

ABSTRACT

VICK, JR., ROBERT LINWOOD. Smart irrigation systems for crop production in the humid climate of the Southeastern United States. (Under the direction of Dr. Mohamed A. Youssef).

A series of irrigation studies was conducted with the goal of improving irrigation scheduling in humid climates for sweetpotato and corn crops. A two-year drip irrigation study was carried out on 'Covington' sweetpotatoes in Kinston, North Carolina in 2013 and 2014 to evaluate three irrigation regimes (Control, Smart, and Timer) and two nitrogen fertilization methods (Fertigated and Side Dressed) across three harvest dates (13, 16, and 19 weeks after transplant) with regards to storage root yield, quality, set, and earliness. Both growing seasons were wetter than normal (488 mm in 2013; 901 mm in 2014), resulting in minimal need for irrigation. The Smart treatment, which was triggered when volumetric soil water content dropped below a threshold of $0.12 \text{ mm}^3 \text{ mm}^{-3}$, only ran twice in 2013 (10 mm total) and once (5 mm total) in 2014, not including water applied during fertigation events. Total yield in 2014 ($51,501 \text{ kg ha}^{-1}$) was 51% greater than total yield in 2013 ($34,010 \text{ kg ha}^{-1}$), which was likely attributed to well-timed rainfall, more so than to the quantity of it. There was no evidence of an irrigation or fertigation treatment main effect on yield or root set; however, at the last harvest, plants of the Smart treatment yielded 12% more than the Control ($46,122 \text{ kg ha}^{-1}$) and 15% more than the Timer ($45,128 \text{ kg ha}^{-1}$), which suggests that minimal, yet properly timed irrigation may increase yield, while over-irrigation could have a detrimental effect.

To assist growers with irrigation scheduling in region such as the southeastern United States, where growing season rainfall is characterized by variability and high intensity, short duration events, a web-based irrigation decision support system (IDSS) was developed and tested. The real-time IDSS incorporates crop growth stage (estimated based on cumulative

growing degree days), soil water status of the root zone (estimated via soil moisture sensors or a soil water balance), and a short-term weather forecast (specifically predicted daily reference evapotranspiration, probability of precipitation, and quantity of precipitation) to calculate a daily irrigation recommendation for the grower.

The IDSS was implemented in a field study in Kinston during the 2014 growing season on corn grown under a variable rate irrigation (VRI) system, which was intended to be used to test the IDSS against routine irrigation and no irrigation plots in the same field. The growing season, however, was one of the wettest in recent history (933 mm), which combined with poor drainage, inherent field variability, and low plant stands resulted in total irrigation applications of only 16 mm in the IDSS-based treatment (Smart) and 32 mm in the routine treatment (Routine). Accordingly, the study focus was shifted away from comparing yield and water use among irrigation treatments to evaluating the soil water balance component of the IDSS against field measured soil moisture and to explaining the variability observed across the field in plant vigor, development, and yield. Overall, the IDSS soil water balance was able to acceptably predict root zone soil water content (NSE = 0.808, RSME = 9.3 mm), but tended to over predict the effects of rainfall events as well as drawdown rates in drying periods. Soil penetration resistance measurements taken at multiple locations across the field revealed the presence of a compaction layer between 150 and 300 mm below the soil surface, with values exceeding the threshold for root impedance in some places as shallow as 50 mm. Maps of maximum penetration values and yield provided visual evidence of correlation between the measures.

A sensitivity analysis of the IDSS and a six-year (2009 – 2014) simulation study across five locations in Eastern North Carolina (Kinston, Lewiston, Lumberton, Rocky

Mount, and Whiteville) was also conducted using CSM-CERES-Maize in the DSSAT suite of crop models. Sensitivity indices (S) were greatest for the effect of year (0.54) and the interaction between year and location (0.24) on seasonal irrigation recommendations, reflecting the dependence of irrigation requirements on rainfall. The effect of rainfall timing was also demonstrated as seasons with comparable cumulative rainfalls had distinctly different irrigation totals depending on when rainfall occurred during the growing seasons.

Simulated corn yields indicated no yield differences between treatments of IDSS-scheduled irrigation based on actual forecast data (9,114 kg ha⁻¹) and based on observed weather data substituted as “perfect” forecasts (9,120 kg ha⁻¹). Both IDSS-based treatments on average yielded 4% more than full irrigation on a fixed schedule (8,762 kg ha⁻¹) and 82% more than no irrigation (5,010 kg ha⁻¹), while reducing seasonal and location variability in yields and increasing responsiveness of irrigation totals to variations in seasonal rainfall. Simulation results suggest that integrating well-timed irrigation with improved fertility management could increase corn yields in Eastern North Carolina by as much as 168%.

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Smart irrigation systems for crop production in the humid climate
of the Southeastern United States

by
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DEDICATION

This work is dedicated to my family and my Lord and Savior, Jesus Christ. I am ever grateful to both for their love and support throughout this journey. I hope my efforts have honored my family and glorified my Lord.

BIOGRAPHY

Robert “Bobby” Linwood Vick, Jr. was born May 31, 1987, in Rocky Mount, North Carolina. Raised in Wilson, North Carolina, he is the only child of Robert and Martha Vick. Agriculture has always been an important part of Bobby’s life – his dad was a tobacco farmer for over thirty years; his mom was a 4-H agent before becoming the first executive director of the Tobacco Farm Life Museum in Kenly, North Carolina; and Bobby raised market hogs and a steer over nine years of 4-H livestock projects – but, it was not until after his graduation from Ralph L. Fike High school in 2005 that Bobby began to recognize his passion for agriculture.

In August 2005, Bobby started his North Carolina State University academic journey. He received a Bachelor of Science in Biological and Agricultural Engineering with concentrations in Agricultural Engineering and Environmental Engineering in 2009. Immediately following completion of his undergraduate degree, Bobby began working on his Master of Science under Dr. Garry Grabow in the same department. Bobby finished his master’s degree in 2012 while transitioning into the BAE Ph.D. program, first under the direction of Dr. Mike Boyette and then under Dr. Mohamed Youssef.

Eleven years removed from the beginning of this academic journey, Bobby’s tenure as a student at NC State is concluding with the completion of his Ph.D. in the summer of 2016. The journey has certainly been challenging and longer than anticipated, but undoubtedly rewarding as well. It has encompassed several monumental life events: the passing of both of Bobby’s dearly loved grandmothers (Grandma Betty and Grandma Lib), his marrying his high school sweetheart, Meredith Sullivan Vick, and the purchase of

Meredith's and his first home. It has afforded Bobby wonderful opportunities to travel, experience, learn, and do, but most importantly to meet and build relationships with people from all over the world. It is these relationships that Bobby cherishes most.

As one journey comes to an end, Bobby looks forward with great anticipation to the journeys of life that remain ahead, eager and willing to meet the next set of friends along the way.

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I am also grateful to the many individuals who have contributed to my research and Ph.D. experience. From professors to fellow graduate students to workers at the Cunningham Research Station in Kinston, each of you have had a part in bringing me to this point, and I thank you. At the serious risk of overlooking someone, thank you specifically to: Shiqi, Wenlong, Tim, Greg, Charles, Andy, Phillip, Evan, Chris, Forrest, Brandon, Julian, Yu, Phil, Dr. Boyette, Dr. Birgand, Dr. Roberson, Ed, Veronica, Beth, Tiffany, Zhimin, Brandon, John, Josh, Laura, and Sarah. And to whom I've forgotten, I am truly sorry. Thank you too.

To my parents: Mama and Daddy, you are the consummate example of loving and supporting parents. Thank you for setting a strong foundation to carry me through wherever life leads and for being there to offer words of encouragement when needed. Thank you for giving me the necessary direction to make wise choices and freedom to make them on my own. I love you.

To my wife: Meredith, thank you, above all, for loving me, encouraging me, supporting me, listening to me, being patient with me, and pushing me. The experience of these gifts in the moment may not have felt as positive as they sound now, for either of us, but I would not be at this point had you not provided them. Who knew getting a Ph.D. was

so hard... for the spouse?! This road is not one I would have wanted to walk alone and I am so thankful that I had you with me to be a rock through it all. You are the strongest person I know. I love you with all my heart and look forward to what God has in store for us.

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CHAPTER 1 - INTRODUCTION

1.1 TRENDS IN AGRICULTURAL IRRIGATION

Irrigation is a vital component of production agriculture across the world. Only about 17% of global cropland is irrigated, but such land accounts for approximately 40% of global food production (FAO, 2002). In the United States, almost half of the harvested crop in 1997 was produced on irrigated land, which accounted for only 16% of the nation's total cropland (USDA-ARS, 2001). These statistics reflect improvements in agriculture production efficiency over the past fifty years that were necessary to meet rapidly increasing demands for food and fiber. Current global agricultural production is between 2.5 and 3 times what it was fifty years ago, despite cultivated land area having only increased by 12% over the same period (FAO, 2011). Over 40% of this increase can be attributed to irrigated areas, which have doubled (FAO, 2011). It is estimated that the amount of irrigated land in developing countries will continue to increase to meet the demands of a growing world population, which is projected to reach 9.7 billion by 2050 (United Nations, 2015). Increases in irrigated production are already occurring, including in regions that have traditionally relied heavily upon rainfed agriculture, such as the humid southeastern United States.

Total irrigated acreage in Alabama, Georgia, North Carolina, and South Carolina increased by 71% from 2002 to 2012 (USDA-NASS, 2003; 2013). Whereas growers in arid climates rely heavily on irrigation for producing crops, growers in humid regions use supplemental irrigation with the intent of increasing crop yields and making crop production more resilient to inherent seasonal and location variability, particularly in rainfall.

The challenges of agricultural water management in the humid southeastern United States have been well documented (Camp et al., 1988; Sadler et al., 2003; Stone et al., 2008; Stone et al., 2010). Seasonal and spatial variability in rainfall means that growers and their management strategies must be prepared to quickly adapt to changing and localized environmental conditions, be it excess rainfall or drought. Coarse-textured soils with physical and chemical barriers that often limit root growth are typical of much of the agricultural land under production in the southeastern Coast Plain. This means as few as five to seven days without rainfall can result in yield-reducing drought stress (Lambert, 1980), particularly if it occurs at a critical stage of crop growth. For growers who are adopting irrigation in such areas, deciding when and how much irrigation to apply remains a common dilemma.

1.2 SMART IRRIGATION

A number of irrigation scheduling tools and resources have been developed to help answer the questions of when and how much to irrigate, most of which are either soil-, plant-, or weather-based, or some combination thereof (IA, 2011), and many of which consist of freely available software designed for personal computers or mobile phones (Andales et al., 2014; Cahn, 2013; Cahoon et al., 1990; Hillyer and Sayde, 2010; Martin et al., 2003; Migliaccio et al., 2013; Peters et al., 2014; Rogers, 2012; Sassenrath et al., 2013; Scherer and Morlock, 2008; Vellidis et al., 2014). A soil-based irrigation scheduling method may be as simple as a "checkbook approach," in which a grower maintains a daily soil water balance, accounting for inputs (i.e., rainfall and irrigation) and outputs (i.e., evapotranspiration) to

estimate when irrigation is needed. More sophisticated systems may include the installation of soil or plant sensors to estimate water stress or onsite weather stations to precisely measure weather parameters that most affect plant water availability and plant water use (i.e., rainfall, temperature, relative humidity, solar radiation, and wind speed). The combination of such scheduling technologies with precision control irrigation hardware constitutes what is broadly referred to as a "smart" irrigation system (IA, 2007). Smart irrigation systems are designed to improve crop water use efficiency by precisely applying the proper amount of water to the crop when it is needed, and in some cases specifically where it is needed. Incorporation of the "where" component in the agricultural realm generally suggests the use of a variable rate irrigation (VRI) system, which falls under the broader umbrella of precision agriculture.

Variable rate irrigation systems allow for spatial variation of water application within a single field and typically consist of a center pivot or lateral move irrigation rig that has onboard global positioning system (GPS), for determining the real-time position of the system in the field, and multiple zones of irrigation nozzles that are independently controlled by a central control panel (Evans et al., 2013). The rate of water applied at any location in the field is governed by the position of the system in the field and a user-defined prescription map that is stored in the controller.

Despite the availability of irrigation scheduling software and precision irrigation systems such as VRI, the adoption rate of such technology has remained low. As recently as 2012, irrigation on only about 10% of irrigated farmland in the United States was scheduled using some type of soil moisture sensor (USDA-NASS, 2013). Less than 1% was based on

computer models, while over 40% was determined using the feel of the soil. The use of VRI is probably less than even that of computer models. Evans et al. (2013) estimated that less than 200 of the approximately 175,000 center pivot and linear move irrigation systems in the United States were equipped with VRI capabilities, and speculated that less than 50% of them were actually being used for zone-controlled water management. The reasons provided for such underutilization included: lack of adequate technical assistance to help with operation and management of VRI systems, perceived complexity of the technology by growers, lack of regulatory economic incentives to help offset costs, and minimal interest among growers to optimize water applications with minimal or no resulting yield returns, except in situations of severe water shortages. In other words, in the mindset of most growers, the value provided by smart irrigation has not yet reached a sufficient level to offset the combined financial, time, and expertise investment required to implement it.

1.3 RESEARCH OBJECTIVES

There exists a need for improved smart irrigation tools and technologies that are reliable, simple to understand and use, and that will produce measurable returns on investment. Such systems may have the most value in humid climates where variable weather patterns, within and across growing seasons, present substantial scheduling challenges and where the irrigated acreage continues to grow. Not only could these systems offer the potential of improving crop yields by providing supplemental irrigation during dry periods, they also could prevent over-irrigation, which can lead to undue plant stress from either excess water in the root zone or leaching of nutrients. The threat of nutrient leaching

should be of particular concern given the coarse texture of many Coastal Plain soils and the presence of nutrient-sensitive water bodies in close proximity to agricultural land in the southeastern United States. Smart irrigation could help mitigate these nutrient and water quality concerns, particularly if integrated with crop nutrient management plans. The potential benefits of such systems are important to traditional agronomic crops, but could also extend to less traditional horticultural and specialty crops as well.

The overall goal of this research was to design and assess two smart irrigation systems, designed specifically for sweetpotato and corn production in the humid southeastern United States. Specific objectives were:

1. Quantify the storage root yield, quality, set, and development effects of drip irrigation and nitrogen fertigation on ‘Covington’ sweetpotatoes.
2. Develop a web-based, real-time irrigation decision support system (IDSS) that incorporates crop growth stage, soil water status, and short-term weather forecast into irrigation recommendations.
3. Compare irrigation water use and corn yield among IDSS-scheduled irrigation, routine irrigation at a fixed depth, and no irrigation via a field study implemented in Kinston, North Carolina.
4. Evaluate the sensitivity of the IDSS to uncertainty in input parameters under different weather conditions for multiple growing seasons and locations across eastern North Carolina.
5. Simulate water use and yield effects of IDSS-scheduled irrigation compared to routine irrigation and no irrigation on corn across multiple growing seasons

and locations in eastern North Carolina using the crop simulation model (CSM) Crop Environment Resource Synthesis-Maize (CERES-Maize) (Jones and Kiniry, 1986) within the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.6.1.0 (Jones et al., 2003; Hoogenboom et al., 2015).

1.4 RESEARCH OVERVIEW

The research presented herein was focused on integrating information-driven irrigation scheduling with conventional crop production practices used in the Coastal Plain of North Carolina. Chapter 2 describes a two-year field study conducted in Kinston, North Carolina that assessed the potential benefits of implementing drip irrigation (applied at a routine interval or based on feedback from in-row soil moisture sensors) compared to non-irrigated production, and nitrogen fertigation compared to traditional side-dressed applications. Chapters 3 through 5 are focused on the development and testing of a novel irrigation decision support system (IDSS) that integrates crop growth stage, real-time soil moisture status, and short-term weather forecast into daily irrigation recommendations to the user. Chapter 3 presents a review of several existing irrigation scheduling technologies and describes the development, including the decision logic, of the IDSS. Chapter 4 describes a field study that was implemented in Kinston with a VRI system to test the IDSS compared to routine and no irrigation on corn in 2014. Numerous challenges were faced during this particular study, including excess rainfall that minimized the need for irrigation, hardware and software failures associated with the IDSS, low plant stands, poor drainage, and inherent

variability that was discovered in the research field. The research objectives were modified due to these challenges and particularly the lack of irrigation applied. Much of the chapter is devoted to the testing of the IDSS predicted soil water balance against field measured soil water contents and to exploring the spatial variability in soil penetration resistance measured across the field and its correlation to the spatial variability in crop growth and yield. The final chapter (Chapter 5) combines a sensitivity analysis of the IDSS and a simulation study of irrigation water use and corn yield under non-irrigated, routine irrigated, and IDSS irrigated production, conducted using CSM-CERES-Maize in DSSAT version 4.6.1.0, across five locations in Eastern North Carolina and six different growing seasons.

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CHAPTER 2 - DRIP IRRIGATION AND FERTIGATION EFFECTS ON YIELD, QUALITY, ROOT SET, AND EARLINESS OF DEVELOPMENT OF 'COVINGTON' SWEETPOTATO IN NORTH CAROLINA

2.1 ABSTRACT

Recent growth in domestic and international demand for sweetpotatoes has led to a steady increase in sweetpotato acreage in North Carolina, the leading sweetpotato producer in the United States. Researchers and growers have expressed interest in drip irrigation and fertigation as possible means to increase sweetpotato yield potential in the traditionally non-irrigated region. A two-year field study was conducted in 2013 and 2014 at the Cunningham Research Station in Kinston, North Carolina, to evaluate three irrigation regimes (Control, Smart, and Timer) and two nitrogen fertilization methods (Fertigated and Side Dressed) with regards to yield, quality, root set, and earliness of development. Timer plots were scheduled to irrigate on Mondays and Thursdays unless bypassed by a standard landscape irrigation rain switch set to 6 mm. The Smart treatment had the potential to run every day, with irrigation only being triggered when more than half of in-plot soil moisture sensors dropped below a volumetric soil water content of $0.12 \text{ mm}^3 \text{ mm}^{-3}$. Nitrogen fertilizer was either side dressed in a single application (Side Dressed) or injected into the irrigation drip tape over seven applications (Fertigated) at a rate of 118 kg N ha^{-1} . Plants from each irrigation by fertilization method plot were hand harvested at approximately 13, 16, and 19 weeks after transplant (Early, Middle, and Late, respectively) and graded as U.S. No. 1s, canners, jumbos, or culls. Weights and counts of roots in each grade were recorded for each harvested plant. Both growing seasons were wetter than normal (488 mm in 2013; 901 mm in 2014)

resulting in minimal need for irrigation. The Timer treatment bypassed approximately half of the scheduled irrigation events and the Smart treatment ran twice (10 mm total) in 2013 and once (5 mm total) in 2014, not including water applied during fertigation events. Total yield in 2014 (51,501 kg ha⁻¹) was 51% greater than total yield in 2013 (34,010 kg ha⁻¹), most likely due to well timed, though heavy, rainfall compared to nearly daily rainfall during the first thirty days of the 2013 growing season. In general, neither irrigation nor fertilization method had a significant effect ($\alpha = 0.05$) on yield or root set; however, both irrigation and fertilization had significant interaction effects with harvest date for multiple storage root grades. Despite there being no difference in marketable yields at the Early harvest among the irrigation treatments, at the Late harvest, Smart irrigated plants yielded 51,858 kg ha⁻¹ marketable roots, which was 12% more than the Late-Control (46,122 kg ha⁻¹) and 15% more than the Late-Timer (45,128 kg ha⁻¹). This suggests that minimal, yet properly timed irrigation, may increase yield, while over-irrigation may have a detrimental effect. There was also evidence that fertigation should have been started earlier in the season and possibly using a different rate schedule. Further research, spanning moisture limited production seasons with different fertigation rates and schedules is recommended to further assess their impact on yield and production efficiency in North Carolina.

