43</td>
<td>$3,537.63</td>
<td>$3,813.77</td>
<td>$3,468.79</td>
</tr>
<tr>
<td>SDI life (years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$342.96</td>
<td>$344.20</td>
<td>$336.77</td>
<td>$313.90</td>
<td>$250.08</td>
<td>$302.06</td>
</tr>
<tr>
<td>10</td>
<td>$26.37</td>
<td>$18.02</td>
<td>$2.03</td>
<td>-$28.81</td>
<td>-$119.38</td>
<td>-$36.14</td>
</tr>
<tr>
<td>15</td>
<td>-$79.16</td>
<td>-$90.70</td>
<td>-$109.56</td>
<td>-$143.05</td>
<td>-$242.53</td>
<td>-$148.88</td>
</tr>
<tr>
<td>20</td>
<td>-$131.92</td>
<td>-$145.07</td>
<td>-$165.35</td>
<td>-$200.17</td>
<td>-$304.11</td>
<td>-$205.25</td>
</tr>
<tr>
<td>25</td>
<td>-$163.58</td>
<td>-$177.69</td>
<td>-$198.82</td>
<td>-$234.44</td>
<td>-$341.05</td>
<td>-$239.07</td>
</tr>
</tbody>
</table>
Fig. 2.1 Layout of the irrigated field and soil-water sensor locations. The center pivot system irrigates between 35 – 40 hectares depending on end gun reach. SDI zone 1 is about 3 hectares and SDI zone 2 is about 6 hectares.
Fig. 2.2 Yield data samples area from Nahunta very fine sandy loam (the blue (light) boxes) and area from Trebloc loam (the red (dark) boxes). This figure shows the SDI zone 2, which is the “fixed daily” scheduled irrigation treatment.
Fig. 2.3 Soil-water content (by volume) for the period 2 May to 26 July: (a). non-irrigated soil-water profile (m/m) and (b). center pivot soil-water profile (m/m). The precipitation and irrigation amount is presented on the alternate y-axis in mm.
Fig. 2.4 Soil-water content (by volume) for the period 2 May to 26 July: (a). SDI zone 1 rep. 2 soil-water profile (m/m) and (b). SDI zone 2 rep. 2 soil-water profile (m/m). The precipitation and irrigation amount is presented on the alternate y-axis in mm.
Fig. 2.5 Center pivot advantage over SDI ($/ha) based on corn price and yield, with a negative value meaning SDI advantage over center pivot (Lamm et al., 2012b).
Fig. 2.6 Center pivot advantage over SDI ($/ha) based on SDI system cost and SDI system life, with a negative value meaning SDI advantage over center pivot (Lamm et al., 2012b).
Fig. 2.7 Center pivot advantage over SDI ($/ha) based on field size and SDI system life, with a negative value meaning SDI advantage over center pivot (Lamm et al., 2012b).
Chapter 3: Analysis of Soil Water Distribution in Soil-Water Sensor Controlled and Grower Scheduled Subsurface Drip Irrigation

Introduction

Subsurface drip irrigation (SDI) use in the United States is on the rise. SDI is defined as “application of water below the soil surface through emitters with discharge rates usually less than 8 Lh\(^{-1}\)” (ASABE 2007). Data from the USGS and USDA-NASS show that the use of microirrigation is increasing across the United States (Kenny et al. 2009, USDA-NASS 2010). The USGS “Estimated Use of Water in the United States in 2005” reported an increase from 3 percent to 7 percent of total area irrigated by microirrigation (Kenny et al. 2009). The USDA-NASS Farm and Ranch Irrigation Survey separates microirrigation into three irrigation types: surface drip, subsurface drip, and low-flow micro sprinklers. The most recently competed survey reported a 59 percent increase in subsurface drip irrigation acreage from 2003 to 2008 and smaller increases in acreage irrigated with surface drip and low-flow micro sprinklers of 23 and 20 percent respectively (USDA-NASS 2010). According to this survey, SDI accounts for 2 percent of total area irrigated in North Carolina.

In order to efficiently use SDI, irrigation frequency and duration must be matched with the climate, soil type, and crop. Different methods have been used to determine irrigation frequency and duration for SDI across the United States. SDI is commonly scheduled based on evapotranspiration, pan evaporation, or soil-water depletion/water balance (Camp 1998). In order to schedule irrigation an understanding of soil physical
properties is required. Knowledge of the soil’s field capacity and wilting point are necessary to limit plant water stress and avoid over irrigation. Automated irrigation has been developed based on these concepts. Automated irrigation typically uses feedback from soil-water sensors, infrared thermometry, and/or rain gauges to determine when to irrigate and actuate relays to initiate irrigation. Microcontrollers can be used to automate the soil-water content measuring process, which enables data to be collected at a higher frequency while reducing labor costs (Fisher 2007).

Evett et al. (2000) studied controlling SDI based on canopy temperature for corn and soybean in a clay loam in Texas. They compared automated drip irrigation of corn with a manually scheduled treatment based on a soil-water balance using neutron probe readings of soil-water content. For the automated control treatments, an optimum threshold temperature was set at 28° C and 27° C for corn and soybean, respectively. For these temperatures, the optimum threshold time was set at 240 and 256 min for corn and soybean, respectively. These time thresholds were based on a previous study which monitored threshold temperatures of well-watered crops and the associated daily mean time (threshold time) spent above the threshold temperature. They also looked at setting the threshold temperature 2° C higher for both corn (30° C) and soybean (29° C). At the 2° C higher temperatures, the optimum threshold times decreased to 160 min for corn and 171 min for soybean. They used both time thresholds for each temperature threshold for a total of four controlled irrigation treatments. The first manual irrigation treatment replenished 100% of the depleted soil-water (to field capacity) as measured by a neutron probe. The other two manual irrigation
treatments replenished 67% and 33% of the full amount. They found that the manual method produced yields that were lower than the automated method yields for corn the first year and were not statistically different in the second year, except for the 33% manual treatment that had statistically lower yields than all other treatments in both years.

