ABSTRACT

KONG VIREAK. Numerical Simulation of Soil-Water Distribution and Root Uptake from Subsurface Drip Irrigation Considering its Design and Management Parameters Using Hydrus-2D. (Under the direction of Dr. Garry L. Grabow).

Subsurface drip irrigation (SDI) systems in the United States are gaining interest since they supply water directly to the root zone, and minimize water loss due to soil evaporation. SDI implementation is increasing even in semi-humid to humid regions such as the southeast. SDI potential lies in increasing water use efficiency and attaining economical production of crops. Realizing the potential of SDI requires optimizing SDI design and management parameters: dripline spacing, dripline depth, emitter spacing, and irrigation treatment vis-a-vis soil type. As field studies require time and resources to install different SDI configurations, numerical modeling offers an alternative to assess the impact of SDI design configurations on soil-water distribution and transpiration. However, little work has been conducted to prove that numerical simulations can be used as SDI management and design tools.

In this study, the computer software package Hydrus-2D was used to simulate transpiration and soil-water distribution from SDI in North Carolina. The objectives of this study were to 1) calibrate the Hydrus-2D model for its subsequent use in evaluating SDI design factors by comparing soil-water distribution results from Hydrus-2D simulations of corn grown on a coastal plain soil to measured soil-water data, and 2) use Hydrus-2D to simulate transpiration from corn under selected dripline depth, dripline spacing, soil type, flow rate, and irrigation treatment to identify designs that tend to maximize transpiration.

Hydrus-2D was calibrated by comparing simulated and measured soil-water content for a period of 45 days from 8 June to 22 July 2011. The Hydrus-2D model simulated soil-water content at 0.15- and 0.30-m depths 0.15, 0.30 and 0.50 m from the dripline. Agreement

between simulated and measured soil-water content was assessed using three indicators: root mean square error (RMSE), mean bias error (ME), and coefficient of determination (r^2). After model calibration, Hydrus-2D was subsequently used to simulate corn transpiration from different SDI design configurations. SDI design configurations were varied by 2 levels of the following design factors: dripline spacing (1.52 and 2.28 m), dripline depth (0.20 and 0.30 m), emitter spacing (0.30 and 0.60 m), soil texture (clay loam and sandy loam), and irrigation treatment (100% and 75% peak daily crop evapotranspiration, ET_c). Two locations were selected to reflect corn growing areas in North Carolina: Salisbury (piedmont) and Kinston (coastal plain). The ratio of actual to potential transpiration (T/T_p) was used as the criterion to evaluate design combinations.

Calibration results showed values of RMSE and ME between simulated and measured soil-water content ranged from 0.012 to 0.091 $m^3\ m^{-3}$, and -0.08 to 0.057 $m^3\ m^{-3}$, respectively indicating that the simulations agree reasonably well with the measured data. The extreme values of RMSE and ME were occurred at locations occupied by the root zone 0.30 m from the dripline at both sensor depths. The coefficient of determination (r^2) ranged between 0.7 and 0.56 at locations 0.15 and 0.50 m from the dripline, respectively.

The modeling of different SDI design configurations predicted that dripline spacing, dripine depth, and irrigation treatment had pronounced effects on T/T_p. Emitter spacing (dripline flow rate) had no significant effect on T/T_p. An irrigation treatment of 100% peak daily ET_c provided greater amounts of water available for transpiration than 75% peak daily ET_c. With the same amount of irrigation water, transpiration was greater at a dripline spacing of alternate row middles (1.52 m). A combination of a dripline spacing of 1.52 m and an installation depth of 0.20 m provided the most water for root water uptake. Based on the results, a dripline spacing of 1.52 m at an installation depth of 0.20 m at the 100% peak daily ET_c irrigation treatment was the most successful design.

Numerical Simulation of Soil-Water Distribution and Root Uptake from Subsurface Drip Irrigation Considering its Design and Management Parameters Using Hydrus-2D

by
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DEDICATION

To my two greatest heroes, my mother and father.
I dearly love you from the bottom of my heart.

BIOGRAPHY

Vireak Kong was born in Kampong Thom, Cambodia, to Chanty Kong and Samnang Toun. Vireak has a sister, Chakrya Kong. Vireak realized his interest in science when he realized he was better at mathematics in high school. Vireak realized his appreciation for agricultural landscapes when his parents took him and his sister on trips to countryside annually during high school summer break. Agricultural landscapes there are beautiful and pristine. There, Vireak would walk rice paddy dams or ride wooden canoes along canals with some of his relatives.

Upon graduation from high school, Vireak decided to blend his appreciation and interest in science, and took up a Bachelor of Science in Agricultural Engineering with a focus on water resources at the Institute of Technology of Cambodia. Vireak also attended the Institute of Foreign Languages and obtained another degree, a Bachelor of Education in English. Vireak was granted a USAID-funded scholarship by HARVEST and moved to the USA to pursue his Master's degree at the department of Biological and Agricultural Engineering, North Carolina State University under the direction of Dr. Garry Grabow.

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CHAPTER 1. REVIEW OF LITERATURE

Introduction

Recent droughts have caused interest in efficient irrigation and water management in agriculture. Efforts are being made to produce more food using less water and without degrading water and soil resources. One of the latest and most advanced methods of irrigation, subsurface drip irrigation (SDI), has proven to be an example of efficient irrigation technology to meet this challenge with the expansion of this practice in the United States. The latest USDA Farm and Ranch Irrigation Survey (USDA-NASS, 2009) reported that the area covered by SDI in the U.S. has jumped from 163,000 to 260,000 ha in the five-year period 2003 to 2008, an increase of 59%.

SDI is compatible with small irregularly-shaped fields commonly found in the southeastern U.S. and has a competitive advantage over pivot and other overhead irrigation methods in these cases (Grabow et al., 2006; Bosch et al., 1998; O'Brien et al., 1998). SDI presents further opportunities for improving water use efficiency by reducing losses to evaporation by not relying on the soil surface for water transmission, all the while improving crop yields (Camp, 1998). Camp (1998) reported that in many cases SDI produced greater or equal crop yields than other irrigation methods and in most cases used less water.

Periodic droughts and uneven rainfall patterns in North Carolina have also led to interest in using SDI for growing crops. SDI is in its infancy in North Carolina (Grabow et al., 2008), and very few SDI studies have previously been conducted. Growers seem not to be fully aware of its benefits. SDI systems have been installed in the Coastal Plain and Piedmont of North Carolina to aid in multiple research initiatives (Grabow et al., 2006; Grabow et al., 2011). As SDI emerges in North Carolina, it is important that research be conducted toward understanding and improving the impact of SDI configurations on crop yields and water use efficiency.

Benefits of Sub-Surface Drip Irrigation (SDI)

Camp and Lamm (2003) defined SDI generally as water application below the soil surface with discharge rates in the same range as drip emitters. The driplines are beneath the surface, and water, nutrients, and pesticides are supplied to the plant's root zone while keeping the soil surface dry. Camp (1998) and Lamm (2002) asserted that drip emitters in SDI systems buried in the soil help to minimize soil evaporation and runoff, conserve water, facilitate heavy trafficability in the field, and elevate longevity of driplines and emitters. Benefits of SDI can be realized in three areas: water and soil, cropping and cultural practices, and system infrastructure (Lamm, 2002).

Advantages pertaining to water and soil may include more efficient water use, improved opportunities for use of degraded waters and greater water application uniformity (Lamm and Camp, 2007; Lamm, 2002). SDI greatly reduces soil evaporation, surface runoff, and deep percolation by efficiently distributing water within the root zone (Lamm and Camp, 2007). A lysimeter study done by Phene et al. (1989) found that SDI reduced soil evaporation by 50% and 75% compared with high and low frequency surface drip respectively. Lamm and Trooien (2002) found that SDI could reduce irrigation water use for corn production by 35% to 55% compared to traditional irrigation methods such as center pivot.

SDI can enhance plant growth, crop yields and quality, boost plant health, and improve fertilizer and pesticide management (Lamm, 2002). Careful management of SDI systems irrigating corn eliminated 25% of irrigation needs while still maintaining top yields of 2.85 $Mg\ ha^{-1}$ (Lamm et al., 1995). Alam et al. (2002) showed that a well-designed SDI system could decrease the volume of applied water by 22% while increasing yields by 7%, compared to using a center pivot sprinkler system. Other investigations showed that when crops were irrigated by SDI, yields were equal to or greater than those irrigated by surface drip (Phene et al., 1987; Camp et al., 1993; Bhattarai et al., 2006).

Advantages related to system infrastructure include ease of automation, decreased energy costs, design flexibility, and less pest damage (Lamm, 2002). Due to being conducive to system automation, SDI is highly likely to avoid over-irrigation, which causes nutrient leaching, and soil surfacing, and under-irrigation, which results in crop stress and thus yield reduction. Automation of irrigation systems based on soil moisture sensors may further improve water use efficiency (Shae et al., 1999).

Automated SDI Systems

Generally, two approaches have been used for irrigation scheduling. One method called "checkbook" involves estimating crop water needs based on evapotranspiration, rainfall, and irrigation. The other approach directly measures soil-water via measurement devices such as neutron probes, granular matric sensors (GMS), or time domain reflectory (TDR). Automated irrigation control is adapted from this approach as automated irrigation control involves using feedback from the soil-water content measurement devices, rain gauges, etc., to schedule irrigation.

In a study done on corn, Caldwell et al. (1994) used a neutron probe to measure soil-water content in order to schedule the irrigation treatment. The authors found that time-based irrigation of seven days and depletion-based SDI produced less drainage under the root zone and higher water use efficiency than more frequent irrigation. Grabow et al. (2004), Meron et al. (1996), and Muñoz-Carpena et al. (2005) used GMS to control SDI and drip irrigation systems using soil-water feedback. Dukes and Scholberg (2004) found SDI irrigation water savings of 23% and 50% by using TDR and commercially available dielectric sensors compared to sprinkler treatments on sweet corn and bell pepper, respectively.

Grabow et al. (2011) used GMS to controll irrigation on corn and soybean in the Piedmont of North Carolina. Sensors were placed at 0.15-, 0.30-, and 0.45-m depths 0.15, 0.38, and 0.76 m from the dripline at an every other row dripline spacing. Irrigation was scheduled based on soil-water status at a threshold level subject to rainfall less than 13 mm over the previous 24 hours. Corn yield for SDI was not statistically different from yields under sprinkler irrigation, but significantly higher than a non-irrigated treatment. For soybean, no statistical differences were found for either yields or water use efficiency for SDI, sprinkler, and non-irrigated treatments.

While sensor-controlled SDI automation can lead to water savings, care must be taken with the selection of dripline depth and dripline spacing, so that yields can be optimized while keeping initial costs down. Wider dripline spacing will lower material and installation cost, but that must be balanced against the system's and soil's capabilities of transmitting adequate water to the root zone. There are many factors to consider when selecting dripline spacing, dripline depth, and emitter spacing in the SDI design process. Soil texture, anticipated marketable yields, and crops to be grown (Bosch et al., 1998) are strong factors to determine SDI configurations. As noted by Lamm et al. (2012), a choice of dripline depth and dripline spacing with regard to soil type is one of the big challenges facing growers considering SDI. Therefore, comparisons of relative differences in crop yield and water use efficiency as effected by dripline spacing, dripline depth, and emitter spacing have often been evaluated, specifically on corn (Grabow et al., 2011; Abat et al., 2010), cotton (Grabow et al., 2006; Camp et al., 1997), and sweet corn (Duke and Scholberg, 2004).

SDI Spacing and Depth Impact on Yield and Water Use Efficiency

Dripline spacing is commonly set at either one dripline per row, or one dripline per alternate row middle. Camp et al. (1998) reported dripline spacing from 0.25 to 5.0 m with narrow spacing mainly for turfgrass and wide spacing normally for vegetable, tree or vine crops. For field corn, dripline spacing is generally one dripline for every two corn rows (Lamm, 2002). Corn is a major irrigated, relatively low value crop in the United States and thus requires a low irrigation system cost to be financially viable. SDI cost can be reduced by using an alternate row dripline spacing, rather than installing a dripline under every row. In a study done in Virginia on a loamy sand soil using SDI spacing of 0.91 (under every row), 1.83 (alternate row middles), and 2.74 m (under every third row), Powell and Wright (1993) found that average corn yields were 100%, 93%, and 94% of maximum.

In a study by Grabow et al. (2011), there was no difference in corn grain yield between dripline spacings of 1.52- or 2.28 m or between either dripline spacing and sprinkler irrigated grain yield. Camp et al. (1997) evaluated 1.0- and 2.0-m dripline spacings for cotton in the Southeastern Coastal Plain and found that the cotton lint yield did not differ between dripline spacings in any study years. In a study done in a sandy soil common to Florida, Dukes and Scholberg (2004) found that dripline placed 0.33-m deep SDI was too deep for optimal corn yields while similar yields were found between 0.23-m deep SDI and sprinkler irrigation, but 0.23-m deep SDI reduced water use 11%. In a study done in a silt loam soil of Great Plains, Arbat et al. (2010) found that emitter spacings of 0.30 to 0.60 m resulted in no difference in corn yield and water use efficiency. Grabow et al. (2006) reported no difference on seed cotton yield and irrigation water use efficiency between dripline spacings of 0.91 and 1.82 m.

In a study done in Georgia, Sorensen et al. (2001b) found that SDI resulted in 38% more yield for peanut compared to non-irrigated treatments, but there was no difference in yield due to dripline spacings, amount of irrigation water applied, or emitter spacing. In a four-year yield study to examine the effects of dripline depth, Lamm and Trooien (2005) reported that yields were slightly less for the deepest (0.61 m) dripline depth and crop water use slightly less was for the 0.51- and 0.61-m depths compared to the 0.20-, 0.30-, and 0.41-m depths. Enciso et al. (2005) looked at the economics of different dripline depths for cotton on a clay loam soil and found that the 0.30-m dripline depth had greater yields and net returns than the 0.20-m dripline depth. Dripline depth for SDI systems generally ranges from 0.02 to 0.70 m (Camp, 1998).

Little or no differences in yield and irrigation water use efficiency under different dripline depth and dripline spacing reported by the above authors indicate that dripline spacing and dripline depth decisions are site and crop system specific. Adequate SDI designs and management have been defined as "the judicious combination of dripline spacing, emitter flow rate, and irrigation duration" (Provenzano, 2007). For SDI designs to be practical, dripline spacing must be a compromise between being wide enough to be financially feasible and narrow enough to provide sufficient amounts of water in the root zone. Dripline depth must be deep enough for cultural practices such as disking, and shallow enough for sufficient water to reach the upper root zone without excessive wet soil evaporation. Modeling differently configured systems may provide insight into SDI configurations and management practices. Soil-water distribution obtained from modeling can be a benchmark for evaluating systems. Of the above studies in this section, only Grabow et al. (2006, 2011) investigated soil-water distribution from SDI and provided formal statistically-based conclusions on how soil-water distributed between dripline spacing and dripline depth.

SDI and Soil-water Distribution Effects

An investigation on soil-water distribution from SDI systems is very crucial in predicting the success of system design (Grabow et al., 2006; Elmaloglou and Diamantopoulos, 2009) as it impacts irrigation scheduling and water use efficiency. However, little research has been conducted on soil-water distribution under SDI systems with most of researchers evaluating only the impact of SDI dripline spacing on crop yields.

Singh et al. (2006) used dimensional analysis to fit a model that predicts the width and depth of wetted volume from discharge and irrigation duration and dripline depth. The authors found that wetting depth increased with dripline depth at all discharge rates investigated for dripline depths ranging from 0.05 to 0.15 m. Camp et al. (1999) found that SDI dripline placed below a compacted soil layer performed poorly due to small pores and slow conductivity in the compacted layer restricting water movement to the root zone.

An investigation of soil-water distribution by Grabow et al. (2006) indicated that there was no difference in the extent of lateral water movement between dripline spacings of 0.91 and 1.82 m in a coastal plain soil for cotton. In a study done in a piedmont clay soil, water from the dripline typically spread laterally from the dripline a distance greater than 0.38 m but less than 0.78 m (Grabow et al., 2011).

Computer modeling has also been used to study SDI soil-water distribution. Cote et al. (2003) simulated soil-water distribution from SDI with a 0.30-m dripline depth for different soil types using Hydrus-2D. The simulation results showed downward water movement and water not reaching the soil surface on a sandy soil, spherical water movement on a silt soil, and little deep percolation in a layered soil.

Application rate, soil type, root water uptake pattern and root distribution, dripline depth, emitter spacing, and irrigation scheduling all impact the vertical and lateral movement of water. As soil-water movement patterns under SDI play a pivotal role in deciding the efficacy of SDI configurations, it is important that soil-water content be accurately measured to assess different SDI configurations. Methods of soil-water estimation range from simple and direct gravimetric measurement procedures to sensors to computer simulations capable of predicting soil-water content over time and space. Therefore, choosing a tool that can accurately predict soil-water distribution is important for development of SDI management strategies and installation guidelines.

Soil-Water Distribution Evaluation Methods

The most direct method of measuring soil-water content is by gravimetric soil-water content determination that requires weighing of a known volume of soil before and after drying. In a study done in Kansas, Arbat et al. (2010) used this method to see the effects of emitter spacing on soil-water redistribution. Although, gravimetric soil-water content is recognized as the simplest method for measuring soil-water content, highly accurate gravimetric determination of soil-water content is time consuming and destructive, rendering it impractical for most purposes other than sensor calibration.

Others have used soil pits for measurement of wetting front advance (Battam et al., 2003; and Skaggs et al., 2004). The disadvantages of soil pits are lower accuracy and system perturbation (i.e. system changes once it is disturbed). Consequently, alternate methods are needed to provide a quick and reliable tool in assessing soil-water content.

Alternatively, Grabow et al. (2006) used an empirical statistical model with measured soil-moisture to test for differences in soil-water content at different distances from the dripline. In this method, the authors used GMS to measure soil-water tension and converted tension to volumetric soil-water content using a soil-water release curve developed from soil cores, to understand water movement and extraction between different SDI dripline spacing. TDR measurements were used by Dukes and Scholberg (2004) as feedback to automate an SDI system. These methods, however, are costly (requiring many sensor devices and installation), time consuming, and laborious (Patel and Rajput, 2008) with accuracy subject to sensors coverage. Soil-water distribution modeling under SDI has captured the attention of researchers (Van Bavels et al., 1973; Mmolawa and Or, 2003; Skaggs et al., 2004; Lazarvoitch et al., 2005; Singh et al., 2006).

Empirical modeling is another method to understand soil-water distribution. Schwartzman and Zur (1986), Singh et al. (2006), and Kandelous et al. (2008) developed empirical models for estimating lateral, and vertical soil-water distribution. Kandelous and Simunek (2010) subsequently found that the empirical model could not provide a good description of the wetting pattern unless the conditions were similar to those for which it was developed.

Analytical modeling is one of the tools used to model soil-water distribution. Analytical solutions have been developed for steady infiltration from a surface point source and a buried point source (Philips, 1984). Cook et al. (2006) used the user-friendly software

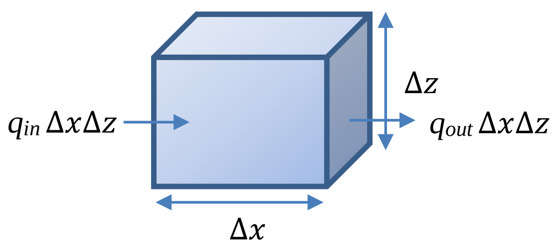
"WetUp" as an analytical tool to understand the SDI wetting pattern from drippers. Mmolawa and Or (2000) developed a two-dimensional analytical model to describe soil-water distribution under transient flow conditions with the presence and absence of plant uptake and found good agreement with measurements of water and solute uptake. The authors also discovered that without plant uptake the analytical model accurately predicted soil-water dynamics from a point source. A major handicap of analytical models is that they often contain many simplifying assumptions pertaining to the linearization of the flow equation (Li et al., 2005) that may not effectively represent the observed reality in drip irrigation management (Kandelous and Simunek, 2010).

Numerical models such as Hydrus-2D (Simunek et al., 1999) are fast and inexpensive methods to simulate water movement for surface and subsurface drip irrigation and have become effective tools for use in SDI soil-water distribution research. Hydrus-2D (Simunek et al., 1999) is a well-known windows-based computer software package used for simulating water, heat, and solute movement in two-dimensional variably-saturated porous media. Hydrus-2D uses the Richards equation for variable flow through which soil-water content can be determined at very small time steps at very fine vertical and lateral resolution. There are many benefits of using Hydrus-2D for modeling soil-water movement including its sound physical basis, its relatively inexpensive cost, and the ability to run many simulations quickly. These qualities make Hydrus-2D a good option for SDI designs that seek to ascertain appropriate dripline spacing and depth under different soil types and irrigation duration (Kandelous and Simunek, 2010) as well as crop root zone extent (Provenzano, 2007). The capacity of Hydrus-2D to simultaneously evaluate soil wetting pattern, soil-water content, and matric potential distribution during and after irrigation makes it a trustworthy and useful tool for designing, monitoring, and managing SDI (Kandelous and Simunek, 2010). Multiple studies have used Hydrus-2D as a tool for soil-water distribution modeling and found it useful (Ajdary et al., 2005; Mailhol et al., 2001; Cote et al., 2003; Jiusheng et al., 2003; Jiusheng et al., 2004; Gardenas et al., 2006; Skaggs et al., 2004).

Hydrus-2D Governing Equation and Input Requirements

Hydrus-2D was developed at the U.S. Salinity Laboratory, Agricultural Research Station, Riverside, California. Hydrus-2D can be used to simulate infiltration, evaporation, root water uptake (transpiration), soil-water storage, deep drainage, groundwater recharge, and lateral flow (Simunek et al., 2012).

The package consists of the SWMS-2D code (Simunek et al., 1994) for simulating water flow, heat, and solute movement in two-dimensional, variably-saturated media. The program numerically solves the Richards equation for the governing water flow using Galerkin-type linear finite element schemes. The flow equation consists of sink terms for water uptake by plant roots as a function of both water and salinity stress. Water uptake by roots is assumed to be zero close to saturation. The Richards equation was derived from the continuity equation and Darcy flux.



The mass balance can be written in two dimensions as:

$$\frac{\Delta\theta}{\Delta t} = \frac{\Delta\left(\sum q_{in} - \sum q_{out}\right)}{\Delta x} + \frac{\Delta\left(\sum q_{in} - \sum q_{out}\right)}{\Delta z}$$

or, (1.1)

$$\frac{\partial\theta}{\partial t} = -\frac{q}{\partial x} - \frac{q}{\partial z}$$

where

θ = volumetric water content ($L^3\,L^{-3}$)

q = water flux (L T^{-1})

t = time (T)

x = horizontal space coordinate

z = vertical space coordinate.

Horizontal and vertical water flux can be defined by Darcy's law as:

$$q_x = -K\frac{\partial H}{\partial x}$$
$$q_z = -K\frac{\partial H}{\partial z} \tag{1.2}$$

where

K = hydraulic conductivity (L T^{-1})

H = hydraulic head (L).

Substituting equation 1.2 into equation 1.1 yields as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial H}{\partial z}\right) \tag{1.3}$$

Substituting for $H=h+z$ (where *h* is the pressure head and z is the position head) for the vertical direction yields as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \tag{1.4}$$

A sink term, *S(h)* (T^{-1}), is introduced in the flow equation for water uptake by plant roots as a function of both water and salinity stress. Equation 1.4 becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S(h) \tag{1.5}$$

The term $S(h)$ represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake. Feddes et al. (1978) defined $S(h)$ as:

$$S(h) = \alpha(h) S_p \quad (1.6)$$

where

$\alpha(h)$ = the water stress response function of the soil-water pressure head ($0 \leq \alpha \leq 1$) (L^{-1})

S_p = the water uptake rate during periods of no water stress when $\alpha(h) = 1$.

When the potential water uptake rate is equally distributed over a two-dimensional rectangular root domain, S_p becomes:

$$S_p = \frac{1}{L_x L_z} S_t T_p \quad (1.7)$$

where

T_p = the potential transpiration rate ($L\ T^{-1}$),

L_z = the length of the root zone (L),

L_x = the width of the root zone (L),

S_t = the width of the soil surface associated with the transpiration process (L).