2.2 INTRODUCTION

2.2.1 US Sweetpotato Production

Sweetpotato [*Ipomoea batatas* (L.) Lam.] is one of the world's most important food crops due to its high nutritional value and its adaptability to various climates and farming

practices (Bovell-Benjamin, 2007). Global sweetpotato production was over 103 Mt in 2013, 69% of which was produced in China (FAO, 2014). While the United States produces only about 1% of the world's sweetpotatoes (1.1 Mt in 2013) (FAO, 2014), sweetpotato production has become an important agricultural business in the United States, generating over \$597 million in revenue in 2013 (USDA, 2015c). Over half of the sweetpotatoes produced in the U.S. are grown in North Carolina, with most of the remainder produced in California, Mississippi, and Louisiana (USDA, 2015b). Less than 5% of the sweetpotato crop in North Carolina is currently irrigated, compared to 95% in California (Felix, 2015) where yields per acre are much higher. In 2013, average sweetpotato yield per area of production land was 80% higher in California (40.3 Mg ha^{-1}) than in North Carolina (22.4 Mg ha^{-1}) (USDA, 2015b).

Nearly 100% of North Carolina sweetpotato growers use drip irrigation on sweetpotato plant beds, from which sweetpotato plants, or slips, are cut to be transplanted for field production. The same growers, however, have been reluctant to invest in irrigation for field production of sweetpotatoes. This is because sweetpotatoes are considered moderately drought tolerant (Hammet et al., 1982; Smittle et al., 1990) and there is typically sufficient rainfall in North Carolina during the growing season to produce reasonable sweetpotato yields. However, some North Carolina growers have begun irrigating a portion of their acreage with overhead or drip irrigation systems and more have expressed interest in irrigation as a possible means to meet a steadily increasing demand for U.S. sweetpotatoes (USDA, 2015a). This demand has been fueled by increased consumer awareness of the nutritional value of sweetpotatoes, increased offerings of processed sweetpotatoes (e.g.,

chips, fries, pre-cut, and pureed) (USDA, 2015a), and increased exports, particularly to Europe (USDA, 2011). Yet to date, there has been minimal research on the potential benefits and challenges associated with drip irrigation in North Carolina sweetpotato production; however, such research is necessary given the growing demand for the crop and the persistent desire of growers to implement crop management strategies that will increase yield and profitability.

In addition to providing better control of soil moisture, the adoption of drip irrigation could also result in more precise nutrient management over the production season by allowing growers to apply fertilizer via the irrigation system, a process known as fertigation. Fertigation is commonly used in the production of other horticultural crops in North Carolina (Southeastern Vegetable Crop Handbook, 2016) and is common in sweetpotato production in California (Stoddard et al., 2013). If drip irrigation were to be more widely embraced by North Carolina growers, the next logical step would be to integrate fertigation into the nutrient management plan.

2.2.2 Sweetpotato Water Requirements

Sweetpotato can withstand moderate drought stress (Hammet et al., 1982; Smittle et al., 1990), but like many crops, it is more susceptible to fluctuations in moisture availability during certain periods of the growing season than others. Several studies have reported that the first 9 to 20 days after transplant (DAT) are critical in determining sweetpotato yield. Togari (1950) reported that growing conditions during the first 20 DAT significantly impacted storage root initiation and thus final yield. In 'Beauregard' plants, lateral root

development has been detected as early as 9 DAT (Villordon et al., 2011) and storage root (those that develop into sweetpotatoes) initiation as early as 13 DAT (Villordon et al., 2009). The number and length of lateral roots during this period are particularly dependent on soil moisture, with soil moisture deficit reducing lateral root count and length by 49 and 103%, respectively (Villordon et al., 2012). Excess soil moisture in the same study reduced lateral root count and length by 75 and 91%, respectively (Villordon et al., 2012), compared to plants kept at ideal soil moisture. Gajanayake et al. (2013) found that the ideal soil moistures for storage root initiation in 'Beauregard' and 'Evangeline' between 14 and 50 DAT were 63% and 75% of field capacity, respectively.

While there is general consensus that soil moisture availability during root initiation is critical in determining the final yield of sweetpotatoes, there is less agreement in the literature on how to properly manage crop water throughout the growing season. Yield increase in sweetpotatoes due to irrigation has been reported (Bowers et al., 1956; Felix et al., 2015; Hammet et al., 1982; Lambeth, 1956; Hernandez and Barry, 1966; Jones, 1961; Thompson et al., 1992), but there is also evidence that over-irrigation can be detrimental to sweetpotato yields (Ghuman and Lal, 1983; Thompson et al., 1992; Watanabe, 1979). Some researchers have taken the approach of using volumetric soil moisture as the primary means for determining when to irrigate sweetpotatoes (Gajanayake et al., 2013; Villordon, 2012), while others have used approaches based on soil water tension (Felix et al., 2015; Smittle et al., 1990).

From their work on characterizing storage root initiation, Smith and Villordon (2012) suggested that the optimum volumetric soil moisture for sweetpotatoes grown in Louisiana

on a silt loam soil was between 0.15 and 0.20 mm³ mm⁻³, which represents about 50% of field capacity. In a similar study conducted in Mississippi, Gajanayake et al. (2013) found the optimum soil moisture content for storage root initiation was 0.168 and 0.199 mm³ mm⁻³ for 'Beauregard' and 'Evangeline' varieties, respectively. It should be noted that these studies were conducted in greenhouses and that plants were harvested prior to full storage root development since the focus of the research was storage root initiation.

Lambeth (1956) reported yield increases of 39, 106, and 113% for plants that were irrigated at 25, 50, and 75% of field capacity, respectively, compared to non-irrigated plants. Other studies have reported yield increases due to irrigation applied when soil moisture was at 20% of total available water (the soil water stored between field capacity and permanent wilting point), but minimal or no improvements of yields when irrigation was initiated before the 20% threshold (Bowers et al., 1956; Hammet et al., 1982, Hernandez and Barry, 1966; Jones, 1961). Thompson et al. (1992) reported on the potential negative impacts if too much irrigation is applied on sweetpotatoes. They observed marketable yield increases as total water applied increased up to 76% of seasonal pan evaporation (E_{pan}), but substantial marketable yield reductions when seasonal irrigation exceeded 76% of E_{pan} . Similarly, Watanabe (1979) and Ghuman and Lal (1983) reported yield reduction due to excessive soil moisture levels.

Additional studies have evaluated sweetpotato irrigation based on soil water tension. Felix et al. (2015) reported highest yields for sweetpotatoes irrigated at 25 and 40 kPa, with significant yield reductions at 80 and 100 kPa. Similarly, Smittle et al. (1990) found that when using a fixed irrigation threshold throughout the season, sweetpotatoes irrigated at

tensions of 25 kPa or 50 kPa yielded higher than those irrigated at 100 kPa, with the caveat that if plants were irrigated at 25 kPa through root enlargement, subsequent irrigations could be delayed until 100 kPa without any yield reductions.

2.2.3 Sweetpotato Nutrient Management

Nutrient requirements for sweetpotatoes vary depending on variety and soil-type, but on average, the crop uses 2.7 kg of nitrogen (N), 0.4 kg of phosphorus (P), and 3.7 kg of potassium (K) per 1,000 kg of harvested storage roots (Stoddard et al., 2013). On typical North Carolina soils, 'Beauregard' plants generally require N at a rate of 56 kg ha⁻¹ (Schultheis et al., 1999), but 'Covington' has shown responsiveness to greater N rates, around 101 kg ha⁻¹ (Yencho et al., 2008). Although fertilizer can be applied preplant, it is generally applied in two or three cultivations following transplant (NCSPC, 2014). Most North Carolina growers apply N fertilizer during the final cultivation at around 28 DAT (NCSPS, 2014) because N uptake by storage roots is at its maximum between 23 and 40 DAT (Smith and Villordon, 2009).

With increases in yields associated with irrigation, it is possible the sweetpotatoes grown under irrigation may also require more N than typically recommended. This is particularly of concern in sandy soils, which are more prone to N leaching. Peterson (1961) compared fertilizer rates of 24N-31P-117K (kg ha⁻¹) to 40N-53P-201K (kg ha⁻¹) in combination with irrigation rates of 25 and 38 mm wk⁻¹ and reported no yield differences associated with fertilizer rate. Similarly, Thompson et al. (1992) applied supplemental N at rates of 0, 45, and 90 kg ha⁻¹ and 0, 30, and 60 kg ha⁻¹ above the base N recommendations for

sites in Mississippi and Georgia, respectively, but saw no differences in yield or quality characteristics in 'Centennial' or 'Jewel'; however, California growers that consistently produce the highest sweetpotato yields per area planted in the United States generally apply N at rates higher than producers in the southeastern United States. Stoddard et al. (2013) published N requirements ranging from 140 to 200 kg ha⁻¹ for "high-yielding, drip-irrigated" fields in California.

In addition to applying higher rates of N to sweetpotatoes, many California producers also inject the N through drip irrigation tape over multiple fertigation events. A four-year study to determine optimum N rates for California sweetpotatoes divided N fertigation events into seven or eight applications per growing season (Stoddard and Weir, 2002). Optimal petiole NO₃-N sufficiency ranges were determined to be 3000 – 5000 ppm during vining and 2000 – 4000 ppm during root bulking. Residual soil nitrate, measured to a depth of 0.9 m, was also less than 10 ppm, indicating most of the applied nitrogen was used by the plants and not leached through the soil.

2.2.4 Study Objectives

Soil moisture and nutrient management in sweetpotatoes is especially dependent upon the variety being produced and the location in which it is grown. Growers in North Carolina could benefit from embracing drip irrigation and fertigation techniques used by other sweetpotato growers across the U.S. Thus, the goal of this study was to evaluate three soil moisture management regimes and two methods of nutrient application on 'Covington,' the

most commonly produced sweetpotato variety in North Carolina (Schultheis, 2016), with regards to yield, quality, root set, and earliness of development.

2.3 MATERIALS AND METHODS

2.3.1 Site Description

The study was conducted during the 2013 and 2014 growing seasons on separate fields at the Cunningham Research Station in Kinston, NC (35° 18' 3"N, 77° 34' 8" W). Both fields have Norfolk loamy sand soils (Fine-loamy, kaolinitic, thermic Typic Kandiudults). The preceding crop in both years was tobacco, which is a commonly rotated crop with sweetpotatoes in Eastern North Carolina.

2.3.2 Experimental Treatments

A strip-plot, split-plot (Steel et al., 1997) experimental design was used with irrigation and nitrogen fertilizer application treatments as between plot factors and harvest as a within plot factor (Appendix A). Main plots were replicated four times across the field in each year.

2.3.2.1 Irrigation

There were three irrigation treatments: minimal irrigation (Control), timer based irrigation (Timer), and “smart” irrigation (Smart). The Control treatment was intended to simulate rainfed production, the most common practice currently used in North Carolina (i.e. no irrigation); however, this management practice did receive a small amount of irrigation water (37 mm in 2013 and 19 mm in 2014), only during fertigation events. The Timer system was scheduled to apply 5 mm of water every Monday and Thursday with a rain

switch to bypass irrigation following a rainfall accumulation greater than 6 mm. The rain switch was originally set in 2013 to 12 mm, but was changed to 6 mm on 8 July 2013 (and for the entirety of the 2014 season) after it was noted that the higher setting was not adequately bypassing irrigation events following rainfall. The Smart system was also set to apply 5 mm of water during each irrigation event, but this system had the opportunity to run on any day of the week versus two specific days assigned to the Timer system. Irrigation in the Smart treatment was triggered on days when the volumetric soil moisture content dropped below $0.12 \text{ mm}^3 \text{ mm}^{-3}$. The soil moisture threshold was determined based on the measured soil water content at 30 kPa ($0.11 \text{ mm}^3 \text{ mm}^{-3}$) from soil water retention curves developed from intact soil cores collected at the beginning of the 2013 growing season and based on prior experience with irrigation management on similar soils. The original intent was to increase the application depth over the course of the growing season as the plant water demands increased; however, due to the wet growing seasons in 2013 and 2014, the application depth remained constant at 5 mm per event.

2.3.2.2 Nitrogen Fertilizer Application Method

Two nitrogen fertilizer application treatments were applied in strips across all irrigation treatments. Nitrogen was side dressed to one half of the field in a single, surface application of granular fertilizer (referred to as Side Dressed from here forward) and was applied to the other half via the drip tape using liquid fertilizer (referred to as Fertigated from here forward) over seven different application events, spanning eight weeks (see Appendix A). The same total amount of elemental nitrogen 118 kg ha^{-1} was applied to the entire field over the course of the season. The differences between field halves were the timing and

method of nitrogen application. Ammonium-nitrate (34-0-0) was surface applied to the Side Dressed half of the field on 10 July 2013 (28 DAT) and 1 July 2014 (22 DAT) at a rate of 118 kg ha⁻¹. Liquid ammonium-nitrate (19-0-0) was applied weekly to the Fertigated half of the field during the periods 16 July – 3 September 2013 and 7 July – 26 August 2014, at the rates shown in Tables 2.1 and 2.2. The seven fertigation events took eight weeks to apply in both years due to heavy rainfall coinciding with a scheduled fertigation event that had to be postponed. During each fertigation event, the irrigation system on the Side Dress side of the field (including the Control rows) ran for the same duration as the fertigation event (applying only water, no fertilizer solution). The Control treatment rows received minimal irrigation to ensure that the entire length of each irrigation row received the same amount of water over the course of the season (i.e., to prevent the Side Dress treatment plots from receiving less water than the Fertigated treatment plots). In 2013, each fertigation event was the same length in time as an irrigation event (1 hour 36 minutes; resulting in approximately 5 mm of water applied). In 2014, the length of fertigation events was shortened to the time required to move all of the ammonium nitrate solution through the system (generally around 35 minutes; resulting in less than 2 mm of water applied).

2.3.2.3 Harvests

Each irrigation by fertilization strip-plot was subdivided into three harvest split-plots, from which a single harvest was collected at either 13 (Early), 16 (Middle), or 19 (Late) weeks after transplant, such that there were three representative harvests from each replicate of each irrigation by fertilization treatment (Appendix A). Harvest subplots were 10.2 m long by three rows (3.2 m) wide. Ten consecutive plants were harvested from a 3.0 m

section of the center row of each harvest subplot. Plants were individually harvested by hand and graded according to the U.S. Department of Agriculture standard (USDA, 2005), which classifies roots as U.S. No. 1 (diameter of 44 to 89 mm and length of 76 to 229 mm), canner (diameter 25 to 44 mm), and jumbo (diameter > 89 mm or length > 229 mm). Sweetpotatoes that were severely misshapen were graded as culls. Counts and weights of each grade of roots were recorded for each harvested plant (240 total plants per harvest). Per plant yields (kg ha^{-1}) were estimated for each root grade by dividing corresponding weights by the representative area of each plant (3.3×10^{-5} ha). Counts, weights, and yields were averaged across subplots prior to the statistical analysis.

2.3.3 Crop Management

Chlorpyrifos (Warhawk[®]), Clomazone (Command[®]), and Flumioxazin (Valor[®]) were applied prior to transplant at rates of 4.7 L ha^{-1} , 2.0 L ha^{-1} , and 0.18 L ha^{-1} , respectively. ‘Covington’ sweetpotato slips were transplanted on thirty-six, 61 m long rows using a two-row transplanter on 12 June 2013 and 9 June 2014. Rows were spaced 1.1 m apart and within row plant spacing was 0.3 m. Fertilizer, 0-15-38 N-P-K analysis, was side dressed at 448 kg ha^{-1} on 8 July 2013 (26 DAT) and 26 June 2014 (16 DAT) and incorporated into the soil across all treatments.

2.3.4 Irrigation System and Instrumentation

Immediately following transplant, John Deere T-Tape drip tape (Deere & Company, Moline, IL) with 0.3 m emitter spacing, rated at 1.02 L hr^{-1} , was laid on the surface of each plant row and secured in place with 150 mm by 25 mm metal sod staples (such as those used

for installing erosion control blankets or landscape fabric). Each drip line was connected to the appropriate layflat header depending on which irrigation treatment the row was assigned (Appendix A). The tail end of each drip line was connected to a separate header that was used during fertigation events. Ball valves installed in the middle and at the distal end of each drip line allowed the system to be converted between irrigation mode and fertigation mode (Appendix A). While in irrigation mode (Appendix A), the mid-line ball valves remained open and the distal end ball valves were closed, so that water was supplied to each row from the appropriate irrigation header line. During fertigation mode (Appendix A), the mid-line valves were closed and the distal end valves were opened, meaning half of each drip line received a water-fertilizer solution from the fertigation header while the other half received water only from the irrigation headers.

The irrigation water source was a pond on the research station. Water was pumped through two 0.61 m (24 in.) Flow-Guard sand filters (Fresno Valves & Castings, Selmas, CA) prior to entering the drip system. Irrigation water volume applied to each irrigation regime was monitored using 25 mm (1in.) water meters (model DLJ 100 with pulse output; Daniel Jerman Company, Hackensack, NJ) in combination with HOBO pendant loggers (Onset Corporation, Pocasset, MA). Irrigation was controlled using a Hunter XC Hybrid controller (Hunter Industries, San Marcos, CA) and each irrigation event (for both the Timer and Smart systems) took 1 hour 36 minutes to complete.

Decagon 5TM soil moisture sensors and Decagon MPS-2 dielectric water potential sensors were installed at a depth of 150 mm (6 in.) in each plant row (excluding buffer rows) in the middle of each half of the field (fertigated and top-dressed) and were connected to

Decagon EM50 and EM50G data loggers (Decagon Devices, Pullman, WA). The loggers recorded volumetric soil moisture and soil water tension in each row every 15 minutes. Each of the soil moisture sensors in the Smart irrigation rows were connected to EM50G data loggers equipped with cellular capabilities that uploaded data to a server for subsequent remote access. Soil moisture levels in the Smart system rows were monitored each afternoon, and irrigation was remotely activated if more than half the Smart soil moisture sensors readings had dropped below $0.12 \text{ mm}^3 \text{ mm}^{-3}$. The treatment layout and soil moisture sensor and data logger configurations are shown in Appendix A.

2.3.5 Weather Data Collection

Over the course of the study, daily measured rainfall, air temperature, relative humidity, solar radiation, wind speed, and daily estimated reference evapotranspiration (ET_o), based on the Food and Agricultural Organization (FAO) 56 Penman-Monteith equation (Allen et al. 1998), were obtained from an onsite North Carolina Environment and Climate Observing Network (NC ECONet) weather station (managed by the State Climate Office of North Carolina). Daily growing degree days accumulated were calculated using the equation:

$$GDD = \frac{T_{\max} + T_{\min}}{2} - T_{\text{base}} \quad [2.1]$$

where,

GDD = daily growing degree days accumulated (GDD)

T_{\max} = maximum daily air temperature (if $T_{\max} > T_{\text{upper}}$, set $T_{\max} = T_{\text{upper}}$) ($^{\circ}\text{C}$)

T_{\min} = minimum daily air temperature (if $T_{\min} < T_{\text{base}}$, set $T_{\min} = T_{\text{base}}$) ($^{\circ}\text{C}$)

T_{base} = base temperature, below which no growth is assumed to occur ($^{\circ}\text{C}$) (taken as 15.5°C ; Villordon et al., 2009)

T_{upper} = upper temperature limit, above which it is assumed the growth rate ceases to increase ($^{\circ}\text{C}$) (taken as 32.2°C ; Villordon et al., 2009).