Dukes and Scholberg (2005) compared time scheduled and controlled irrigation of sweet corn with driplines installed at depths of 0.23- and 0.33-m below the soil surface in a sandy soil in Florida. In both years the sensor controlled irrigation at a depth 0.23-m produced a statistically higher yield than the time scheduled irrigation at the same depth and the sensor controlled irrigation at a depth of 0.33-m. In the first year there was no statistical difference in the yields for sensor controlled at 0.23-m depth and time scheduled at 0.33-m, but the second year yields for the sensor controlled were statistically higher.

Grabow et al. (2011) compared soil-water sensor controlled SDI (dripline spacings of 1.52- and 2.28-m) with sprinkler irrigation scheduled using manual soil-water sensor readings for corn and soybean in a clay loam in North Carolina. Based on 4 years of yield data for both corn and soybean, the yield for corn was statistically higher for both dripline spacings of controlled SDI than a non-irrigated treatment but not statistically different than sprinkler irrigation yields for either of the dripline spacings. There was no statistical difference among irrigation treatments for soybean yield.

An important component of SDI applicability in North Carolina is the soil-water distribution in agricultural soils found there. Soil-water distribution is not easily predicted. Thorburn et al. (2003) conducted a study on soil wetting from buried drip emitters based on
soil texture and concluded that soil texture is not a reliable predictor of soil wetting. They found the only trustworthy way to determine soil-wetting is through site specific tests. Grabow et al. (2006) found that water moved laterally to the midpoint of driplines spaced 0.91- and 1.81-m in a sandy loam in North Carolina. However, the movement of water to the midpoint of the 1.81-m spaced driplines could be attributed to a clay pan layer found 0.3-m below the soil surface, which was just below the dripline placed 0.23-m below the surface.

Since SDI applies water via underground driplines rather than wetting the entire surface as with sprinkler irrigation systems, it is critical to understand the soil-water distribution of such systems and evaluate potential water stress that may occur with SDI. Hiler and Clark (1971) came up with a stress day index concept to quantify the amount of stress on a crop during the growing season. The stress day index equation is:

\[ SDI = \sum_{i=1}^{n} (SD_i \times CS_i) \]  

where SDI stands for stress day index, SD is stress day factor and CS is crop susceptibility factor. The stress day factor equation is:

\[ SD = 1 - \frac{E}{E_d} \]  

\[ E = \frac{\psi_s - \psi}{R_s + R_p} \]  

\[ E_w = \frac{\psi_s - \psi_w}{R_s + R_p} \]
where SD is the stress day factor, E is transpiration rate, $\psi$ is leaf water potential, $\psi_s$ is soil water potential, $\psi_w$ is critical leaf water, $R_s$ is soil resistance to flow, $R_p$ is plant resistance, $E_w$ is a supply function, and $E_d$ is potential evaporation. When $E_d \sim E_w$, then $E = E_d$ and therefore the stress day factor is 0. When $E_d > E_w$, then $E = E_w$ and the stress day factor is between 0 and 1. The stress day factor can be approximated using this equation:

$$SD = E_d \times |\psi_s|$$ (3.5)

where SD is the stress day factor, $E_d$ is daily evaporative demand and $|\psi_s|$ is the absolute value of the integrated soil water potential in the root zone measured in early morning. This stress day factor approximation focuses on soil water potential in the root zone, which is where SDI driplines are located.

The goal of this research is to monitor and study the soil-water distribution for SDI in North Carolina Trebloc loam. This chapter presents soil-water data from one year of corn production in the Coastal Plain of North Carolina. One objective of this study was to compare the soil-water distributions of sensor controlled and grower scheduled SDI in loam soil and results are presented in this chapter.

**Material and Methods**

**Site Description**

The field for this study is located in the Coastal Plain near Rowland, North Carolina. The dominant soil types are Nahunta very fine sandy loam (fine-silty, siliceous, and thermic
Aeric Paleaquults), Aycock very fine sandy loam (fine-silty, siliceous, and thermic Typic Paleudults), and Trebloc loam (fine-silty, siliceous, and thermic Typic Paleaquults) (USDA Web Soil Survey 2013). A 9 hectare subsurface drip irrigation (SDI) system was installed on 14 March 2011 (Fig. 3.1). The field is under a no-till corn – winter wheat – soybean rotation. Corn was planted on April 15, 2011 in rows 0.51-m apart and a planting density of about 94,000 seeds per ha (38,000/ac).

**SDI Installation and Instrumentation**

Typhoon 13 mil 16 mm diameter drip tape (Netafim USA Fresno, CA) with 0.91 liter per hour emitters at 0.60-m spacing was installed in March 2011. The drip tape was installed at 1.02-m spacing (alternate row middles) 0.25-m below the soil surface. The 9-ha are split into two zones: zone 1 (roughly 3-ha) used data collected from Echo EC-5 soil-water sensors (Decagon Devices, Inc. Pullman, WA) and a tipping bucket rain gauge (Davis Instruments Vernon Hills, IL) to control irrigation and zone 2 (roughly 6-ha) was programmed to irrigate daily and thus is referred to as “fixed daily” scheduled irrigation. The soil-water sensors and rain gauge were connected to a CR10X logger/controller (Campbell Scientific Inc. Logan, Utah) that logged soil-water and rainfall data for input to an algorithm inside the logger that made daily irrigation decisions, based upon current soil-water status and a user-defined soil-water threshold and a rainfall threshold. The soil-water threshold in zone 1 was initially set at 22% (soil-water by volume), but was increased to 23% on 17 May 2011 to trigger an irrigation sooner to verify that the system was working. The soil-water threshold was developed assuming a field capacity of 30% by volume. The precipitation threshold was set
at 13 mm (over the past 24 hours) and the soil-water threshold was evaluated against a four hour moving average of soil-water content of all sensors in zone 1. Irrigation was initiated automatically using an electrical pulse signal sent from the logger/controller to the Netafim NMC Junior irrigation controller (Netafim USA Fresno, CA) located about 0.4 kilometers away at the opposite side of the field (Fig. 3.1). When either the soil-water content or precipitation was above the threshold the internal logger program would not enable the irrigation cycles program in the Netafim controller. The algorithm in the Campbell logger made a daily decision (yes/no) based on the soil-water content and precipitation readings at 5:50 AM EDT. If both rainfall and soil-water thresholds indicated irrigation, then two irrigation cycles of 2:15 duration each occurred in SDI zone 1 beginning at 6:00 AM and ending at 9:45 AM EDT. Irrigation in zone 2 was accomplished daily in two irrigation cycles of 1:30 duration each at 8:15 AM and noon daily, unless overridden by the grower.