Equation 1.7 may be generalized by introducing a non-uniform distribution of the potential water uptake rate over a root zone of arbitrary shape (Vogel, 1988):

$$S_p = b(x,z) S_t T_p \quad (1.8)$$

The actual water uptake distribution is then obtained by substituting equation 1.8 into equation 1.6:

$$S(h) = \alpha(h) b(x,z) S_t T_p \quad (1.9)$$

where, $b(x, z)$ denotes the dimensionless spatial distribution of unstressed root water uptake (L^2 L^{-2}). This function describes the variation of the potential extraction term, S_p, over the root zone. For the non-uniform cases, Vrugt et al. (2001) defined $b(x, z)$ as:

$$b(r,z) = \left[\left(1-\frac{z}{z_m}\right)\right]\left[1-\frac{r}{r_m}\right]e^{-\left[\left(\frac{p_z}{z_m}\right)|z^*-z|+\left(\frac{p_r}{r_m}\right)|r^*-r|\right]} \tag{1.10}$$

where

r_m = the maximum rooting length in the horizontal direction (L)

z_m = depth direction (L)

p_z, z^*, p_r and r^* = empirical parameters that can describe non-symmetrical root geometries.

Soil Hydraulic Parameter Requirements for Hydrus-2D

Hydrus-2D requires initial water content distribution and the van Genuchten soil hydraulic parameters (i.e. a soil-water release curve and hydraulic conductivity). These are important in investigating water flow. Soil water release curve parameters may be obtained using suction and pressure plate procedures on field cores (Grabow et al., 2006; Grabow et al., 2011). Alternatively, these parameters may be obtained from Rosetta (Schaap et al., 2001) using soil physical properties (Skaggs et al., 2004).

The van Genuchten functions (van Genuchten, 1980) for water retention and hydraulic conductivity are defined as:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left(1+|\alpha h|^n\right)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{1.11}$$

$$K(h) = K_s S_e^l \left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \tag{1.12}$$

and

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r},\; m = 1 - \frac{1}{n} \tag{1.13}$$

where

θ_s = the saturated volumetric water content ($L^3\ L^{-3}$)

θ_r = the residual water content ($L^3\ L^{-3}$)

K_s = the saturated hydraulic conductivity ($L\ T^{-1}$)

l = pore size distribution

S_e = effective water content ($L^3\ L^{-3}$)

α = empirical constant (L^{-1})

m, n = empirical constant with m= 1-1/n, and h = pressure head (L). The empirical constants are fitting parameters that define the shape of the curve.

Root Distribution and Root Water Uptake

Plant root distribution is one of the most important processes in modeling subsurface water flow and solute dynamic. Root water uptake (and soil-water distribution pattern) interactively determine the success of SDI design and management strategies. Root water uptake is equivalent to water lost by plant transpiration. Sufficient irrigation water must be applied to the root zone to provide enough water to the plant to prevent plant stress, as inadequate water results in plant stress and reduced root water uptake. Therefore, root water uptake is a strong surrogate to infer the success of SDI design, installation, and management strategies.

Root water uptake and root distribution for a crop under SDI can be influenced by soil hydraulic properties, dripline spacing and dripline depth, and irrigation quantity and frequency (Camp et al., 1998). Water should be applied to the root zone but not at a higher rate than the plant can uptake (Gardenas et al., 2005). The amount of irrigation water supplied to meet crop water demands can be applied in several fashions. Irrigation can be set to fully and partially replace daily evapotranspiration in a daily or every other day basis. Each irrigation regime or strategy will result in a different soil-water distribution pattern, thus yielding different root distribution and root water uptake (Gitz, 2006).

Clothier and Green (1994) reported that knowledge of crop root distribution and water uptake pattern is essential to matching irrigation system design and management with crop requirements. Gardenas et al. (2005) claimed that water uptake by plant roots determines spatial and temporal patterns of available soil-water. In an attempt to aid drip irrigation design, Coelho and Or (1996) expanded the plant uptake function by fitting a function better describing temporal and spatial change in uptake intensity.

In a study done on alfalfa, Kandelous et al. (2012) used Hydrus-2D to model soil-water distribution and concluded that root distribution has a large effect on optimal applied irrigation water, irrigation water scheduling, and deep percolation loss. Coelho and Or (1999) added that irrigation scheduling schemes that depend on monitoring soil-water status must take root water extraction patterns into account. Coelho and Or (1999) used TDR sensors to measure water uptake at high spatial and temporal distribution. Potential factors affecting root system patterns include spatial and temporal variations in soil-water availability and soil matric potential (Feddes et al., 1976; Michelakis et al., 1993). These factors can be solved in Hydrus-2D, which simulates two-dimensional axially symmetric water flow and root water uptake based on finite element numerical solutions of the flow equations (Simunek et al., 1999).

Model Calibration

There are two main situations that require model calibration before the model can be operated in order for its subsequent use for practical purposes (e.g., SDI design and management strategies). Model calibration is needed when simulated characterizations for a particular problem are different from those to which it was intended. Hydrus-2D may work well for one field site, but it may not work equally well for other sites. Another motivation for model calibration is when some input parameters are missing or not independently measured. Found in Simunek et al. (2012), Simunek and Hopmans (2002) defined model calibration as the process of fitting within reasonable ranges the input parameters (e.g. soil hydraulic parameters or root water distribution) and initial or boundary conditions of a model for a particular problem until the simulated model results and the observed or measured variables (e.g. pressure heads, water content, concentrations, various fluxes) closely match. As the definition dictates, the success of model calibration is when the measured data and the outputs produced are within some acceptable level of precision and accuracy.

There are two steps in the calibration process. The first step involves using the existing data to calibrate the model and to estimate all necessary input parameters while the second validation process compares simulated and measured data outputs using the estimates of parameters calibrated found in the first process (Simunek and de Vos, 1999). The second process determines the success of model calibration such that the model responses are within acceptable ranges of accuracy. This two-process calibration is often hailed as historical validation (Simunek et al., 2012). Hydrus-2D calibration has been carried out in many studies. For example, Bufon et al. (2012) found that Hydrus-2D simulations of volumetric soil-water content were accurate within $\pm$3% when compared to measured values obtained with TDR probes using a soil-specific calibration. The authors suggested that the model be used to evaluate irrigation strategies. Kool et al. (2014) used Hydrus 2D/3D to predict hourly evapotranspiration and found that the predictions compared well with measured data. Kandelous and Simunek (2010) found that Hydrus-2D provided more accurate estimates than analytical models for soil with different soil texture. Skaggs et al. (2004) compared Hydrus-2D simulations of water infiltration and redistribution from drip irrigation with a 0.60-m installation depth in a sandy loam soil by gravimetric sampling. The authors found good agreement between simulated and gravimetrically obtained soil-water data. This result, showing that Hydrus-2D can be a relatively powerful tool for designing and investigating drip irrigation management practices, is similar to that reported by Ben-Gal et al. (2004), Provenzano (2007), and Li et al. (2005).

Hydrus-2D is a physically based model and thus needs no calibration when all required input parameters (i.e. soil hydraulic parameters for water flow) are independently determined (Simunek et al., 2012), and simulated conditions for a particular problem are as those to which it was intended. However, input parameters are difficult to measure. There is little evidence in the literature in which all required input parameters have been independently determined. As noted by Simunek et al. (2012), in most applications one or two parameters required by the model may be lacking. That is, Hydrus-2D requires calibration in almost all situations in which it is first used.

Estimation of Soil Hydraulic Properties

Hydrus-2D needs soil hydraulic properties for its primary input. Two methods may be used to determine soil hydraulic properties: laboratory and in situ measurements. Hydrus-2D has code for estimating soil hydraulic parameters as per calibration. Soil hydraulic parameters can be estimated by a catalog of average parameters for 12 textural classes of the USDA textural triangle (Carsel and Parrish, 1988) or pedotransfer functions (Schaap et al., 2001) using the Rosetta program. Rosetta is a pedotranser function software package that uses a neural network model to estimate hydraulic parameters from soil texture and related data such as bulk density. Skaggs et al. (2004) estimated soil hydraulic parameters by Carsel and Parrish estimates (Carsel and Parrish, 1988), and full Rosetta, and found that the predictions with Rosetta matched with the measured data more closely than the data obtained with Carsel and Parrish estimates. Field data or laboratory measurements can be used together with Rosetta functions and other independent flow parameters to calibrate the Hydrus-2D models (Simunek et al., 2012).

Review of SDI Research using Hydrus-2D

Although an increase in SDI research has occurred recently (Lamm et al., 2012), the literature generally lacks good information on how dripline spacing and dripline depth affect both lateral and vertical movement of water. Comprehensive knowledge of this is necessary to develop SDI installation guidelines and irrigation strategies that growers could use to obtain high yields. Examining all possible placement of the drip tape and all possible SDI scheduling strategies through field experiments requires extensive time and sizeable resources. However, numerical simulation models, such as Hydrus-2D, can be used to predict the soil-water distribution for different ranges of dripline spacing, dripline depth, and irrigation strategies in a fast and inexpensive fashion. However, little work has been done to justify that the model can be used to develop design guidelines and irrigation management strategies. Furthermore, Hydrus-2D has not been calibrated under SDI cropping systems and dripline spacings and depths found in North Carolina.

Research Objectives

The primary objectives of this study were to:

1) Calibrate the Hydrus-2D model for its subsequent use in evaluating SDI design factors by comparing soil-water distribution results from Hydrus-2D simulations of corn grown on a coastal plain soil to measured soil-water data.
2) Use Hydrus-2D to simulate root water uptake (transpiration) from corn under selected dripline depth, dripline spacing, soil type, dripline flow rate (emitter spacing), and irrigation treatment to identify designs that tend to maximize transpiration.

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CHAPTER 2. CALIBRATION OF HYDRUS-2D TO MEASURED SOIL-WATER DATA

Introduction

As concerns proliferate over limited water supplies in the United States, interest in the use of subsurface drip irrigation (SDI) over conventional irrigation is increasing. SDI is one of the high-performance irrigation technologies that can overcome the challenges of limited or restricted water supplies and has been implemented in arid and semi-arid regions for many years. Even in semi-humid to humid regions, where rainfall is significant, its implementation is increasing. Although SDI is a relatively new option to North Carolina producers, it is becoming more popular as producers learn of its many benefits (Grabow et al., 2008). The latest USDA Farm and Ranch Irrigation Survey (USDA-NASS, 2009) reported that the area covered by SDI in the U.S. has increased from 163,000 to 260,000 ha in the five-year period 2003 to 2008, an increase of 59%.

SDI is defined as "the application of water below the soil surface by microirrigation emitters with discharge rates usually less than 7.5 L h^{-1}" (Lamm et al., 2012; Lamm and Camp, 2007; ASAE, S526.2 2001). SDI has numerous potential advantages. SDI allows almost all portions of the field to be irrigated efficiently. Irrigation water is precisely controlled by delivering to the root zone directly. SDI can maintain soil-water distribution at a level favorable to plant growth (Camp, 1998). The field surface remains dry, curtailing weed growth, when the driplines are placed deep enough.

These advantages of SDI can be realized through proper design and management with regard to site conditions and cropping systems (Lamm, 2002). One of the challenges proponents of SDI face is a choice of dripline spacing and dripline depth with regard to crops to be grown, soil texture and irrigation strategies. For SDI designs to be practical, dripline spacing must be a compromise between being wide enough to be financially feasible and narrow enough to provide sufficient amounts of water in the root zone. Dripline depth must be deep enough for cultural practices such as disking, and shallow enough for sufficient water to reach the upper root zone without excessive wet soil evaporation. Modeling of different SDI configurations has the potential to improve installation and management guidelines.

A comprehensive understanding of the mechanism of SDI soil-water distribution in the soil profile is imperative for proper SDI design and management. Knowledge of soil-water distribution can be obtained from tools ranging from simple and direct gravimetric measurement procedures to soil-water sensors to computer numerical simulations capable of spatially and temporally predicting soil-water content. Choosing a tool that can accurately predict soil-water distribution is important to efficiently design and manage SDI systems.

Arbat et al. (2010) used gravimetric measurement to see the effects of emitter spacing on soil-water redistribution. A drawback of gravimetric determination is that limited soil-water distribution data can be obtained due to laborious and time-consuming work and its destruction to soils rendering it impractical for most purposes.

Grabow et al. (2006) used an empirical statistical analysis with measured soil-moisture data from nests of granular matrix sensors to look at differences in soil-moisture at different distances from the dripline. Kandelous et al. (2008) developed empirical models for estimating soil-water distribution. Cook et al. (2006) developed a user-friendly software, called “WetUp” (Cook et al., 2003), as an analytical tool to understand wetting patterns from buried sources such as SDI. A major handicap of analytical models is that they often contain many simplifying assumptions pertaining to the linearization of the flow equation that may not effectively represent observed reality in drip irrigation management (Kandelous and Simunek, 2010; Li et al., 2005).

A number of numerical models have been developed to simulate plant growth, water flow, and solute movement (Simunek et al., 1999). Hydrus-2D is a well-known Windows-based computer software package used to simulate two dimensional water, pressure head, and solute movement in porous media. The program numerically solves the Richards equation for saturated and unsaturated water flow. Multiple studies have used Hydrus-2D and found it useful for SDI soil-water distribution modeling. For instance, Cote et al. (2003) used Hydrus-2D to simulate both soil-water and solute movement under SDI. Kandelous and Simunek (2010) used Hydrus-2D to simulate wetting patterns and compared predictions by Hydrus-2D with field and laboratory data, WetUp, and empirical models. Provenzano (2007) also evaluated wetted soil volume under SDI using Hydrus-2D.

Model calibration is needed when conditions are not the same to those that are used to formulate the model. A model may work well for one field site, but it may not work equally well for other sites. Another reason for model calibration is when some input parameters are missing or not independently measured. Simunek and Hopmans (2002) defined model calibration as the process of adjusting within reasonable ranges the input parameters (e.g. soil hydraulic parameters and root distribution) and initial or boundary conditions of a model for a particular problem until the simulated model results and the observed or measured variables (e.g., pressure head, soil-water content, concentration, various fluxes) closely match. A model is judged to be successfully calibrated when measured data and model output are within some acceptable level of precision (Simunek et al., 2012) or accuracy.

Physically based models such as Hydrus-2D often need little calibration, when all required input parameters (e.g. soil hydraulic parameters for water flow and root distribution) are independently determined (Simunek et al., 2012), and simulated conditions for a particular problem are as those to which it was intended. However, input parameters are difficult to independently measure, and measurement may be insufficient due to spatial variability. For instance, root water uptake distribution and the root reduction function parameter are of the Hydrus-2D inputs that are difficult to experimentally obtain because the relationship between wetting and rooting pattern is difficult to determine.

There is little evidence in the literature of studies in which all required input parameters have been independently determined. In most scenarios one or two parameters required by the model is missing (Simunek et al., 2012). Hydrus-2D has options to determine missing parameters. For example, when soil hydraulic parameters are lacking, users can use pedotransfer functions as obtained by Schaap et al. (2001) using their Rosetta program for estimating soil hydraulic parameters from soil textural properties. Rosetta can also be used in a combination with field-determined data to estimate soil hydraulic parameters for calibrating Hydrus-2D (Simunek et al., 2012). Comparison between predicted soil-water content by Hydrus-2D and field observed data has been carried out in some studies using some of input parameters estimated with the Rosetta program (Ben-Gal et al., 2004; Provenzano, 2007; Skaggs et al., 2004; Bufon et al., 2012).

Ben-Gal et al. (2004) compared observed data to simulated soil-water content and found that the simulated soil-water content obtained with Hydrus-2D closely matched observed values. Wang et al. (2013) validated Hydrus-2D by comparing predicted soil-water content under SDI with measured soil-water data from field experiments and found that there was good correspondence between simulations and field observations. Bufon et al. (2012) found that soil-water content from Hydrus-2D was accurate within $\pm$3% when compared to measured soil-water data obtained from TDR soil-water sensors. The authors used field measured soil data combined with the pedotransfer function Rosetta to estimate the van Genuchten soil hydraulic properties. Liu et al. (2013) used Hydrus-2D to predict the temporal variation of soil-water content in a drip irrigated cotton field and found that their Hydrus-2D predictions agreed well with the field observations. Skaggs et al. (2004) compared the Hydrus-2D simulations of water infiltration and redistribution from drip irrigation with a 0.06-m installation depth in a sandy loam soil with gravimetric samplings and found satisfactory agreement.

The study herein consisted of calibrating Hydrus-2D for its use in evaluating SDI designs and management practices. There were two reasons for model calibration. Mainly, the Hydrus-2D model must first be tested with field data specific to intended scenarios (i.e. corn, NC soils, NC climate, etc.) to provide confidence for design and management use. Secondly, all required input data for any particular site is not likely to be found or independently determined for simulation purpose. Usually, there are at least one or two input parameters or variables missing.

The primary objective of this study was to investigate the accuracy of Hydrus-2D in estimating soil-water distribution for SDI on a coastal plain soil. The model incorporated irrigation, soil evaporation, crop transpiration, precipitation, and root water uptake.

Materials and Methods

Site Description

Hydrus-2D calibration required both input data for the model and measured soil-water data for comparison. Soil-water content data during the period of irrigation from DOY 159 (8 June) to DOY 203 (22 July) 2011 were used in this study. The field site from which data for model calibration were obtained is located in the coastal plain near Rowland, North Carolina, coordinates 34°32′7″N 79°17′33″W, and elevation of 45 m above sea level. The dominant soil types at the field site is Nahunta very fine sandy loam, Aycock very fine sandy loam, and Trebloc loam (USDA Web Soil Survey, 2014)

The SDI irrigated area was divided into two irrigation zones: zone 1 (approximately 3 ha) and zone 2 (approximately 6 ha). Soil-water content data used for model assessments were measured by Echo EC-5 soil-water sensors (Decagon Devices, Inc. Pullman, WA). Sensor nests were located at 0.15- and 0.30-m depths 0.15, 0.30, and 0.51 m (mid-dripline) from the dripline in both zones. The layout of the soil-water sensors is shown in figure 2.1. There were two replications of the soil-water sensors in both 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. Details on the field site, instrumentation, and irrigation scheduling setup can be found in Owens (2013).

Numerical Simulation Using Hydrus-2D

Soil-water distribution below the soil surface was simulated using the computer modeling Hydrus-2D (Simunek et al., 2008). Hydrus-2D can simulate two dimensional variably-saturated water flow, heat movement, and transport of solutes. Hydrus-2D numerically solves the Richards equation for variably-saturated water flow. The model also includes sink terms for root water uptake, which affect the spatial distribution of soil-water. In this study, the flow problem was considered to be a line source with water flow and distribution being a two-dimensional process.

The Richards equation is the governing equation solved for water flow in homogenous and isotropic soil:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S(h) \qquad (1.14)$$

where

θ = volumetric water content ($L^3\ L^{-3}$)

h = soil-water pressure head (L)

t = time (T)

x = horizontal space coordinate

z = vertical space coordinate

K = hydraulic conductivity ($L\ T^{-1}$)

$S(h)$ = root water uptake (T^{-1}).

Soil hydraulic properties were modeled using the van Genuchten model (van Genuchten, 1980) as described in equation 1.11. For this study, numerical simulations were obtained for a rectangular transport domain. The flow domain was defined as 0.50 m wide and 1.0 m deep, representing a cross-section from dripline to mid-dripline. Only one side, as depicted in figure 2.2, of the presumed symmetrical profile was simulated. The corn plant was located at the middle of the domain, 0.25 m from the dripline (fig. 2.2). The dripline was located at the edge of the rectangular domain as a 0.8-cm radius semi-circle, 0.25 m below the soil surface. The transport domain was discretized into 6114 triangular finite elements (3150 nodes) using an unstructured finite element. Observation nodes, as depicted in figure 2.2, were assigned at 0.15- and 0.30-m depths 0.15, 0.30, and 0.50 m from the dripline to coincide with the locations of the soil-water sensors.

Initial and Boundary Conditions

The boundaries for the Hydrus-2D model are shown in figure 2.3. A time-variable atmospheric boundary condition was used at the upper water flow boundary condition. The atmospheric boundary condition included fluxes of precipitation, evaporation (E) and potential transpiration (T_p). Water was assumed to evaporate at potential evaporation rates when the soil surface was below a threshold value (hCritA) of -10000 cm H_2O of pressure head. At the bottom of the soil profile, a free drainage boundary condition was imposed. This boundary condition assumes a unit gradient along the lower boundary because the water table at this site was assumed to be deep enough to not influence root zone soil-water dynamics. A variable flux boundary was used at the dripline emitter. The water flux at the variable flux boundary was calculated based on the rated 0.91 L h^{-1} emitter discharge flow rate, the dripline circumference, and the emitter spacing:

$$water\ \ flux\,(cm\,h^{-1}) = \frac{emitter\ discharge\ \ flow\,rate\,(L\,h^{-1})}{dripline\,circumference\,(cm)\times emitter\ spacing\,(m)}\times 10 \qquad (1.15)$$

During water application, the dripline boundary was set to a constant water flux of 2.97 cm h^{-1}. When irrigation ended, flux was set to zero. At both sides of the domain, a zero-flux boundary was imposed during and after irrigation due to symmetry (Skaggs et al., 2004).

Additionally, Hydrus-2D requires initial soil-water content, precipitation, irrigation, and spatial root distribution (fig. 2.4). Initial soil-water content was estimated using data from Echo EC-5 soil-water sensors. Between the soil surface and 0.40 m depth, the initial soil-water content at 6 sensor locations for both replications of both zones was set equal to the measured soil-water content one hour prior to the start of simulations (table 2.1). Initial soil-water content was set equal between sensor midpoints in both horizontal and vertical dimensions, and for soil-water content at the domain edges was set equal to soil-water content measured by the closet sensor. From 0.40-m depth to the bottom of the domain, initial soil-water content was assumed to be at field capacity as plant extraction would be expected to be nil below this depth.

Parameters and Variable Inputs

Soil Physical Properties

Hydrus-2D requires soil hydraulic parameters: θ_r, θ_{sat}, α, n, l for use in defining a soil-water release curve, and K_{sat}. Undisturbed core soil samples were taken from the soil profile to determine particle size distribution, bulk density, soil-water retention to develop a soil-water release curve. The samples were taken using cylindrical samplers 0.076 m in diameter and 0.076 m long. The soil cores were extracted at 0.15- and 0.30-m depths at three locations at different distances from a dripline.

Bulk density (ρ_b) was determined as the soil sample dry mass divided by the cylinder volume. Particle size distribution was determined by the hydrometer method and classified using the USDA scheme (fig. 2.5). A soil-water release curve was developed by subjecting the soil cores to successively higher pressures ranging from 1 to 1500 kPa. Measured values for the soil properties are shown in table 2.2.

The data were fit to the van Genuchten model (van Genuchten, 1980) using all of data (both 0-0.15 and 0.15-0.30 m):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \qquad (1.16)$$

where

θ_s = the saturated volumetric water content (L^3 L^{-3})

θ_r = the residual water content (L^3 L^{-3})

α , *m*, and *n* = empirical constant with $m = 1-1/n$

h = pressure head (L).

Residual and saturated soil-water content, α, and n were estimated by fitting the van Genuchten (1980) soil-water retention model to the field-determined soil-water data at 0.15- and 0.30-m depths using a nonlinear least squares procedure in R (R Development Core Team 2012). The soil-water release curve is shown in figure 2.6.

Irrigation and Precipitation

During irrigation, the variable flux was set equal to the calculated water flux of the dripline. SDI zone 1 was irrigated by two irrigation cycles of 2:15 duration beginning at 6:00 am and ending at 9:45 am (Owens, 2013). Zone 2 irrigation was programmed daily in two irrigation cycles of 1:30 duration occurring at 8:15 am and 12:00 pm (Owens, 2013). Measured hourly precipitation rates were imposed as part of the atmospheric boundary. During the simulation period, there were 15 rainfall events.

Crop Transpiration and Soil-water Evaporation

Daily evaporation (E) and transpiration (T_p) were estimated using the dual crop coefficient procedure– FAO 56 (Allen, 1998) as follows:

$$ET_c = \left(K_{cb} + K_e\right) ET_0 \qquad (1.17)$$

where

ET_c = crop evapotranspiration (mm)

K_{cb} = basal crop coefficient

K_e = soil evaporation coefficient

ET_o = reference evapotranspiration (mm).

ET_o was computed with Ref-ET (Allen, 1998) using climatic data obtained from a Model 700 Watchdog Weather Station (Spectrum Technologies, Inc., Plainfield, Illinois). The weather data included minimum, average and maximum 2-m temperature (Celsius), 10-m average wind speed (m s^{-1}), 2-m average relative humidity (%), daily precipitation (mm), solar radiation (W m^{-2}). ET_o during the simulation period is shown in figure 2.7.