2.3.6 Plant Tissue and Soil Nutrient Analysis

Plant tissue and soil samples were collected from each of the six combinations of the irrigation (Control, Smart, Timer) by fertilization (Fertigated, Side Dressed) treatments on three dates in 2013 (16 July, 12 August, and 11 September) and on four dates in 2014 (1 July, 21 July, 18 August, and 10 September) to monitor the nitrogen status of the plants and soil over the course of the growing season. During each sampling event, young, fully mature leaves were randomly harvested from approximately twenty plants to create a composite sample for each fertilization by irrigation treatment. Similarly, approximately ten soil samples were collected from within treatment rows to a depth of 150 mm using a standard 25 mm soil probe and combined to form composite samples. The first plant tissue and soil samples collected in 2013 were taken six days after the Side Dressed plots had received N, but prior to the start of the first N fertigation event. In 2014, initial samples were collected prior to both Side Dressed and Fertigated N being applied. Plant tissue samples were dried, ground, and analyzed for $\text{NO}_3 + \text{NO}_2\text{-N}$ content. Soil samples were analyzed using a LECO CN-2000 (LECO Corporation, St Joseph, MI) dry combustion macro-analyzer to determine carbon (C) and N contents.

2.3.7 Statistical Analysis

Yield and root set (count) data were analyzed using the PROC MIXED procedure in Statistical Analysis Software (SAS Version 9.4; SAS Institute, Inc., Cary, NC). Appropriate analysis of variance (ANOVA) was generated based on the strip-plot, split-plot design (Steel et al., 1997) for yield and root set for each grade of sweetpotato (U.S. No. 1, Canner, Jumbo, and Cull), as well as for marketable grades (U.S. No. 1, Canner, and Jumbo combined) and total (all grades combined). Irrigation treatment, fertilization method, harvest, and all possible interactions among the three were modeled as fixed effects. Year, replication nested within year, replication by irrigation nested within year, replication by fertigation nested within year, and replication by irrigation by fertigation nested within year were modeled as random effects. Mean separation tests were conducted with the LSMEANS statement using $\alpha = 0.05$.

2.4 RESULTS AND DISCUSSION

2.4.1 Weather

The 2013 and 2014 growing seasons were two of the wettest growing seasons on record among eighteen years (1997 – 2014) of continuous rainfall data available for the Cunningham Research Station, particularly in the early months of the growing seasons (Figure 2.1). Rainfall totals in June 2013 (253 mm) and June 2014 (294 mm) were 2.1 and 2.4 times the long-term mean rainfall in June, respectively. Combined June and July rainfall amounts in 2013 (393 mm) and 2014 (580 mm) were the two highest totals for that period

among the eighteen years of continuous data. The next highest June and July rainfall total was 332 mm in 2007, 15% less than in 2013 and 42% less than in 2014.

Rainfall during the months of June and July are of particular interest because it is usually during these months that the North Carolina sweetpotato crop is in the critical stage of development (20 - 40 DAT), when yield potential is being determined and when plants are most susceptible to drought or excess water stress. The amount of total rainfall received during this period is important, but possibly even more important is the timing and frequency of the rainfall.

Rainfall in the 2014 growing season (Figure 2.2A) was generally of greater magnitude than in 2013 (Figure 2.2B); however, it was more frequent in 2013 than in 2014, especially in the first 20 DAT. This is evidenced in the nearly continuous slope of the total cumulative rainfall plot for the beginning of the 2013 season (Figure 2.3A), compared to the "stair-step" nature of the plot early in the 2014 season. Fifteen of the first twenty days after transplant in 2013 had rainfall of at least 2.5 mm, including three days with greater than 23 mm of rainfall each, which resulted in the soil staying in a nearly continuous state of saturation. Comparatively, there were only ten days with at least 2.5 mm of rainfall during the first forty days after transplant in 2014, and five of them had more than 50 mm of rainfall. Although rainfall amounts in 2014 were typically greater than those in 2013, much of the 2014 rainfall was presumably lost to runoff or deep percolation since the magnitudes of the events exceeded the water holding capacity of the soil and as evidenced by steep declines in recorded soil moisture values during days immediately following such events. Additionally,

the longer periods between rainfall events in 2014 compared to 2013 allowed soil moisture drawdown to occur and prevented waterlogging.

Despite having substantially different rainfall patterns in the 2013 and 2014 growing seasons, growing degree day accumulations, cumulative ET_o , and daily minimum and maximum temperatures followed similar trends (Figures 2.6A – 2.6C). Daily maximum temperatures during the first thirty days after transplant were lower in 2013 (when the almost daily rainfall occurred) than in 2014; however, growing degree day accumulation was similar to 2014 as even the cooler daily maximum temperatures in 2013 mostly stayed near the upper temperature threshold ($32.2^{\circ} C$) used for calculating growing degree days.

2.4.2 Irrigation

Due to the abundance of rainfall during both growing seasons, there was essentially no need for irrigation throughout the study. The Smart irrigation treatment applied a total of 10 mm of irrigation in 2013 over two irrigation events (Figure 2.4B), one on 16 September (96 DAT) and the other on 19 September (99 DAT), both of which followed the first harvest (Table 2.3). The Smart treatment applied 5 mm water in a single event in 2014, on 4 September (87 DAT) (Figure 2.5B). These irrigation totals do not include water applied during fertigation events, which totaled 37 mm in 2013 and 19 mm in 2014 (Table 2.3; Figures 2.4 and 2.5). The Timer treatment applied 91 mm of water in 2013 (not including fertigation) (Figure 2.7C), bypassing 18 of 36 possible irrigation events, and 81 mm of water in 2014 (not including fertigation) (Figure 2.5C), bypassing 15 of 31 possible irrigation events.

There were fewer irrigation opportunities in 2014 because the irrigation system was not fully operational until 22 DAT versus being fully functional 6 DAT in 2013. While the rain switch did effectively reduce irrigation totals from what they would have been without it, the Timer treatment still ran more than was necessary in both years, suggesting that a rain switch alone will not suffice if over-irrigation is to be prevented. In fact, during periods of extended rainfall in both seasons there were occasions when station personnel turned the irrigation controller completely off, meaning some of the bypassed irrigation events may have been a product simply of the controller manually being turned off instead of the rain switch automatically bypassing an irrigation event.

2.4.3 Soil and Plant Nutrients

The average soil N level for the Side Dressed plots ($18.3 \mu\text{g g}^{-1}$) was 9.2 times higher than in the Fertigated plots ($2.0 \mu\text{g g}^{-1}$) at the first sampling date in 2013 (34 DAT) (Figure 2.6). This likely was a result of the samples being collected six days after the side dress application of N, yet prior to the first N fertigation event. In 2014, despite the first soil samples being taken prior to any N fertilizer being applied (22 DAT), the average soil N level in the Side Dressed plots ($26.6 \mu\text{g g}^{-1}$) was still substantially higher than that in the Fertigated plots ($6.5 \mu\text{g g}^{-1}$) (Figure 2.8); however, the standard deviation of the soil N levels comprising the Side Dressed composite sample was $20.0 \mu\text{g g}^{-1}$, indicating this high average reading may have been erroneous. Similarly high variability (standard deviation = $12.6 \mu\text{g g}^{-1}$) was also observed in the second Side Dressed soil N samples collected in 2013 (61 DAT). Outside of this unexplainable variability, the general soil N dynamics across both seasons

reflected the timing of N fertilizer application for both N fertilization methods. The average soil N in the Side Dressed plots generally started at more elevated levels early in the season and trended downward as the season progressed. The soil N in the Fertigated plots was less dynamic across both years, remaining between 1 and 6 $\mu\text{g g}^{-1}$ consistently, but there was evidence of a slight increase in soil N in the Fertigated plots between 60 and 70 DAT as the cumulative N applied approached the total N applied in the Side Dressed plots early in the seasons.

Plant tissue N levels were similarly responsive to fertilizer timing in both seasons for both fertilization methods (Figures 2.7 and 2.9). Plant tissue N was greatest in the Side Dressed plots early in both seasons, following the side dress N application, but then decreased at a linear rate in both years to 3.2% N prior to the first harvest. The Fertigated plots exhibited more consistent plant N levels throughout the seasons, with the plant N levels at the end of both seasons being slightly higher in the Fertigated plots than the respective levels in the Side Dressed plots. Plant N levels remained slightly above or within the suggested range of 3.3 to 4.5% (Mills and Jones, 1996) across both fertilization treatments for the better part of both seasons, never exceeding the toxic level (7%) defined by Jiang (2013); however, the downward seasonal trend in plant tissue N in the Side Dressed plots as well as the final plant N level of 3.2% in Side Dressed plots just prior to harvest in both years suggest that the Side Dressed plants may have experienced mild N stress, while the Fertigated plants remained at a satisfactory N level. These observations also suggest that fertigation may have led to greater N uptake, higher fertilizer use efficiency, and less N leaching than the side dress application of N. If so, properly timed fertigation could reduce

total N application requirements in sweetpotato production, thus reducing fertilizer costs, while enhancing productivity and protecting ground and surface water.

Despite these potential benefits of fertigation evidenced in this study, there were also disadvantages. Most importantly, relying on irrigation water as the method of delivering N fertilizer to the crop during wet growing seasons presented situations in which a choice had to be made between waiting for drier conditions to apply fertilizer, at the risk of inducing nutrient stress, or applying N when needed at the risk of compounding plant stress due to excess water, while also increasing the potential for N leaching in a near saturated soil profile.

Also, in both seasons it was observed that vine color was a darker green and growth was more vigorous in the Side Dressed plots than in the Fertigated plots around 30 to 50 DAT; however, as fertigation continued, vine growth and color in the Fertigated plots appeared to eventually match what was exhibited earlier in the Side Dressed plots. This suggests that fertigation events should have been started earlier than they were, or have had greater proportions of the total N applied earlier in the fertigation schedule when potential for vine growth was at its highest. The fertigation schedule and rates were based on research conducted in California (Stoddard and Weir, 2002) since California is the primary state where fertigation of sweetpotatoes is routinely practiced. The growing season in California is typically longer than in North Carolina; the plants in the referenced study were harvested 159 DAT, compared to 133 DAT for the Late harvest in this study. Had the fertigation schedule been based off of percent of growing season instead of simply days after transplanting, the fertigation events would have started five to ten days earlier than they did

and could have been consolidated to a five- to six-week schedule instead of seven to eight weeks.

2.4.4 Yield, Quality, Root Set, and Earliness

Irrigation, as a main effect, did not significantly impact yield (Table 2.4) or root set (Table 2.5) probably due to the above normal rainfall early and throughout the production season in both study years. There were significant interaction effects between harvest and irrigation on jumbo yield ($p = 0.0023$) and on marketable yield ($p = 0.0198$), and evidence of this interaction effect on total yield ($p = 0.0502$) (Table 2.4). Late harvested plants in the Smart irrigation treatment yielded the most jumbos ($16,330 \text{ kg ha}^{-1}$), 41% more than the Late-Control ($11,596 \text{ kg ha}^{-1}$) and 64% more than the Late-Timer ($9,974 \text{ kg ha}^{-1}$) (Table 2.6; Figure 2.10). Similarly, the Late-Smart combination yielded 12% more marketable roots ($51,858 \text{ kg ha}^{-1}$) than the Late-Control ($46,122 \text{ kg ha}^{-1}$) and 15% more than Late-Timer ($45,128 \text{ kg ha}^{-1}$), neither of which were statistically different from the marketable root yields of the Middle-Smart ($43,209 \text{ kg ha}^{-1}$) and Middle-Timer ($42,137 \text{ kg ha}^{-1}$) treatments (Table 2.6; Figure 2.10).

The yield data presented in Table 2.6 and Figure 2.10 suggests that the Smart irrigation events, which only occurred late in both the 2013 and 2014 growing seasons, led to an increased rate of root sizing in the Smart treatment, compared to the Control and Timer treatments, from the Early harvest through the Late harvest. There was no statistical difference in marketable yields among the Control ($35,921 \text{ kg ha}^{-1}$), Timer ($35,127 \text{ kg ha}^{-1}$), and Smart ($32,620 \text{ kg ha}^{-1}$) treatments at the Early harvest (Table 2.6; Figure 2.10); however,

despite applying an average of seven times more water than the Smart treatment over the six weeks between the Early and Late harvests across both years, the Timer marketable yield only increased by 28%, whereas the Smart marketable yield increased 59% during the same period. This increase was particularly evidenced in the difference between jumbo yields from the Middle (6,155 kg ha⁻¹) to Late (16,330 kg ha⁻¹) harvest within the Smart treatment (Figure 2.10), an increase of 165%, without negatively impacting the U.S. No. 1 yield (i.e., the increase in jumbo yield did not come at the expense of a decrease in the more valuable U.S. No. 1 yield). This supports that minimal, yet properly timed, irrigation can increase yield, while also conserving water compared to over-irrigation. Likewise, over-irrigation not only wastes water, it may compromise yield, as reflected by the higher Late-Control marketable yield (42,122 kg ha⁻¹) compared to the Late-Timer marketable yield (45,128 kg ha⁻¹).

Yields and root sets were generally not affected by nitrogen fertilizer application method, except for canners ($p = 0.0355$; Table 2.5), which were produced in slightly greater numbers per hill when Side Dressed versus Fertigated. There were interaction effects of fertilization method and harvest on canner, jumbo, and cull yields (Table 2.4), as well as root set for U.S. No. 1 roots, jumbos, and culls (Table 2.5). The Late harvest-Fertigated plants produced 33% more jumbos by root count (0.65 jumbo roots per hill) and 36% more by weight (14,554 kg jumbos ha⁻¹) than the Late-Side Dressed treatment (0.49 jumbo roots per hill; 10,712 kg jumbos ha⁻¹) (Tables 2.6 and 2.7); however, there was no difference in jumbo yield between Fertigated and Side Dressed at either the Early or Middle harvests. There was some evidence of an interaction effect between nitrogen fertilizer application method and

harvest on U.S. No. 1 yields ($p = 0.0800$; Table 2.4, Table 2.6, and Figure 2.11). U.S. No. 1 yield for the Middle-Fertigated treatment ($31,085 \text{ kg ha}^{-1}$) was similar to that for the Late-Side Dressed treatment ($33,828 \text{ kg ha}^{-1}$), which is an indication that maximum U.S. No. 1 yields could possibly be reached in a shorter time after transplant with fertigation than when using a typical side dress method of applying nitrogen.

Harvest was the only significant main effect on both yield (Table 2.4) and root set (Table 2.5). Average U.S. No. 1, jumbo, cull, marketable, and total yields increased 15, 29, 421, 139, 38 and 41% respectively from the Early to Late harvest (Table 2.6). Only the canner yield decreased (29%) from Early to Late, presumably because roots that would have been graded as canners if harvested earlier in the season grew into larger, more valuable, root grades as harvest was delayed. Likewise, the number of canner roots per hill decreased from Early to Middle to Late harvest (Table 2.7), while the number of jumbo and cull roots increased. There was no difference in the number of total roots per hill by harvest since total root set is determined early in the growing season, after which only the distribution of roots per grade is affected by time.

There was substantial variation in yield and root set from 2013 to 2014. P-values for the random effect of year on yield were less than 0.029 for all root grades except jumbos ($p = 0.0819$) (Table 2.4). Year-to-year variation in root set was similar (Table 2.5). U.S. No. 1 ($36,072 \text{ kg ha}^{-1}$) and total ($51,501 \text{ kg ha}^{-1}$) root yields in 2014 were 49 and 51% higher than in 2013, respectively (Table 2.8). Similarly, plants in 2014 averaged about one more total storage root per hill than in 2013 (Table 2.8).

The increase in yield from 2013 to 2014 may be attributable to the differences in rainfall patterns between seasons. Both years had more than adequate total seasonal rainfall, but the beginning of the 2013 season was consistently wet, as previously noted, whereas rainfall events in 2014 were of larger magnitude, but further spread out (Figures 2.2 and 2.3A). The nearly daily rainfall in the first 30 DAT of 2013 likely led to the reduction in root set due to higher than needed soil moisture conditions (Villordon et al., 2012) and thus limited the yield potential for the rest of the season. Extended wet weather was also conducive to weed pressure from yellow nutsedge (*Cyperus esculentus* L.), which affected some parts of the field and may have reduced yields.

2.5 SUMMARY AND CONCLUSIONS

This study was designed to evaluate the potential benefits of drip irrigation and fertigation in field production of sweetpotatoes in Eastern North Carolina. The 2013 and 2014 growing seasons were two of the wettest in recent history at the study site in Kinston, North Carolina, thus limiting the need for irrigation. Not including fertigation events, the Smart irrigation treatment ran twice in 2013 and a single time in 2014, applying a total of 10 and 5 mm, respectively. The Timer treatment applied substantially more water (91 mm in 2013 and 81 mm in 2014), but with no benefits to yield, root set, or earliness compared to either the Smart or Control treatments, evidencing the limitations of a time based irrigation schedule, particularly during a wet growing season and in a region where precipitation amount and timing are highly variable.

Total yields in 2014 – when rainfall was of generally greater magnitude, but also more spread out – were 51% higher than in 2013 – when frequent, moderate rainfall occurred, particularly early in the season. This supports the findings of Villordon et al. (2012) that soil water logging during the first 20 days after transplant may detrimentally affect yield.

While neither irrigation nor fertigation had pronounced impacts on yield or root set in general, there was limited evidence that the use of irrigation or fertigation may increase yield, particularly of jumbos, when plants are harvested later in the season. This could have implications on sweetpotato production targeted for the processing industry, which generally prefers larger roots that result in less waste during processing (e.g., cutting fries).

Soil N, plant tissue N, and visual observations of vine growth during both growing seasons suggest that fertigation may have been more beneficial had it been started earlier in the season. Fertigation rates and timing were based on days after transplant according to practices used in California, where the growing season is three to four weeks longer than in North Carolina. Possible considerations for future studies might be to start fertigation five to ten days earlier (18 – 23 DAT) and consolidate the fertigation schedule to five or six weeks to proportionally match the North Carolina growing season

Further investigation is necessary to evaluate irrigation and fertilization practices when sweetpotatoes are grown under moisture limited conditions encountered in North Carolina. Combined irrigation and fertigation systems are vital to sweetpotato production in arid regions such as California, and similar benefits may be extended to humid regions if managed properly. Sweetpotato yield increases by irrigation in humid climates have been

well documented (Bowers et al., 1956; Hammet et al., 1982, Hernandez and Barry, 1966; Jones, 1961, Lambeth, 1956, Thompson et al., 1992), but additional work is needed to investigate the potential interaction effects of combined irrigation and nutrient management systems. Drip irrigation and fertigation during production seasons with limited moisture have been reported to be beneficial for other crops, including cotton (Dougherty et al., 2009; Veeraputhiran et al., 2005), okra (Danso et al., 2015), and tomato (Kennedy et al., 2013; Hanson and May, 2003), and it is conceivable that similar benefits could be recognized in sweetpotatoes.