SDI has been applied in pulses to reduce or eliminate water coming to the surface during irrigation events, referred to as “surfacing”, and to promote lateral movement of the water from the driplines (Grabow et al. 2011). Zone 1 was set to irrigate in two pulses that totaled 6.50 mm. The grower scheduled the irrigation for SDI Zone 2 to occur daily in two pulses totaling 4.33 mm.

Soil-water sensors were installed at 0.15- and 0.30-m depth, 0.15-, 0.30-, and 0.51-m (mid-dripline) from the dripline in both the sensor controlled and “fixed daily” treatments. The sensors 0.15-m below the surface were above the dripline and the 0.30-m deep sensors were below the dripline and were used to monitor water movement in the soil profile. There
were two replications in zone 1 and zone 2 each replication consisting of 6 soil-water sensors (2 depths at 3 distances from the dripline) for a total of 24 sensors (Fig. 3.2). The sensors were installed in a Trebloc loam soil and were queried every 10 minutes.

Data Analysis

Soil-water data were evaluated using time series plots, summary statistics, and soil-water deficit. Soil-water content was plotted against day of year (DOY) and was grouped by replication. Bad data, resulting from sensor failure (generally found to occur as a result of intense electrical storms) were purged from the data set prior to evaluation. Cumulative soil-water content profiles were derived by integrating the measurements from sensors at 0.15- and 0.30-m over 0.381-m and converting to a depth using a midpoint method as follows: the sensors readings from the sensor 0.15-m below the soil surface were multiplied by 0.228-m (distance from the soil surface to the midpoint between sensors) and the readings from the 0.30-m depth sensor were multiplied by 0.152-m (distance from the midpoint between sensors to a point 0.075-m below the lower sensor). The first day of irrigation for both SDI treatments was 9 June 2011. There was an electrical storm on or shortly after 29 June 2011 that caused a number of the sensors to malfunction. Some of the sensors began working later in the growing season, but some of them never recovered. Therefore, the cumulative soil-water content was plotted from 9 June to 29 June 2011 to observe a period when the sensors were working properly, and when corn water use was high.

In order to quantify the amount of plant-stress caused by low soil-water content, a soil water deficit was calculated as follows:
where \( SWD \) is soil-water deficit (mm x d), \( SW_t \) is the soil-water threshold which was set to 87.6 mm (0.23 m/m, based on 381 mm profile depth), and \( SW_i \) is the soil-water content (mm) for period \( i \). Using the cumulative soil-water contents a soil-water deficit was calculated for each treatment from 9 June (first day of irrigation) to 22 July (last day of irrigation).

**Results and Discussion**

**Rainfall and Applied Irrigation**

The SDI irrigated field received 247 mm of rainfall from 15 April (plant) to 22 July (last irrigation). The 30 year average rainfall (1981 – 2010) from 1 May to 31 July for this area is 326 mm (NOAA 2012). There were 22 irrigation events for zone 1 totaling 127 mm and 26 irrigation events for zone 2 totaling 82.6 mm. Zone 1 called for irrigation 38 times between 5 June and 23 July, the final day of irrigation, but due to a temporarily bad fiber optic unit at the Campbell Scientific logger/controller that did not allow the irrigation pulse signal to be transmitted to the Netafim irrigation controller and the grower turning the system off following rainfall events there were only 22 irrigation events. Since this system is controlled by soil-water content the system may not have called for irrigation 38 times if the system was left on and there were no bad fiber optic receivers. During the same time period zone 2, which is set to irrigate daily, would have irrigated 50 times. There were only 26 irrigation events during the 50 days due to the grower turning the system off after rainfall events. The soil-water traces were monitored from 3 May to 25 July 2011. To monitor the
soil-water content when the majority of sensors were functional, the cumulative soil-water content were plotted from 9 June to 29 June 2011. During this time period there were 10 rainfall events totaling 66.8 mm, 12 irrigation events adding up to 84.4 mm in zone 1, and 12 irrigation events totaling 41.8 mm in zone 2.

**Soil-Water Distribution**

The soil-water traces were plotted and grouped by zone and replication (Figs. 3.3 – 3.6). The sensors that were 0.30-m from the dripline were closest to a corn row at 0.05-m distance. The sensors closest to the dripline (0.15-m from the dripline) were 0.10-m from a corn row and the sensors that were 0.51-m from the dripline were 0.25-m from corn rows on both sides. The sensors 0.51-m from the dripline were also farthest from extraction, so a less variable trace would be expected.