Basal crop coefficients were calculated based on corn growth periods. Corn growth periods are divided into four growth stages for purpose of crop curve characterization. The initial stage, crop development, mid-season stage, and late season stages were set to 20, 35, 40, and 20 days respectively (Allen, 1998). The basal crop coefficient (K_{cb}) for field corn during the initial stage was set to 0.15, during the mid-season stage 1.15, and during the late-season stage 0.5 (Allen, 1998). The simulation period occurred only during the mid-season stage so only $K_{cb\text{-}mid}$ was used to calculate crop transpiration. K_{cb} was adjusted to the climate of North Carolina using the following equation (Allen, 1998):

$$K_{cb} = K_{cb\,(Tab)} + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{\min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \qquad (1.18)$$

where

$K_{cb\,(Tab)}$ = the table value for $K_{cb\ mid}$ or $K_{cb\ end}$ (if ≥0.45) taken from the basal crop coefficients Kc for no stressed, well-managed crops in sub humid climates table-FAO 56

u_2 = the mean value for daily wind speed at 2-m height during the mid- or late- season growth stage (m.s^{-1}) for 1 m $s^{-1} \leq u_2 \leq$ 6 m s^{-1}

RH_{min} = the mean value for daily minimum relative humidity during the mid or late season growth stage (%) for $20\% \leq RH_{min} \leq 80\%$

h = the mean plant height (assuming 2 m) during the mid or late season stage (m) for $20\% \leq RH_{min} \leq 80\%$.

The basal crop coefficient curve is shown in figure 2.8. Daily E and T_p are shown in figure 2.9. Daily soil evaporation was determined by multiplying ET_o by the soil evaporation coefficient K_e. Soil evaporation occurred following rainfall, and soil evaporation due to SDI was negligible. K_e was calculated using the following equation (Allen, 1998):

$$K_e = K_r \left(K_{c\,max} - K_{cb} \right) \leq f_{ew} K_{c\,max} \qquad (1.19)$$

where

K_e = soil evaporation coefficient

K_{cb} = basal crop coefficient

$K_{c\,max}$ = maximum value of K_c following rain or irrigation

K_r = dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the topsoil

f_{ew} = fraction of the soil that is both exposed and wetted, i.e., the fraction of soil surface from which most evaporation occurs.

$K_{c\,max}$ is an upper limit on the evaporation and transpiration from cropped surface. K_{cmax} was calculated using the following equation (Allen, 1998):

$$K_{c\,max} = \max\left(\left\{ 1.2 + \left[0.4\left(u_2 - 2\right) - 0.004\left(RH_{\min} - 45\right) \right] \left(\frac{h}{3} \right)^{0.3} \right\}, \left\{ K_{cb} + 0.05 \right\} \right) \qquad (1.20)$$

where

u_2 = mean value for daily wind speed at 2-m height during the period of calculation (initial, development, mid-season, or late-season)

RH_{min} = mean value for daily minimum relative humidity during the period of calculation (initial, development, mid-season, or late-season)

h = mean maximum plant height during the period of calculation (initial, development, mid-season, or late-season) (m)

K_{cb} = basal crop coefficient.

K_r represents the soil evaporation reduction coefficient. When the soil surface is wet following the rainfall, the soil surface condition is in the energy limiting stage (stage 1), and K_r is 1. K_r is less than 1 when the cumulative depth of evaporation D_e exceeds readily evaporable water. K_r was calculated using the following equation (Allen, 1998):

$$K_{r,i} = \frac{TEW - D_{e,i-1}}{TEW - REW} \tag{1.21}$$

where

$D_{e,\,i-1}$ = cumulative depth of evaporation from the soil surface layer at the end of the previous day

TEW = maximum cumulative depth of evaporation from the soil surface layer when K_r =0

REW = cumulative depth of evaporation at the end of stage 1.

Spatial Root Distribution and Root Water Uptake

Root water uptake in the Hydrus-2D model was modeled based on potential transpiration, the water stress function by Feddes et al. (1978), and assumed root distribution. Root water uptake in Hydrus-2D was calculated as follows:

$$S(x,z) = \alpha(x,z)\,b(x,z)\,L_t T_p / \omega_c \tag{1.22}$$

where

S = the volume of water removed per unit time from a unit volume of soil due to plant water uptake ($L\ T^{-1}$)

α = the water stress function that reduces root water uptake from its maximum possible values due to water stress (L^{-1})

b = the normalized water uptake distribution ($L^2\ L^{-2}$)

L_t = the wetted radius of soil surface associated with transpiration process (L)

T_p = the potential transpiration rate (L T^{-1})

ω_c = the water stress index

x, z = horizontal and vertical domain directions respectively.

Following Jarvis (1989), a critical water stress index ω_c was introduced to compensate for reduced water uptake from stressed parts of the root zone by an increased uptake from other less stressed areas. The $S(x,z)$ represents either compensation at $0<\omega_c<1$ or no-compensation at $\omega_c=1$. In the dearth of literature on a critical water stress index for field corn, ω_c was set equal to 0.8 to allow for a modest level of water uptake compensation.

In the absence of root measurements, Feddes' parameters of the stress response function for field corn were obtained from the existing database implemented in Hydrus-2D. The Feddes parameter *PO*, the value of pressure head, h_1, below which roots start to extract water from the soil, was set equal to -10 cm (0.98 kPa). *POpt*, the value of pressure head, h_2, below which roots extract water at the maximum possible rate, was set equal to -25 cm (-2.45 kPa). The value of the limiting pressure head, h_3, below which roots can no longer extract water at the maximum rate, *P2H*, was set equal to -8000 cm (-784.54 kPa) (when a potential transpiration rate equals to 0.5 cm day^{-1}). When a potential transpiration rate equals 0.1 cm day^{-1}, the value of pressure head, h_3, (*P2L*) was set equal to -12000 cm (-1176.80 kPa). The value of pressure head, h_4, below which root water uptake ceases, *P3*, was set equal to -24000 cm (-2353.60 kPa).

The value of h_3 is determined based on the following linear interpolation:

$$\begin{aligned} h_3 &= P2H + \frac{P2L - P2H}{0.5 - 0.1}\left(0.5 - T_p\right) && \text{for } 0.1 < T_p < 0.5 \\ h_3 &= P2L && \text{for } T_p \le 0.1 \\ h_3 &= P2H && \text{for } T_p \ge 0.5 \end{aligned} \tag{1.23}$$

The simulated water stress reduction function, *h,* was determined as follows:

$$\alpha(x,z)=\begin{cases}1 & (h \geq h_4 \; or \; h \leq h_1) \\ \dfrac{h_1-h}{h_1-h_2} & (h_2 < h < h_1) \\ 1 & (h_3 \leq h \leq h_2) \\ \dfrac{h-h_4}{h_3-h_4} & (h_4 < h < h_3)\end{cases} \tag{1.24}$$

The Vrugt model (Vrugt et al., 2001) was used to delineate the root distribution for corn under subsurface drip irrigation:

$$b(r,z)=\left[\left(1-\frac{z}{z_m}\right)\right]\left[1-\frac{r}{r_m}\right]e^{-\left[\left(\frac{p_z}{z_m}\right)|z^*-z|+\left(\frac{p_r}{r_m}\right)|r^*-r|\right]} \tag{1.25}$$

where

r_m = the maximum rooting length in the horizontal direction (L)

z_m = the maximum rooting depth in the direction respectively (L)

z^* and r^* = depth and lateral distance with maximum root density respectively (L)

p_z, and p_r = empirical parameters that can describe non-symmetrical root geometries.

The root distribution was normalized (≤ 1) and discretized into associated finite meshed nodes. In the absence of root measurements, the lateral root extent from the stalk was set equal to 0.20 m, and the maximum depth was set equal to 0.36 m (personal communication, Heiniger). The depth of maximum intensity was set equal to 0.20 m, and the width of maximum intensity was set equal to 0 m (centerline of corn plant). During the simulation period from 8 June to 22 July, a non-expanding and static root system was assumed. The normalized root distribution map is shown in figure 2.4.

Assessment Methods

Model simulations were carried out for a 45-day period from 8 June to 22 July, and predicted soil-water content values were output on an hourly time step. To check the performance of the Hydrus-2D model, comparison was made between simulated soil-water content and measured soil-water content at the 24 sensor locations. Due to the sensor malfunctioning as a result of intense electrical storms, bad data were removed from the dataset prior to model assessments. For each sensor, only available soil-water data from functioning sensors were used to assess the model performance.

Assessments were done over the 45-day period using midnight comparison. Agreement between measured and simulated soil-water content was assessed using the root mean squared error (*RMSE*), and the mean bias error (*ME*) (Deb et al., 2013) which are defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\theta_{sim} - \theta_{obs}\right)^2}{n}} \qquad (1.26)$$

$$ME = \frac{\sum_{i=1}^{n}\left(\theta_{sim} - \theta_{obs}\right)}{n} \qquad (1.27)$$

where

n = the total number of observed and simulated pairs

θ_{obs}= ith observation of soil-water content

θ_{sim}= ith simulated value for evaluated soil-water content

θ_{avg} = the mean of observed soil-water content.

The RMSE value indicates a magnitude of the mean difference between measured and simulated soil-water content. Positive values of ME indicate an over-prediction tendency, and negative values of ME reflect an under-prediction tendency.

Additionally, the accuracy of Hydrus-2D was evaluated using the coefficient of determination (r^2) from a simple linear regression of $\theta_{sim}$and θ_{obs}. The coefficient of determination (r^2) ranges from 0 to 1 with higher values meaning less error variance. Typically, values greater than 0.5 mean the simulation model is acceptable (Moriasi et al., 2007). The slope (b) and the intercept (a) of the regression were used to evaluate over-prediction and under-prediction of the simulated values. For good agreement of comparison, the intercept (a) should be close to zero, and the slope (b) should be close to 1.

Results and Discussion

There was generally good correspondence between measured and simulated soil-water content during the simulation period. The Hydrus-2D model's average mass balance error [%] was below 1% and 0.4% in SDI zone 1 and zone 2 respectively. The mass balance error represents the sum of absolute change in water storage (balancing of inflows and outflows). A mass balance error below 1% is acceptable, reflecting adequate discretization (PC-progress discussion forum, Simunek).

Statistics of ME, RMSE and r^2 of Modeled and Measured Soil-Water Content

Statistics of ME and RMSE of simulated and measured soil-water content for both SDI zones and replications are presented in figures 2.10-2.11. Comparisons between simulated soil-water content and measured soil-water data from 8 June (159) to 22 July (203) are shown in figures 2.12-2.17. The ME values ranged from -0.08 to 0.057 $m^3\,m^{-3}$ 0.30 m from the dripline at both depths. At the locations closest to the dripline (0.15 m), the ME values ranged from -0.02 to 0.013 $m^3\,m^{-3}$, and from -0.056 to 0.012 $m^3\,m^{-3}$ at the locations farthest from the dripline (0.50 m). The RMSE values 0.30 m from the dripline at both depths were the most extreme. The RMSE values 0.15 and 0.50 m from the dripline at both depths varied from 0.012 to 0.058 $m^3\,m^{-3}$. Other studies (Skaggs et al., 2004; and Buffon et al., 2012) showed a similar magnitude of RMSE (0.02-0.05). Skaggs et al. (2004) and Buffon et al. (2012) compared Hydrus-2D soil-water content to field measured data during a period without precipitation. Even though precipitation occurred during the study period, which made simulated scenarios more complex than their simulated scenarios, RMSE values were similar. Low values of ME and RMSE between modeled and measured soil-water content in both SDI zones suggest that Hydrus-2D can be used with confidence to model soil-water dynamics from subsurface drip irrigation.

The values of the coefficient of determination (r^2), and corresponding slope and intercept values of simple linear regression models for specific locations are shown in figures 2.13, 2.15, and 2.17. As seen in figure 2.13 for the location at a 0.15-m depth 0.15 m from the dripline, the coefficient of determination (r^2) is 0.68 with slope of 1.07 (~1). The intercept was not significantly different from 0 (Pr>0.3035) that in conjunction with slope indicates a good model fit. Similar conclusions can be drawn from figures 2.15 and 2.17. Overall, the observed level of accuracy for the model predictions indicates that Hydrus-2D is a suitable tool for investigating the design and management of SDI systems in the Coastal Plain of North Carolina.

Spatial Prediction of Soil-Water Content

Dissatisfactory predictions of soil-water content 0.30 m from the dripline at both depths led to the conclusion that Hydrus-2D was particularly unable to simulate the soil-water content within the root zone. Discrepancies at the root zone could be mainly attributed to the lack of directly measured data on root distribution and the water stress reduction function. Soil-water content was under-predicted in the root zone. This was more likely due to the actual rooting depth of maximum intensity being shallower than the modeled rooting depth, and the maximum actual depth not extending to a maximum modeled depth of 0.36 m, thus leading to less plant extraction in reality. Experimentally characterizing the corn's root zone would have helped enhance the correspondence between modeled and measured soil-water content at the area of root zone.

Furthermore, the deviations could also be attributed to the Feddes' reduction parameters not being reflective of the corn in North Carolina. These reduction parameters were selected from the existing database and do not take differences among corn varieties into account. There is some uncertainty on the estimates of the Feddes' uptake parameters, leading to greater plant extraction. For instance, the value of the pressure head, h_4, below which root water uptake ceases was set equal to -2353.60 kPa. Plant available water commonly ranges from field capacity to wilting point. The values of the pressure head, h_4, used allowed root water extraction when the soil-water pressure head fell below -1500 kPa (wilting point).

The simulated soil-water content matched the corresponding measured data reasonably well at the locations closest to and farthest from the dripline. It was anticipated that high soil-water gradients would lead to some temporal and spatial discrepancies of the model. However, as shown in figures 2.12, 2.14, and 2.16, large discrepancies did not occur, and temporal variations of the modeled soil-water content were reasonably consistent with those of the measured soil-water content at both distances from the dripline, suggesting that Hydrus-2D can predict spatial and temporal variations of soil-water content despite the high magnitude of soil-water gradients due to irrigation or precipitation.

Locations closest to the dripline yielded closer correspondence between simulated and measured soil-water content than the locations farthest from the dripline. For instance, comparison of soil-water content 0.15 m from the dripline had RMSE values between 0.012 and 0.033 $m^3\,m^{-3}$. For comparison of soil-water content 0.50 m from the dripline, RMSE values varied between 0.018 and 0.058 $m^3\,m^{-3}$. Deviations of soil-water content 0.50 m from the dripline could be attributed to irrigation water not extending to 0.50 m from the dripline in the model due to a high clay fraction (low hydraulic conductivity).

It is also important to note ME values at 0.15-m depth were positive and at 0.30-m depth negative indicating the model over-predicted the soil-water content at 0.15-m depth and under-predicted at 0.30-m depth. Overestimation of the soil-water content at 0.15-m depth may be attributed to greater infiltration of rainwater and lower soil evaporation in the model than in reality. A depth of 0.15 m would be more strongly influenced by infiltration of rainwater in the model, and soil evaporation provided to Hydrus-2D may have been under-estimated, thus leading to a greater simulated soil-water content than the reality.

Underestimation of the soil-water content at a depth of 0.30 m may be attributed to the modeled rooting depth being deeper than the actual rooting depth, thus leading to plant extraction in the model being more pronounced from the relatively deep modeled root zone than in reality. Other physical phenomenon such as the existence of preferential flow that is not considered in Hydrus-2D would also explain that the modeled soil-water content at a depth of 0.30 m was under-predicted.

Conclusions and Recommendations

SDI is one of the most efficient irrigation methods in helping conserve scarce water resources. An investigation on soil-water distribution from SDI systems is very crucial in predicting the success of SDI design. Numerical modeling is a fast and inexpensive approach to investigating soil-water distribution from SDI. In this study, Hydrus-2D simulations were carried out to investigate soil-water distribution from SDI, North Carolina. Soil-water content values obtained with Hydrus-2D were compared to measured data to check the performance of Hydrus-2D in order for its subsequent use in evaluating SDI designs and management practices.

In spite of some deviations, comparison between simulated and measured soil-water content values showed a good match. Values of ME and RMSE ranged from -0.056 to 0.013 $m^3\ m^{-3}$, and from 0.012 to 0.058 $m^3\ m^{-3}$ respectively exclusive of the locations 0.30 m from the dripline at both depths. Based on the calculated ME of the simulations, the model slightly under-predicted soil-water content, indicating modeled water extraction was greater than in reality. Acknowledging the intricacy of the simulated scenarios and the assumed homogenous and isotropic soil properties in the model, a long simulation period (45 days) with successive irrigation events and rainfall, and the lack of the measured root distribution, the Hydrus-2D model performed reasonably well in predicting soil-water distribution from subsurface drip irrigation and therefore can be reliably used as a cost-efficient tool to design and manage SDI systems.

Critical factors that made the modeled soil-water content deviate from the field observations were found to be root parameters (both root distribution and extent, and the water stress reduction function), and soil hydraulic properties. The findings of this study clearly demonstrated that root distribution and the root reduction function need to be accurately represented, and more accurate measurements of root zone density would substantially improve the performance of the model. The accuracy of the simulations also depends on the quality of soil hydraulic parameter estimates. Accurate saturated hydraulic conductivity and saturated and residual soil-water content are necessary for good predictions. Thereby, the study herein serves the basis for future focus of soil hydraulic parameters and especially root distribution parameters.

Hydrus-2D calibration studies should be conducted with better estimates of critical factors obtained through experimental measurement. Furthermore, while root water distribution can be experimentally determined, the water stress reduction function parameters are very difficult to obtain experimentally. Thus, it is suggested that a model calibration be performed on the water stress reduction parameters, especially to fine-tune the pressure head h_3 and h_4, which are indicators of dry stress.

Although this study concluded that the model is able to simulate soil-water content, irrespective of irrigation scheduling (sensor controlled or fixed daily irrigation treatment), comparison between modeled and observed soil-water content should be further studied under different irrigation frequencies, especially between pulsed and continuous irrigation scenarios. Because pulsed and continuous irrigation may have an impact on leaching and may be varyingly used in soils with different textures by growers, a future complementary study on calibrating Hydrus-2D under different irrigation frequency may be helpful.

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TABLES AND FIGURES

Table 2.1. Observed initial soil volumetric water content at sensor locations.

Zone & Replication	Sensor location	Soil-water content ($m^3\ m^{-3}$)
Zone 1 Replication 1	0.15 m d 0.15 m dl	0.186
	0.15 m d 0.30 m dl	0.18
	0.15 m d 0.51 m dl	0.174
	0.30 m d 0.15 m dl	0.239
	0.30 m d 0.30 m dl	0.172
	0.30 m d 0.51 m dl	0.249
Zone 1 Replication 2	0.15 m d 0.15 m dl	0.167
	0.15 m d 0.30 m dl	0.165
	0.15 m d 0.51 m dl	0.177
	0.30 m d 0.15 m dl	0.246
	0.30 m d 0.30 m dl	0.268
	0.30 m d 0.51 m dl	0.29
Zone 2 Replication 1	0.15 m d 0.15 m dl	0.144
	0.15 m d 0.30 m dl	0.203
	0.15 m d 0.51 m dl	0.191
	0.30 m d 0.15 m dl	0.219
	0.30 m d 0.30 m dl	0.251
	0.30 m d 0.51 m dl	0.264
Zone 2 Replication 2	0.15 m d 0.15 m dl	0.239
	0.15 m d 0.30 m dl	0.194
	0.15 m d 0.51 m dl	0.206
	0.30 m d 0.15 m dl	0.269
	0.30 m d 0.30 m dl	0.244
	0.30 m d 0.51 m dl	0.281

Table 2.2. Soil particle distribution, USDA classification, saturated hydraulic conductivity, and soil-water content at five levels of pressure from soil cores obtained near sensor locations of the field.

Depth	Sand	Silt	Clay	USDA	Ksat	Bulk density	Soil-water content (g/g)				
m	%	%	%	Class.	cm h^{-1}	g cm^{-3}	0.1bar	0.33bar	1.0bar	5.0bar	15bar
0.15	46	30.6	23.4	Loam	2.45	1.51	0.262	0.183	0.151	0.099	0.084
0.15	42.5	23.9	33.6	Clay loam	4.46	4.46	0.298	0.222	0.171	0.123	0.108
0.15	46.5	35	18.5	Loam	0.79	1.54	0.312	0.214	0.162	0.094	0.077
0.3	45	34.6	20.5	Loam	0.39	1.55	0.290	0.210	0.166	0.103	0.086
0.3	45.6	36.4	18	Loam	1.35	1.52	0.272	0.195	0.145	0.085	0.068
0.3	41.7	28.4	29.9	Clay loam	10.72	1.55	0.325	0.260	0.191	0.131	0.115

Note: The soil cores were extracted from three locations at 0.15- and 0.30-m depths totaling 6 samples.

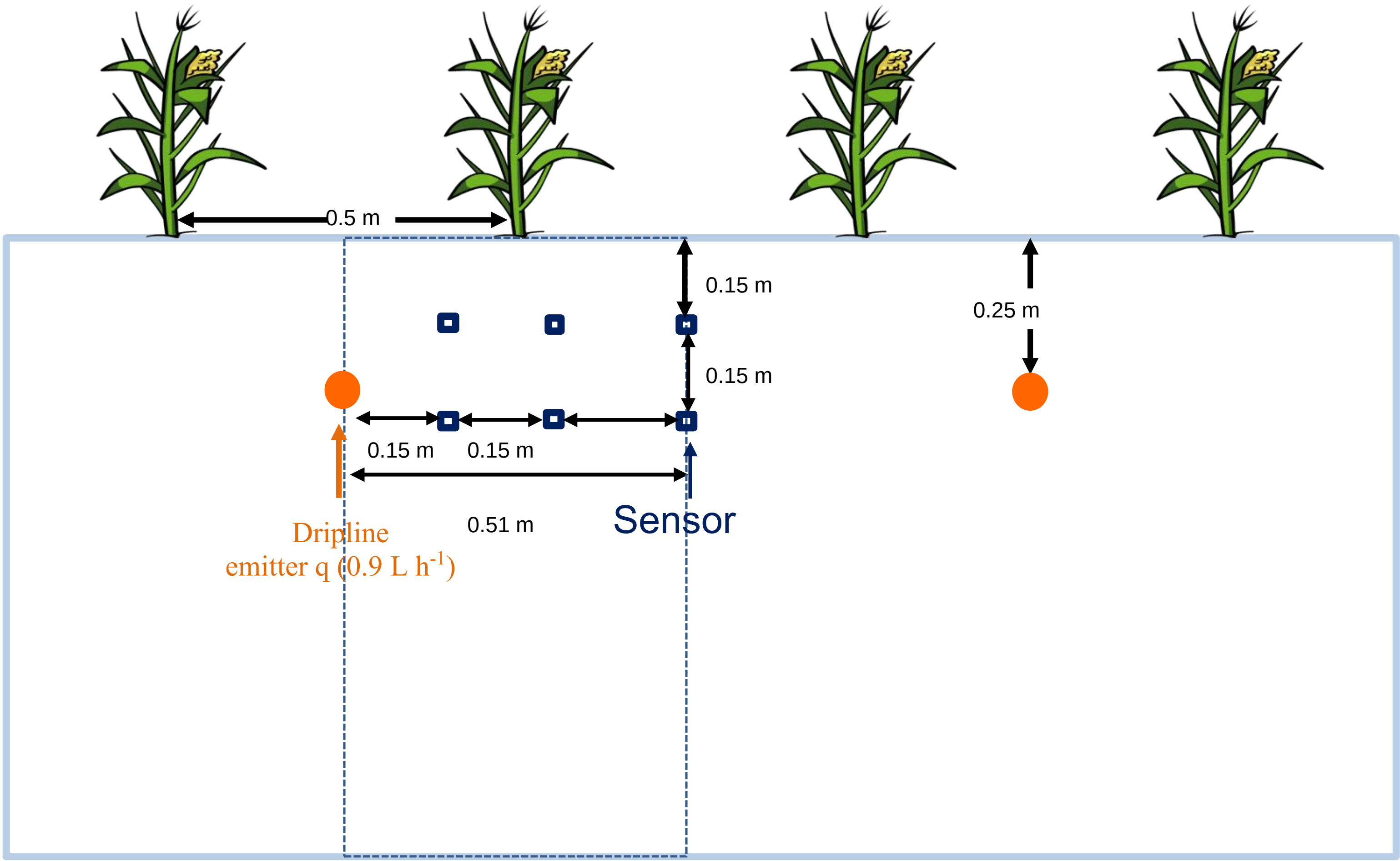


Figure 2.1. Locations of the soil-water sensors in the soil profile (cross-section view) used to measure soil-water content. Figure not to scale.