Despite the potential benefits of fertigation, including yield increases and the ability to precisely control the timing of nitrogen application with it, this study highlights some of the challenges of using fertigation, particularly in a wet year. Relying on irrigation as the application mechanism of nitrogen fertilizer in a wet year may result in plant roots being subjected to extended periods of root inundation and challenges in getting the required nutrients to the crop. This could also increase the potential for leaching as nitrogen may be applied to a soil profile that is already at or near saturation. However, in general, the ability to distribute nitrogen applications over the course of the growing season, as opposed to surface applying all of it on one date early in the season, should reduce the chances for nitrogen losses to leaching or runoff and allow for improved fertilizer use efficiency.

Potential in realizing the benefits of a combination drip irrigation and fertigation system in sweetpotato in North Carolina would be more certain with further study of the timing and rates of fertilizer application in conjunction with improved irrigation management application practices. Real-time decision support systems that account for weather variability

in making fertilization and irrigation recommendations should also be considered. Other logistical challenges, including the placement of drip tape after transplant and the removal of it at or prior to harvest, will also need to be addressed before widespread adoption of the practice can be expected.

Although this study did not demonstrate any consistent yield advantage for North Carolina growers, given the extremely wet growing seasons, continued research would seem appropriate. There would seem to be potential of improving and reaching higher yields in North Carolina, particularly during seasons with more limited moisture, similar to those that are currently being achieved in California with the use of irrigation and fertigation.

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2.7 TABLES

Table 2.1. 2013 fertigation schedule.

Date	DAT	Nitrogen Applied (kg ha ⁻¹)
Jul. 16	34	11
Jul. 22	40	17
Jul. 29	47	17
Aug. 5	54	22
Aug. 12	61	17
Aug. 19	68	0 ^a
Aug. 26	75	17
Sep. 3	83	17

^aFertigation skipped due to heavy rainfall.

Table 2.2. 2014 fertigation schedule.

Date	DAT	Nitrogen Applied (kg ha ⁻¹)
Jul. 7	28	11
Jul. 14	35	17
Jul. 21	42	17
Jul. 29	50	22
Aug. 5	57	0 ^a
Aug. 12	64	17
Aug. 18	70	17
Sep. 26	78	17

^aFertigation skipped due to heavy rainfall.

Table 2.3. Cumulative water received by crop via irrigation, fertigation, and rainfall through each harvest in each year.

Harvest	DAT		Cumulative Water Applied (mm)							
			Timer Irrigation		Smart Irrigation		Fertigation		Rainfall	
	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
Early	91	93	51	51	0	5	37	19	487	793
Middle	112	112	76	71	10	5	37	19	487	864
Late	133	133	91	81	10	5	37	19	488	901

Table 2.4. Analysis of Variance (ANOVA) for each yield by root grade model.

Grade	Source	DF	SS	MS	Error DF	F	p Value
US No. 1	Harvest	2	405910313	202955157	84	5.58	0.0053
	Irr	2	153925532	76962766	14	1.6	0.2359
	Harvest*Irr	4	209410533	52352633	84	1.44	0.2284
	Fert	1	493000	493000	7	0.01	0.9391
	Harvest*Fert	2	189484641	94742320	84	2.6	0.0800
	Irr*Fert	2	40355045	20177522	14	0.82	0.4609
	Harvest*Irr*Fert	4	335379432	83844858	84	2.3	0.0650
	Rep(Year)	6	368500815	61416803	9.5312	0.6	0.7236
	Rep*Irr(Year)	14	671639446	47974246	14	1.95	0.1123
	Rep*Fert(Year)	7	550400818	78628688	14	3.19	0.0307
	Rep*Irr*Fert(Year)	14	344852383	24632313	84	0.68	0.7904
	Year	1	5101238822	5101238822	6	83.06	<.0001
	Residual	84	3056508218	36387003			
	Canner	Harvest	2	33215894	16607947	84	4.49
Irr		2	5401595	2700797	14	0.73	0.4988
Harvest*Irr		4	26858076	6714519	84	1.81	0.1336
Fert		1	22534004	22534004	7	2.14	0.1873
Harvest*Fert		2	32045183	16022591	84	4.33	0.0162
Irr*Fert		2	13376091	6688046	14	1.66	0.2246
Harvest*Irr*Fert		4	21682368	5420592	84	1.47	0.2201
Rep(Year)		6	53857152	8976192	5.8014	0.88	0.5624
Rep*Irr(Year)		14	51712317	3693737	14	0.92	0.5614
Rep*Fert(Year)		7	73876765	10553824	14	2.63	0.0588
Rep*Irr*Fert(Year)		14	56245682	4017549	84	1.09	0.3821
Year		1	73193053	73193053	6	8.15	0.0290
Residual		84	310787622	3699853			
Jumbos		Harvest	2	2504973774	1252486887	84	48.22
	Irr	2	15012834	7506417	14	0.12	0.8895
	Harvest*Irr	4	470893679	117723420	84	4.53	0.0023
	Fert	1	14953687	14953687	7	0.62	0.4572
	Harvest*Fert	2	231743640	115871820	84	4.46	0.0144
	Irr*Fert	2	985771	492886	14	0.01	0.9858
	Harvest*Irr*Fert	4	11855034	2963759	84	0.11	0.9772
	Rep(Year)	6	289842989	48307165	6.189	0.91	0.5439
	Rep*Irr(Year)	14	890277903	63591279	14	1.84	0.1328
	Rep*Fert(Year)	7	169106753	24158108	14	0.7	0.6728
	Rep*Irr*Fert(Year)	14	483576786	34541199	84	1.33	0.2078
	Year	1	210526516	210526516	6	4.36	0.0819
	Residual	84	2182058191	25976883			

Table 2.4 continued.

Grade	Source	DF	SS	MS	Error DF	F	p Value
Culls	Harvest	2	45858256	22929128	84	6.33	0.0027
	Irr	2	2166017	1083008	14	0.21	0.8157
	Harvest*Irr	4	10285399	2571350	84	0.71	0.5871
	Fert	1	14778884	14778884	7	1.59	0.2482
	Harvest*Fert	2	27696611	13848306	84	3.83	0.0257
	Irr*Fert	2	3904555	1952278	14	1.45	0.2678
	Harvest*Irr*Fert	4	11080608	2770152	84	0.77	0.5508
	Rep(Year)	6	31976309	5329385	12.043	0.4	0.8630
	Rep*Irr(Year)	14	73371430	5240816	14	3.89	0.0079
	Rep*Fert(Year)	7	65210798	9315828	14	6.92	0.0011
	Rep*Irr*Fert(Year)	14	18854861	1346776	84	0.37	0.9793
	Year	1	109193303	109193303	6	20.49	0.0040
	Residual	84	304072269	3619908			
Marketable	Harvest	2	4150022822	2075011411	84	39.79	<.0001
	Irr	2	191164214	95582107	14	1.40	0.2801
	Harvest*Irr	4	646125982	161531495	84	3.10	0.0198
	Fert	1	2503165	2503165	7	0.02	0.8935
	Harvest*Fert	2	490873	245437	84	0	0.9953
	Irr*Fert	2	101334787	50667394	14	1.37	0.2857
	Harvest*Irr*Fert	4	356151815	89037954	84	1.71	0.156
	Rep(Year)	6	349387546	58231258	9.1696	0.36	0.8866
	Rep*Irr(Year)	14	958869098	68490650	14	1.85	0.1300
	Rep*Fert(Year)	7	909410961	129915852	14	3.52	0.0216
	Rep*Irr*Fert(Year)	14	517003023	36928787	84	0.71	0.7603
	Year	1	8927941137	8927941137	6	153.32	<.0001
	Residual	84	4380140383	52144528			
Total	Harvest	2	5064481375	2532240687	84	45.85	<.0001
	Irr	2	174164292	87082146	14	1.01	0.3900
	Harvest*Irr	4	547358643	136839661	84	2.48	0.0502
	Fert	1	5117513	5117513	7	0.04	0.8412
	Harvest*Fert	2	35199202	17599601	84	0.32	0.7280
	Irr*Fert	2	131414939	65707470	14	1.62	0.2323
	Harvest*Irr*Fert	4	335065839	83766460	84	1.52	0.2047
	Rep(Year)	6	448424658	74737443	10.177	0.45	0.8265
	Rep*Irr(Year)	14	1209511624	86393687	14	2.13	0.0842
	Rep*Fert(Year)	7	828737938	118391134	14	2.92	0.0415
	Rep*Irr*Fert(Year)	14	566756756	40482625	84	0.73	0.7356
	Year	1	11011845944	1.1012E+10	6	147.34	<.0001
	Residual	84	4638891182	55224895			

Table 2.5. Analysis of Variance (ANOVA) for each root set by root grade model.

Grade	Source	DF	SS	MS	Error DF	F	p Value
US No. 1	Harvest	2	1.000842	0.500421	84	1.59	0.2095
	Irr	2	1.075113	0.537556	14	0.99	0.3958
	Harvest*Irr	4	0.928142	0.232036	84	0.74	0.5684
	Fert	1	0.021879	0.021879	7	0.02	0.8955
	Harvest*Fert	2	2.364592	1.182296	84	3.76	0.0272
	Irr*Fert	2	1.108863	0.554431	14	1.14	0.3466
	Harvest*Irr*Fert	4	2.013142	0.503286	84	1.60	0.1815
	Rep(Year)	6	4.566554	0.761092	6.4709	0.62	0.7147
	Rep*Irr(Year)	14	7.593012	0.542358	14	1.12	0.4181
	Rep*Fert(Year)	7	8.252878	1.178983	14	2.43	0.0743
	Rep*Irr*Fert(Year)	14	6.784818	0.48463	84	1.54	0.1140
	Year	1	17.76271	17.76271	6	23.34	0.0029
	Residual	84	26.3987	0.31427			
Canner	Harvest	2	6.050113	3.025056	84	9.91	0.0001
	Irr	2	0.357196	0.178598	14	0.81	0.4652
	Harvest*Irr	4	3.924913	0.981228	84	3.21	0.0166
	Fert	1	5.850352	5.850352	7	6.75	0.0355
	Harvest*Fert	2	0.704766	0.352383	84	1.15	0.3202
	Irr*Fert	2	0.783307	0.391654	14	0.75	0.4902
	Harvest*Irr*Fert	4	2.637552	0.659388	84	2.16	0.0805
	Rep(Year)	6	2.398082	0.39968	2.4555	0.71	0.6786
	Rep*Irr(Year)	14	3.091484	0.22082	14	0.42	0.9403
	Rep*Fert(Year)	7	6.063294	0.866185	14	1.66	0.1986
	Rep*Irr*Fert(Year)	14	7.304818	0.521773	84	1.71	0.0688
	Year	1	1.652296	1.652296	6	4.13	0.0883
	Residual	84	25.64307	0.305275			
Jumbos	Harvest	2	5.022196	2.511098	84	51.23	<.0001
	Irr	2	0.014384	0.007192	14	0.06	0.9389
	Harvest*Irr	4	0.649392	0.162348	84	3.31	0.0143
	Fert	1	0.012192	0.012192	7	0.31	0.5954
	Harvest*Fert	2	0.465946	0.232973	84	4.75	0.0111
	Irr*Fert	2	0.017717	0.008859	14	0.14	0.8723
	Harvest*Irr*Fert	4	0.022309	0.005577	84	0.11	0.9773
	Rep(Year)	6	0.73572	0.12262	5.4793	1.38	0.3611
	Rep*Irr(Year)	14	1.590408	0.113601	14	1.77	0.1490
	Rep*Fert(Year)	7	0.275898	0.039414	14	0.61	0.7364
	Rep*Irr*Fert(Year)	14	0.899297	0.064235	84	1.31	0.2187
	Year	1	0.083859	0.083859	6	0.68	0.4399
	Residual	84	4.11724	0.049015			

Table 2.5 continued.

Grade	Source	DF	SS	MS	Error DF	F	p Value
Culls	Harvest	2	0.468307	0.234154	84	5.87	0.0041
	Irr	2	0.05112	0.02556	14	0.48	0.6308
	Harvest*Irr	4	0.114635	0.028659	84	0.72	0.5820
	Fert	1	0.076775	0.076775	7	0.98	0.3544
	Harvest*Fert	2	0.266155	0.133077	84	3.33	0.0404
	Irr*Fert	2	0.015009	0.007504	14	0.23	0.7958
	Harvest*Irr*Fert	4	0.118038	0.02951	84	0.74	0.5679
	Rep(Year)	6	0.298498	0.04975	8.5866	0.50	0.7935
	Rep*Irr(Year)	14	0.75145	0.053675	14	1.66	0.1769
	Rep*Fert(Year)	7	0.546593	0.078085	14	2.42	0.0759
	Rep*Irr*Fert(Year)	14	0.452561	0.032326	84	0.81	0.6564
	Year	1	0.821289	0.821289	6	16.51	0.0066
	Residual	84	3.353281	0.03992			
Marketable	Harvest	2	1.20862	0.60431	84	1.72	0.1847
	Irr	2	2.642995	1.321497	14	2.33	0.1336
	Harvest*Irr	4	2.46026	0.615065	84	1.75	0.1458
	Fert	1	6.033164	6.033164	7	2.86	0.1344
	Harvest*Fert	2	0.156745	0.078372	84	0.22	0.8002
	Irr*Fert	2	4.166745	2.083372	14	2.89	0.0889
	Harvest*Irr*Fert	4	0.55026	0.137565	84	0.39	0.8136
	Rep(Year)	6	5.961415	0.993569	5.495	0.51	0.7835
	Rep*Irr(Year)	14	7.933464	0.566676	14	0.79	0.6703
	Rep*Fert(Year)	7	14.7427	2.106101	14	2.92	0.0416
	Rep*Irr*Fert(Year)	14	10.08583	0.720416	84	2.05	0.0228
	Year	1	33.51928	33.51928	6	33.74	0.0011
	Residual	84	29.45287	0.350629			
Total	Harvest	2	2.460312	1.230156	84	1.88	0.1595
	Irr	2	0.540938	0.270469	14	0.40	0.6765
	Harvest*Irr	4	1.81	0.4525	84	0.69	0.6007
	Fert	1	2.736267	2.736267	7	1.01	0.3492
	Harvest*Fert	2	0.386701	0.193351	84	0.29	0.7453
	Irr*Fert	2	4.248993	2.124497	14	1.78	0.2045
	Harvest*Irr*Fert	4	2.800694	0.700174	84	1.07	0.3775
	Rep(Year)	6	3.979132	0.663189	4.0632	0.30	0.9077
	Rep*Irr(Year)	14	9.41934	0.67281	14	0.56	0.8520
	Rep*Fert(Year)	7	19.03054	2.718648	14	2.28	0.0898
	Rep*Irr*Fert(Year)	14	16.69795	1.192711	84	1.82	0.0487
	Year	1	52.14043	52.14043	6	78.62	0.0001
	Residual	84	55.06729	0.655563			

Table 2.6. Average yields by root grade for irrigation, nitrogen fertilizer application method, harvest, harvest by irrigation, and harvest by nitrogen fertilizer application method.

Treatment	Average Yield (kg ha ⁻¹)					
	U.S. No. 1s	Canners	Jumbos	Culls	Marketable ^a	Total ^b
Control	28912	3409	7453	1679	39773	41452
Smart	31437	3313	7813	1579	42563	44142
Timer	30011	3763	7023	1845	40797	42672
Significance	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>
Fertigated	30061	3099	7752	2031	40912	42944
Side Dressed	30178	3890	7107	1391	41176	42567
Significance	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>
Early	28051 b	4083 a	2423 c	993 b	34556 c	35549 c
Middle	30146 ab	3495 ab	7233 b	1768 a	40874 b	42643 b
Late	32163 a	2906 b	12633 a	2371 a	47702 a	50074 a
Significance	<i>0.0053</i>	<i>0.0141</i>	<i><0.0001</i>	<i>0.0027</i>	<i><0.0001</i>	<i><0.0001</i>
Early x Control	28503	3402	4016 def	473	35921 d	36393
Early x Smart	27587	4079	954 f	1242	32620 d	33861
Early x Timer	28062	4767	2298 ef	1264	35127 d	36392
Middle x Control	27028	3503	6746 cd	2045	37276 cd	39321
Middle x Smart	33305	3749	6155 cde	1317	43209 b	44526
Middle x Timer	30105	3235	8797 bc	1944	42137 bc	44081
Late x Control	31204	3322	11596 b	2520	46122 b	48641
Late x Smart	33418	2110	16330 a	2180	51858 a	54038
Late x Timer	31867	3287	9974 bc	2415	45128 b	47543
Significance	<i>NS</i>	<i>NS</i>	<i>0.0023</i>	<i>NS</i>	<i>0.0198</i>	<i>NS</i>

Note: Values with the same letter in a column by section do not differ significantly ($\alpha = 0.05$). NS indicates the effect was not a significant predictor of yield for the associated grade.

^aMarketable yield is the sum of U.S. No. 1s, Canners, and Jumbos.

^bTotal yield is the sum of U.S. No. 1s, Canners, Jumbos, and Culls.

Table 2.6 continued.

Treatment	Average Yield (kg ha ⁻¹)					
	U.S. No. 1s	Canners	Jumbos	Culls	Marketable ^a	Total ^b
Early x Fertigated	28602	3090 bc	2650 d	706 c	34342	35048
Early x Side Dressed	27500	5075 a	2195 d	1280 bc	34770	36050
Middle x Fertigated	31085	3656 b	6051 c	2284 ab	40792	43076
Middle x Side Dressed	29207	3335 bc	8415 bc	1253 bc	40957	42210
Late x Fertigated	30498	2552 c	14554 a	3104 a	47604	50708
Late x Side Dressed	33828	3261 bc	10712 b	1639 bc	47801	49440
<i>Significance</i>	<i>NS</i>	<i>0.0162</i>	<i>0.0144</i>	<i>0.0257</i>	<i>NS</i>	<i>NS</i>

Note: Values with the same letter in a column by section do not differ significantly ($\alpha = 0.05$). NS indicates the effect was not a significant predictor of yield for the associated grade.

^aMarketable yield is the sum of U.S. No. 1s, Canners, and Jumbos.

^bTotal yield is the sum of U.S. No. 1s, Canners, Jumbos, and Culls.

Table 2.7. Average root set by root grade for irrigation, nitrogen fertilizer application method, harvest, and harvest by irrigation.

Treatment	Average Root Set (number of storage roots per hill)					
	No. 1s	Canners	Jumbos	Culls	Marketable ^a	Total ^b
Control	3.43	1.57	0.34	0.18	5.35	5.54
Smart	3.58	1.69	0.33	0.18	5.60	5.65
Timer	3.37	1.59	0.32	0.22	5.28	5.50
Significance	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>
Fertigated	3.45	1.41	0.34	0.22	5.20	5.42
Side Dressed	3.47	1.82	0.32	0.17	5.61	5.70
Significance	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>
Early	3.48	1.87 a	0.11 c	0.12 b	5.46	5.44
Middle	3.35	1.62 b	0.31 b	0.22 a	5.28	5.5
Late	3.56	1.36 c	0.57 a	0.25 a	5.49	5.74
Significance	<i>NS</i>	<i>0.0001</i>	<i><0.0001</i>	<i>0.0041</i>	<i>NS</i>	<i>NS</i>
Early x Fertigated	3.61 ab	1.57	0.12 d	0.08 c	5.73	5.38
Early x Side Dressed	3.34 b	2.17	0.11 d	0.15 bc	5.25	5.51
Middle x Fertigated	3.36 ab	1.45	0.25 c	0.25 ab	5.62	5.32
Middle x Side Dressed	3.35 b	1.78	0.37 bc	0.18 bc	5.49	5.67
Late x Fertigated	3.38 ab	1.22	0.65 a	0.32 a	5.3	5.57
Late x Side Dressed	3.73 a	1.51	0.49 b	0.19 bc	5.07	5.92
Significance	<i>0.0272</i>	<i>NS</i>	<i>0.0111</i>	<i>0.0404</i>	<i>NS</i>	<i>NS</i>

Note: Two means with the same letter in a column by section do not differ significantly ($\alpha = 0.05$). NS indicates the effect was not a significant predictor of root set for the associated grade.