In sensor controlled SDI zone 1 replication 1 (Fig. 3.3), the highest soil-water content was at 0.30-m depth at 0.15- and 0.51-m from the dripline. On 29 June 2011 (DOY 180) the 0.30-m depth sensors 0.15- and 0.30-m from the dripline malfunctioned and never recovered. The water content at 0.30-m depth was higher early in the growing season as the roots had not yet reached this depth. As the season progressed the soil-water content at 0.30-m depth were more closely related to the 0.15-m depth as the rooting depth increased. The lowest soil-water content occurred at 0.15- and 0.30-m depths 0.30-m from the dripline. These sensors were closest to a corn row being only 0.05-m away and this could explain their lower soil-water readings.
In sensor controlled SDI zone 1 replication 2 (Fig. 3.4), soil-water content was initially highest at 0.30-m depth 0.30- and 0.51-m from the dripline. The soil-water content at 0.15-m depth 0.15-m from the dripline displayed the most variation, especially after irrigation began with a soil-water content high of 0.309 and a low of 0.143 m/m (Table 3.2). The soil-water content at 0.15-m depth showed larger water extraction during early periods of little to no rain. This is due to greater plant uptake and evaporation occurring in the upper 0.15-m of the soil profile.

In the “fixed daily” scheduled SDI zone 2 replication 1 (Fig. 3.5), the soil-water content at 0.30-m depth were higher than the soil-water content at 0.15-m depth for the duration of the monitoring period. In this replication, all but two sensors (both the 0.15- and 0.30-m depths 0.15-m from the dripline) malfunctioned around 29 June 2011 (DOY 180) and never recovered. The 0.15-m depth sensor 0.51-m from the dripline reported soil-water content that was constantly fluctuating and was removed from Fig. 3.5 around 13 May 2011 (DOY 133). The soil-water content 0.15-m from the dripline showed more response to irrigation events at both depths due to proximity to the dripline.

In the “fixed daily” scheduled SDI zone 2 replication 2 (Fig. 3.6), the soil-water content at 0.30-m depth were greater for all distances from the dripline than the soil-water content at 0.15-m depth initially. The soil-water content at 0.30-m depth trended more closely to the soil-water content at 0.15-m depth after irrigation began on 9 June 2011 (DOY 160). The soil-water content at 0.30-m depth 0.30-m from the dripline showed large peaks after precipitation events that were not characteristic of the other soil-water content readings.
at 0.30-m depth. This could be due to more local void space or temporary perching above a clay layer.

The soil-water content at 0.30-m depth had higher mean soil-water content than the soil-water content at 0.15-m depth in every location except at 0.30-m from the dripline in the SDI sensor controlled (zone 1) first replication (Tables 3.1 – 3.4). This could be due to the lack of soil-water content data obtained from the 0.30-m depth sensor as the 0.15-m depth sensor had 11,599 readings and the 0.30-m depth sensor had only 7,653 due to sensor failure around 29 June 2011 (DOY: 180). There were several sensors that had malfunctions after this date and could be sensor damage due to an electrical storm. The standard deviation was generally greater for the soil-water content at depth of 0.15-m. This is likely due to evaporation, plant uptake, and precipitation affecting the upper portion of the soil profile disproportionately. The soil-water content at 0.15-m depth showed larger spikes for precipitation events than the soil-water content at 0.30-m depth. This could be due to the precipitation induced wetting front not extending to a depth of 0.30-m or residual soil-water at 0.30-m due to lower plant extraction at this depth.

Due to malfunctions to multiple sensors the cumulative soil-water content profiles (shown in Figs. 3.3-3.6) were not plotted after 29 June 2011 (DOY 180). To get a better view of the effects of irrigation on soil-water, the plots begin on 9 June 2011 (DOY 160), the date of the first irrigation. The “fixed daily” treatment called for irrigation each day for a total of 21 irrigation events, however due to the system being turned off by the grower following precipitation events there were only 12 actual irrigation events. The sensor controlled
treatment called for 16 irrigation events, but due to the system being turned off by the grower following precipitation events there were only 12 actual irrigation events.

The cumulative soil-water content was plotted for both replications of both zones (Figs. 3.7 – 3.10). The soil-water content 0.15-m from the dripline showed a more pronounced response to irrigation events, as they were closer to the dripline showing spikes after irrigation events followed by pronounced declines due to evaporation and plant uptake. This characteristic was less evident in soil-water content 0.30- and 0.51-m from the dripline where a more typical response was a gradual increase in soil-water following an irrigation event.

In sensor controlled SDI zone 1 replication 1 (Fig. 3.7), the cumulative soil-water content at 0.15-m from the dripline was similar to the soil-water content 0.51-m from the dripline. The cumulative soil-water content at 0.30-m from the dripline was lower than the soil-water content at 0.15- and 0.51-m and did not display spikes, but rather a constant soil-water level that shows moderate increases and decreases. The cumulative soil-water content 0.30-m from the dripline (closest to a corn row) exhibited lower values due to crop uptake coupled with slower response time and less irrigation reaching 0.30-m from the dripline than 0.15-m from the dripline.

In sensor controlled SDI zone 1 replication 2 (Fig. 3.8), the cumulative soil-water content 0.15-m from the dripline showed quicker spikes and drops than the sensors farther from the dripline. The response of each irrigation event can be clearly seen for these sensors. The cumulative soil-water content 0.30- and 0.51-m from the dripline show more gradual
increases and decreases in cumulative soil-water content. Variations in soil-water content spikes after irrigation between replications and zones at 0.15-m distance from the dripline could be due to the relative placing of sensors to the emitters. The cumulative soil-water content 0.30-m from the dripline was higher than the cumulative soil-water content 0.51-m from the dripline throughout this period suggesting that less water extended to 0.51-m from the dripline. However, the gradual increase in cumulative soil-water content 0.51-m from the dripline shows that the water was able to reach mid-dripline (0.51-m).