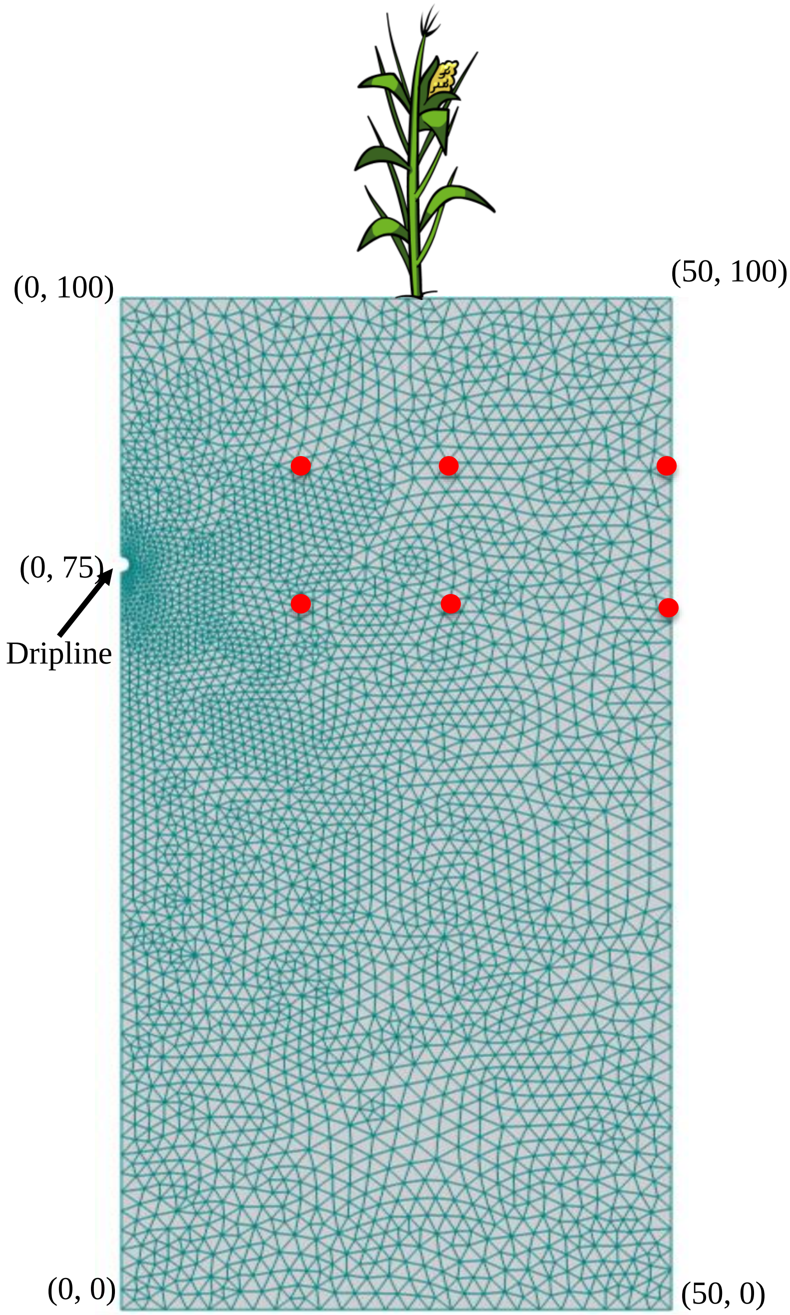


Figure 2.2. Domain geometry and generated unstructured finite element mesh for Hydrus-2D simulations. Coordinates in cm.

Note: The domain was discretized into 6114 triangular finite elements (3150 nodes). Red dots represent observation nodes in the Hydrus-2D model that coincided with the locations of the soil-water sensors. Figure not to scale.

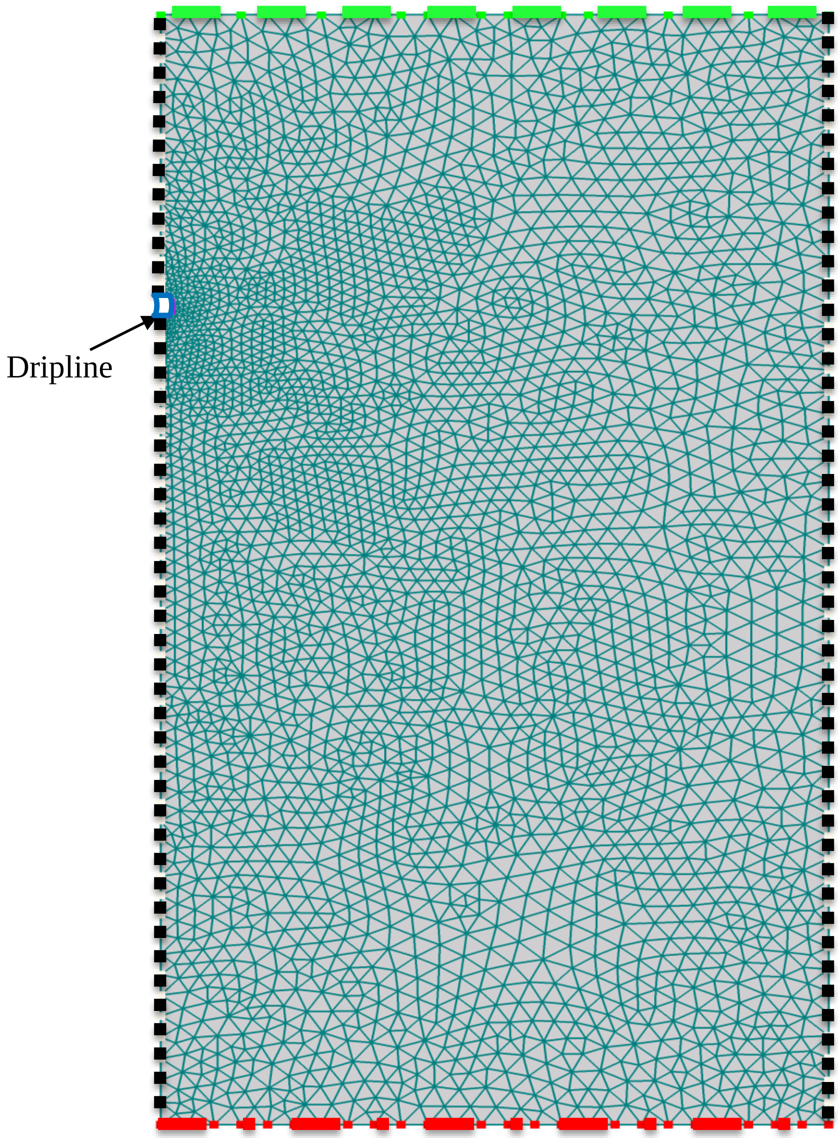


Figure 2.3. Boundaries used for Hydrus-2D simulations.

Note: Blue line around a half-circle emitter represents variable flux boundary (i.e. irrigation). Green dashes represent atmospheric boundary (i.e. precipitation, soil evaporation, crop transpiration). Black dots represent no flux boundary. Red dash dots represent bottom boundary (i.e. free drainage). Figure not scale.

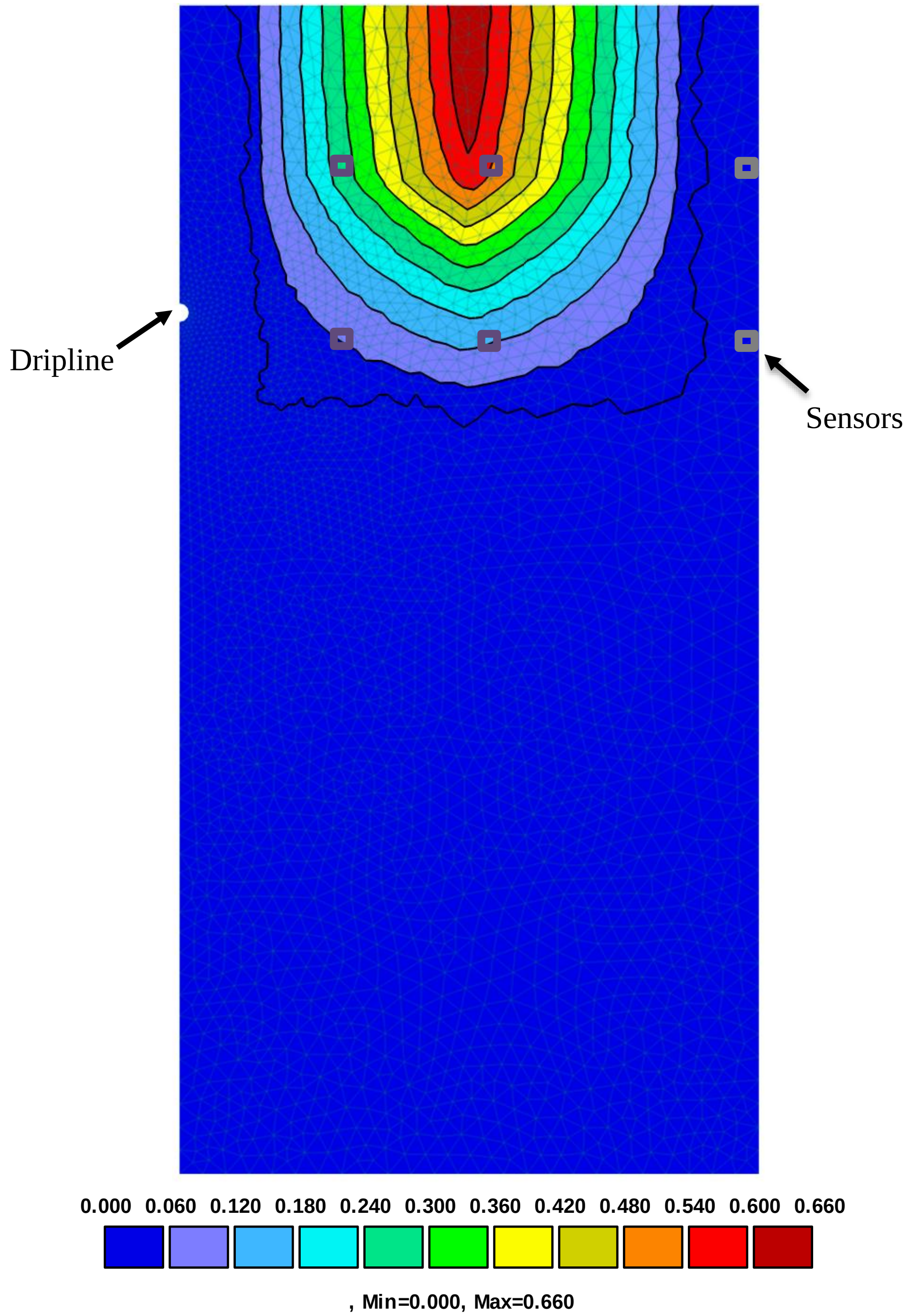


Figure 2.4. Normalized root distribution used for Hydrus-2D.

Note: The root distribution was normalized from 1 to 0 (from maximum root presence to no root presence). The lateral root extent from the stalk was 0.20 m, and the maximum depth was 0.36 m. The depth of maximum intensity was 0.20 m. Figure not to scale.

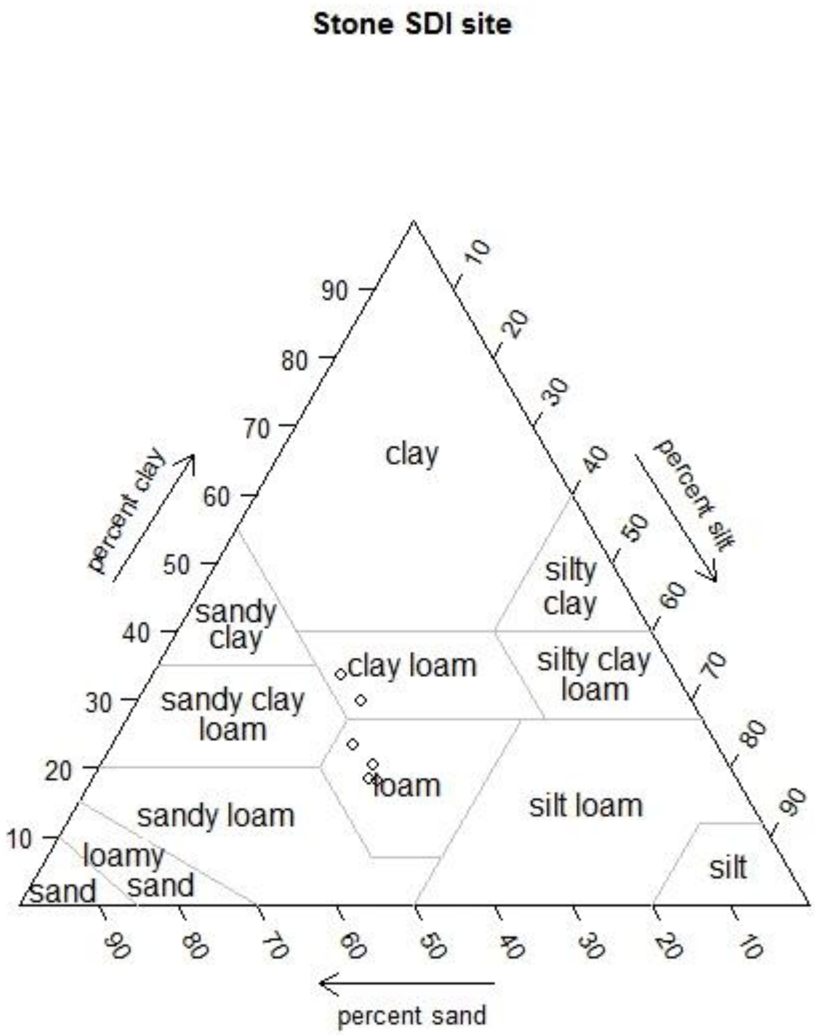


Figure 2.5. USDA triangle soil texture for Trebloc loam soil at study location.

Note: The small six circles represent the soil classification of six samples. Soil texture was determined from core samples taken at 0.15- and 0.30-m depths from three locations in the field.

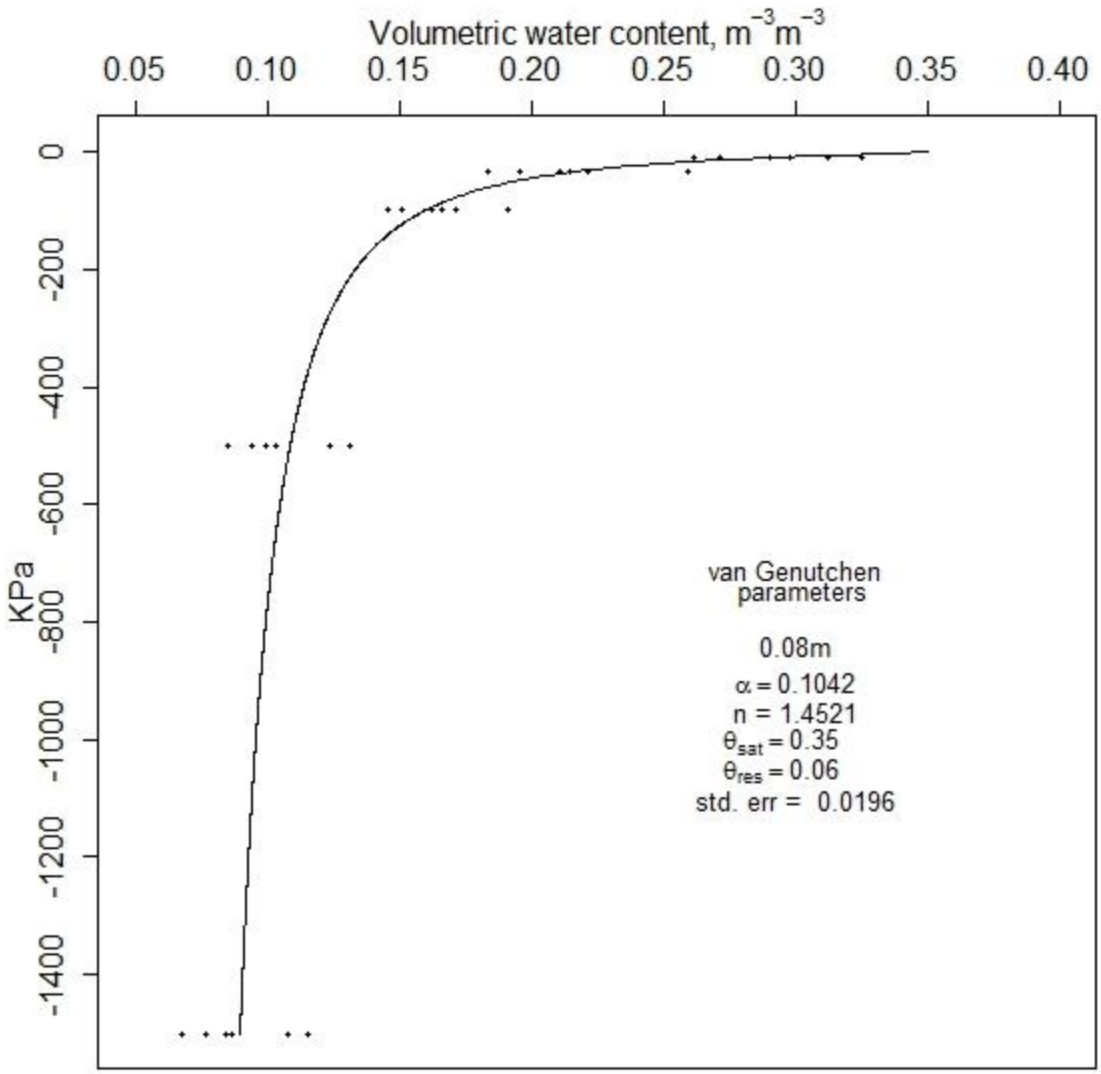


Figure 2.6. Soil-water release curve for Trebloc loam soil at study location.

Note: Curve was derived from soil core samples taken at 0.15- and 0.30-m depths each at three random locations. Small dots represent laboratory data. van Genuchten model used to fit data.

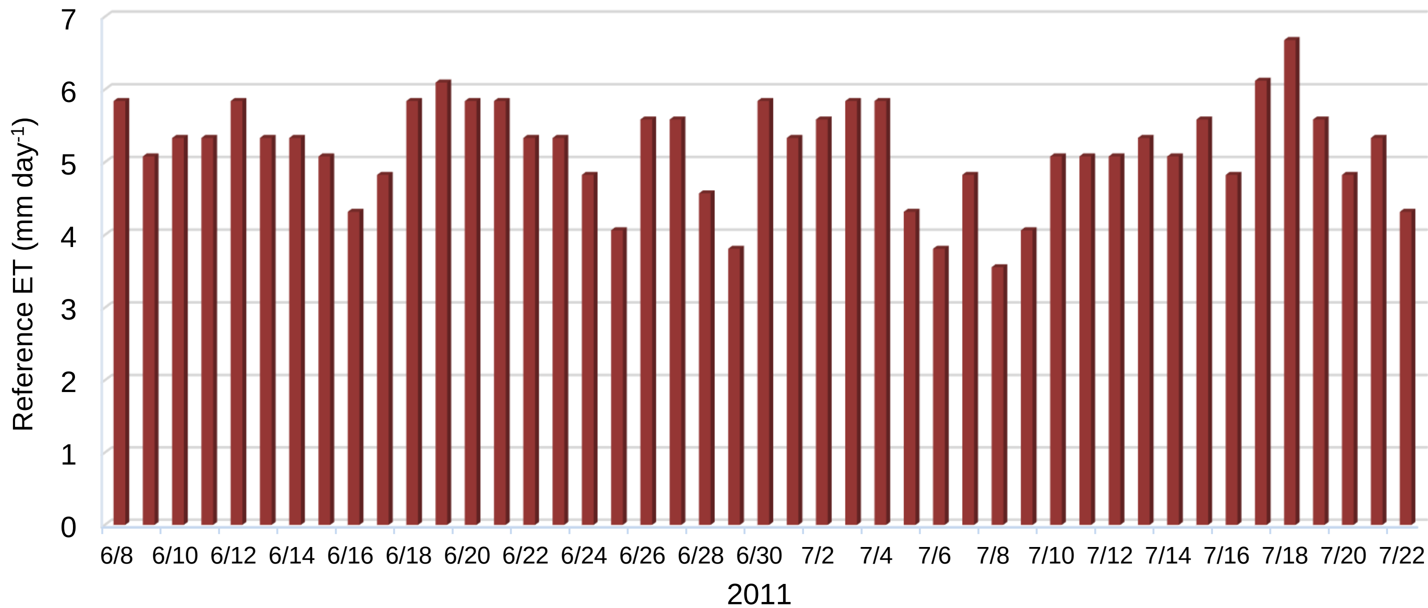


Figure 2.7. Daily reference evapotranspiration (mm day^{-1}) for the simulation period from 8 June to 22 July 2011.

Note: Daily weather data were collected by a Model 700 Watchdog Weather Station (Spectrum Technologies, Inc., Plainfield, Illinois).

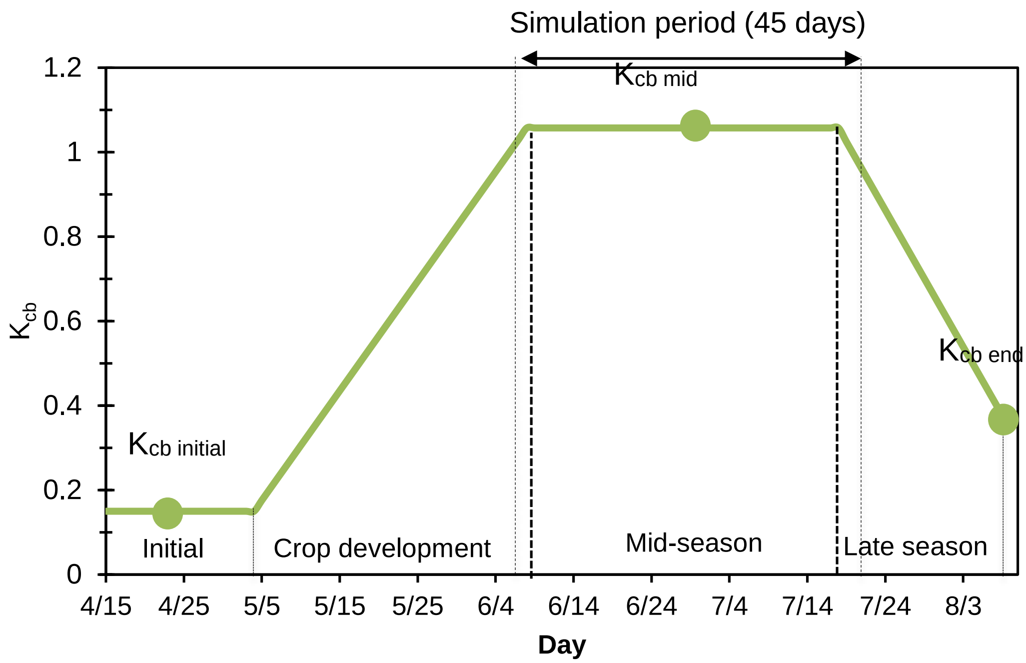


Figure 2.8. Basal crop coefficient (K_{cb}) for field corn using growth stage durations of 20, 35, 40 and 20 days for initial, crop development, midseason, and late season respectively using the daily dual crop coefficient procedure from Allen (1998).

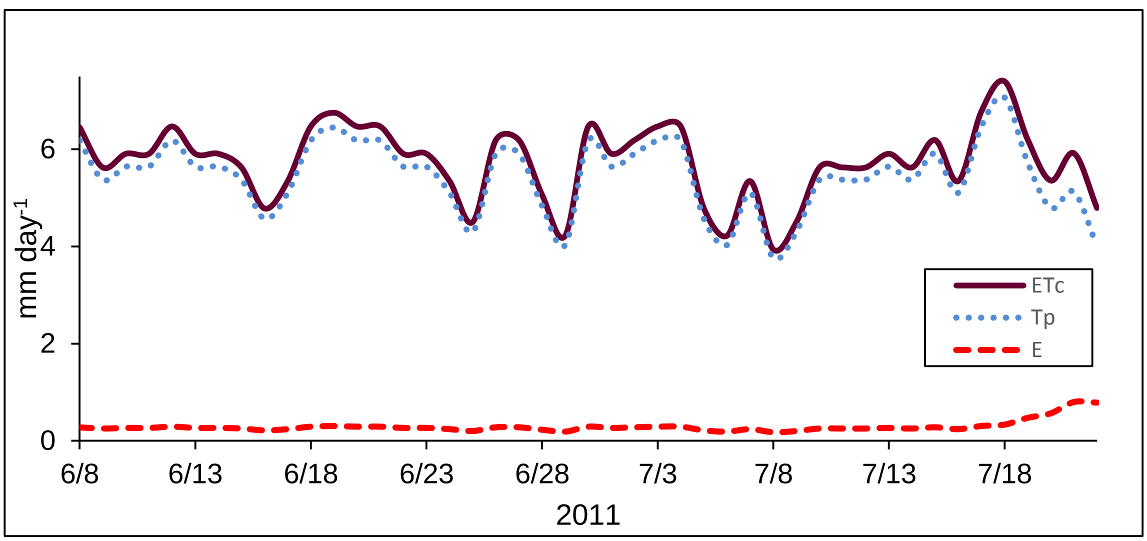


Figure 2.9. Crop evapotranspiration (ET_c), transpiration (T_p) and soil evaporation (E) from 8 June to 22 July 2011. Crop evapotranspiration was calculated using the dual crop coefficient method.