^aMarketable root set is the sum of U.S. No. 1s, Canners, and Jumbos.

^bTotal root set is the sum of U.S. No. 1s, Canners, Jumbos, and Culls.

Table 2.8. Average yield and root set by year for each root grade and irrigation treatment within root grade.

Grade / Irrigation	Yield (kg ha ⁻¹)		Root Set (roots per hill)	
	2013	2014	2013	2014
US No. 1s	24168	36072	3.11	3.82
Control	22890	35086	3.08	3.81
Smart	25611	37263	3.23	3.93
Timer	24003	36020	3.03	3.71
Canners	2782	4208	1.51	1.72
Control	2721	4079	1.48	1.66
Smart	2597	4028	1.52	1.85
Timer	3027	4499	1.53	1.65
Jumbos	6220	8639	0.31	0.36
Control	5944	8944	0.31	0.38
Smart	7093	8533	0.33	0.34
Timer	5624	8422	0.29	0.35
Culls	840	2582	0.12	0.27
Control	606	2731	0.09	0.27
Smart	880	2278	0.13	0.23
Timer	1035	2714	0.14	0.30
Marketable	33170	48919	4.93	5.90
Control	31556	48109	4.86	5.84
Smart	35301	49824	5.07	6.12
Timer	32654	48940	4.85	5.71
Total	34010	51501	5.05	6.17
Control	32161	50841	4.95	6.11
Smart	36181	52102	4.94	6.35
Timer	33689	51655	4.99	6.02

2.8 FIGURES

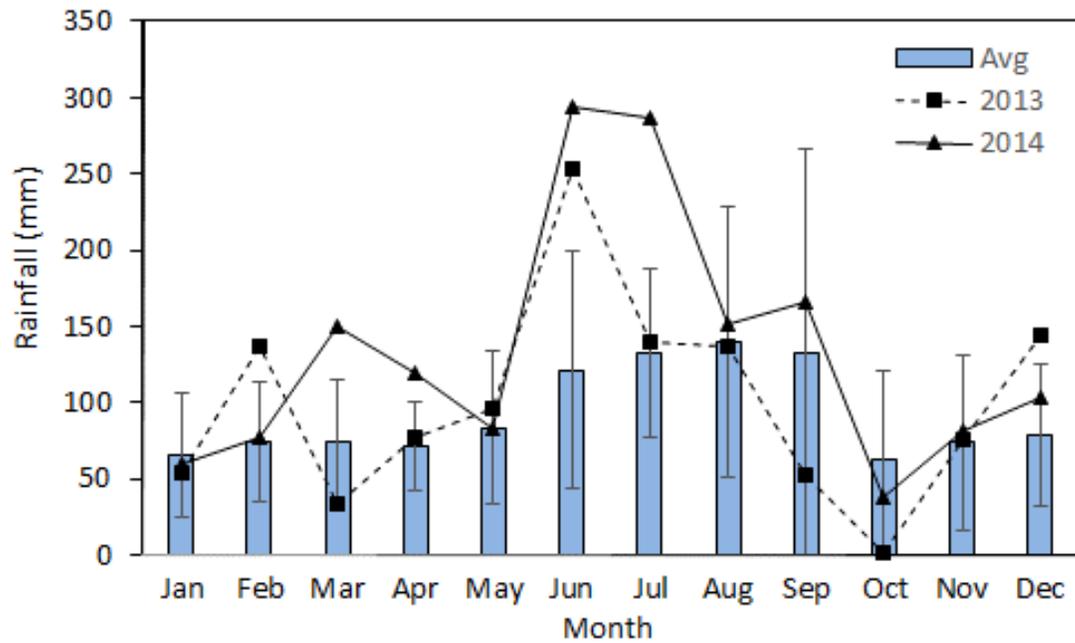


Figure 2.1. Average monthly rainfall recorded at the Cunningham Research Station in Kinston, NC between 1997 and 2014, compared to monthly rainfall at the station in 2013 and 2014. Note: Error bars represent the average value plus or minus one standard deviation.

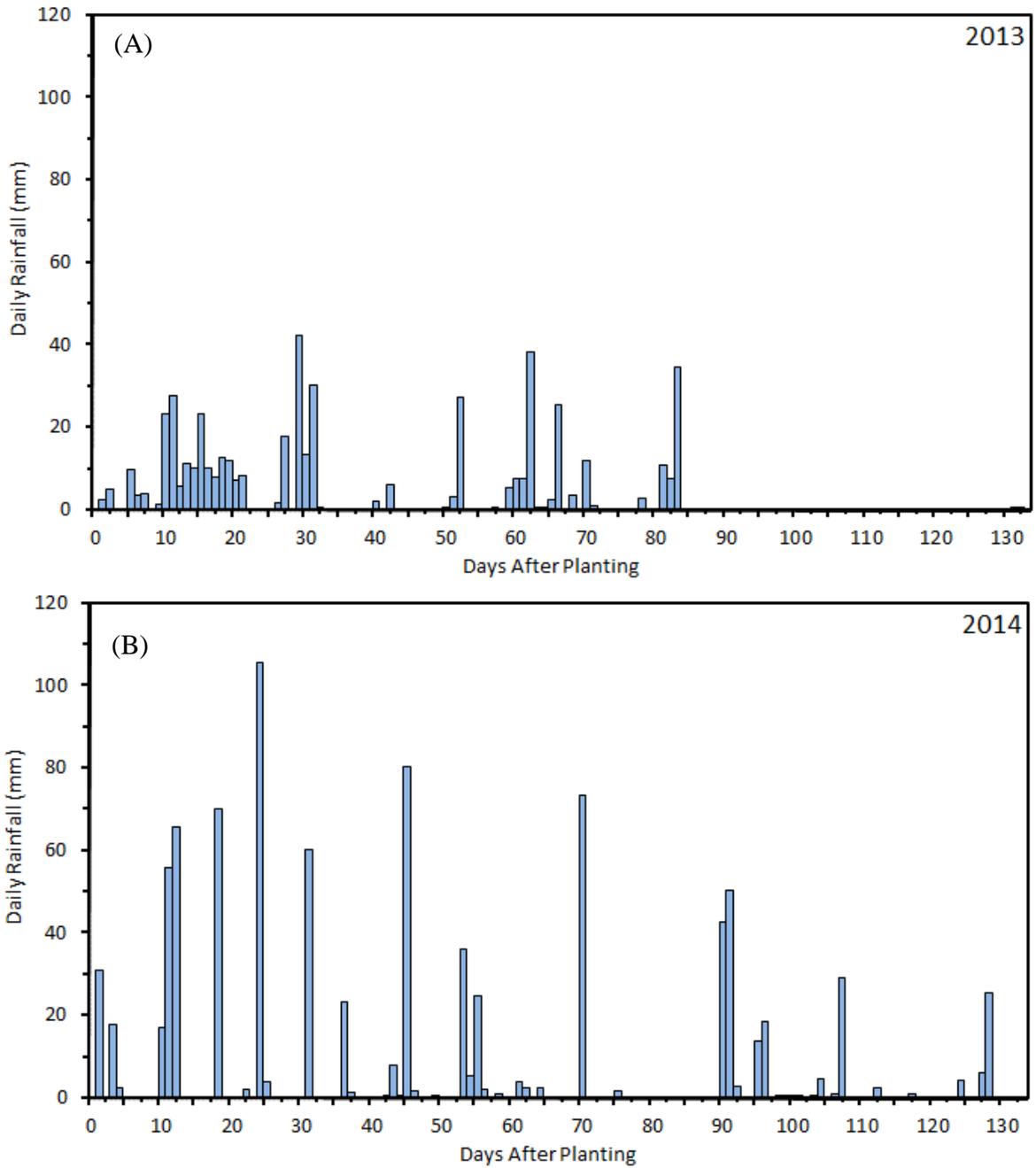


Figure 2.2. Daily rainfall during the 2013 (A) and 2014 (B) growing seasons at the Cunningham Research Station in Kinston, NC.

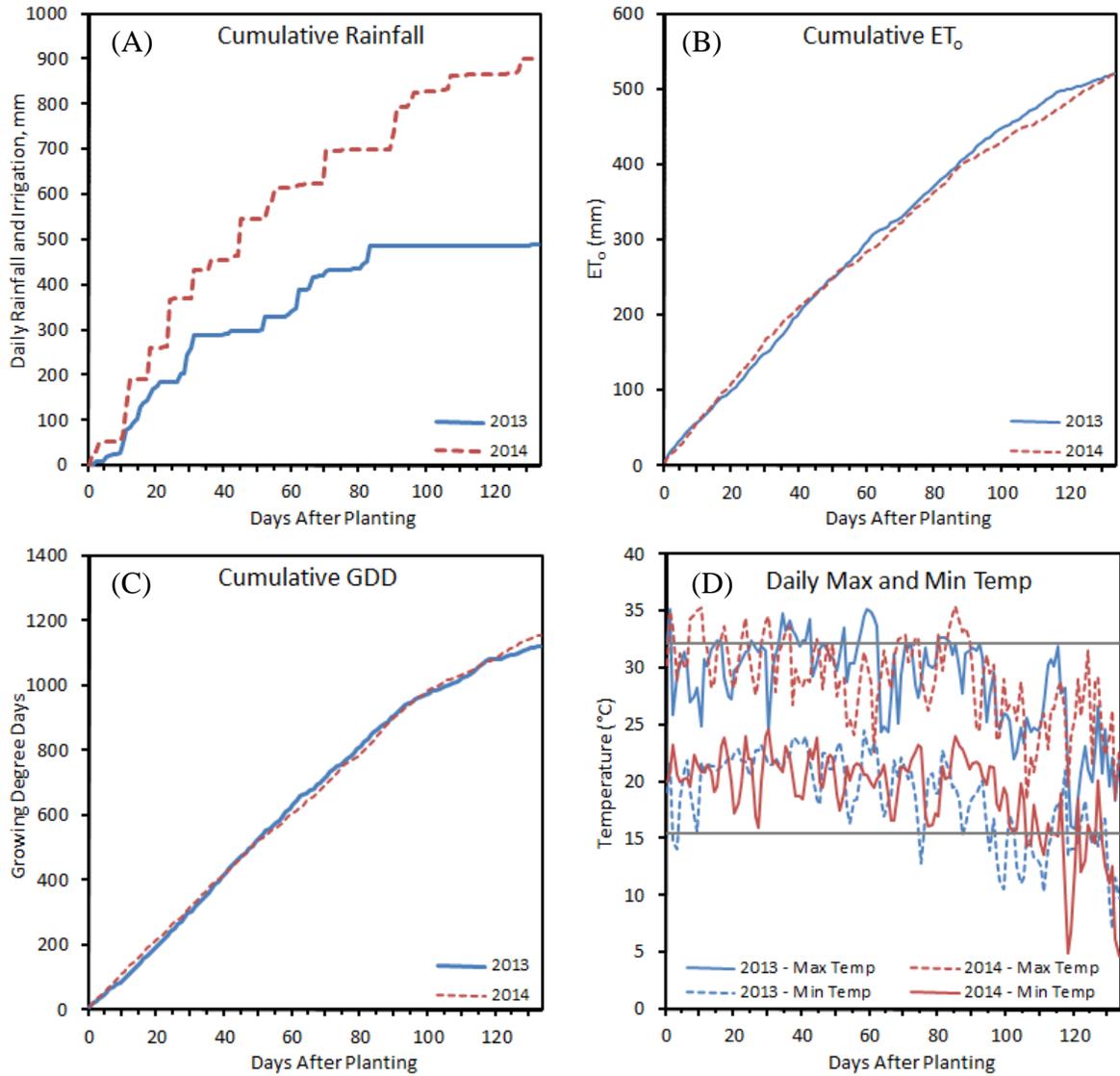


Figure 2.3. Cumulative rainfall (A), ET_0 (B), growing degree days (C), and daily maximum and minimum temperatures (D) during the 2013 and 2014 growing seasons. Note: Slips were transplanted on 12 June 2013 and 9 June 2014. 2013 harvests were 91, 112, and 133 DAT. 2014 harvests were 93, 112, and 133 DAT. Horizontal lines in plot D represent the upper temperature (32.2° C) and base temperature (15.5° C) used in calculating growing degree days.

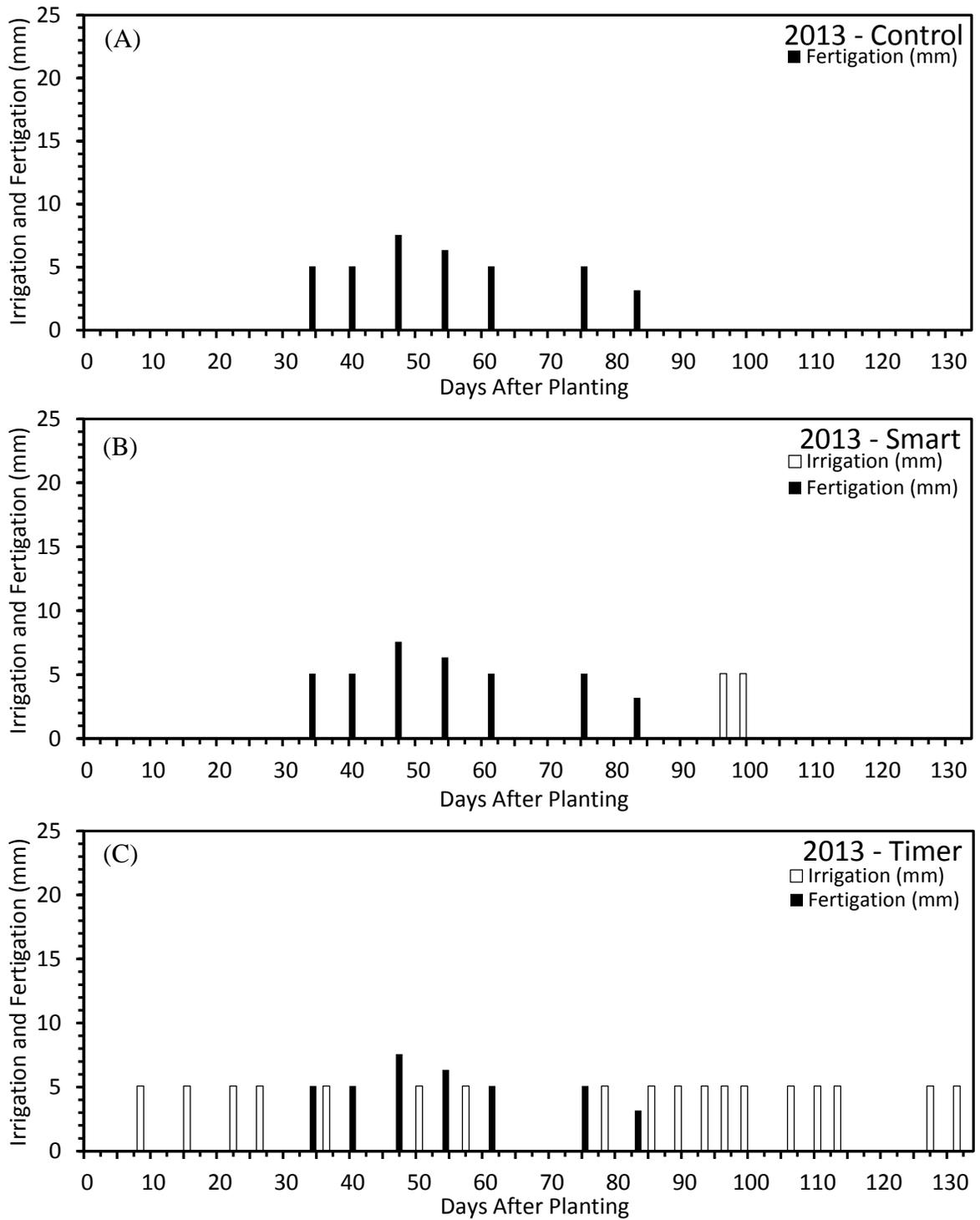


Figure 2.4. Irrigation and fertigation in 2013 for Control (A), Smart (B), and Timer (C) irrigation treatments.

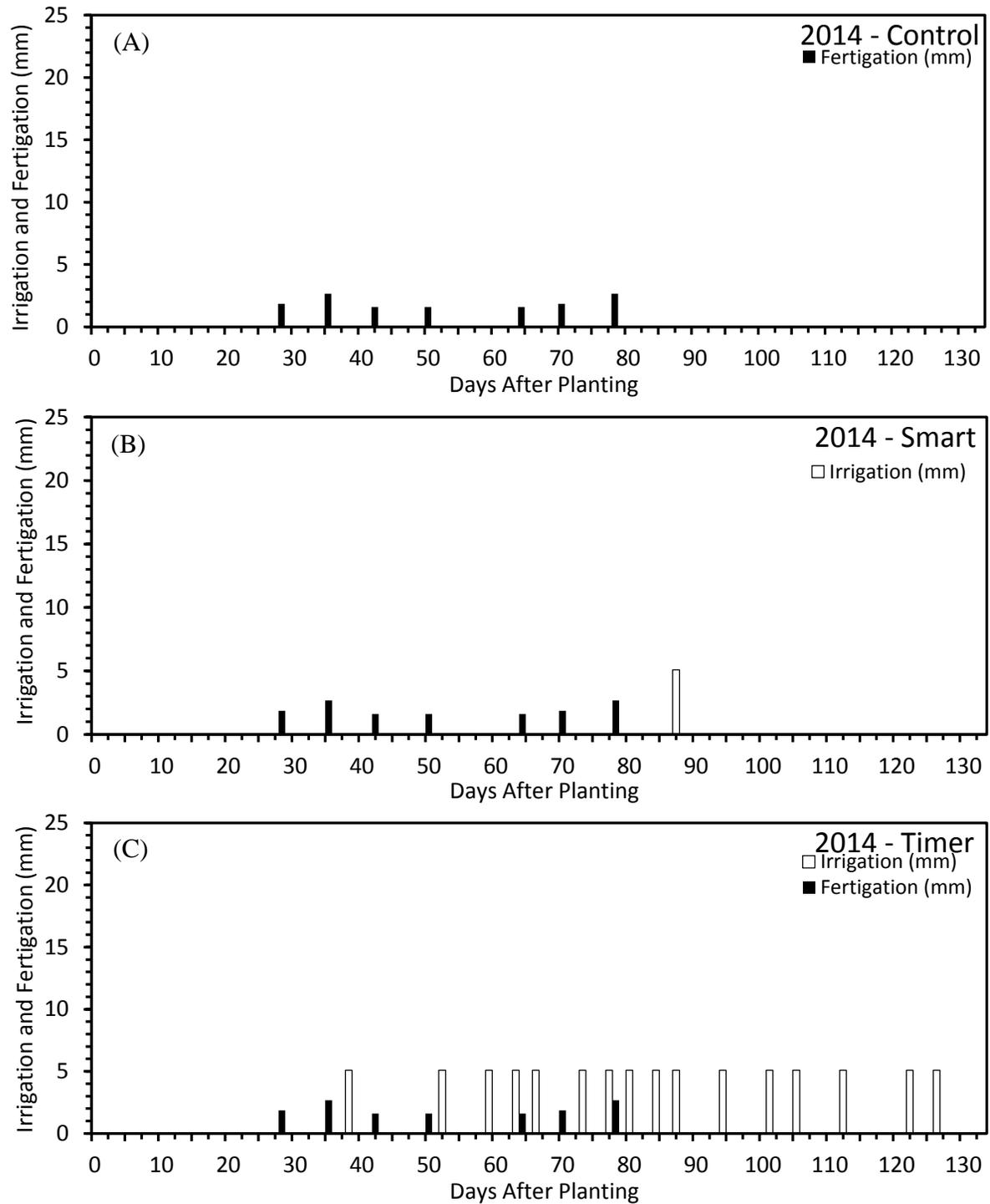


Figure 2.5. Irrigation and fertigation in 2013 for Control (A), Smart (B), and Timer (C) irrigation treatments.