In “fixed daily” scheduled SDI zone 2 replication 1 (Fig. 3.9), plotting of the cumulative soil-water content at 0.30- and 0.51-m from the dripline were omitted. This was due a faulty sensor at both locations. The cumulative soil-water content that was 0.15-m from the dripline showed that large precipitation events had a large effect on the cumulative soil-water content and the irrigation events had small effects, mainly slowing the rate of soil-water drawdown.

In “fixed daily” scheduled SDI zone 2 replication 2 (Fig. 3.10), the cumulative soil-water content 0.30-m from the dripline showed relatively large spikes after precipitation events but showed little responses to irrigation events. Substantial response to irrigation events can be seen in the cumulative soil-water content 0.15-m from the dripline. The “fixed daily” scheduled treatment applied less water than the sensor controlled treatment and this can be seen in the smaller responses to irrigation events with the largest responses corresponding to precipitation events.
To show the differences between the cumulative soil-water content of the “fixed daily” scheduled and the sensor controlled irrigation, cumulative soil-water content 0.15-m from the dripline for zone 1 replication 2 were plotted alongside cumulative soil-water content 0.15-m from the dripline in zone 2 replication 1 (Fig. 3.11). Cumulative soil-water content in zone 1 showed large responses to both irrigation and precipitation. The “fixed daily” cumulative soil-water content show larger responses to precipitation events than irrigation events. This is due to the sensor controlled treatment receiving larger irrigation events then the “fixed daily” scheduled treatment. The cumulative soil-water content for the “fixed daily” and sensor controlled treatments was similar during periods where there were no irrigation events.

The cumulative soil-water content had the largest range (38.56 mm) in zone 1 replication 2 at 0.15-m from the dripline (Table 3.5). The highest mean cumulative soil-water content was 0.15-m from the dripline in zone 2 replication 2. The minimum cumulative soil-water content for zone 2 replication 2 0.15-m from the dripline was 94.49 mm, which was greater than the maximum soil-water content for zone 1 replication 1 0.15 m from the dripline. Zone 2 received less irrigation than zone 1, so this higher soil-water content could be due to differences in internal drainage among the replications. Also, the soil-water content was much higher initially (on 9 June) than the other three replications 0.15-m from the dripline. There were smaller decreases in cumulative soil-water content due to plant extraction in zone 2 replication 2 (Fig. 3.10) than the other three cumulative soil-water content profiles 0.15-m from the dripline (Figs. 3.7 – 3.9) during periods where there were no
irrigation or precipitation events. The ranges and standard deviations of soil-water content were generally smaller farther from the dripline (Tables 3.5 – 3.7). The lowest mean cumulative soil-water content was 0.30-m from the dripline (Table 3.6) in zone 1 replication 1. These sensors were closest to a corn row and the lower soil-water content could be attributed to crop uptake. The cumulative soil-water content 0.51-m from the dripline (Table 3.7) had the most similar means between replications and being farthest from the dripline were therefore least influenced by irrigation treatments.

The soil-water deficit (equation 3.6) was calculated for each irrigation treatment and is indicative of stress throughout the growing season. Due to missing data some replications were omitted from calculations. The center pivot treatment had the lowest average soil-water deficit of 14.6 mm-d (Table 3.10). The non-irrigated treatment had the highest average soil-water deficit of 114.7 mm-d (Table 3.10). The grower scheduled SDI had a lower soil-water deficit average than the sensor controlled (Tables 3.8 and 3.9). The initial soil-water content was not the same across the treatments and this led to differing soil-water-deficits due to lower initial soil-water content. To further look at the trends in the data the maximum drawdown rates (mm/d) were noted (Tables 3.8, 3.9, and 3.10). The lowest maximum drawdown rate was found in the sensor controlled SDI treatment of 1.90 mm/day (Table 3.8). However, the sensor controlled SDI treatment had missing data due to sensor failure. The greatest maximum drawdown rate of 6.50 mm/day was found in the center pivot (Table 3.10).
Summary and Conclusions

The soil-water content at 0.30-m depth was initially higher due to shallow root depth during the early plant development stages. When plant root depth increased and irrigation was introduced to the system, soil-water content showed less variation across depths and distances from the dripline. The sensor controlled SDI treatment applied 42.6 mm more irrigation than the “fixed daily” treatment between 9 June and 29 June 2011. These larger irrigation events can be clearly seen in the cumulative soil-water content. The soil-water content farther from the dripline generally had smaller standard deviations and ranges in cumulative soil-water content.

Based on increases in soil-water content and cumulative soil-water content (to a depth of 0.381-m) following irrigation events, it can be concluded that water reached mid-dripline (0.51-m from the dripline). The gradual and less dramatic increases in soil-water content 0.51-m from the dripline after irrigation imply that it was taking longer for the wetting front to reach mid-dripline than areas closer to the dripline (0.15- and 0.30-m from the dripline). The means of soil-water content and cumulative soil-water content at 0.51-m from the dripline suggest that an adequate amount of water reached mid-dripline. This implies that alternate row middle spacing of driplines is sufficient for a Trebloc loam soil. The cumulative soil-water content data show that less water reaches mid-dripline. Therefore, it would not be recommended to employ dripline spacings greater than 1.02-m for corn production in Trebloc loam or any coarser textured soils, unless a relatively impervious soil
layer existed at a depth just below normal dripline installation depth and a higher flow tape was used.
REFERENCES