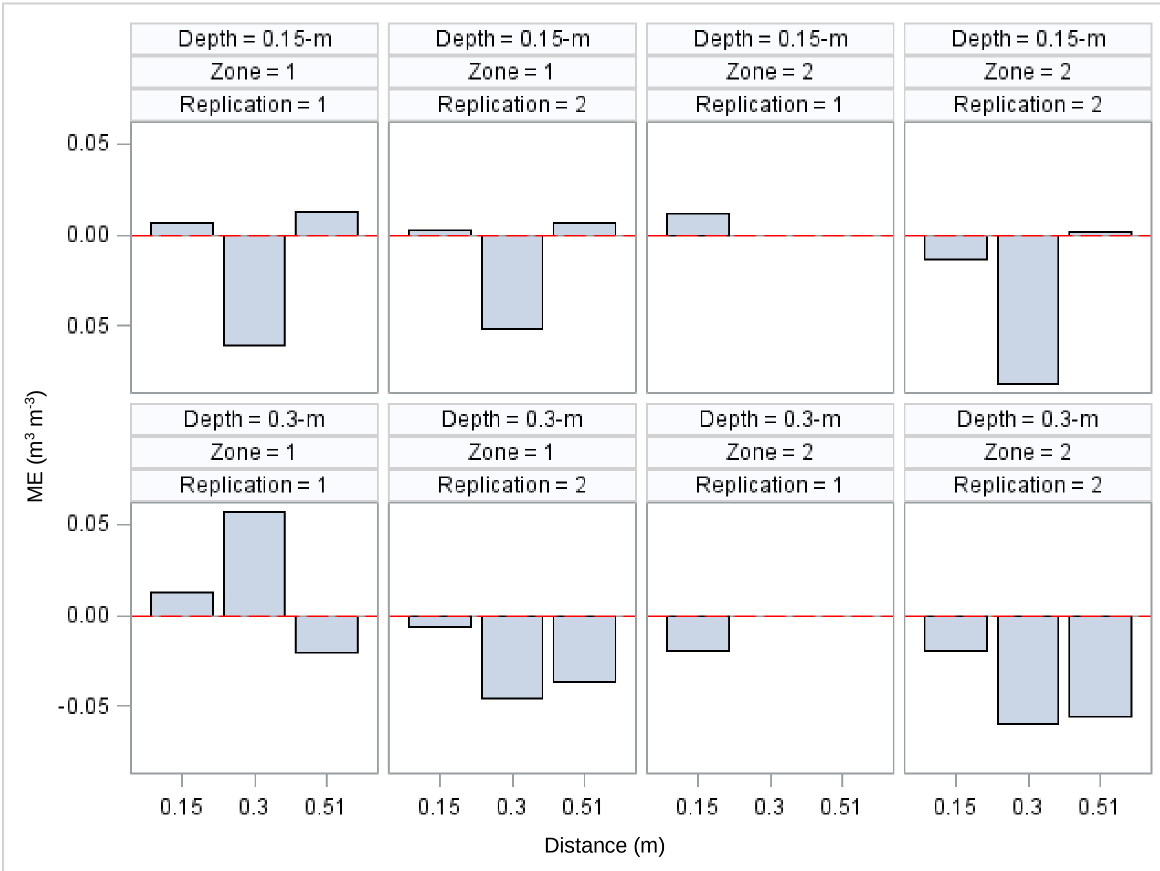


Figure 2.10. Mean bias Error (ME) for measured and modeled soil-water data by depth and distance from the dripline for both SDI zones and replications.

Note: Red dashes indicate a critical value at which no bias displays.

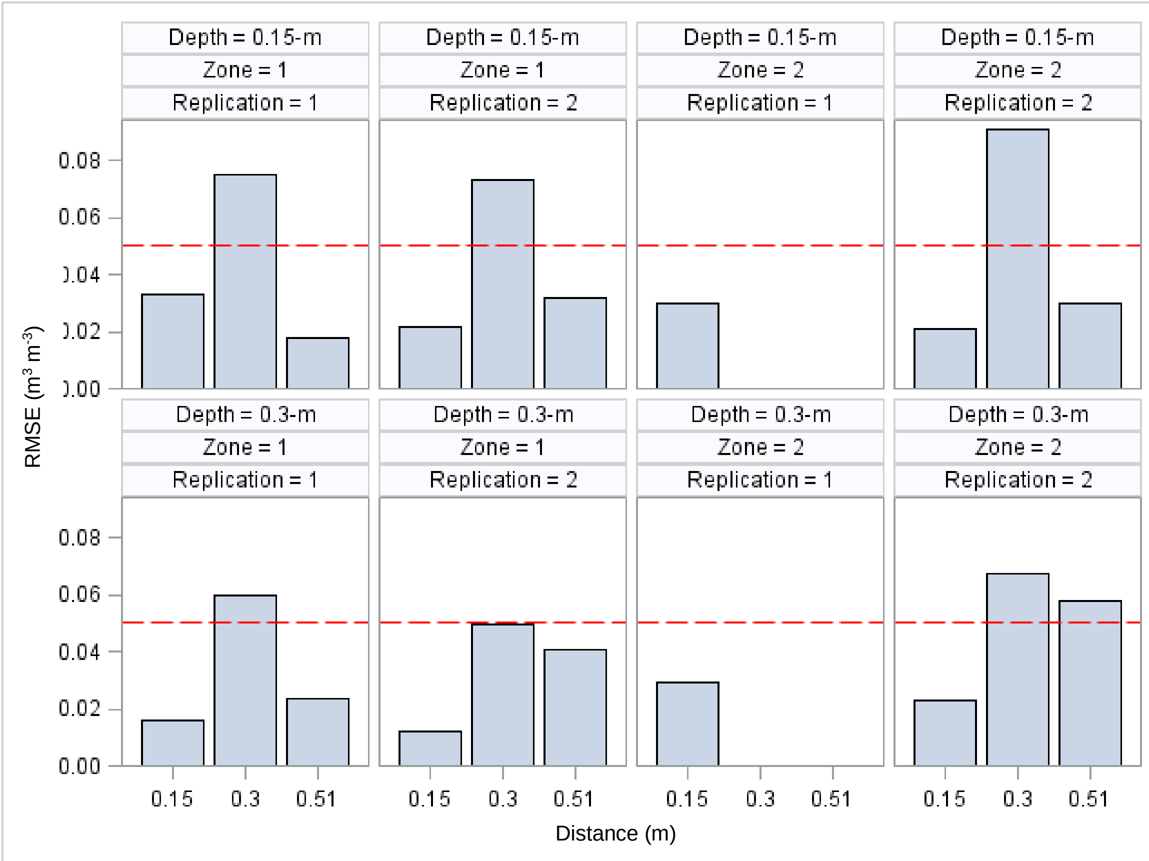


Figure 2.11. Root Mean Square Error (RMSE) for measured and modeled soil-water data by depth and distance from the dripline for both SDI zones and replications.

Note: Red dashes represent a RMSE value below which comparisons between measured and modeled soil-water content are acceptable.

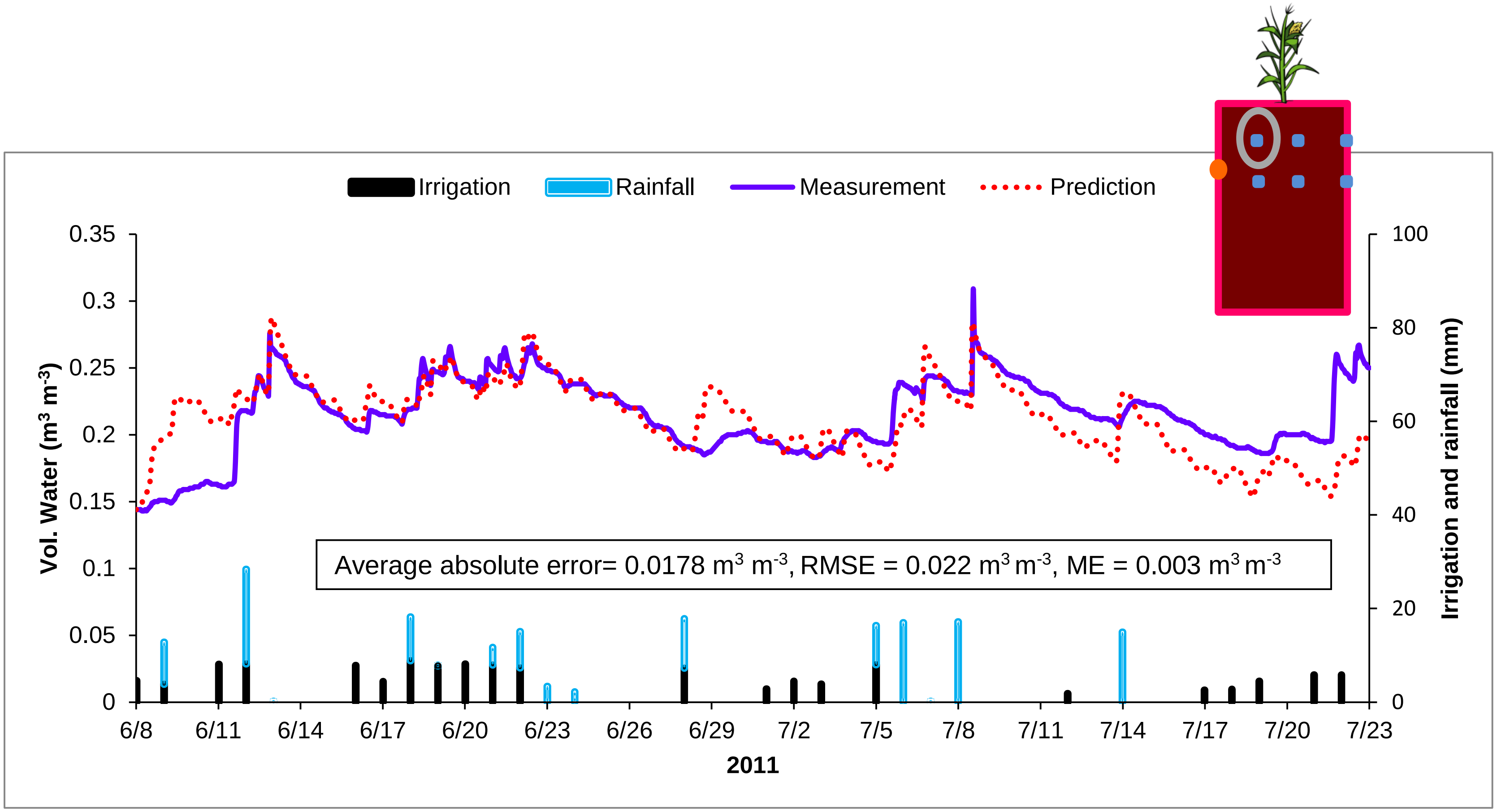
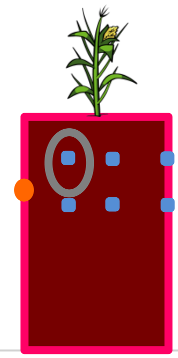


Figure 2.12. Time series of simulated and measured soil-water data at 0.15-m depth 0.15 m from the dripline during the simulation period from day of the year (DOY) 159 to DOY 203 (8 June to 22 July 2011).



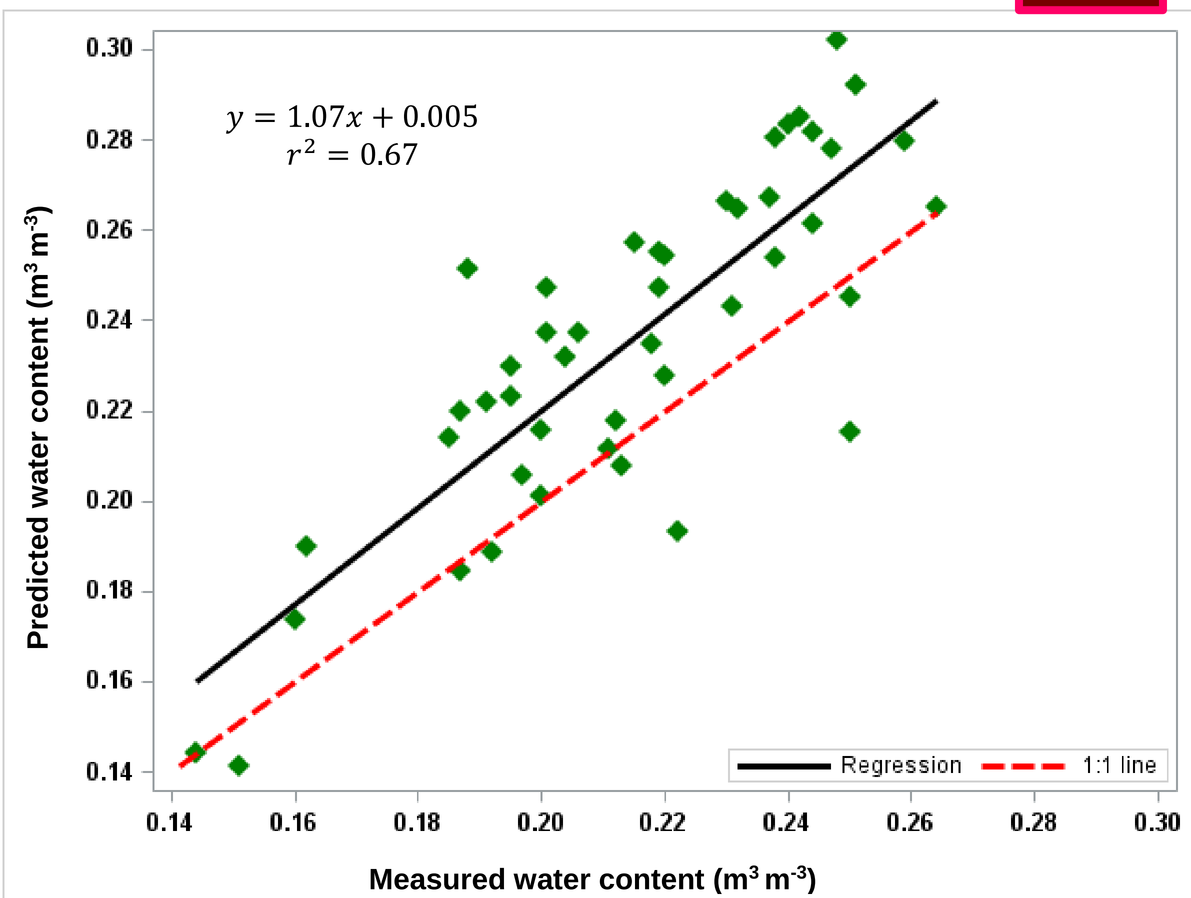


Figure 2.13. Measured soil-water data vs. simulated soil-water content at 0.15-m depth 0.15 m from the dripline.

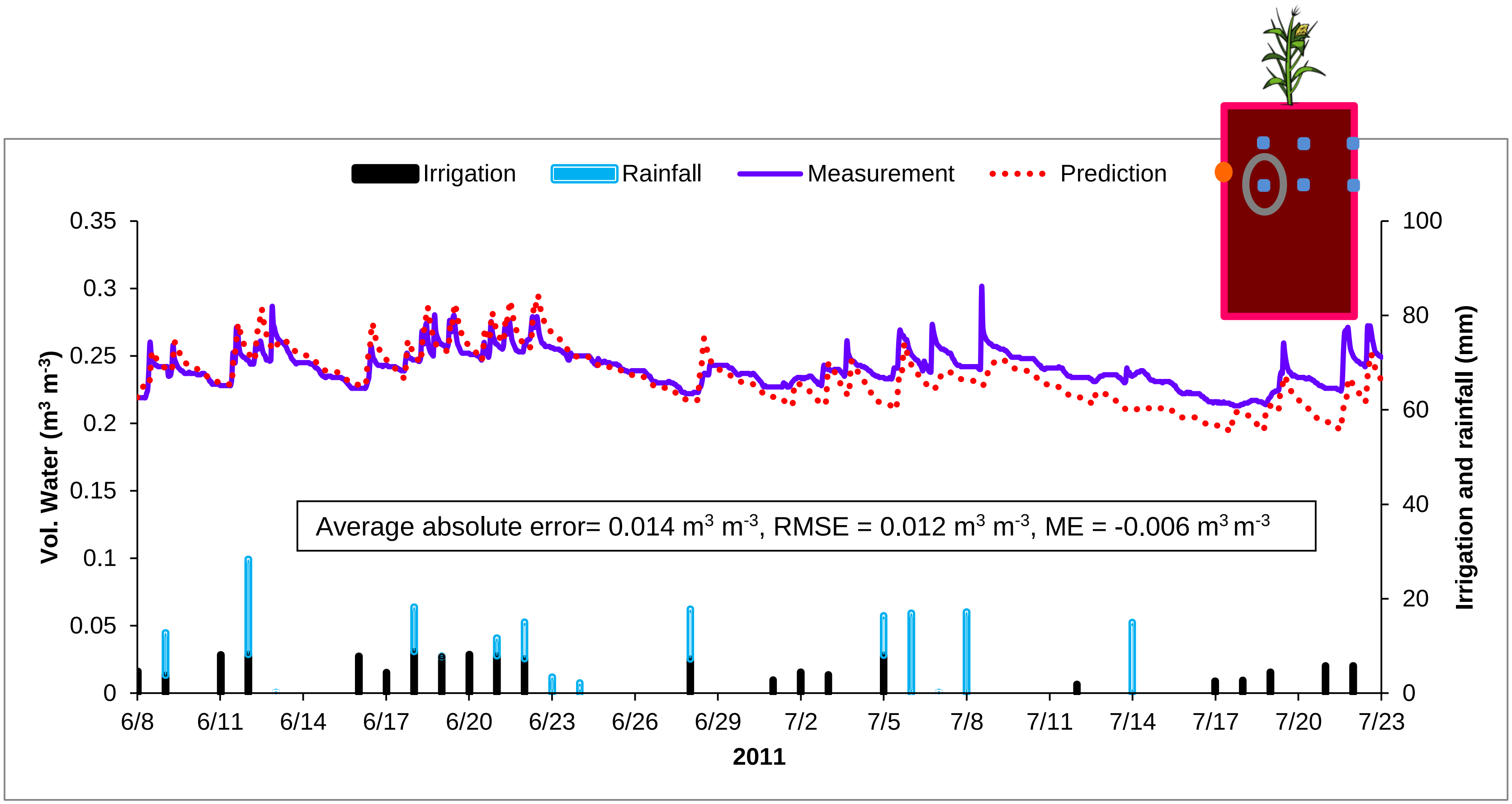
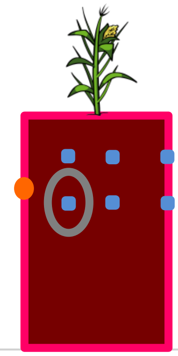


Figure 2.14. Time series of simulated and measured soil-water data at 0.30-m depth 0.15 m from the dripline during the simulation period from day of the year (DOY) 159 to DOY 203 (8 June to 22 July 2011).



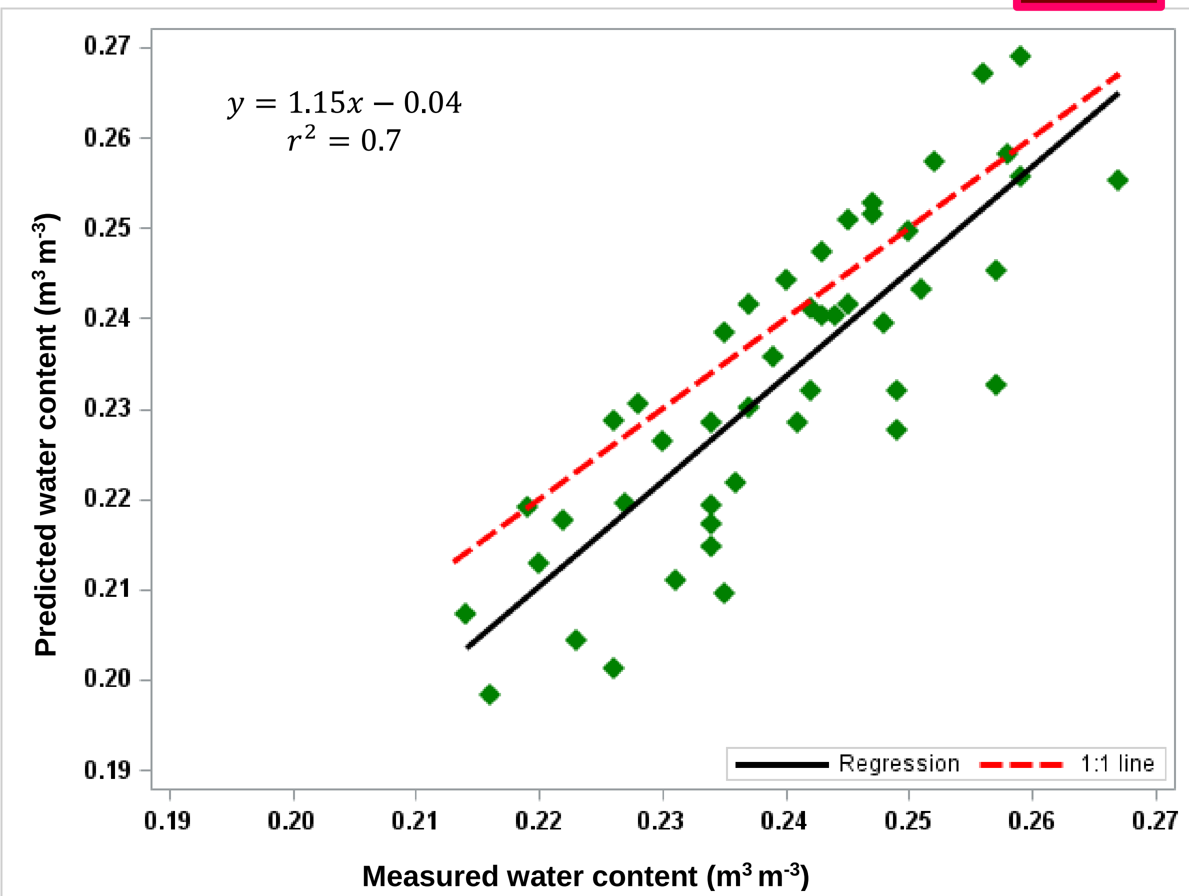


Figure 2.15. Measured soil-water data vs. simulated soil-water content at 0.30-m depth 0.15 m from the dripline.

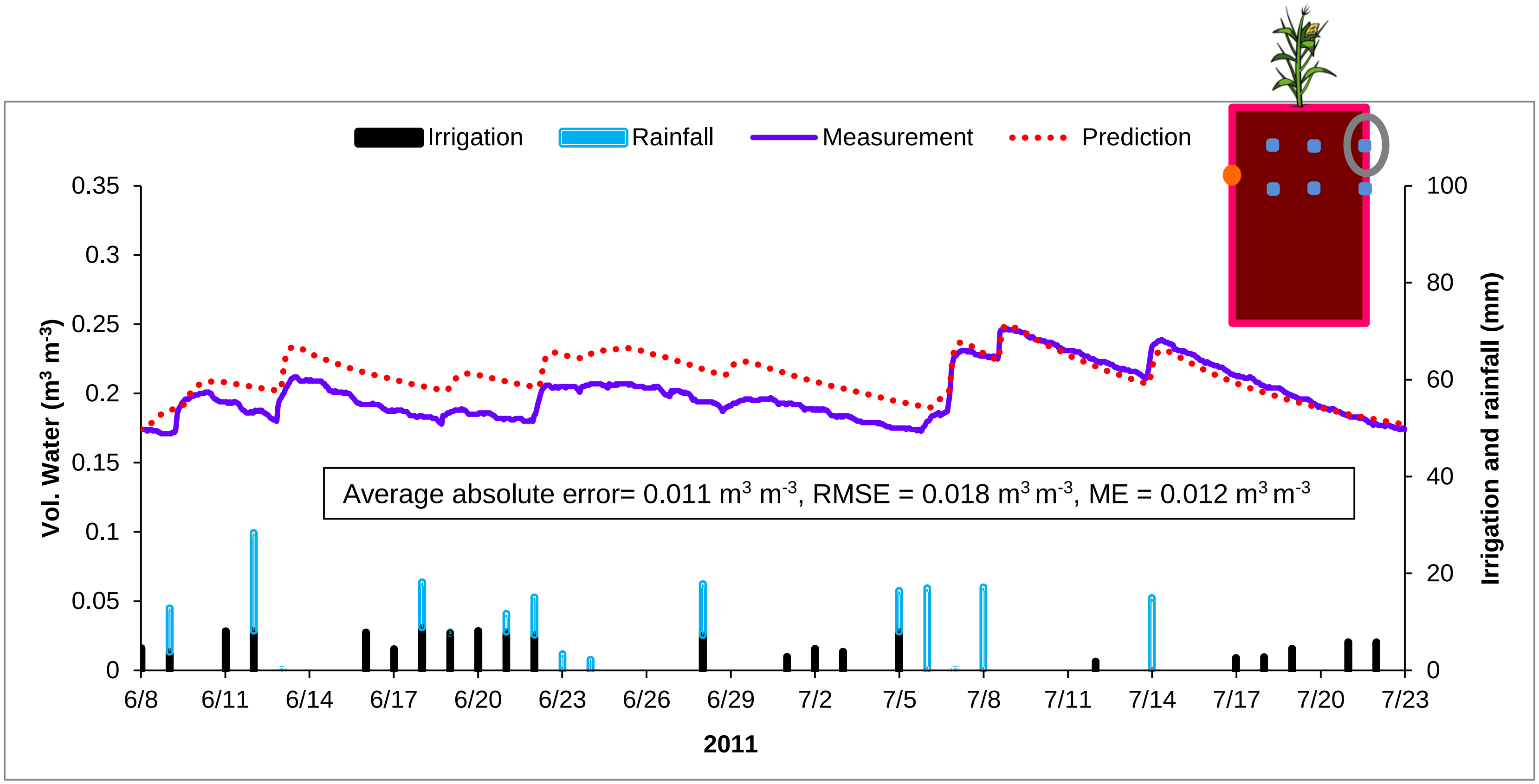


Figure 2.16. Time series of simulated and measured soil-water data at 0.15-m depth 0.50 m from the dripline during the simulation period from day of the year (DOY) 159 to DOY 203 (8 June to 22 July 2011).