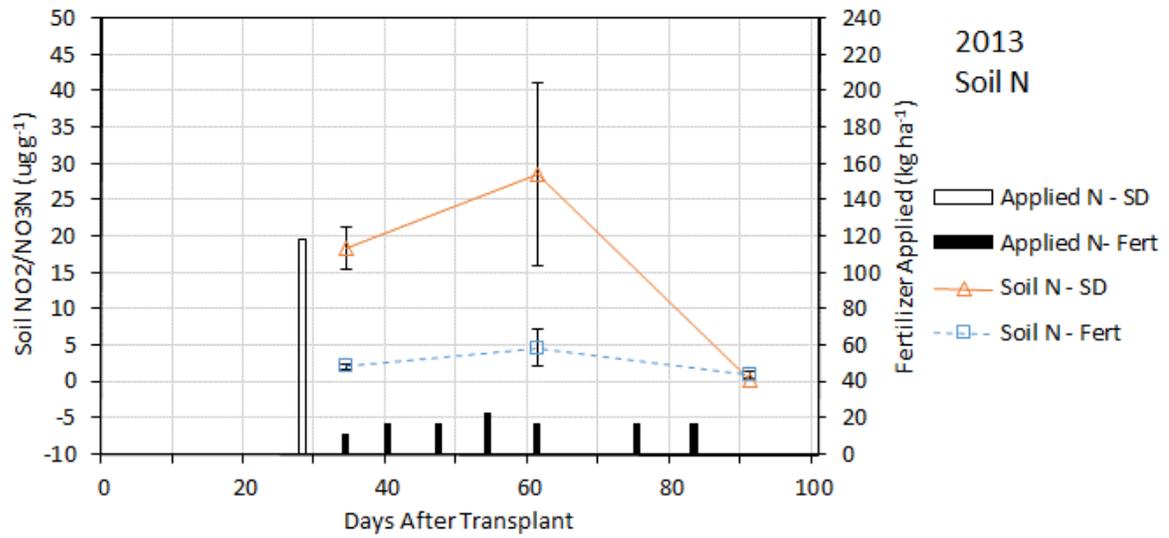


Figure 2.6. Nitrogen fertilization events and variation of NO₃+NO₂-N content of the top 150 mm soil layer over the 2013 growing season.

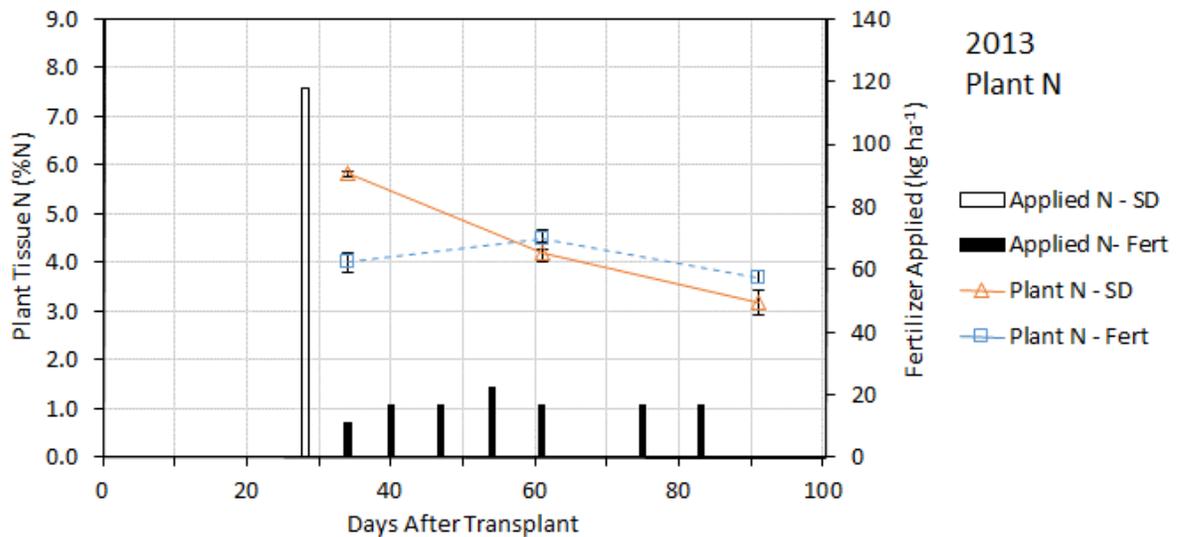


Figure 2.7. Nitrogen fertilization events and variation of plant nitrogen content over the 2013 growing season.

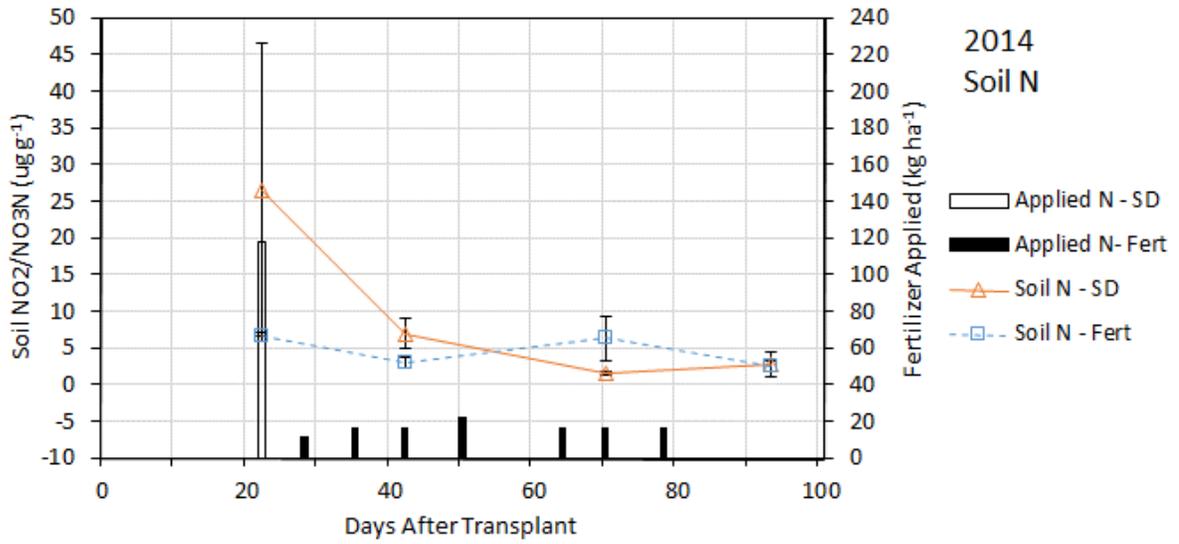


Figure 2.8. Nitrogen fertilization events and variation of NO₃+NO₂-N content of the top 150 mm soil layer over the 2014 growing season.

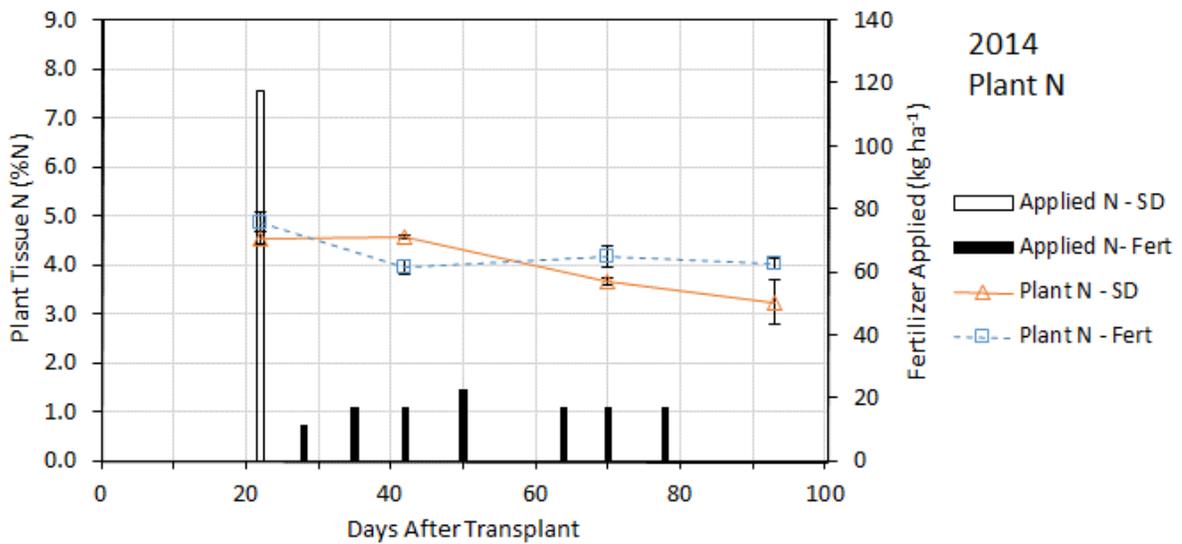


Figure 2.9. Nitrogen fertilization events and variation of plant nitrogen content over the 2013 growing season.

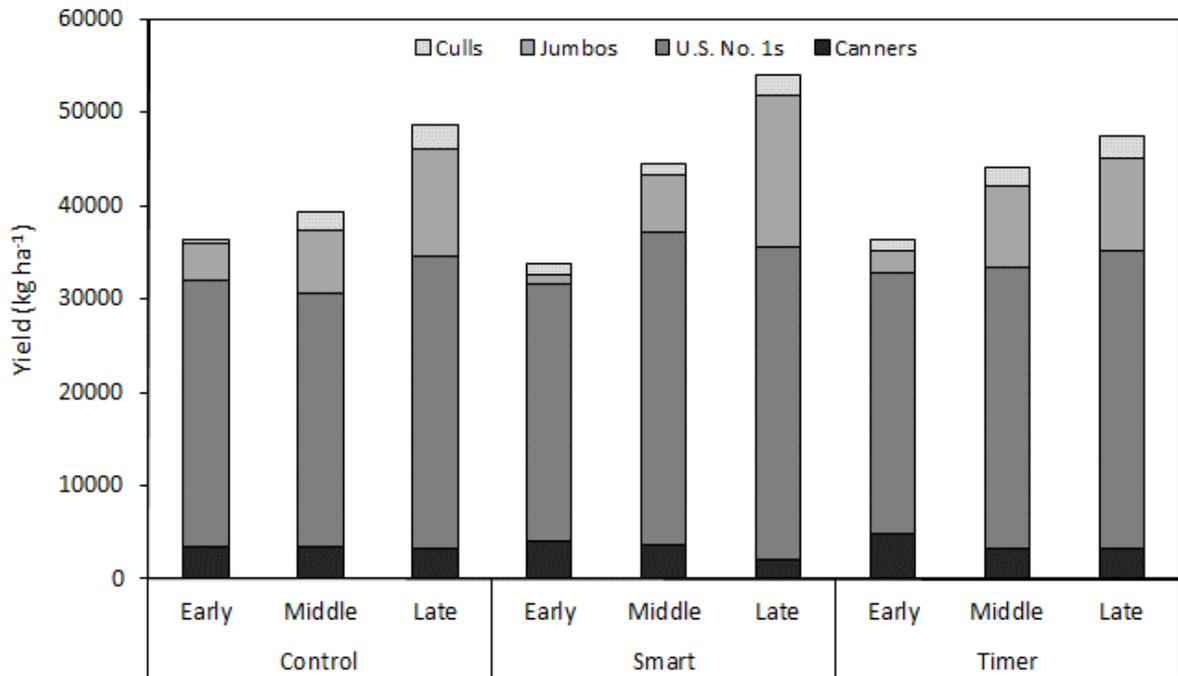


Figure 2.10. Yield for each root grade by harvest and irrigation treatment.

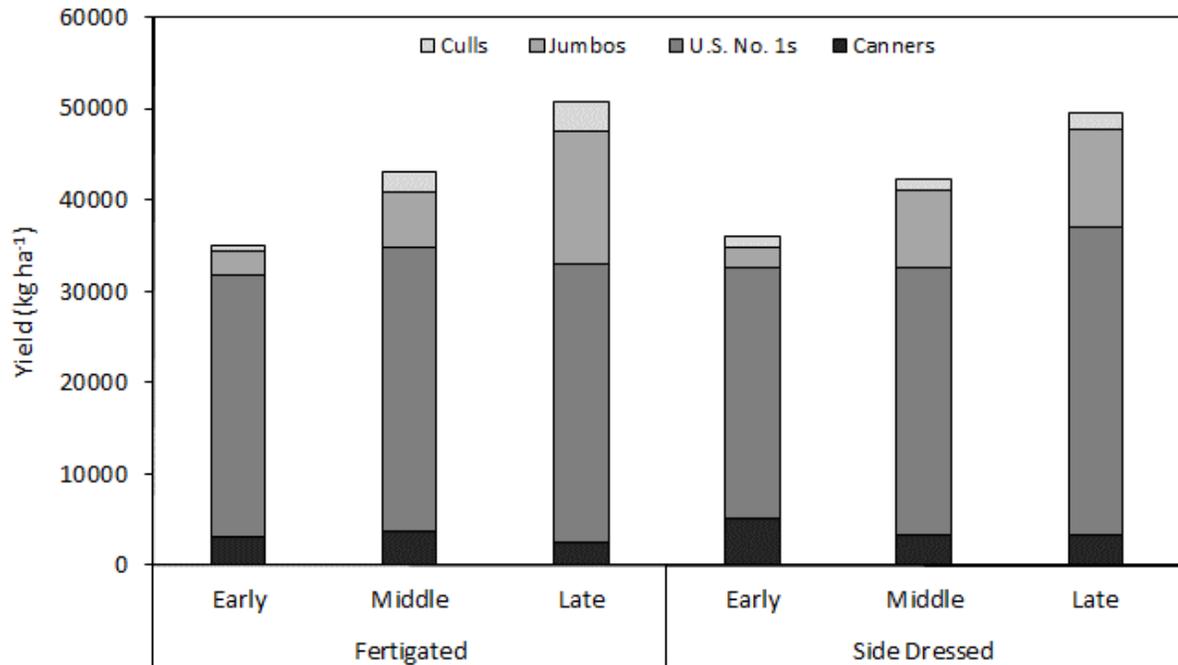


Figure 2.11. Yield for each root grade by harvest and nitrogen fertilizer application treatment.

CHAPTER 3 - A NOVEL DECISION SUPPORT SYSTEM FOR “SMART” IRRIGATION SYSTEMS IN THE HUMID SOUTHEASTERN UNITED STATES

3.1 ABSTRACT

Crop yields in the southeastern United States are largely dependent upon rainfall patterns, which are characterized in the region by substantial seasonal and spatial variability. The timing, more so than the quantity, of rainfall is particularly critical for crops, such as corn, known to be more susceptible to drought at different stages of growth than others. While rainfed production is still the most common practice in the southeastern United States, many growers have invested in, or at minimum expressed interest in, irrigation as a means to minimize the risk of catastrophic yield loss due to drought and to increase crop yields. To aid such growers in irrigation scheduling, a web-based, irrigation decision support system (IDSS) has been developed to provide daily irrigation recommendations based on the current growth stage of the crop, the real-time soil water status in the root zone, and short-term weather forecast. The IDSS was intentionally designed with minimal input or update requirements of the user, with daily observed weather data and forecast weather data being automatically accessed at runtime. The model uses a soil water balance to predict the daily soil water status of the root zone for the current day through the next specified opportunity for irrigation, providing a recommended depth of irrigation to apply if the forecasted soil water depletion exceeds growth stage dependent management allowed depletion (MAD). The depth of irrigation recommended depends upon irrigation settings specified by the user, which should reflect the user’s scheduling objective, whether to minimize crop stress without

regard to how much water is used, to maximize potential rainfall benefit with greater risk of subjecting the crop to some degree of drought stress, or somewhere in between. By incorporating forecasted weather into the irrigation decision, the IDSS reduces the risk of waiting too long to start irrigation as well as minimizing the potential for over-irrigation caused by frequent occurrences of irrigation followed by rainfall. This may provide the direct benefits of increased crop yield, improved crop water use efficiency, and reduced nutrient loss via leaching and runoff.

3.2 INTRODUCTION

Irrigation has long been critical for agricultural production in arid and semi-arid regions of the world. Irrigation allows for approximately 40% of the world's food production to be concentrated on only 17% of agricultural lands (FAO, 2002). In the United States, crops produced on irrigated land accounted for almost half of harvested crop sales in 1997, but only 16% of the nation's total cropland (USDA-ARS, 2001). In recent years, interest and investment in irrigation has increased in less traditionally irrigated, humid regions, such as the southeastern United States, where crop production primarily depends on rainfall. Total irrigated acreage in Alabama, Georgia, North Carolina, and South Carolina increased by 71% from 2002 to 2012 (USDA-NASS, 2003; 2013). Whereas growers in arid climates rely solely on irrigation for growing crops, growers in humid regions are turning to irrigation to increase yield and make crop production more resilient to weather variability, which leads to production of more food and fiber on less agricultural land.

Despite this expansion of irrigation, growers have been slow to adopt technologies and tools aimed at improving irrigation scheduling. As recently as 2012, only about 10% of irrigated farmland in the United States used soil moisture sensors for scheduling irrigation (USDA-NASS, 2013). Less than 1% of irrigated land was scheduled using computer models, while over 40% was accomplished using the “feel” of the soil.

Growers are investing in irrigation to increase yield potential and to guard against yield losses during extended periods without rainfall during the growing season. The issue with rainfall in humid climates is typically not the quantity of rainfall received, but rather its timing. Even in regions like eastern North Carolina, which typically receives 1,120 to 1,420 mm of annual rainfall (SCO-NC, 2016), it is not uncommon to have prolonged periods without rainfall during the growing season. If such conditions occur during the critical growth stages of crop development, yield reductions can be devastating unless irrigation is available. In addition to seasonal rainfall variability, spatial rainfall variability is common also, with areas of relatively close proximity receiving drastically different rainfall during the same growing season. In addition, most Coastal Plain soils restrict root growth to less than 300 to 450 mm, and midseason rainfall occurs often as short duration, high intensity events resulting in only a fraction of the rainfall actually benefiting the crop. Due to these factors, there is a need for more readily embraced and effective irrigation scheduling tools that maximize crop quality and production potential while conserving water resources.

Sadler et al. (2003) discussed many of the challenges to irrigation management in humid climates, including the possibility of rain occurring just after an irrigation event. Likewise, a grower might forgo an irrigation event in anticipation of a rainfall event that fails

to occur, leaving his crop in a stressed condition. The primary challenge facing growers who are considering irrigation is how to manage two main issues: when to irrigate and how much to apply.