**TABLES AND FIGURES**

Table 3.1 Statistics of soil-water content (m$^3$m$^{-3}$) by depth (d) and distance (dl) from the dripline for sensor controlled SDI zone 1 replication 1 from 3 May to 25 July.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15m d 0.15m dl</td>
<td>11599</td>
<td>0.221</td>
<td>0.021</td>
<td>0.178</td>
<td>0.300</td>
<td>0.122</td>
</tr>
<tr>
<td>0.30m d 0.15m dl</td>
<td>7653</td>
<td>0.257</td>
<td>0.011</td>
<td>0.223</td>
<td>0.284</td>
<td>0.061</td>
</tr>
<tr>
<td>0.15m d 0.30m dl</td>
<td>11599</td>
<td>0.199</td>
<td>0.022</td>
<td>0.121</td>
<td>0.256</td>
<td>0.135</td>
</tr>
<tr>
<td>0.30m d 0.30m dl</td>
<td>7653</td>
<td>0.190</td>
<td>0.020</td>
<td>0.152</td>
<td>0.228</td>
<td>0.076</td>
</tr>
<tr>
<td>0.15m d 0.51m dl</td>
<td>11598</td>
<td>0.207</td>
<td>0.025</td>
<td>0.132</td>
<td>0.275</td>
<td>0.143</td>
</tr>
<tr>
<td>0.30m d 0.51m dl</td>
<td>11598</td>
<td>0.258</td>
<td>0.026</td>
<td>0.207</td>
<td>0.302</td>
<td>0.095</td>
</tr>
</tbody>
</table>

Table 3.2 Statistics of soil-water content (m$^3$m$^{-3}$) by depth (d) and distance (dl) from the dripline for sensor controlled SDI zone 1 replication 2 from 3 May to 25 July.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15m d 0.15m dl</td>
<td>11599</td>
<td>0.216</td>
<td>0.030</td>
<td>0.143</td>
<td>0.309</td>
<td>0.166</td>
</tr>
<tr>
<td>0.30m d 0.15m dl</td>
<td>11599</td>
<td>0.244</td>
<td>0.014</td>
<td>0.208</td>
<td>0.312</td>
<td>0.104</td>
</tr>
<tr>
<td>0.15m d 0.30m dl</td>
<td>11599</td>
<td>0.240</td>
<td>0.017</td>
<td>0.196</td>
<td>0.278</td>
<td>0.082</td>
</tr>
<tr>
<td>0.30m d 0.30m dl</td>
<td>10211</td>
<td>0.273</td>
<td>0.009</td>
<td>0.250</td>
<td>0.296</td>
<td>0.046</td>
</tr>
<tr>
<td>0.15m d 0.51m dl</td>
<td>10401</td>
<td>0.230</td>
<td>0.027</td>
<td>0.185</td>
<td>0.320</td>
<td>0.135</td>
</tr>
<tr>
<td>0.30m d 0.51m dl</td>
<td>10401</td>
<td>0.273</td>
<td>0.014</td>
<td>0.242</td>
<td>0.316</td>
<td>0.074</td>
</tr>
</tbody>
</table>
### Table 3.3
Statistics of soil-water content (m³ m⁻³) by depth (d) and distance (dl) from the dripline for “fixed daily” scheduled SDI zone 2 replication 1 from 3 May to 25 July.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15m d 0.15m dl</td>
<td>11599</td>
<td>0.205</td>
<td>0.027</td>
<td>0.156</td>
<td>0.266</td>
<td>0.110</td>
</tr>
<tr>
<td>0.30m d 0.15m dl</td>
<td>11599</td>
<td>0.264</td>
<td>0.015</td>
<td>0.237</td>
<td>0.322</td>
<td>0.085</td>
</tr>
<tr>
<td>0.15m d 0.30m dl</td>
<td>7653</td>
<td>0.193</td>
<td>0.034</td>
<td>0.128</td>
<td>0.264</td>
<td>0.136</td>
</tr>
<tr>
<td>0.30m d 0.30m dl</td>
<td>7653</td>
<td>0.272</td>
<td>0.013</td>
<td>0.251</td>
<td>0.312</td>
<td>0.061</td>
</tr>
<tr>
<td>0.15m d 0.51m dl</td>
<td>1010</td>
<td>0.233</td>
<td>0.005</td>
<td>0.224</td>
<td>0.245</td>
<td>0.021</td>
</tr>
<tr>
<td>0.30m d 0.51m dl</td>
<td>7653</td>
<td>0.290</td>
<td>0.013</td>
<td>0.266</td>
<td>0.328</td>
<td>0.062</td>
</tr>
</tbody>
</table>

### Table 3.4
Statistics of soil-water content (m³ m⁻³) by depth (d) and distance (dl) from the dripline for “fixed daily” scheduled SDI zone 2 replication 2 from 3 May to 25 July.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Std Dev</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15m d 0.15m dl</td>
<td>7653</td>
<td>0.241</td>
<td>0.021</td>
<td>0.186</td>
<td>0.272</td>
<td>0.086</td>
</tr>
<tr>
<td>0.30m d 0.15m dl</td>
<td>7654</td>
<td>0.274</td>
<td>0.009</td>
<td>0.252</td>
<td>0.331</td>
<td>0.079</td>
</tr>
<tr>
<td>0.15m d 0.30m dl</td>
<td>11599</td>
<td>0.232</td>
<td>0.022</td>
<td>0.183</td>
<td>0.278</td>
<td>0.095</td>
</tr>
<tr>
<td>0.30m d 0.30m dl</td>
<td>11409</td>
<td>0.263</td>
<td>0.015</td>
<td>0.232</td>
<td>0.338</td>
<td>0.106</td>
</tr>
<tr>
<td>0.15m d 0.51m dl</td>
<td>11409</td>
<td>0.229</td>
<td>0.023</td>
<td>0.197</td>
<td>0.291</td>
<td>0.094</td>
</tr>
<tr>
<td>0.30m d 0.51m dl</td>
<td>11409</td>
<td>0.286</td>
<td>0.013</td>
<td>0.265</td>
<td>0.313</td>
<td>0.048</td>
</tr>
</tbody>
</table>
Table 3.5 Cumulative soil-water content (mm) statistics 0.15-m from the dripline for both sensor controlled (1-1 and 1-2) and “fixed daily” scheduled (2-1 and 2-2) from day of year 160 (9 June) to 180 (29 June).