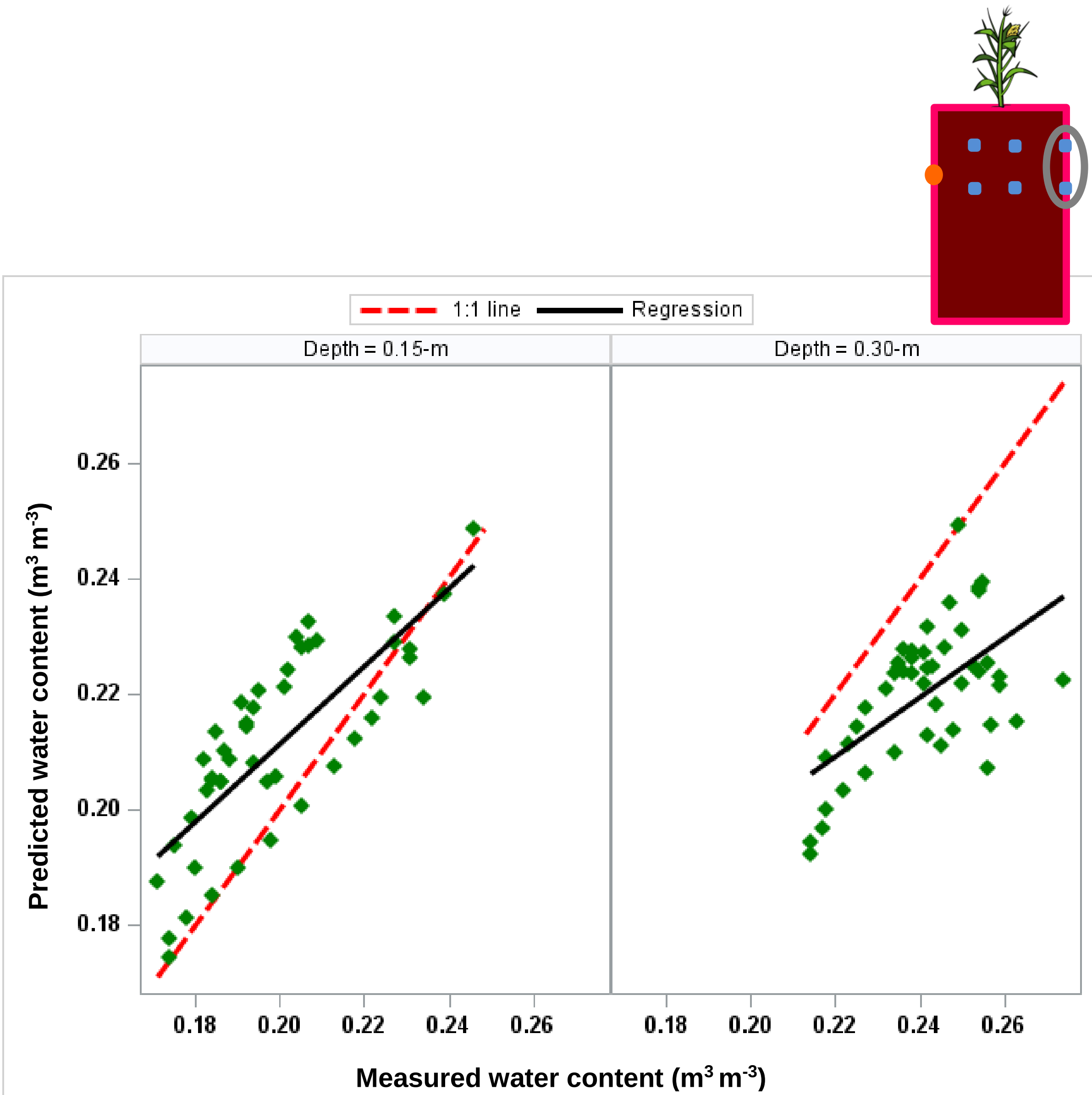


Figure 2.17. Measured soil-water data vs. simulated soil-water content at 0.15- and 0.30-m depth 0.51 m from the dripline during the simulation period from day of the year (DOY) 159 to DOY 203 (8 June to 22 July 2011).

CHAPTER 3. IMPACT OF SUBSURFACE DRIP IRRIGATION DESIGN AND MANAGEMENT FACTORS ON RELATIVE TRANSPIRATION IN CORN

Introduction

As the world's population increases, competition for the world's water resources is simultaneously surging. The allotment of water between environmental, urban, and agricultural water use is becoming a pressing issue. Critical efforts are being made to use water in a sustainable manner in each of these sectors. In the area of agriculture, care must be directed to producing optimum yield using less water to help conserve water resources.

Irrigation water withdrawals for agricultural use in the United States totaled approximately 128,000 million gallons per day in 2005 with the state of North Carolina contributing to the national withdrawals up to 5,000 million gallons per day (USGS, 2005). In some regions in the United States, water allocation for irrigation is restricted by hydrogeological or institutional constraints (Lamm et al., 2012). Drip irrigation is an example of an efficient micro-irrigation technology that helps address these constraints and its use has been growing in the United States. Sub-surface drip irrigation (SDI) presents even further opportunities for water efficiency by reducing losses to evaporation and eliminating irrigation runoff and deep percolation while improving crop yields (Camp, 1998; Lamm, 2012). The latest USDA Farm and Ranch Irrigation Survey (USDA-NASS, 2009) reported that the area covered by SDI in the U.S. has jumped from 163,000 to 260,000 ha in the five-year period 2003 to 2008, an increase of 59%.

SDI applies water below the soil surface through emitters. The potential advantages of SDI systems depend to a considerable extent on how properly systems are configured and managed with regard to site conditions and cropping systems. However, the success of an

SDI system from one field site to another is not entirely predictable since SDI objectives can be very site specific (Lamm, 2002). Therefore, modeling of different SDI configurations or designs has the potential to offer broad installation and management guidelines. While the design of a system seeks to maintain high yields and water use efficiency by applying water directly to the crop root zone, another goal is to keep the operation and installation cost as low as possible. Design variables commonly incorporate dripline spacing, dripline depth, and emitter spacing vis-a-vis cropping rotation and soil texture while SDI management is focused mainly on irrigation strategies in addition to maintenance.

Dripline spacing is determined by soil characteristics and the cropping system (Grabow et al., 2008). Generally, dripline spacing is set one dripline per row or one dripline per alternate row middle. Camp et al. (1998) reported dripline spacing from 0.25 to 5.0 m with narrow spacing mainly for turfgrass and wide spacing normally for vegetable, tree or vine crops. For field corn, dripline spacing is generally one dripline for every two corn rows (Lamm, 2002). There have been many studies conducted to investigate the effect of dripline spacing on yields. For instance, in a study by Grabow et al. (2011), no difference in corn grain yield was found between dripline spacing of 1.52 (alternate row middles) or 2.28 m (under every third row). In a study done in Virginia on a loamy sand soil using SDI spacings of 0.91 (under every row), 1.83 (alternate row middles) and 2.74 m (under every third row), Powell and Wright (1993) found that average corn yields were 100%, 93%, and 94% of maximum, respectively.

Another key design variable is dripline installation depth. Dripline depth should be shallow enough to provide adequate water for the root zone, but deep enough that cultural practices and traffic can be accommodated without damaging the SDI system. Commonly, driplines should be installed at a deeper depth in finer textured soils and at a shallower depth in coarser textured soil (Lamm and Camp, 2007; Grabow et al., 2008). Deeper dripline depth will reduce soil evaporation and surfacing. Shallower dripline depth will likely promote weed germination and soil surface wetting and evaporation but reduce deep percolation. Dripline installation depth for SDI systems generally ranges from 0.02 to 0.70 m (Camp, 1998). Dripline depth should be placed relative to the root zone extent. For corn, driplines are installed in the 0.30- to 0.50-m depth range since these crops have extensive root systems that function properly at greater depths (Lamm and Camp, 2007). However, soils in North Carolina may not be suitable for driplines to be placed at the deeper end of the depth range due to their restrictive layers that inhibit root zone extent, but driplines should be placed deep enough to avoid damage from tillage equipment (Grabow et al., 2008). According to a study on the effect of flooding duration on maize roots, maize roots could extend to 0.85 m (Victor, 1994). In a four-year study to examine the effects of dripline depth on yields, Lamm and Trooien (2005) reported that corn yield was unaffected with driplines installed at 0.20 and 0.51 m, but yields were slightly less for the deepest (0.61 m) dripline depth evaluated. Enciso et al. (2005) looked at the economic impact of different dripline depths for cotton on a clay loam soil and found that a 0.30-m dripline depth had greater net returns than a 0.20-m dripline depth.

Dripline emitter spacing ranges from 0.10 to 0.76 m (Lamm and Camp, 2007). Driplines with greater emitter spacing are less subject to clogging and allow for more expensive emitters to be used (Lamm and Camp, 2007). Hydraulically speaking, closer emitter spacing means higher dripline flow rates and wider emitter spacing lower dripline flow rates. Lower dripline flow rates may be called for on heavy textured soils, like clay, so that the discharge rate does not exceed the hydraulic conductivity of the soil, so that a phenomenon called 'surfacing' (Grabow et al., 2008) is not induced. Many studies have been conducted to investigate the effect of emitter spacing on yields. One of these studies was conducted by Arbat et al. (2010) who found no significant differences in corn yield and water use efficiency for emitter spacings of 0.30 and 0.60 m.

The performance of SDI systems can be greatly influenced by the soil type. System design characteristics (i.e. dripline spacing, dripline depth, and emitter spacing) must take soil texture and structure into account. For instance, driplines should not be placed deep in a sandy soil as the rate of vertical percolation in the soil will limit lateral movement of water to the root zone. Irrigation strategies should also consider soil texture. Ghali and Svehlik (1988) found that daily irrigation at a rate equal to the evapotranspiration was appropriate for a medium textured soil. For coarse-textured sandy soils, a greater water application rate with short and frequent pulse of applied water can minimize cumulative deep percolation losses (Lamm and Camp, 2007).

Irrigation scheduling also plays a major role in designing and managing SDI systems. Irrigation scheduling may take many forms such as calendar date or visual assessment. Other techniques are based on soil-water status and water balance methods such as the checkbook method. The strategies in this category include directly measuring soil-water status via measurement devices such as neutron probes, granular matric sensors (GMS), time domain reflectory (TDR), etc., to determine when to irrigate (Evans et al., 1996). Grabow et al. (2011) used GMS to control SDI irrigation frequency on corn and soybean in the Piedmont of North Carolina. The authors found that corn yields for the SDI and sprinkler treatments were significantly higher than a non-irrigated treatment. The "checkbook" method involves estimating crop water needs based on evapotranspiration, rainfall, and irrigation (Evans et al., 1996). This is considered an excellent method of determining when to irrigate for corn (Heiniger et al., 2000).

Crop water uptake and response are greatly influenced by SDI design characteristics. Sufficient irrigation water must be applied to the root zone to provide enough water to replace soil-water depleted by evaporation and transpiration. Inadequate water results in plant stress and reduced root water uptake, thus resulting in decreased yields. For optimum SDI designs and management, a water application rate will be equal to root-zone depletion due to transpiration when other possible water loss is minimized (Lamm and Camp, 2007). This implies that root water uptake may be used as a surrogate to infer the success of SDI design, installation, and management strategies.

Frequent droughts and uneven rainfall patterns in North Carolina have led to interest in using more efficient irrigation systems to provide supplemental water for growing crops. Because SDI is in its infancy in North Carolina, small-scale systems were installed in the Coastal Plain and Piedmont region of North Carolina in 2001 to aid in multiple research studies (Grabow et al., 2006; Grabow et al., 2011). Although research on SDI has increased recently (Lamm et al., 2012), no research has focused on identifying SDI design performance across several design variables and criteria in North Carolina. Therefore, an evaluation of SDI design variables in conjunction with crop and soil characteristics typical of North Carolina is called for. As examining several possible dripline placements with different irrigation management strategies through field studies requires extensive time and resources, simulation modeling is an alternative way to evaluate the impact of different ranges of dripline spacing and depth on root water uptake for different soil types and irrigation strategies.

Field corn *(Zea mays L.*) is a major irrigated relatively low value crop in the United States that responds well to irrigation. The use of irrigation for corn production in North Carolina has been on the rise in the past 30 years (Heiniger et al., 2000). However, the disadvantages of irrigation in corn production originate from the high initial cost of the equipment, and the cost of operation and maintenance (Heiniger et al., 2000). Thus, it requires a cost-efficient irrigation system to be financially viable. SDI can be economically feasible for corn production by using an alternate row dripline spacing, rather than installing a dripline under every row.

The objective of this study was to use Hydrus-2D to simulate root water uptake (transpiration) from field corn under selected dripline depth, dripline spacing, soil type, dripline flow rate (emitter spacing), and irrigation treatment (irrigation depth) combinations to identify designs that tend to optimize transpiration. The selections of the analyzed levels of the design and operational factors were based primarily on the typical range found in North Carolina.

Materials and Methods

Numerical Hydrus-2D Simulations

The Hydrus-2D package (Simunek, 1998) was used to simulate plant root water uptake for assessing differences in SDI performance resulting from different combinations of design variables. Hydrus-2D can be used to simulate infiltration, evaporation, root water uptake (transpiration), soil-water storage, deep drainage, groundwater, and lateral flow (Simunek et al., 2012). The package consists of the SWMS-2D code (Simunek et al., 1994) for simulating water flow, heat, and solute movement in two-dimensional, variably saturated media. The program numerically solves the Richards equation for the governing water flow in homogenous and isotropic soil. The flow equation consists of a sink term for water uptake by plant roots as a function of both water and salinity stress. This study focused on water stress as soil salinity is not a major concern in North Carolina.

Experimental Design for Identifying Optimum SDI Systems

Four major design and management factors of subsurface drip irrigation were considered in this study: (1) dripline spacing, (2) dripline depth, (3) emitter spacing (dripline flow rate), and (4) irrigation treatment. Soil type was also introduced, even though, it was not considered as a design factor since growers have no choice in selecting their preferred soil type. Soil type (textural class) was varied in the simulations to evaluate the interaction of the four factors stated above, given different soil type, on SDI system performance.

Corn and Modeled Sites

Two locations representing two soil types were chosen for the simulations: Salisbury, and Kinston, NC. These locations reflect a range of corn production environments in NC and have weather stations operated by the State Climate Office of North Carolina. The monthly average reference evapotranspiration (ET_o) for the two locations are shown in figure 3.1. Typical soils for these locations were used in the simulations. The dominant soil types in the

Salisbury area are Mecklenburg clay loam, Mecklenburg loam, Lloyd clay loam, and Pacolet sandy clay loam (Web Soil Survey, 2014). Clay loam was chosen to be a simulated soil to represent the Salisbury area. In the Kinston area, the dominant soil types are Goldsboro loamy sand, Lynchburg sandy loam, Norkfolk loamy sand, Pantego loam, and Rains sandy loam (Web Soil Survey, 2014), and the simulated soil was sandy loam.

Planting dates were based on locations. In both the coastal plain and piedmont regions, corn yield decreases with planting postponed to 15 April, yet corn should no be planted until soil temperatures reach 12^{o}C at a 0.50-m depth (Heiniger et al., 2000). In the coastal plain, 12^{o}C soil temperatures occur from March 20 to March 25, and in the piedmont from March 25 to April 5 (Heiniger et al., 2000). For Salisbury (piedmont), a modeled planting date of 11 April was imposed. This planting date is the same as one of the years in a 4-year study by Grabow et al. (2011). For Kinston (coastal plain), a planting date of 5 April was used, which is about a week earlier than typical planting dates in the piedmont of Salisbury. The modeled planting dates for both locations were based on soil temperatures reaching 12^{o}C at a 0.50-m depth.

Phenologic stage V10 (about a week prior to tassel) to kernel milk stage R3 was the modeled period (30 days). During this period, the corn rooting depth extends to a maximum depth and remains static (Evans and Sneed, 2005), and crop water demand is at peak (Heiniger et al., 2000). Growing degree days (GDDs) were calculated from the assumed planting dates to relate temperature to corn growth and to determine when the phenologic stage V10 (about a week prior to tassel) would occur. About 1135 GDDs are required to reach the tassel stage (VT) (Neild and Newman, 1987). GDDs were calculated as follows:

$$GDD = \frac{T_{\max} + T_{\min}}{2} + T_{base} \quad (3.1)$$

where, T_{base} or base temperature is set to 50^{o}F. T_{min} is limited to 50^{o}F, and T_{max} is limited to 86^{o}F.

Weather data from 1982-2013 for both locations were obtained from the State Climate Office of North Carolina database from which to select a year in which the simulation period would represent the "design" year for simulation. The weather data included minimum, average and maximum 2-m temperature (Celsius), 10-m average wind speed (m s^{-1}), 2-m average relative humidity (%), daily precipitation (mm), solar radiation (W m^{-2}) and reported reference evapotranspiration (ET_o) (mm). Daily ET_o from 1982-2013 was generated from Ref-ET (Allen, 2003) using the weather data from both locations. The ASCE standardized Penman-Monteith equation (ASCE-EWRI, 2005) was used to compute ET_o. Weather data for Salisbury from 1990-1995 and for Kinston from 1982-1996 were unavailable from the State Climate Office of North Carolina database. Total annual ET_o from 1982-2013 is tabulated in table 3.1. The year 2008 was selected as the year from which the simulated period was selected for both locations. This selection was based on the total annual ET_o nearest the 80^{th} percentile of the 16 years of available data (1996-2013). This year also experienced little rainfall in the months of June and July at both modeled locations.

Modeled Dripline Design Parameters

A 16 mm diameter drip tape was chosen as the dripline type for use in the simulations. An emitter flow rate of 0.95 L h^{-1} was used in all simulations (refer to chapter 2). Two dripline spacings were simulated for this study. One placed the dripline under alternate row middles, which resulted in a dripline spacing of 1.52 m for a corn row spacing of 0.76 m, a row spacing reflecting about 80% of planted corn acreage in North Carolina (Heiniger et al., 2000). The other spacing simulated was configured as driplines placed under every third row, thereby resulting in a 2.28-m dripline spacing.

Two dripline installation depths were simulated. The range of dripline installation depths for field corn is between 0.30 and 0.50 m (Lamm et al., 2007). Soils in North Carolina often have a restrictive layer that limits the root zone depth (Grabow et al., 2008). Thus, driplines should be placed above the restricted layer but deep enough to avoid damage from tillage equipment. The selection of two modeled depths was considered with respect to rooting characteristics of the corn. A dripline depth of 0.20 m was selected, which was equivalent to the modeled depth of maximum root intensity. The deeper depth selected for this study was 0.30 m.

The Hydrus-2D model requires a time-variable flux boundary to represent the water flux of the dripline. Two levels of water flux were used in all simulations. As a water flux is a function of an emitter discharge rate, emitter spacing, and the dripline circumference (See equation 3.6), the two levels of water flux were realized by selecting two emitter spacings. An emitter spacing of 0.60 m was used to simulate the lower flow rate, and an emitter spacing of 0.30 m was selected to simulate the higher flow rate (double the flow rate of 0.60-m emitter spacing).

Modeled Irrigation Management Strategies

Two levels of irrigation, equivalent to 100% and 75% of peak daily crop water requirements (ET_c) over the simulation period (100% and 75% peak daily ET_c), were used in the simulations. The 75% of peak daily ET_c irrigation level simulated deficit irrigation that may be intentional (inadequate water supply) or unintentional. ET_c or crop water requirements were computed using the following equation:

$$ET_c = K_{cb} \times ET_0 \tag{3.2}$$

where

K_{cb} = basal crop coefficient

ET_o= reference evapotranspiration (mm).

Water conveyance efficiency and water application efficiency were not incorporated in calculating the irrigation levels. The two irrigation level depths were achieved by varying the irrigation duration. The irrigation duration was calculated as follows:

$$\text{Irrigation duration}\,(h) = \frac{\text{Target irrigation level (mm)}}{\text{application rate}\,(mm\ h^{-1})} \tag{3.3}$$

Application rate was calculated using the following equation:

$$\text{Application rate}\,(mm\ h^{-1}) = \frac{\text{Discharge rate}\,(L\ h^{-1})}{\text{Dripline spacing (m)} \times \text{Emitter spacing (m)}} \tag{3.4}$$

Computed irrigation durations are presented in table 3.2. A daily irrigation frequency was used in all simulations. The target depth was achieved in one and two pulses for the clay loam soil and three and four pulses in the simulations using the sandy loam soil for the 75% and 100% peak daily levels respectively. Multiple pulses were modeled for the sandy loam soil to minimize deep percolation and for the clay loam soil to minimize surfacing.

Combining two dripline spacings (1.52 and 2.28 m), two dripline depths (0.20 and 0.30 m), two soil types (clay loam and sandy loam), two emitter spacings (0.30 and 0.60 m), and two irrigation treatments (100% and 75% peak daily crop evapotranspiration, ET_c) yielded 32 SDI simulations. Scenarios describing the different SDI design combinations for corn are presented in table 3.3.

Modeled Domain Geometry

The simulations conducted using Hydrus-2D assumed a homogenous soil throughout the modeled domain. Due to symmetry, only one side of the presumed symmetrical profile was simulated. For this study, the numerical simulations were obtained for a rectangular transport domain. Four different flow domains representing all possible combinations of dripline spacing and distance of the corn row from the dripline were used in the simulations. Two flow domains were defined as 0.76 m wide and 1.0 m deep, representing a cross-section from dripline to mid-dripline, with driplines 0.20 and 0.30 m below the soil surface. The corn plant was located at the middle of the domain, 0.38 m from the dripline.

The other two flow domains were defined as 1.14 m wide and 1.0 m deep, with drip emitters 0.20 and 0.30 m below the soil surface. Two corn plants (rows) were located in these domains, one located directly above the dripline (at one edge of the domain), and another 0.76 m from the dripline and 0.38 m from the other side of the domain. The simulated domain geometries are shown in figures 3.2 and 3.3.

Boundary Conditions

The boundary conditions for the Hydrus-2D model included an atmospheric boundary condition (soil surface), a variable flux boundary (dripline emitter) and a free drainage boundary condition (bottom of domain). The simulations were conducted during the period of full canopy. No precipitation was assumed over the simulation period so as to simulate the design based on the most extreme condition. Thus, crop evapotranspiration (ET_c) was set equal to potential crop transpiration (T_p) and imposed as an atmospheric boundary condition at the top edge of the flow domain, and soil evaporation was set to zero. Daily ET_c (T_p) was calculated using the dual crop coefficient procedure FAO 56 (Allen et al., 1998). ET_c was computed from the product of ET_o and the basal crop coefficient K_{cb}. K_{cb} was adjusted to the climate in the Piedmont and Coastal Plain of North Carolina using the following equation (Allen, 1998):

$$K_{cb\,mid} = K_{cb\,mid\,(Tab)} + \left[0.04\left(u_2 - 2\right) - 0.004\left(RH_{\min} - 45\right)\right]\left(\frac{h}{3}\right)^{0.3} \qquad (3.5)$$

where

$K_{cb\,mid\,(Tab)}$ = value for $K_{c\,mid}$ taken from table 12-FAO 56

u_2 = the mean value for daily wind speed at 2-m height during the mid- or late- season growth stage (m s^{-1}) for 1 m $s^{-1} \leq u_2 \leq$ 6 m s^{-1}

RH_{min}	=	the mean value for daily minimum relative humidity during the mid- or late season growth stage (%) for $20\% \leq RH_{min} \leq 80\%$
h	=	the mean plant height (assuming 2 m) during the mid-season stage.