Several tools and resources have been developed to assist growers with these issues. Such tools are generally soil-, plant-, or weather-based, or some combination thereof (IA, 2011). A soil-based irrigation scheduling method may be as simple as a "checkbook approach," in which a grower maintains a daily soil water balance, accounting for inputs (e.g., rainfall and irrigation) and outputs (e.g., evapotranspiration) to estimate when irrigation is needed. More sophisticated systems may include the installation of soil sensors to estimate soil water content or soil matric potential, plant sensors to estimate drought stress, or onsite weather stations to measure weather variables that most affect plant water availability and plant water use (i.e., rainfall, temperature, relative humidity, solar radiation, and wind speed). The combination of more sophisticated scheduling technologies with irrigation control hardware constitutes what is broadly referred to as a "smart" irrigation system (IA, 2007). Smart irrigation systems aim to improve crop water use efficiency by precisely applying the proper amounts of water to the crop when and where they are needed. Incorporation of the "where" component in the agricultural realm generally suggests the use of a variable rate irrigation system.

Variable rate irrigation (VRI) systems allow for spatial variation of water application within a single field and typically consist of a center pivot or lateral move irrigation system that has an onboard global positioning system (GPS), for determining the real-time position of the unit in the field, and multiple zones of irrigation nozzles that are independently

controlled by a central control panel (Evans et al., 2013). The rate of water applied at any location in the field is governed by the position of the system in the field and a user-defined prescription map that is stored in the controller. Regardless of whether VRI is incorporated into a system or a single application rate is used for an entire field, appropriately answering when and how much water to apply is the critical component of any smart irrigation system.

Several governmental and academic institutions have developed freely available software to assist growers with irrigation scheduling (Andales et al., 2014; Cahn, 2013; Cahoon et al., 1990; Hillyer and Sayde, 2010; Martin et al., 2003; Migliaccio et al., 2013; Peters et al., 2014; Rogers, 2012; Sassenrath et al., 2013; Scherer and Morlock, 2008; Vellidis et al., 2014). Some of these tools exist as standalone applications to be installed on a user's personal computer, while many developed or modified in recent years have been designed as web-based applications, accessible from anywhere with internet access, including on platforms such as smart phones. The increase in the number of such applications available has gone hand-in-hand with the increase and improvement of state weather networks that provide real-time access to local weather conditions, which in many cases are directly and automatically accessed by the irrigation scheduling application.

Most of the irrigation scheduling applications available today are based on some version of the soil water balance presented in the Food and Agriculture Organization (FAO) Irrigation and Drainage Paper Number 56 (FAO-56) (Allen et al., 1998) and aim to predict the current soil water status and crop water demand. One of the oldest publicly available irrigation scheduling tools, the Arkansas Irrigation Scheduler (Cahoon et al., 1990), relies on a soil water balance and has been developed for cotton, soybeans, grain sorghum, and corn.

Originally the Arkansas Irrigation Scheduler required users to input daily air temperature and effective precipitation to update the soil water balance; however, the application is now available in an online interface that automatically acquires temperature data from a state weather network that is used for evapotranspiration (ET) estimation. The user is still required to input daily rainfall and irrigation data to update the model, but the initial setup is intentionally simple, only requiring the user to select generic crop and soil types from which many of the specific parameters necessary for the soil water balance are inferred. Since the early 2000s, many similar state or regional irrigation scheduling tools have been developed. The Arizona Irrigation Scheduling System (AZSCHED) (Martin et al., 2003) is a standalone (not web-based) application designed for 28 different crops in Arizona that accesses real-time ET data from the Arizona Meteorological Network (AZMET). Online irrigation applications include: CropManage (Cahn, 2013), developed by the University of California; Colorado Water Irrigation Scheduler for Efficiency (WISE) (Andales et al., 2014); Mississippi Irrigation Scheduling Tool (MIST) (Sassenrath et al., 2013); KanSched3 (Rogers, 2012); North Dakota Agricultural Weather Network (NDAWN) Irrigation Scheduler (Scherer and Morlock, 2008); Irrigation Management Online (IMO) (Hillyer and Sayde, 2010); and Washington Irrigation Scheduler (Peters et al, 2014). Each of these applications functions on a soil water balance and automatically retrieves data from weather networks within the regions it represents. There are varying degrees of customization offered by each application. KanSched3 allows users to configure a layered soil profile by specifying the percentage of the total profile depth comprised by each individual soil layer. Both the NDAWN Irrigation Scheduler and Colorado WISE have built-in GIS functionality that

allows the user to identify a field on a map and have soil data automatically retrieved from online soil databases.

With so many people using smart phones to access the internet today, developers of irrigation scheduling applications such as the Washington Irrigation Scheduler and Colorado WISE have introduced mobile versions of their web applications. While these web applications still require the user to navigate to them via a web browser, other researchers have developed standalone mobile applications that can be downloaded directly to the user's smart phone. The University of Florida and the University of Georgia have worked together to launch six different mobile irrigation scheduling applications designed for citrus, urban lawns, strawberry, cotton, avocado and vegetable (Migliaccio et al., 2013; Vellidis et al., 2014). These applications also use a soil water balance approach and automatically retrieve weather data from a network of weather stations to update the current crop and soil water status. Additionally, some of these apps provide five-day weather forecast of high and low temperature, relative humidity, probability of rainfall, and wind speed to the user, although this information is not directly used in the calculation of the irrigation recommendation.

The need for a forecasting component in irrigation scheduling applications is an element that is particularly important for humid regions of the United States and it is a need that has not yet been met. IMO, developed by Oregon State University, provides the user a daily updated forecast of water use predicted through the remainder of the season, but this information is based on historical weather data for the location. At any point in the growing season, KanSched3 forecasts crop water use for the next five days based on the average reference ET for the previous five days, but there is no consideration of the current weather

forecast. The addition of this forecast component to an irrigation scheduling tool to estimate both potential crop water demand and rainfall, would be particularly beneficial to growers in the southeastern United States.

Each of the applications presented heretofore are to some degree "blind to the future," several of them being so entirely. In other words, the primary function of these tools is to predict the current soil water status and crop-water demand at any point during the growing season, recommending irrigation to the user only once soil water depletion has exceeded some management threshold. Though proven effective in reducing overall irrigation amounts while increasing yields, this approach is still problematic on some levels. For one, by waiting until a certain level of depletion has occurred to trigger or recommend irrigation, it may subject the crop to further stress before irrigation can be applied. System constraints may limit the acreage that can be irrigated on any given day or the amount of water that can be delivered. Thus, just because a crop is not in a stressed condition on a given day, does not necessarily mean that it will not be in a stressed condition by the time the next irrigation opportunity comes around (e.g., in a few days). Similarly, a grower may be faced with a scenario in which a crop is approaching stressed conditions, but there is rain in the forecast that would delay a previously scheduled irrigation should the rainfall actually occur. Such a scenario is common in humid regions like the southeastern United States. Undoubtedly, growers in such positions already incorporate the weather forecast into their irrigation decision; however, such a decision is subjective and largely a guess based on their experience with similar weather and crop conditions from the past.

There is a need for an irrigation scheduling tool that incorporates rainfall and evapotranspiration forecasts into real-time irrigation recommendations. Part of the reason that rainfall forecasts are not incorporated into most irrigation scheduling tools presently available may be because regions of the United States that are most dependent on irrigation for crop production also tend to receive little if any rainfall during the growing season; thus, it stands to reason that the primary concern of irrigation schedulers is predicting crop water use, not rainfall that is unlikely to occur. Additionally, the development of tools that incorporate rainfall forecast into the irrigation decision process may have been slow in progression because of the high level of uncertainty in rainfall forecasts. Rainfall prediction tools have improved in recent years, but the reality is that it is still difficult to accurately predict rainfall amounts, particularly more than a day or two in advance. This is particularly true of convective, afternoon thunderstorms that are typically localized and sporadic yet are very common sources of rainfall during the most critical growth stages of crops in the humid southeastern United States. Recognizing these difficulties, it seems logical that attempting to incorporate some sort of rainfall forecast into irrigation scheduling in humid climates would be more beneficial than the present approach of leaving it entirely up to the subjective experience of the grower.

To address this problem, a web-based, irrigation decision support system (IDSS) has been developed to provide irrigation recommendations based on crop growth stage, real-time soil water status, and short-term weather forecast. The framework for the IDSS has been developed so that weather data, weather forecasts, and eventually soil moisture data can be automatically accessed and retrieved by the application from the data sources specified by

the user. This will reduce the day-to-day user input requirements while integrating a rainfall forecast into the irrigation decision process.

3.3 DEVELOPMENT OF THE IRRIGATION DECISION SUPPORT SYSTEM

The IDSS aims to answer the questions of when to irrigate and how much water to apply. It does so by providing a daily irrigation recommendation to the user based on the current soil water status in the crop root zone, short-term weather forecast, and crop growth stage. The model accounts for the interaction among these three major components and arrives at an irrigation recommendation that satisfies given conditions specified by the user, such as possible irrigation days, irrigation management criteria to be used in calculating the irrigation depth when irrigation is recommended (e.g., percentage of soil water reservoir to refill with irrigation), the number of days to forecast ahead, and whether or not soil moisture sensors will be used to monitor the soil profile in real-time. The IDSS uses a soil water balance based on the principles described in FAO-56 (Allen et al., 1998).

3.3.1 Description of IDSS Components

Any effective irrigation scheduling technique should provide an accurate estimation or measurement of extractions and additions of water to the soil water reservoir in conjunction with a basic understanding of plant water demands over time. The system by which various, interdependent flow processes occur between the soil, plants, and the atmosphere has been referred to as the soil-plant-atmosphere continuum (SPAC) (Philip, 1966; Hillel, 2004) and is illustrated in Figure 3.1. The underlying principal is that water flow is always from a state of higher energy potential to one that is lower.

Based on the theory of the SPAC, the IDSS and its subroutines have been broken down into three basic categories: soil, plant, and atmosphere (Figure 3.2). The processes within each of these categories are not completely independent and they are handled accordingly by the IDSS. The IDSS is designed to provide the user with daily updated estimates of the status of the SPAC system elements, as well as their forecasted states for the next number of days as defined by the user and the number of days forecasted by the weather forecast source. The IDSS relies upon minimal static inputs that are defined by the user at the beginning of the season and several dynamic variables that are updated on a daily basis using current weather data, weather forecast, and data obtained either from field installed soil moisture sensors or a running soil water balance for estimating the current soil water content.

The current IDSS functions as a web application on the ASP.NET framework, although it was designed with the intent that it could easily be expanded to function on other platforms such as ones for mobile devices. The application logic was written using the C# programming language in Visual Studio Ultimate 2013 (Microsoft, Redmond, WA). A detailed flow chart of the daily decision logic is presented in Figure 3.3. The current IDSS uses weather data from any of the forty-two ECONet weather stations that are part of the Climate Retrieval and Observations Network of the Southeast (CRONOS) Database supported by the State Climate Office of North Carolina (SCO-NC). Weather forecasts are accessed from the National Weather Service (NWS) for the latitudes and longitudes corresponding to each of the ECONet weather stations. The current configuration of the IDSS and its data retrieval subroutines limits collection of weather data and weather forecasts to these forty-two sites, but the model code could easily be changed to retrieve weather

forecasts for any location in the continental US given their coordinates are specified by the user. Likewise, the IDSS could be expanded to accept weather data from additional weather stations beyond the ECONet, so long as the necessary weather parameters are available. The following sections explain with greater detail the three major components of the SPAC (soil, plant, and atmosphere), the subroutines that the IDSS uses to represent them, and the necessary inputs required to run the model.

3.3.2 Soil Components

The soil components of the IDSS are focused primarily on estimating the extent of the soil water reservoir and the amount of soil water within it at any given time over the growing season.

3.3.2.1 Definition of the Soil Water Reservoir

The volume of water that a soil can hold is governed by its porosity, but how readily available the water is to a plant depends primarily on the size of the solid particles (texture) comprising the soil. When all of the pore space in a soil is completely filled, it is saturated. Even under saturated conditions, usually a tiny fraction of the pore space remains occupied with entrapped air. Any water added to the soil beyond saturation will be lost to surface runoff or deep percolation (i.e., downward movement of water below the root zone). Over time, the rate of drainage due to the downward force of gravity decreases to a point that free drainage is considered negligible. This point, referred to as field capacity (FC), is typically associated with a soil water potential of -10 to -33 kPa and is the upper limit to plant available water. Water continues to be removed from the soil profile beyond field capacity

primarily by the process of evapotranspiration (ET), which is the combination of evaporation from the soil surface and plant transpiration. If ET continues without soil water being replenished (either by rainfall or irrigation), then the soil water will eventually be depleted to a point at which the adhesive forces holding the water to the soil particles will be so great that water can no longer be extracted by plant roots. This condition is known as the permanent wilting point (PWP) (soil water potential of -1500 kPa). The soil water held between field capacity and permanent wilting point is considered available to the plant and referred to as total available water (TAW). A representation of the soil water reservoir is shown in Figure 3.4.

3.3.2.2 Sizing the Soil Water Reservoir

Saturation, field capacity, and permanent wilting point are typically expressed on a volumetric basis (i.e., volume of water per total volume of soil). For the purposes of irrigation scheduling, and specifically the use of a soil water balance, it is necessary to express soil water content in depth units. Such a conversion introduces a dependency on the crop and can be determined using the equation:

$$SWR_{\text{depth}} = SWR_{\text{volumetric}} \times RD \quad [3.1]$$

where,

SWR_{depth} = soil water reservoir level (saturation, FC, PWP, etc.) expressed as depth of water (mm)

$SWR_{\text{volumetric}}$ = soil water reservoir level (saturation, FC, PWP, etc.) expressed as volume of water per volume of soil ($\text{mm}^3 \text{mm}^{-3}$)

RD = root zone depth (mm).

Due to its dependency on the root zone depth, the soil water reservoir, as expressed in terms of depth of water, will change over the course of the growing season as the plant roots grow. An example of how this change might look over the course of the growing season is shown in Figure 3.5, which includes a representation of how the user defined irrigation criteria may change with time as well. The IDSS updates the depth equivalents of the soil water reservoir levels (saturation, field capacity, permanent wilting point, etc.) on a daily basis using the calculated root depth of the specified crop. Root depth is estimated as a function of days after planting and is explained further in this chapter in section 3.3.3.1 (Root Growth).

3.3.2.3 Readily Available Water

Although in theory water is available to the plant until the PWP is reached, the rate of plant water uptake decreases markedly as the PWP is approached due to the water being more tightly bound to the soil (Allen et al., 1998). There is a threshold at which point the atmospheric demand for water from the plant exceeds the extraction rate of the roots, which is expressed by a depletion factor (p) that represents the fraction of total available water that can be depleted before plant stress occurs (Figure 3.6). The depth equivalent of this fraction is referred to as Readily Available Water (RAW) and is calculated as:

$$RAW = p TAW \quad [3.2]$$

The depletion factor can range between 0 and 1 and is a function of the evapotranspiration rate of the plant, which is governed by atmospheric conditions and plant

growth stage. A constant value for p may be assumed throughout the crop growing season or for specific stages of crop development. Allen et al. (1998) also provided means for adjusting p using daily calculated crop evapotranspiration (ET_c). The IDSS requires the user to specify a p value for each crop growth stage as discussed further in the Plant Components subsection 3.3.3.3 (Growth Stages). The logic could easily be expanded to account for variations in p due to ET_c .

Management allowed depletion (MAD) is very similar to the depletion factor and the two may at times be used interchangeably; however, MAD takes into account management strategies and economic factors that are not technically included in the selection of p . As with values of p , the IDSS requires that the user specify a MAD for each growth stage of the crop being considered, to account for different management strategies according to crop drought susceptibility during different stages of development. The IDSS uses predicted exceedance of MAD during the forecast period to determine if irrigation should be applied.

3.3.2.4 Soil Layering

While the soil water reservoir has been presented in the context of a homogenous soil profile, in reality, it is common for the portion of the soil profile that constitutes the plant root zone to be made up of multiple soil layers. The IDSS allows the user to specify as many soil layers as desired to describe the effective root zone of the plant as demonstrated in Figure 3.7. For each soil layer, the user must specify the depth to the top of the layer, the thickness of the layer, and the volumetric water contents corresponding to saturation, field capacity, and permanent wilting point for the layer. For the IDSS to function properly, the

composite profile represented by the user-defined soil layers should extend at least to the maximum expected rooting depth.

3.3.2.5 Real-Time Estimation of Soil Water Status

Each run of the IDSS requires an estimate of the current soil water status of the plant root zone. This value may come from a soil water balance running concurrently with the IDSS or from soil moisture sensors installed in the profile of interest. For the sake of simplicity, flexibility to the end user, and to preserve memory requirements to run the IDSS, a built-in soil water balance for estimating the current soil water status using observed weather data is not currently included in the IDSS; however, this option could be added with relative simplicity.

If soil moisture sensors are used to estimate real-time soil water status, the IDSS requires a volumetric soil moisture estimate for each soil layer as defined by the user each time the model is run. These values are used with the current estimated plant root depth (calculated based on days after planting) to calculate the total depth of water in the root zone using the equation:

$$SW = \sum_{i=1}^{n-1} \theta_i L_i + \theta_n \left(RD - \sum_{i=1}^{n-1} L_i \right) \quad [3.3]$$

where,

SW = total depth of water in the root zone (mm)

n = number of layers within root zone with the nth layer being the deepest

θ_i = measured volumetric soil water content for layer i (mm³ mm⁻³)

θ_n = measured volumetric soil water content for the nth layer (mm³ mm⁻³)

L_i = thickness of layer i (mm)

RD = current root depth of the crop (mm)

This method ensures that the composite estimate of soil water in the root zone is only affected by the soil moisture sensors in the root zone and that the influence of each sensor reading is based on the depth of the layer that the sensor represents. The IDSS does not automatically retrieve soil moisture data presently, although this functionality could be added. Sensors and data loggers that are accessible over the web or that automatically transmit data to cloud based storage are readily available, which would be needed to incorporate this feature.

3.3.2.6 Forecasted Soil Water Status

At each run of the IDSS, after the estimate of the current soil water status has been updated, the soil water status is forecast for each future day as specified by the user and constrained by the forecast data available. This forecast is actually performed twice: first with no irrigation and second using the irrigation recommendation calculated by the IDSS based on the soil water forecast. The ending soil water status of the root zone is forecast for each day based on the beginning soil water status of the current day using the following soil water balance equation:

$$SW_{\text{end}} = SW_{\text{beg}} + \text{RGW} + I - ET_{\text{c,adj}} + P - \text{RO} - \text{DP} \quad [3.4]$$

where,

SW_{end} = depth of soil water in the root zone at the end of the day (mm)

SW_{beg} = depth of soil water in the root zone at the beginning of the day (equal to

SW_{end} for previous day) (mm)

RGW = depth of the soil water added to the root zone due to daily root growth (mm)

I = net irrigation (mm)

$ET_{\text{c,adj}}$ = adjusted crop evapotranspiration (mm)

P = precipitation (mm)

RO = water loss to runoff (mm)

DP = water loss to deep percolation below the root zone (mm).

Inputs to the soil water balance are provided from the weather forecast data, which is discussed further in section 3.3.4 (Atmosphere Components). The source of the weather data (observed or forecasted) is not critical as long as it provides reliable forecast estimates for each of the following: daily minimum temperature, daily maximum temperature, daily reference evapotranspiration (ET_o), and daily rainfall. The terms of the soil water balance are added or subtracted in the order that they appear in Equation 3.4.