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15 m from dripline 1-1</td>
<td>2833</td>
<td>85.62</td>
<td>91.29</td>
<td>79.25</td>
<td>12.04</td>
</tr>
<tr>
<td>0.15 m from dripline 1-2</td>
<td>2881</td>
<td>87.60</td>
<td>108.66</td>
<td>70.10</td>
<td>38.56</td>
</tr>
<tr>
<td>0.15 m from dripline 2-1</td>
<td>2881</td>
<td>84.36</td>
<td>99.36</td>
<td>74.07</td>
<td>25.30</td>
</tr>
<tr>
<td>0.15 m from dripline 2-2</td>
<td>2833</td>
<td>99.08</td>
<td>103.17</td>
<td>94.49</td>
<td>8.69</td>
</tr>
</tbody>
</table>

Table 3.6 Cumulative soil-water content (mm) statistics 0.30-m from the dripline for both sensor controlled (1-1 and 1-2) and “fixed daily” scheduled (2-1 and 2-2) from day of year 160 (9 June) to 180 (29 June). Summary statistics omitted for zone 2 rep 1 (2-1) due to sensor malfunction.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30 m from dripline 1-1</td>
<td>2570</td>
<td>65.99</td>
<td>68.81</td>
<td>64.54</td>
<td>4.27</td>
</tr>
<tr>
<td>0.30 m from dripline 1-2</td>
<td>2570</td>
<td>93.43</td>
<td>101.12</td>
<td>83.13</td>
<td>17.98</td>
</tr>
<tr>
<td>0.30 m from dripline 2-2</td>
<td>2833</td>
<td>93.53</td>
<td>103.78</td>
<td>80.47</td>
<td>23.32</td>
</tr>
</tbody>
</table>

Table 3.7 Cumulative soil-water content (mm) statistics 0.51-m from the dripline for both sensor controlled (1-1 and 1-2) and “fixed daily” scheduled (2-1 and 2-2) from day of year 160 (9 June) to 180 (29 June). Summary statistics omitted for zone 2 rep 1 (2-1) due to sensor malfunction.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.51 m from dripline 1-1</td>
<td>2881</td>
<td>81.98</td>
<td>89.46</td>
<td>74.83</td>
<td>14.63</td>
</tr>
<tr>
<td>0.51 m from dripline 1-2</td>
<td>2570</td>
<td>85.55</td>
<td>93.12</td>
<td>80.39</td>
<td>12.73</td>
</tr>
<tr>
<td>0.51 m from dripline 2-2</td>
<td>2881</td>
<td>89.62</td>
<td>91.82</td>
<td>87.71</td>
<td>4.11</td>
</tr>
</tbody>
</table>
Table 3.8 Summary Statistics for soil-water deficit for Sensor Controlled SDI.

<table>
<thead>
<tr>
<th></th>
<th>15 cm Rep 1</th>
<th>30 cm Rep 1</th>
<th>51 cm Rep 1</th>
<th>15 cm Rep 2</th>
<th>30 cm Rep 2</th>
<th>51 cm Rep 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Condition (mm)</td>
<td>81.5</td>
<td>75.1</td>
<td>71.4</td>
<td>84.3</td>
<td>81.8</td>
<td></td>
</tr>
<tr>
<td>Threshold (mm)</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
</tr>
<tr>
<td>Deficit (mm*day)</td>
<td>46.1</td>
<td>261.2</td>
<td>175.1</td>
<td>7.6</td>
<td>55.8</td>
<td></td>
</tr>
<tr>
<td>Sum using 10-min data (mm)</td>
<td>6634</td>
<td>37614</td>
<td>25221</td>
<td>1099</td>
<td>8028</td>
<td></td>
</tr>
<tr>
<td>Max 10 min deficit</td>
<td>8.38</td>
<td>15.54</td>
<td>17.53</td>
<td>4.50</td>
<td>7.24</td>
<td></td>
</tr>
<tr>
<td>Max Drawdown (mm/day)</td>
<td>3.06</td>
<td>2.36</td>
<td>4.57</td>
<td>1.96</td>
<td>1.90</td>
<td></td>
</tr>
<tr>
<td>Max Total Water Content (mm)</td>
<td>91.3</td>
<td>97.9</td>
<td>116.3</td>
<td>101.1</td>
<td>102.9</td>
<td></td>
</tr>
<tr>
<td>Min Total Water Content (mm)</td>
<td>79.2</td>
<td>72.1</td>
<td>70.1</td>
<td>83.1</td>
<td>80.4</td>
<td></td>
</tr>
<tr>
<td>Min Water Content (m/m)</td>
<td>0.208</td>
<td>0.189</td>
<td>0.184</td>
<td>0.218</td>
<td>0.211</td>
<td></td>
</tr>
<tr>
<td>Average Deficit mm*day</td>
<td>109.2</td>
<td>mm*day</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.9 Summary Statistics for soil-water deficit for “Fixed Daily” Grower Scheduled SDI.