A free drainage boundary condition was imposed along the bottom of the soil profile because the water table was assumed to be far below the simulated domain. A variable flux boundary was imposed along the emitter circumference. The water flux of the drip emitter boundary was calculated based on the rated 0.95 L h^{-1} emitter discharge flow rate, and the dripline surface area between emitters:

$$water\ \ flux\,(cm\,h^{-1}) = \frac{Emitter\ discharge\ \ flow\,rate\,(L\,h^{-1})}{Dripline\,circumference\,(cm)\times emitter\ spacing\ (m)}\times 10 \qquad (3.6)$$

As the emitter flux is distributed over the emitter spacing, it represents an average dripline discharge rate as a line source. Depending on modeled emitter spacing, the water flux varied between 3.15 and 6.2 cm h^{-1}. During water application, the dripline boundary had a constant water flux. For the other two boundaries (both sides of domain), a zero water flux boundary was assigned.

Initial Conditions

The initial soil-water content (θ_i) was assumed to be uniform across the transport domains. The θ_i values and effective water content (S_e) in all soil types were assumed using:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (3.7)$$

where

θ = the volumetric water content and set equal to initial soil-water content (L^3 L^{-3})

θ_s = the saturated volumetric water content ($L^3\ L^{-3}$)

θ_r= the residual water content ($L^3\ L^{-3}$).

Initial soil-water content was set equal to management-allowed depletion (MAD) from the soil surface to a depth of 0.50 m and below 0.50-m depth to field capacity as little extraction would be expected below 0.5 m. MAD is the amount of water the irrigation manager allows to be depleted from the root zone prior to irrigation (Huffman et al., 2011). The amount of depleted water can be expressed in terms of depth of depleted water using the following equation (Huffman et al., 2011):

$$RAW = MAD \times AW \tag{3.8}$$

where

RAW = readily available water (mm)

MAD= Management allowed depletion (%)

AW= Plant available water (mm).

The amount of soil-water that can be used by plants at field capacity is referred to as plant available water (*AW*) and was calculated as follows (Huffman et al., 2011):

$$AW = \left(FC_v - PWP_v\right) \times D_r \tag{3.9}$$

where

D_r = depth of the root zone (L)

FC_v = volumetric field capacity ($L^3\ L^{-3}$)

PWP_v = volumetric wilting point ($L^3\ L^{-3}$).

Typical values for MAD based on maximum evapotranspiration rates of crops grouped can be found in table 15.4 (Huffman et al., 2011, p. 358). As seen in table 15.4, a MAD of 55% is recommended for maize at an ET_c rate of 6 mm per day. However, a MAD of 30% was selected for initial water content for all simulations to ensure that the crop would not suffer from water stress before soil-water from the dripline moved laterally to the root zone.

Soil Hydraulic Properties

Hydrus-2D requires the van Genuchten water release curve model parameters θ_r, θ_{sat}, α, n, l, and K_s. These parameters can be obtained from Rosetta (Schaap et al., 2001), a pedotransfer function software package that uses a neural network model to predict hydraulic parameters from soil texture and related data. Skaggs et al. (2004) estimated soil hydraulic parameters by Carsel and Parrish estimates (Carsel and Parrish, 1988), and Rosetta, and found that the predictions with Rosetta matched with the measured data more closely than those obtained with Carsel and Parrish. In all simulations, the van Genuchten parameters for both the sandy loam and clay loam soils were obtained from the Rosetta program, available within Hydrus-2D, using the appropriate soil classification. The generic values of soil hydraulic properties used herein were similar to those obtained by Grabow et al. (2006, 2011) for similar soils.

Root Distribution and Water Uptake Parameters

Soil-water flow in the flow domain is influenced by water uptake by plant roots. The root density distribution was normalized (≤ 1) and discretized into associated finite meshed nodes using the model of Vrugt et al. (2001). See equation 2.12 in chapter 2 for the root density distribution model. The maximum root depth associated with 90% of corn roots 60 days after corn planting was set equal to 0.35 m (Skaggs, 1980). The depth of maximum root intensity was set equal to 0.2 m, and the lateral root extent from the stalk was set equal to 0.2 m (personal communication, Heiniger). Currently, Hydrus-2D does not have an algorithm to simulate a growing root system. Thus, a static root system was assumed in all simulations coinciding with the simulated mid-growth-stage corn when the leaf area index of the corn canopy is relatively constant. The normalized root distribution maps for both domains are shown in figures 3.2 and 3.3.

The effects of pressure head on root water uptake at any point at the root zone were simulated using the Feddes model (Feddes et al., 1978). With the lack of detailed information on the Feddes' root reduction parameters, the default data available in Hydrus-2D were used to obtain the parameters for corn. See Chapter 2 for the different pressure heads used in the simulations that drove the root water uptake rates from nodes in the root domain. A critical water stress index (ω_c) (<1) was introduced to allow for water uptake to compensate for reduced water uptake from stressed parts of the root zone. The water stress index ranges from 0 to 1 with lower values indicating more compensation. A relatively high value of ω_c (0.9) was used, reflecting agricultural crop's less ability to compensate against water stress (Simunek and Hopmans, 2009).

SDI Design Combinations Analysis

A total of thirty-two 30-day simulations, as detailed in table 3.3, was conducted for combinations of two different soil types, two dripline spacings, two dripline depths, two emitter spacings, and two irrigation treatments. Transpiration (T) was generated by the model varied based on SDI design combinations. The optimum design for each design combination is assumed to be the scenarios that resulted in the highest ratio of transpiration to potential evapotranspiration (T/T_p).

Although, the experimental design for identifying optimum SDI systems did not account for replication, the number of possible replicate observations was assumed to be small; hence, the study design herein was considered to be 'almost unreplicated factorial'. T/T_p values were used to construct a linear statistical model based upon the levels of the four factors in the simulation runs using effect screening for tests of pseudo-significance in JMP Pro version 11 (SAS Institute, Inc. 2004). The model was used to test for active effects among the contrasts of those factor levels. The tests of pseudo-significance use the Lenth (1989) method for deciding which contrasts are statistically significant in the analysis of effect screening (unreplicated) experiments. Pseudo Standard Error (PSE) was used for evaluating the statistical significance of individual effect estimates. Boxplots were constructed to display variation in least squares means T/T_p values by treatment.

Results and Discussion

Soil-water Distribution

GDDs for field corn in both Salisbury and Kinston are tabulated in tables 3.4-3.5. In Salisbury (piedmont), the calculated GDDs indicated that the V10 stage would occur on 8 June. Although the calculated GDDs indicated that the V10 stage would occur on 02 June in Kinston (coastal plain), for the simulation period of peak ET_c the two locations were set to be simulated over the same dates, beginning on 8 June 2008. For all simulation scenarios, the mass balance error (%) of the model on average was 0.5% indicating the model was adequately discretized.

The same size and shape of the wetting front after the first irrigation event were observed in all simulations. When irrigation ended, pronounced soil-water reduction occurred in the root zone. While the horizontal advancing of wetting front was greater in the clay loam soil, the vertical advancing of the wetting front below the dripline was greater in the sandy loam soil and is likely attributed to greater capillarity in the clay loam soil and less water holding capacity in the sandy loam soil. Furthermore, it was generally observed that for all simulation scenarios the wetting front advanced at a greater rate vertically than laterally.

T/T_p by Treatment

Least squares means of statistical model predicted T/T_p treatment are shown in table 3.6. Variation of T/T_p by treatment are presented via boxplots in figure 3.4. Dripline depth, dripline spacing, and irrigation treatment main effects were all statistically significant at the

α=0.05 level. Emitter spacing (or dripline flow rate) was not significant (pseudo p-values = 0.3112). This would indicate that dripline flow rate had no impact on transpiration regardless of dripline spacing, and dripline depth as the applied water amounts were identical at a given irrigation treatment.

Dripline depth had a significant impact on T/T_p (pseudo p-values <0.0001). T/T_p least squares means were 0.048 lower with a dripline depth of 0.30 m (deeper dripline depth) (table 3.6). The greater transpiration rates at a dripline depth of 0.20 m (shallower dripline depth) may be due to the greater extraction rates from the zone of maximum root density located in the top 0.20 m of the soil profile. Generally, root-water was extracted more strongly from shallow roots near the soil surface. This finding is analogous to the results of a study from Patel and Rajput (2007) who found that a shallow dripline depth of 0.10 m resulted in higher potato yield. This finding also corroborates a study by Dukes and Scholberg (2004) who found that dripline placed 0.33-m deep SDI was too deep for optimal corn yields.

Dripline spacing had a pronounced effect on T/T_p (pseudo p-values <0.0001). T/T_p least squares means for a dripline spacing of 2.28 m (every third row spacing) were 0.056 lower than a dripline spacing of 1.52 m (alternate row middle spacing). The appreciable reduction in transpiration at the dripline spacing of 2.28 m may be attributed to the limited lateral advancing of the wetting front. Higher soil-water content values were observed adjacent to the dripline during the entire simulation period, thereby leading to the conclusion that with a wider dripline spacing, much of the irrigation water was not transmitted into the root zone.

Irrigation treatment had a significant effect on T/T_p (pseudo p-values <0.0001). As expected, at the lower irrigation amount, transpiration (root water uptake) decreased as the amount of water storage in the soil was not enough to offset deficit water application, thus causing plant stress. The 100% peak daily ET_c irrigation treatment had the highest T/T_p least squares means at 0.71, whereas the 75% peak daily ET_c irrigation treatment had a value of 0.645.

T/T_p by Treatment Combination

T/T_p least squares means are presented in figures 3.5-3.8 for each treatment combination. Interactions between dripline depth and dripline spacing were significant (pseudo p-values <0.0001). At a dripline spacing of 1.52 m, T/T_p least squares means were significantly reduced with a dripline depth of 0.30 m. This reduction may be attributed to the dripline depth of 0.30 m not being able to transmit water to the upper root zone region, leading to rather low root water uptake there. However, there was no dripline depth effect on T/T_p when the dripline was placed at a dripline spacing of 2.28 m. This may be more likely due to the extent of the wetting front not extending laterally completely into the root zone of the corn rows between driplines so the shallow dripline depth had little compensating impact. The treatment combination that yielded the highest T/T_p least squares mean values (0.752) was a combination of the dripline depth of 0.20 m and the dripline spacing of 1.52 m (fig. 3.5).

Dripline spacing also significantly interacted with irrigation treatment (pseudo p-values < 0.0001). Dripline spacing had a pronounced effect on T/T_p for the 100% peak daily ET_c irrigation treatment, however, there was no significant differences in T/T_p between a dripline spacing of 1.52 m and 2.28 m for the 75% peak daily ET_c irrigation treatment. This result may be attributed to an insufficient amount of water to offset soil-water deficit in the root zone at both dripline spacings. Nevertheless, when the amount of irrigation water increased, downward movement of water also increased. Deep percolation became more pronounced under the 100% peak daily ET_c irrigation treatment, therefore resulting in a greater difference in transpiration between dripline spacings. This would indicate it is important to control the advancing of wetting front by regulating irrigation water amount with respect to soil hydraulic properties as soil hydraulic properties dictate the water movement (i.e. capillary force and drainage rate). A combination of the dripline spacing of 1.52 m and the 100% peak daily ET_c irrigation treatment yielded the highest T/T_p least squares means of 0.734 (fig. 3.6). The interactions between dripline depth and irrigation treatment were insignificant (pseudo p values = 0.6168). The treatment with the highest T/T_p least squares means was a combination of the shallower dripline depth and 100% peak daily ET_c irrigation treatment at 0.734 (fig. 3.7). A combination of the dripline spacing of 1.52 m, 100% peak daily ET_c irrigation treatment and the dripline depth of 0.20 m yielded the highest T/T_p least squares means of 0.801 (fig. 3.8).

Conclusions and Recommendations

The major goal of experimental and theoretical studies of agricultural systems is to seek sustainable systems that can increase water application and water use efficiency. An extensive assessment of proposed irrigation water management practices and irrigation system designs is called for to identify such systems. For SDI systems, evaluations of combinations of dripline depth and spacing and irrigation treatment on efficiency metrics are called for. A numerical model is a good tool for speeding the assessment of SDI design and management scenarios. The study herein used Hydrus-2D to model the effect of dripline spacing, dripline depth, emitter spacing, and irrigation treatment on actual root water uptake under SDI in different modeled soil type to identify designs that tend to optimize transpiration.

Understanding root water uptake under SDI helps to develop efficient irrigation configurations as the root distribution has a major effect on system design and irrigation management. The results of all simulations indicated that the factor levels were sufficiently varied to provide a range of T/T_p. As dripline flow rates do not appear to be a critical factor, wide emitter spacing can be used with SDI designs to reduce cost. Given the two levels of irrigation treatment and modeled generic soil hydraulic properties, a dripline spacing of 2.28 m may be too wide to support a transpiration rate required for an acceptable irrigated yield. Therefore, given the modeled soil hydraulic properties with the condition of no rainfall, dripline should not be spaced under every third row for field corn rows spaced at 0.76 m. Although simulation results also established that full irrigation treatment (100% peak ET_c) during a peak ET_c period provided greater amounts of water available for root water uptake than the partial irrigation treatment (75% peak ET_c), deep percolation increased as the amount of irrigation water increased for sandy loam. This study further revealed that dripline depth had more of an impact on vertical rather than lateral movement of water. A dripline depth of 0.20 m provided better water distribution for plant roots than a dripline depth of 0.30 m. As expected, the wetting front associated with the shallower dripline depth extended to near the soil surface, thus resulting in increased transpiration. Therefore, it is recommended that a dripline depth no greater than 0.20 m be used. Overall, SDI with a dripline spacing of 1.52 m at an installation depth of 0.20 m at 100% peak daily ET_c irrigation treatment was the most efficient SDI design for corn for the 2 levels of those 3 factors tested, regardless of emitter spacing.

Hydrus-2D is a good tool for simulating transpiration and soil-water distribution. However, the execution of the numerical model calls for relatively extensive knowledge of input parameters (i.e. soil hydraulic parameters, and root water uptake distribution). T/T_p least squares means by all treatment and treatment combinations were below 1; however, the simulations herein did not take into account rainfall, and root compensation was limited by the selection of a high value for ω_c. Thus, the simulations are considered to be conservative. If the critical stress index was set to below 0.5, root extraction would be stronger, and thus the model would result in T/T_p close to unity.

Study results further recognize that root zone extent and water uptake distribution need to be accurate for designing and managing SDI systems. Not only does it have a large effect of optimal use of applied irrigation water, but also it dictates where water would be extracted and thus where the dripline should be installed. Caution also must be exercised to obtain accurate soil hydraulic properties, as variations in water holding capacity, capillary forces, and drainage rates have a great effect on the movement of water from the dripline.

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TABLES AND FIGURES

Table 3.1. Annual reference evapotranspiration ET_o (mm) from 1982-2013 generated by Ref-ET (Allen, 2003).

Year	Total annual ET_o (mm)	
	Salisbury	Kinston
1982	796.11	----
1983	1039.24	----
1984	1048.92	----
1985	1104.74	----
1986	1263.78	----
1987	1220.42	1702.89
1988	580.2	1632.64
1989	1115.1	1877.95
1996	1337.26	2197.14
1997	956.45	1526.89
1998	1017.49	1470.31
1999	968.62	1217.08
2000	919.76	1082.64
2001	965.09	1072.84
2002	1059.31	1275.77
2003	978.84	1307.33
2004	1000.01	1315.32
2005	993.85	1334.93
2006	1045.09	1349.43
2007	1118.06	1442.8
2008	1032.02	1386.68
2009	949.35	1239.59
2010	988.79	1440.02
2011	1004.7	1402.98
2012	999.9	1299.1
2013	927.13	1243.58

Note: ET_o in 2008 is closest to the 80^{th} percentile of years listed for both locations. Years not included at both locations are attributed to missing weather data.

Table 3.2. Calculated irrigation durations and Hydrus-2D variable flux in regard to dripline spacing and emitter spacing.

Locations	Dripline spacing	Emitter spacing	Variable flux	Discharge rate	Water requirements	Irrigation duration	
						100% peak daily ET_c	75% peak daily ET_c
(Soil types)	(m)		(cm h^{-1})	(L h^{-1})	(mm)	(h)	
Salisbury (Clay loam)	1.52	0.3	6.3	0.95	6.3	3	2.3
	2.28					4.5	3.4
	1.52	0.6	3.15			6.1	4.5
	2.28					9.1	6.8
Kinston (Sandy loam)	1.52	0.3	6.3		7.65	3.7	2.8
	2.28					5.5	4.1
	1.52	0.6	3.15			7.4	5.5
	2.28					11	8.3

Note: Different water requirements in Salisbury and Kinston, NC, were used to calculate supplied amounts of water. The water flux of the drip emitter boundary was calculated based on the emitter flow rate, the drip emitter surface area, and the emitter spacing. The diameter of the dripline is 1.6 cm. Two levels of irrigation, equivalent to 100% and 75% of peak daily crop water requirements (ET_c) during the simulation period (100% and 75% peak daily ET_c), were used in the simulations.

Table 3.3. Simulation scenarios derived from varying levels of different factors: Dripline depth, dripline spacing, dripline flow rate, irrigation treatment, and soil type.

Simulation scenario	Dripline depth	Dripline spacing	Dripline flow rate	Irrigation treatment	Soil type
1	Shallow	2x	Low	Full	Sandy loam
2	Shallow	2x	Low	Partial	Sandy loam
3	Shallow	2x	High	Full	Sandy loam
4	Shallow	2x	High	Partial	Sandy loam
5	Shallow	3x	Low	Full	Sandy loam
6	Shallow	3x	Low	Partial	Sandy loam
7	Shallow	3x	High	Full	Sandy loam
8	Shallow	3x	High	Partial	Sandy loam
9	Deep	2x	Low	Full	Sandy loam
10	Deep	2x	Low	Partial	Sandy loam
11	Deep	2x	High	Full	Sandy loam
12	Deep	2x	High	Partial	Sandy loam
13	Deep	3x	Low	Full	Sandy loam
14	Deep	3x	Low	Partial	Sandy loam
15	Deep	3x	High	Full	Sandy loam
16	Deep	3x	High	Partial	Sandy loam
17	Shallow	2x	Low	Full	Clay loam
18	Shallow	2x	Low	Partial	Clay loam
19	Shallow	2x	High	Full	Clay loam
20	Shallow	2x	High	Partial	Clay loam
21	Shallow	3x	Low	Full	Clay loam
22	Shallow	3x	Low	Partial	Clay loam
23	Shallow	3x	High	Full	Clay loam
24	Shallow	3x	High	Partial	Clay loam
25	Deep	2x	Low	Full	Clay loam
26	Deep	2x	Low	Partial	Clay loam
27	Deep	2x	High	Full	Clay loam
28	Deep	2x	High	Partial	Clay loam
29	Deep	3x	Low	Full	Clay loam
30	Deep	3x	Low	Partial	Clay loam
31	Deep	3x	High	Full	Clay loam
32	Deep	3x	High	Partial	Clay loam

Note: Dripline depth: Shallow (0.20 m) and Deep (0.30 m), Dripline spacing: 2x (1.52 m) and 3x (2.28 m), Flow rate: High (an emitter spacing of 0.30 m) and Low (0.60 m), Irrigation treatment: Full (100% peak daily ET_c) and Partial (75% peak daily ET_c).

Table 3.4. Corn growing degree days (GDD) for the 2008 corn growing season for Salisbury for a planting date of 11 April.

Date	T_{max} (F)	T_{min} (F)	GDD	Cumulative GDD
4/11/2008	79.88	52.88	16.38	16.38
4/12/2008	70.88	54.32	12.60	28.98
4/13/2008	60.44	50	5.22	34.20
4/14/2008	52.16	50	1.08	35.28
4/15/2008	60.98	50	5.49	40.77
4/16/2008	69.26	50	9.63	50.40
4/17/2008	77.54	50	13.77	64.17
4/18/2008	81.14	50	15.57	79.74
4/19/2008	71.6	52.16	11.88	91.62
4/20/2008	64.94	50	7.47	99.09
4/21/2008	67.82	50	8.91	108
4/22/2008	69.62	53.42	11.52	119.52
4/23/2008	71.78	51.08	11.43	130.95
4/24/2008	80.6	50	15.30	146.25
4/25/2008	81.14	52.16	16.65	162.90
4/26/2008	83.3	60.26	21.78	184.68
4/27/2008	71.78	58.64	15.21	199.89
4/28/2008	70.52	53.24	11.88	211.77
4/29/2008	60.44	50	5.22	216.99
4/30/2008	66.92	50	8.46	225.45
5/1/2008	76.82	50	13.41	238.86
5/2/2008	79.16	57.74	18.45	257.31
5/4/2008	79.7	54.14	16.92	291.78
5/5/2008	74.66	53.96	14.31	306.09
5/6/2008	78.8	50	14.40	320.49
5/7/2008	80.96	50	15.48	335.97
5/8/2008	80.06	63.86	21.96	357.93
5/9/2008	82.4	63.14	22.77	380.70
5/10/2008	81.5	58.64	20.07	400.77
5/11/2008	67.46	52.88	10.17	410.94
5/12/2008	66.38	51.26	8.82	419.76

Table 3.4 (continued)

5/13/2008	72.86	50	11.43	431.19
5/14/2008	74.3	50	12.15	443.34
5/16/2008	79.7	52.88	16.29	477.63
5/18/2008	76.82	50	13.41	503.82
5/19/2008	77.54	50	13.77	517.59
5/20/2008	83.48	55.4	19.44	537.03
5/21/2008	75.38	50	12.69	549.72
5/22/2008	81.32	50	15.66	565.38
5/23/2008	81.5	52.16	16.83	582.21
5/24/2008	75.92	54.32	15.12	597.33
5/25/2008	79.7	50	14.85	612.18
5/26/2008	83.12	56.12	19.62	631.80
5/27/2008	86	63.86	24.93	656.73
5/28/2008	70.88	53.6	12.24	668.97
5/29/2008	73.94	53.96	13.95	682.92
5/30/2008	81.86	57.56	19.71	702.63
5/31/2008	86	68.36	27.18	729.81
6/1/2008	86	63.5	24.75	754.56
6/2/2008	86	61.7	23.85	778.41
6/3/2008	85.82	61.7	23.76	802.17
6/4/2008	86	70.88	28.44	830.61
6/5/2008	86	67.64	26.82	857.43
6/6/2008	86	71.96	28.98	886.41
6/7/2008	86	70.7	28.35	914.76
6/8/2008	86	67.64	26.82	941.58
6/9/2008	86	68	27	968.58
6/10/2008	86	67.46	26.73	995.31
6/12/2008	86	66.02	26.01	1048.32
6/13/2008	86	67.82	26.91	1075.23
6/14/2008	86	68.36	27.18	1102.41
6/15/2008	86	66.74	26.37	1128.78

Table 3.5. Corn growing degree days (GDD) for the 2008 corn growing season for Kinston for a planting date of 5 April.