<table>
<thead>
<tr>
<th></th>
<th>15 cm Rep 1</th>
<th>30 cm Rep 1</th>
<th>51 cm Rep 1</th>
<th>15 cm Rep 2</th>
<th>30 cm Rep 2</th>
<th>51 cm Rep 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Condition (mm)</td>
<td>75.3</td>
<td></td>
<td></td>
<td>98.8</td>
<td></td>
<td>80.7</td>
</tr>
<tr>
<td>Threshold (mm)</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
</tr>
<tr>
<td>Deficit (mm*day)</td>
<td>220.3</td>
<td></td>
<td></td>
<td>0.0</td>
<td></td>
<td>30.0</td>
</tr>
<tr>
<td>Deficit Sum using 10-min data (mm)</td>
<td>31729</td>
<td></td>
<td></td>
<td>0</td>
<td></td>
<td>4326</td>
</tr>
<tr>
<td>Max 10 min deficit (mm)</td>
<td>14.48</td>
<td></td>
<td></td>
<td>0.00</td>
<td></td>
<td>7.16</td>
</tr>
<tr>
<td>Max Drawdown (mm/day)</td>
<td>3.17</td>
<td></td>
<td></td>
<td>2.45</td>
<td></td>
<td>2.09</td>
</tr>
<tr>
<td>Max Total Water Content (mm)</td>
<td>106.2</td>
<td></td>
<td></td>
<td>103.2</td>
<td></td>
<td>107.1</td>
</tr>
<tr>
<td>Min Total Water Content (mm)</td>
<td>73.2</td>
<td></td>
<td></td>
<td>94.5</td>
<td></td>
<td>80.5</td>
</tr>
<tr>
<td>Min Water Content (m/m)</td>
<td>0.192</td>
<td></td>
<td></td>
<td>0.248</td>
<td></td>
<td>0.211</td>
</tr>
<tr>
<td>Average Deficit mm*day</td>
<td>83.5</td>
<td>mm*day</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.10 Summary Statistics for soil-water deficit) for Non-Irrigated and Grower Scheduled Center Pivot.

<table>
<thead>
<tr>
<th></th>
<th>Non-Irrigated</th>
<th></th>
<th>Center Pivot</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rep 1</td>
<td>Rep 2</td>
<td>Rep 1</td>
<td>Rep 2</td>
</tr>
<tr>
<td>Initial Condition (mm)</td>
<td>82.3</td>
<td>97.5</td>
<td>83.4</td>
<td>94.7</td>
</tr>
<tr>
<td>Threshold (mm)</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
<td>87.6</td>
</tr>
<tr>
<td>Deficit (mm*day)</td>
<td>229.1</td>
<td>0.3</td>
<td>27.4</td>
<td>1.7</td>
</tr>
<tr>
<td>Sum using 10-min data (mm)</td>
<td>32995</td>
<td>46</td>
<td>3940</td>
<td>251</td>
</tr>
<tr>
<td>Max 10 min deficit</td>
<td>16.95</td>
<td>0.85</td>
<td>8.15</td>
<td>5.99</td>
</tr>
<tr>
<td>Max Drawdown (mm/day)</td>
<td>3.99</td>
<td>3.17</td>
<td>6.57</td>
<td>4.71</td>
</tr>
<tr>
<td>Max Total Water Content (mm)</td>
<td>106.5</td>
<td>118.6</td>
<td>119.9</td>
<td>114.0</td>
</tr>
<tr>
<td>Min Total Water Content (mm)</td>
<td>70.7</td>
<td>86.8</td>
<td>79.5</td>
<td>81.6</td>
</tr>
<tr>
<td>Min Water Content (m/m)</td>
<td>0.186</td>
<td>0.228</td>
<td>0.209</td>
<td>0.214</td>
</tr>
<tr>
<td>Average Deficit mm*day</td>
<td>114.7 mm*day</td>
<td></td>
<td>14.6 mm*day</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3.1 Field layout with soil-water sensor and controller locations. The Netafim NMC Junior Irrigation Controller and pump headworks are located on the other side of the field 0.4 km from the Campbell Scientific logger/controller. Aerial image obtained from ESRI data server (ESRI 2010).
Fig. 3.2 Layout of the soil-water sensor clusters in the two SDI zones. Each sensor cluster (represented by a dot on the map) has sensors at 0.15- and 0.30-m depths located 0.15-, 0.30-, and 0.51-m from the dripline. Aerial image obtained from ESRI data server (ESRI 2010).
Fig. 3.3 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for sensor controlled SDI zone 1 rep. 1. Corn plant date was 15 April (DOY 105).
Fig. 3.4 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for sensor controlled SDI zone 1 rep. 2. Corn plant date was 15 April (DOY 105).
Fig. 3.5 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for “fixed daily” scheduled SDI zone 2 rep. 1. Corn plant date was 15 April (DOY 105).
Fig. 3.6 Soil-water content (m/m) by day of year (DOY) at various depths x distances from the dripline for “fixed daily” scheduled SDI zone 2 rep. 2. Corn plant date was 15 April (DOY 105).
Fig. 3.7 Cumulative soil-water content (mm) for sensor controlled SDI zone 1 rep. 1 to 0.381-m depth with irrigation and rain (mm) on the alternate y-axis for the incremental distances indicated. Corn plant date was 15 April (DOY 105).
Fig. 3.8 Cumulative soil-water content (mm) for sensor controlled SDI zone 1 rep. 2 to 0.381-m depth with irrigation and rain (mm) on the alternate y-axis for the incremental distances indicated. Corn plant date was 15 April (DOY 105).
Fig. 3.9 Cumulative soil-water content (mm) for “fixed daily” scheduled SDI zone 2 rep. 1 to 0.381-m depth with irrigation and rain (mm) on the alternate y-axis for the incremental distances indicated. Corn plant date was 15 April (DOY 105). Cumulative soil-water content omitted for 0.30- and 0.51-m from dripline due to sensor failures.
Fig. 3.10 Cumulative soil-water content (mm) for "fixed daily" scheduled SDI zone 2 rep. 2 to 0.381-m depth with irrigation and rain (mm) on the alternate y-axis for the incremental distances indicated. Corn plant date was 15 April (DOY 105).
Fig. 3.11 Cumulative soil-water content (mm) for sensor controlled and “fixed daily” scheduled SDI 0.15-m from the dripline to 0.381-m depth with irrigation and rain (mm) on the alternate y-axis for the incremental distances indicated. Corn plant date was 15 April (DOY 105).