Date	T_{max} (F)	T_{min} (F)	GDD	Cumulative GDD
4/5/2008	69.44	60.44	14.94	14.94
4/6/2008	63.68	50	6.84	21.78
4/7/2008	53.96	50	1.98	23.76
4/8/2008	60.08	50	5.04	28.80
4/9/2008	64.94	50	7.47	36.27
4/10/2008	77.18	55.4	16.29	52.56
4/11/2008	80.96	58.46	19.71	72.27
4/12/2008	83.12	61.88	22.50	94.77
4/13/2008	68.72	51.44	10.08	104.85
4/14/2008	58.1	50	4.05	108.90
4/15/2008	58.1	50	4.05	112.95
4/16/2008	65.66	50	7.83	120.78
4/17/2008	77	50	13.50	134.28
4/18/2008	84.56	50	17.28	151.56
4/19/2008	81.5	55.58	18.54	170.10
4/20/2008	77	50	13.50	183.60
4/21/2008	68.18	51.98	10.08	193.68
4/22/2008	72.14	57.38	14.76	208.44
4/23/2008	74.12	57.74	15.93	224.37
4/24/2008	78.8	55.94	17.37	241.74
4/25/2008	80.24	55.4	17.82	259.56
4/26/2008	83.84	59.9	21.87	281.43
4/27/2008	83.84	59.9	21.87	303.3
4/28/2008	83.84	59.9	21.87	325.17
4/29/2008	83.84	59.9	21.87	347.04
4/30/2008	65.12	50	7.56	354.6
5/1/2008	76.1	60.08	18.09	372.69
5/3/2008	82.4	60.26	21.33	412.29
5/4/2008	81.68	63.86	22.77	435.06
5/5/2008	75.74	60.08	17.91	452.97
5/6/2008	76.46	55.22	15.84	468.81
5/7/2008	83.12	56.66	19.89	488.70

Table 3.5 (continued)

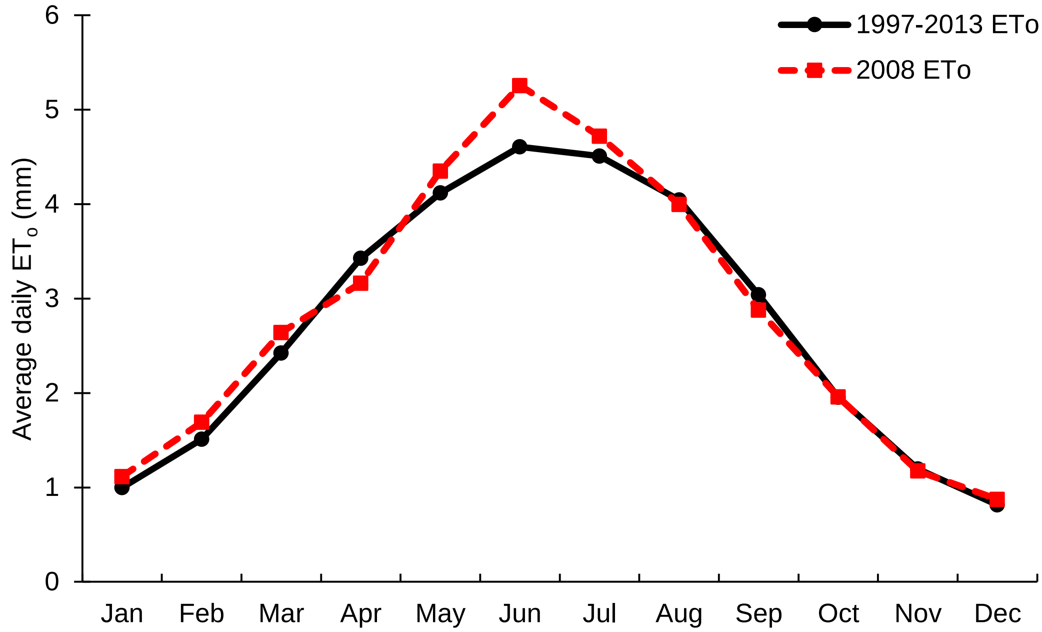
5/10/2008	81.32	56.66	18.99	552.96
5/11/2008	76.46	51.8	14.13	567.09
5/13/2008	69.44	50	9.72	584.37
5/14/2008	75.92	50	12.96	597.33
5/15/2008	78.62	61.88	20.25	617.58
5/16/2008	83.12	63.86	23.49	641.07
5/17/2008	76.46	53.78	15.12	656.19
5/18/2008	81.5	57.74	19.62	675.81
5/19/2008	78.08	58.1	18.09	693.9
5/20/2008	86	61.88	23.94	717.84
5/21/2008	75.02	56.3	15.66	733.50
5/22/2008	77.9	53.06	15.48	748.98
5/23/2008	77.72	54.32	16.02	765
5/24/2008	73.4	56.66	15.03	780.03
5/25/2008	79.16	51.08	15.12	795.15
5/26/2008	84.02	52.7	18.36	813.51
5/27/2008	86	62.24	24.12	837.63
5/28/2008	70.7	53.96	12.33	849.96
5/29/2008	76.64	54.14	15.39	865.35
5/30/2008	85.46	54.86	20.16	885.51
5/31/2008	86	68.36	27.18	912.69
6/1/2008	86	69.44	27.72	940.41
6/2/2008	83.48	65.12	24.30	964.71
6/3/2008	86	59	22.50	987.21
6/4/2008	86	69.08	27.54	1014.75
6/5/2008	86	75.56	30.78	1045.53
6/6/2008	86	75.2	30.60	1076.13
6/7/2008	86	76.28	31.14	1107.27
6/8/2008	86	74.48	30.24	1137.51

Table 3.6. Comparison of least squares means of T/T_p by treatment.

Treatment	Levels of treatment	T/T_p least squares means
Dripline depth	Shallow (0.20 m)	0.702 a
	Deep (0.30 m)	0.654 b
Dripline spacing	1x (1.52 m)	0.701 a
	2x (2.28 m)	0.645 b
Flow rate (emitter spacing)	Low (0.6-m emitter spacing)	0.679 a
	High (0.3-m emitter spacing)	0.677 b
Irrigation treatment	Full (100% peak daily ET_c)	0.71 a
	Partial (75% peak daily ET_c)	0.645 b
Soil type	Clay loam	0.667 a
	Sandy loam	0.689 b

Note: Different letters denote significant differences at the α=0.05 level.

(a)



(b)

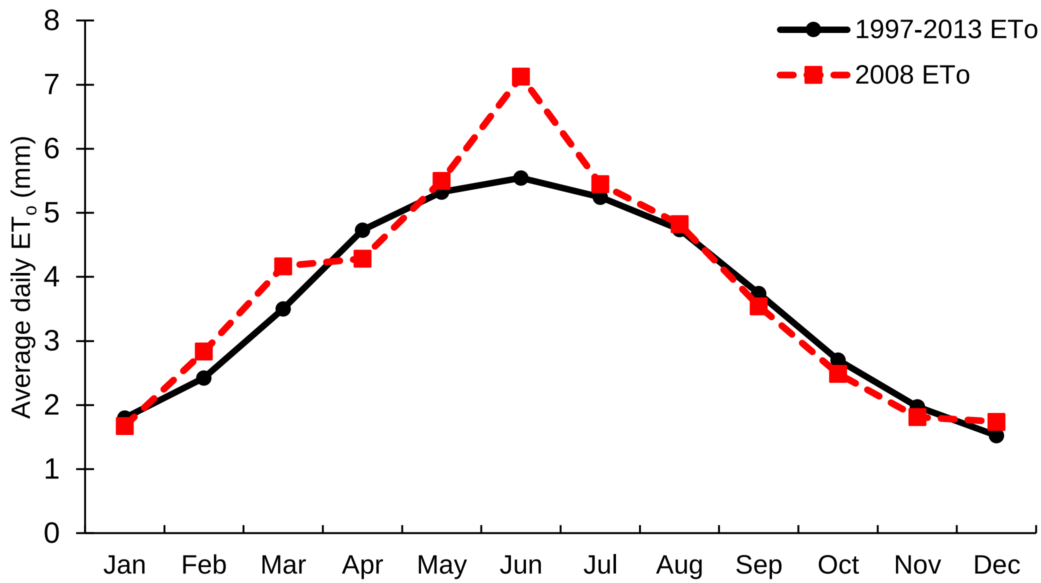


Figure 3.1. Monthly average daily reference evapotranspiration (1997-2013) compared with the simulated year, 2008 in (a) Kinston and (b) Salisbury, NC.

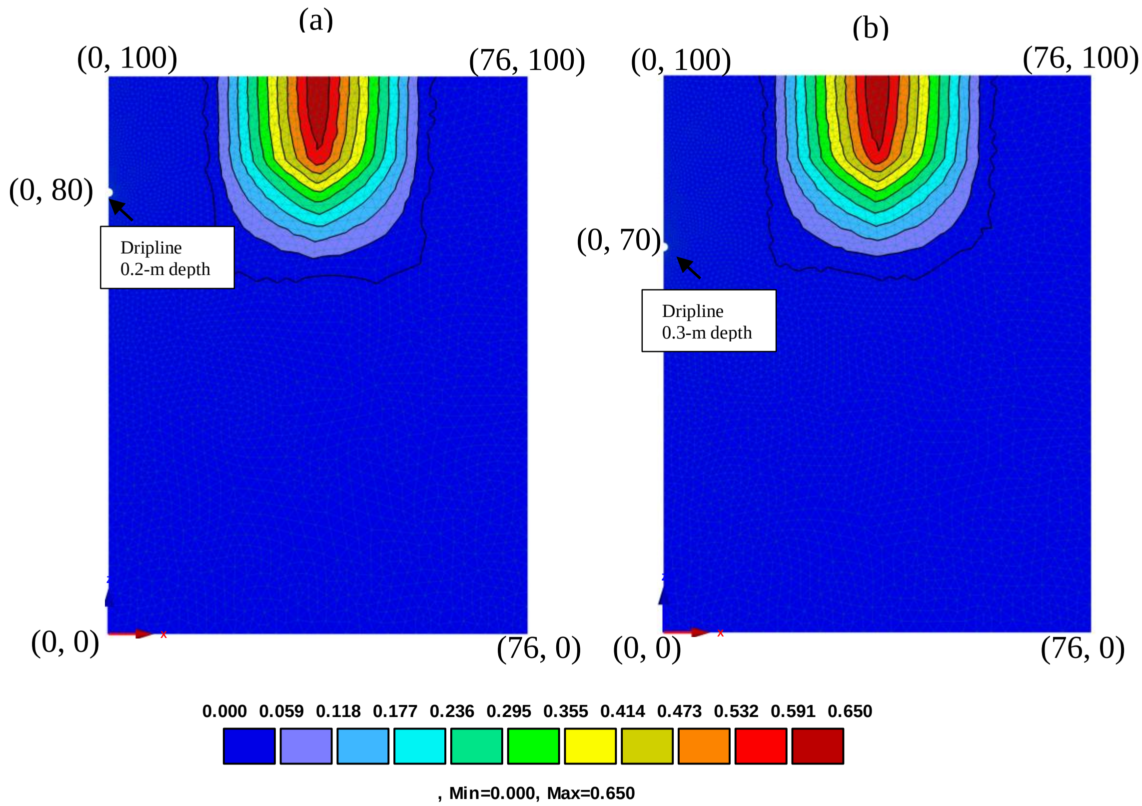


Figure 3.2. Domain geometry and normalized root distribution used for Hydrus-2D simulations. Coordinates in cm.

Note: The domain was defined as 0.76 m wide and 1.0 m deep. The drip emitter was located at (a) a 0.20-m depth, and (b) a 0.30-m depth. A corn plant was located at the middle of the domain. The root distribution was normalized from 0 to 1. Figures not to scale.

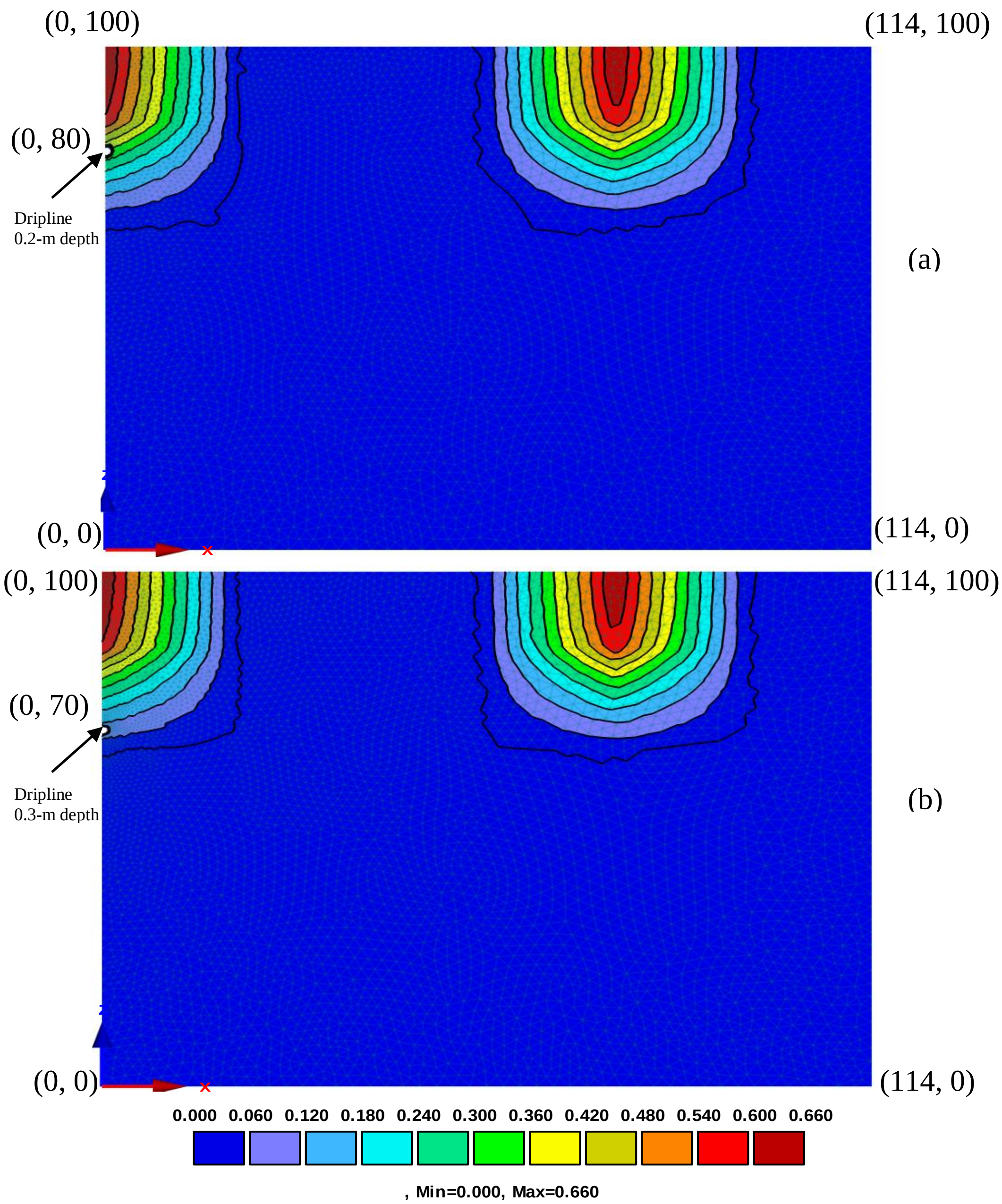


Figure 3.3. Domain geometry and normalized root distribution used for Hydrus-2D. Coordinates in cm.

Note: The domain was defined as 1.14 m wide and 1.0 m deep. The drip emitter was located at (a) a 0.20-m depth, and (b) a 0.30-m depth. Figures not to scale.

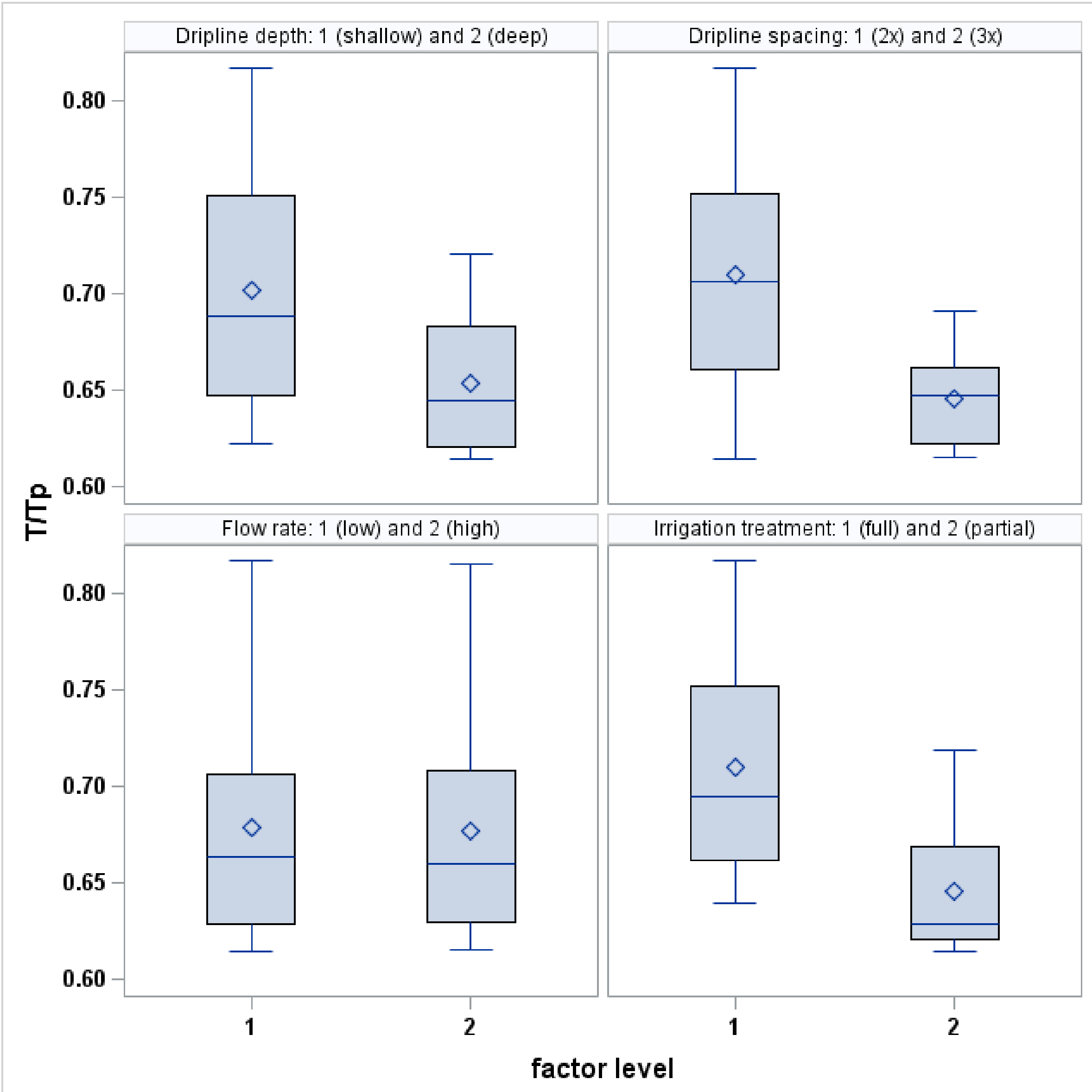


Figure 3.4. Distribution of T/T_p by dripline spacing, dripline depth, irrigation treatment, and emitter spacing.

Note: dripline spacing: 2x (1.52 m) and 3x (2.28 m), dripline depth: shallow (0.20 m) and deep (0.30 m), irrigation treatment: full (100% peak daily ET_c*) and partial (75% peak daily* ET_c*), and flow rate: low (an emitter spacing of 0.60 m) and high (an emitter spacing of 0.30 m).*

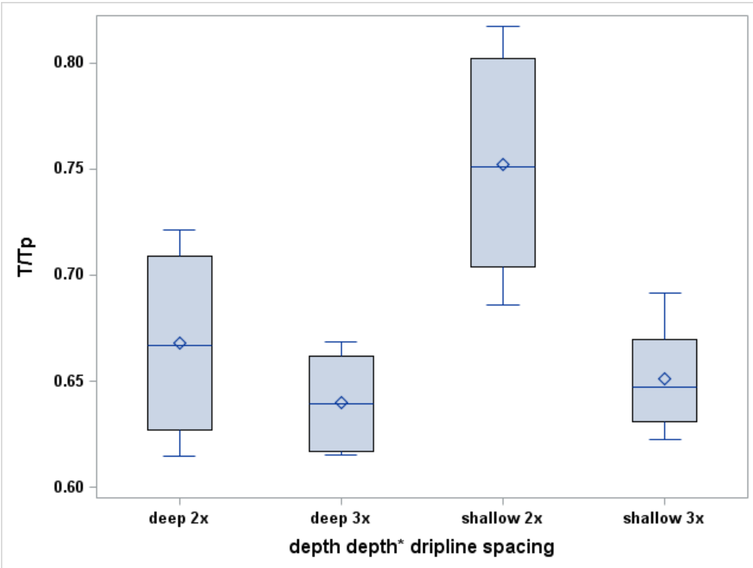


Figure 3.5. Distribution of T/T_p by dripline depth*dripline spacing.

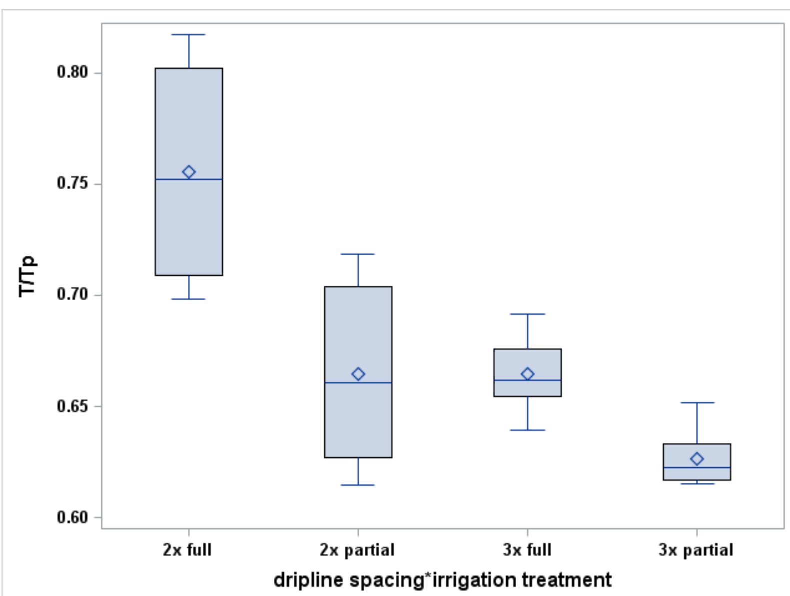


Figure 3.6. Distribution of T/T_p by dripline spacing*irrigation treatment.

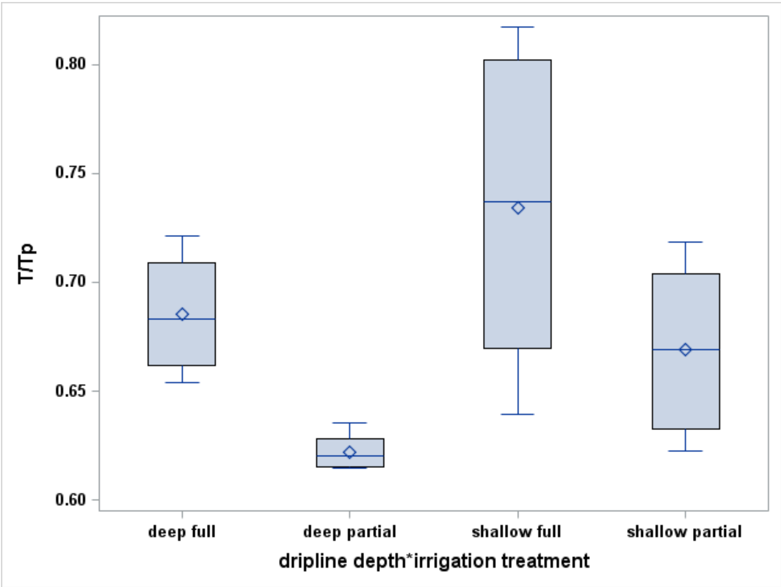


Figure 3.7. Distribution of T/T_p by dripline depth*irrigation treatment.

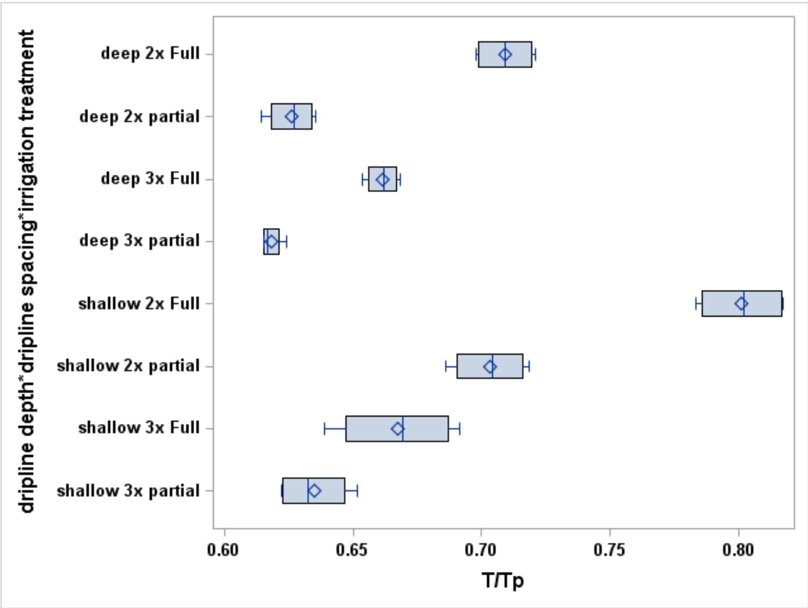


Figure 3.8. Distribution of T/T_p by dripline depth*dripline spacing*irrigation treatment.