3.3.2.7 Forecasted Soil Water Balance Components

Root Growth Water. Root Growth Water (RGW) is the amount of water added to the soil water reservoir (as defined by the total root depth) based on root growth from one day to the next. This term only applies during the stages of growth before maximum root depth has been reached, when active root growth is still taking place. The RGW for any day is calculated by the IDSS by multiplying the calculated depth of root growth for a given day by the volumetric representation of FC for the layer into which the root growth occurred.

This assumes the layers below the root zone have been sufficiently wetted by previous rainfall to remain at FC at the time of root entry into the layer.

Irrigation. The initial forecast soil water balance is run assuming no irrigation for any of the forecast days in order to determine if irrigation will be needed. If the current day is an irrigation opportunity day and the initial forecast soil water balance suggests that irrigation should be applied, the soil water balance will be re-run, setting irrigation on the first day of the forecast soil water balance (the current day) equal to the IDSS recommended irrigation depth.

Adjusted Crop ET. Adjusted crop evapotranspiration ($ET_{c,adj}$) is the forecasted amount of water that will be lost from the root zone due to evapotranspiration for each day. This value is calculated using the forecasted crop ET (ET_c) (explained further in section 3.3.3.2) multiplied by a crop stress coefficient (K_s). K_s is a function of the soil water depletion (D), relative to field capacity, and ranges from 0 to 1. It is used to account for the reduction in soil water extraction by plant roots when the soil water reservoir is depleted beyond the depth of RAW. K_s is represented visually in Figure 3.8 and is calculated as:

$$K_s = 1 \quad \text{for } D \leq \text{RAW} \quad [3.5]$$

and

$$K_s = \frac{\text{TAW} - D}{(1 - p) \text{TAW}} \quad \text{for } D > \text{RAW} \quad [3.6]$$

where,

K_s = crop stress coefficient (0 – 1)

$D = FC_{\text{depth}} - SW$ = soil water depletion, relative to field capacity (mm)

FC_{depth} = field capacity of the root zone represented as depth of water (mm),

calculated similarly to SW in Equation 3.3, replacing θ_i with $\theta_{i,FC}$

SW = depth of soil water currently in the root zone (mm)

RAW = readily available soil water (mm), as calculated using Equation 3.2

TAW = total available soil water in the root zone at field capacity (mm)

p = depletion factor (0 – 1).

Rainfall. The rainfall amount added in the forecasted soil water balance is based on the forecasted probability of precipitation, the forecasted quantity of precipitation, and a rainfall probability threshold (RPT) associated with the predicted growth stage of the crop. The IDSS requires the user to enter a RPT for each crop growth stage, which is used to determine whether or not a forecasted rainfall event will be credited to the soil water balance. The details of how the forecasted daily rainfall depths are calculated by the IDSS are explained in section 3.3.4.2 (Weather Forecast). Forecasted daily rainfall that meets the RPT criterion is added in its entirety to the soil water balance. Effective rainfall, which replenishes root zone soil water, is calculated as the depth of forecasted daily rainfall that would not cause the soil water content to exceed saturation. Any additional rainfall is considered lost to runoff or deep percolation. No rainfall is deducted for canopy interception since this effect is offset by not decreasing calculated ET_c rates following rainfall.

Runoff. Any water added to the soil profile (rainfall or irrigation) in excess of the depth required to return the profile to saturation is considered lost to runoff. Realistically, such water could be lost to runoff or deep percolation; however, for the purpose of the IDSS the specific amount of water lost to runoff versus deep percolation is not important, only the

total amount lost via both pathways. The deep percolation term is reserved for water lost between saturation and field capacity, when gravitational drainage is occurring. The model assumes that no runoff will occur prior to the soil profile being saturated (i.e., the infiltration rate is assumed to be sufficient to prevent surface runoff or ponding prior to saturation).

Deep Percolation. Deep percolation is the last term of the soil water balance calculated on a daily basis and depends on the soil drainage rate (SLDR) specified by the user in configuring the IDSS. As stated previously, any water loss that occurs while the soil is at saturation is attributed to runoff by the model. The IDSS also functions under the assumption that drainage ceases once the soil profile is at or below field capacity, hence the deep percolation term will only have a nonzero value when the soil water is between saturation and field capacity. If the soil water is between field capacity and saturation, then drainage is calculated as:

$$DP = (SW - FC_{\text{depth}}) \times \text{SLDR} \quad [3.7]$$

where,

SW = depth of soil water currently in the root zone (mm)

FC_{depth} = field capacity of the root zone represented as depth of water (mm)

SLDR = soil drainage rate (day⁻¹)

This method of calculating drainage is the same procedure used in the Crop Simulation Model - Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003) and described by Ritchie (1998). The relationship between percent excess water (defined here as water between field capacity and saturation) and days after saturation for various SLDR assuming no other inputs (e.g. rainfall) or outputs (e.g. ET) is shown in Figure

3.9. A possible improvement to this component of the IDSS in the future could be to add a saturated hydraulic conductivity term (K_{sat}) for the soil that the calculated drainage would not be allowed to exceed. This would allow for simulation of an impervious layer (e.g. plow pan) that may reduce the rate of downward water movement sufficiently to cause water to “stack up” in the profile.

Capillary Rise. Presently, the IDSS operates under the assumption that the water table is sufficiently deep such that the supply of soil water to the root zone via capillary rise is negligible. Capillary rise could easily be added as a positive term to Equation 3.4; however, a new subroutine would have to be added to the model to handle its calculation. One possible option would be to integrate the IDSS with another hydrological model such as DRAINMOD (Skaggs, 1978) for fields with shallow water tables or poor drainage.

3.3.2.8 Irrigation Decision Process

Once the forecast soil water balance has run assuming no irrigation, the IDSS determines if irrigation should be recommended. If the current day is an irrigation opportunity and the forecasted soil water status at the end of any forecasted days prior to the next irrigation opportunity or a forecasted rainfall that would return the soil water content to FC is less than the management allowed depletion depth, then the IDSS will recommend irrigation. Daily irrigation opportunities are defined in the initial setup of the IDSS by the user and specify when the irrigation system has the potential to run. The user has three options for defining irrigation opportunities in the IDSS setup:

1. **Days of Week:** Specify days of the week when irrigation can occur (e.g., Monday, Wednesday, and Friday)

2. **Irrigation Interval:** Specify a set irrigation interval between irrigation opportunities (e.g., every three days)
3. **Manual Entry:** Manually enter each day of the year when the system is available to run.

The depth of irrigation recommended depends on the irrigation criteria specified by the user. Figure 3.10 illustrates the different irrigation options that the user can select from.

They are:

1. **Refill to Field Capacity:** The irrigation recommendation is calculated as the depth of water required to return the soil water from its current state to field capacity. (Figure 3.10, Option 1, pink line)
2. **Refill to Specified Point:** The irrigation recommendation is calculated as the depth of water required to return the soil water from its current state to a depth specified by the user as a percent of field capacity. This option ensures the availability of a storage space in the soil water reservoir for possible rainfall. (Figure 3.10, Option 2, orange line)
3. **Minimal Irrigation:** The irrigation recommendation is calculated as the minimal depth of water necessary (not to exceed field capacity) to prevent the forecast soil water status from dropping below management allowed depletion prior to the next irrigation opportunity. (Figure 3.10, Option 3, green line)
4. **Maximize Potential Rainfall Benefit:** The irrigation recommendation is calculated using the same procedure as for the *minimal irrigation* option, but then further reduced by a depth equal to the maximum accepted daily rainfall

forecast prior to the next irrigation opportunity. (Figure 3.10, Option 4, purple line).

The irrigation recommendation is then compared to an optional minimum irrigation depth (if provided by the user) before being returned from the model. Even if the irrigation recommendation is less than the minimum specified threshold, it will still be returned, but it will be flagged accordingly to alert the user.

Once the irrigation recommendation has been calculated, a second soil water balance is forecasted using the calculated irrigation recommendation depth as the depth of irrigation on the first day, to give the user an idea of how applying irrigation will affect the soil water status over the forecast days. It should be noted that regardless of the irrigation option selected by the user, the forecast soil water status assuming the application of the irrigation recommendation still may predict periods of deficit soil water conditions. If the current RAW is less than the cumulative net soil water losses prior to the next irrigation opportunity, then a forecasted deficit will occur regardless of the amount of irrigation applied. Such a scenario would suggest that the user should consider decreasing the number of days between irrigation opportunities, at least for that particular portion of the season.

The irrigation recommendation is directly calculated based on the forecasted status of the soil water reservoir, which is a function not only of the soil parameters discussed thus far, but also of the plant and atmospheric components of the SPAC. The following section discusses the plant subroutines of the IDSS.

3.3.3 Plant Components

Plant components of the IDSS are focused on processes related to growth and development of the crop. The daily calculated crop growth parameters pertain to both canopy and root development and are a function of user defined inputs, time (i.e. days after planting), and temperature. Just as it does for the soil components of the model (section 3.3.2), the IDSS predicts current and future status of the plant components as well.

3.3.3.1 Root Growth

Root growth is a fundamental component of plant development. In addition to absorbing and conveying water and nutrients from the soil to the rest of the plant, roots also provide anchorage for the plant structure (Hillel, 2004). In terms of the IDSS, root depth determines the size of the soil water reservoir and daily root growth affects water inputs of the soil water balance, as described previously.

Cumulative root depth is calculated by the IDSS on a daily basis, based on days after planting (DAP), user-specified maximum effective rooting depth (RD_{max}), and the user specified days to maximum effective rooting depth (Days to RD_{max}). A graphical representation of root depth over time as calculated by the IDSS is shown in Figure 3.11.

Root depth is calculated by:

$$RD = RD_{max} \left(\frac{DAP}{Days\ to\ RD_{max}} \right) \quad \text{for } DAP < Days\ to\ RD_{max} \quad [3.8]$$

and

$$RD = RD_{max} \quad \text{for } DAP \geq Days\ to\ RD_{max} \quad [3.9]$$

where,

RD = root depth (mm)

DAP = days after planting (days)

RD_{max} = maximum effective root depth (mm)

Days to RD_{max} = days after planting required to reach RD_{max} (days)

3.3.3.2 Crop Coefficient

Multiplication of reference evapotranspiration (ET_o) by a crop coefficient (K_c) to estimate crop evapotranspiration (ET_c) is a widespread method that has been used for many years (Doorenbos and Pruitt, 1977; Jensen et al., 1990; Allen et al., 1998). The crop coefficient is often estimated from a crop curve that accounts for different water use rates of plants during different stages of development. The IDSS uses a method presented by Allen et al. (1998) to generate a crop curve that relates K_c to days after planting. The general form of the crop curve is shown in Figure 3.12. The curve is developed based on user's inputs for lengths of each developmental stage and their associated K_c values. During each run of the IDSS, K_c is calculated for each forecasted day from the user defined crop curve. The K_c and forecast ET_o values from the atmospheric component are transferred to the soil subroutines to be used in the forecast daily soil water balance.

Multiple studies have investigated the use of cumulative heat units to determine K_c (Irmak et al., 2013; Nielson and Hinkle, 1996; Sammis et al., 1985), which accounts for seasonal variations in crop development that is not accounted for with the simple days after planting approach. Adding this option to the IDSS could be an improvement in the future; however, the decision to use the traditional days after planting approach was chosen for the present IDSS because localized data relating K_c to heat units is not readily available. Finding

local K_c values as a function of time can be difficult also; however, Allen et al. (1998) presents methods for adjusting crop curve parameters based on historical, local wind speed and humidity data, which makes the days after planting approach more adaptable to different locations for the time being (such adjustment is suggested when locally generated K_c estimates are not available).

3.3.3.3 Growth Stages

Growth and development of agricultural crops can be broken up into vegetative and reproductive stages of growth. Crops experience varying degrees of susceptibility to drought stress with regards to yield depending on growth stage and the severity of the stress (Hiler and Clark, 1971; Doorenbos, 1979). This varying degree of sensitivity is particularly important for irrigation scheduling (Hiler et al., 1974) as growers should lean on the side of caution during periods of high susceptibility, yet may be more willing to tolerate some levels of stress during other stages when crop susceptibility is less. It is important that any tool for irrigation scheduling take into account not only changing crop water demand over the season, but also changing water stress sensitivity.

The IDSS incorporates crop sensitivity to drought stress into its decision via a management allowed depletion term that the user specifies for each growth stage of the considered crop. The user can define as many growth stages as he or she desires. In addition to a MAD value, the user must specify a p value, a rainfall probability threshold (used in processing the weather forecast data), and cumulative growing degree days required for each defined growth stage. The IDSS uses the cumulative growing degree days to determine the current and forecasted growth stage for each run of the model. While the IDSS could easily

be altered to allow the user to specify stages of development simply based on time (i.e., days after planting), the use of growing degree days (based on time and temperature) provides a much better estimate of crop development across growing seasons, and growing degree day requirements for different stages of development are readily available for many crops.

Daily growing degree days are calculated by the IDSS using the equation:

$$\text{GDD} = \frac{T_{\text{max}} + T_{\text{min}}}{2} - T_{\text{base}} \quad [3.10]$$

where,

GDD = daily growing degree days accumulated (GDD)

T_{max} = maximum daily air temperature (if $T_{\text{max}} > T_{\text{upper}}$, use $T_{\text{max}} = T_{\text{upper}}$) (°C)

T_{min} = minimum daily air temperature (if $T_{\text{min}} < T_{\text{base}}$, use $T_{\text{min}} = T_{\text{base}}$) (°C)

T_{base} = base temperature, below which no growth is assumed to occur (°C)

T_{upper} = upper temperature limit, above which it is assumed the growth rate ceases to increase (°C).

The user must specify upper and base temperatures for the desired crop, although default values for these parameters could easily be integrated into future versions of the IDSS, which would allow the user to simply select the crop of interest. Such is true for the defined growth stages and their default values as well.

The IDSS calculates accumulated growing degree days based on observed weather data and predicts future growing degree days based on temperature forecast when calculating the irrigation recommendation. The irrigation recommendation uses the forecasted growing degree days to predict crop growth stage at time of irrigation and in the days to follow, and

the corresponding MAD that should be used for each. Likewise, the forecasted growth stage determines the RPT used to include or exclude forecast rainfall events. The processing of rainfall forecast and other weather inputs to the IDSS is discussed further in the Atmosphere Components section (3.3.4) below.

3.3.4 Atmosphere Components

The atmosphere components of the IDSS deal with weather (previously observed and forecasted) at the field of interest. The IDSS is currently configured to automatically retrieve observed weather data from any of forty-two ECONet weather stations and weather forecasts from the NWS corresponding to the ECONet site; however, it could be modified to accept weather observations and forecasts from any source as long as the necessary weather parameters are provided. The atmosphere subroutines of the IDSS are focused on collection and processing of data that are then used by soil and plant subroutines.

3.3.4.1 Observed Weather Data

To calculate the growing degree days accumulated each day of the growing season (from which the cumulative growing degree days and corresponding growth stage are calculated), the IDSS requires observed daily minimum and maximum temperatures for the field location or a location nearby. If soil moisture sensors are not being used to update the current soil moisture status of the field, then daily rainfall and reference evapotranspiration will be needed by the user as inputs into the concurrently running soil water balance. It is worth reiterating that the current IDSS does not maintain a running soil water balance using observed data, but this functionality could be added in the future.

3.3.4.2 Weather Forecast

Each daily run of the IDSS requires daily weather forecasts at minimum from the current day through the next irrigation opportunity. These data are used to forecast soil water reservoir and crop status, which are used to determine the irrigation recommendation for the current day. The daily forecast parameters required by the model are: minimum temperature, maximum temperature, reference evapotranspiration, probability of precipitation, and quantity of precipitation. Because many weather forecast providers, such as the National Weather Service, provide weather forecast data on hourly intervals, the current IDSS is configured to accept hourly forecast data, which are then converted to daily data as described below.

The National Weather Service, a division of the National Oceanic and Atmospheric Administration (NOAA), generates seven-day (168-hour) forecasts at a 5 km spatial resolution or better for the entire United States and US territories. These forecasts are updated on an hourly basis and made freely available over the internet via the National Digital Forecast Database (NDFD) (Glahn and Ruth, 2003). NDFD data are available via a number of web APIs or through the NWS web interface (www.weather.gov). Weather forecast data currently used by the IDSS are collected and stored hourly from the NWS by a separate web service operated at North Carolina State University (NCSSU). The API used by the server can be accessed at:

<http://forecast.weather.gov/MapClick.php?lat=XXXX&lonYYYY&FcstType=digitalDWML>, where XXXX and YYYY are the latitude and longitude, respectively, in decimal degrees for the location of interest.

The NCSU web service collects and stores forecasts from the above URL for the latitude and longitude of each of the ECONet weather stations on an hourly basis. The weather forecast modules of the IDSS read and process weather forecast data as follows.

Temperature Forecast. Forecasted daily minimum and maximum temperatures are required to forecast the growing degree days and respective growth stages for each run of the IDSS. Hourly forecast data collected at 12 AM of the current day are read by the IDSS. The raw forecast data contains hourly temperature forecast for the next 168 hours, which the IDSS processes to determine the minimum and maximum temperatures for each of the seven forecast days. If the user were to choose an alternative forecast source with a different number of forecast hours, the IDSS would process the forecast data for the number of full days ahead corresponding to the number of forecast hours.

Reference Evapotranspiration Forecast. Reference evapotranspiration (ET_o) forecasts are necessary for the IDSS to run the forecast soil water balance. Forecast ET_o (sometimes referred to as FRET) are not presently available from the NDFD via the interfaces discussed previously. In recent years, some regional offices of the NWS have started providing seven-day ET_o forecast calculated using NDFD forecast data and the ASCE-EWRI Standardized ET_o method (ASCE-EWRI, 2005) as described by Snyder et al. (2009). The NDFD forecasts do not include estimates of solar radiation, a necessary input for calculating ET_o , but they do include forecast percent cloud cover. Forecast percent cloud cover is used to estimate the ratio of actual to potential sunshine hours, which is used to forecast solar radiation following the procedures of Doorenbos and Pruitt (1977). Nautiyal et al. (2014) reported strong correlation ($R^2 = 0.88$) between calculated solar radiation based on

the Doorenbos and Pruitt method and measured solar radiation in central North Carolina. They also found solar radiation calculations based on percent possible sunshine substantially more reliable than those calculated using the Hargreaves and Samani temperature based method (Hargreaves and Samani, 1985). The NCSU web service that collects and stores forecast data for the IDSS calculates forecast ET_o at the time of data collection using the same procedures as Snyder et al. (2009).

Rainfall Forecast. The inclusion of rainfall forecasts in the irrigation recommendation decision is the primary distinction between the IDSS and other currently available irrigation scheduling tools, as well as what makes it so potentially beneficial to humid regions, like the southeastern United States.

There are two components to rainfall forecasts that are used by the IDSS: 1) the probability of precipitation (POP) and 2) the quantitative precipitation forecast (QPF). POP is the probability that a measureable rainfall event (greater than or equal to 1/100th of an inch) will occur during the forecast interval for the location of interest and QPF is the depth of liquid precipitation expected during that period. As with the other weather forecast data, POP and QPF are retrieved on an hourly basis by the NCSU web service and converted to daily rainfall estimates by the IDSS.

The IDSS uses the hourly POPs, hourly QPFs, and user specified RPTs to calculate forecast daily rainfall that is used in the forecast soil water balance. The RPT indicates the degree of certainty required in the POP to accept a QPF as true. The user must specify a RPT for each defined growth stage in accordance with the varying plant susceptibility to drought stress. Each time the model runs, the RPT is determined for each of the forecast days based

on the forecast growth stage. If an hourly POP exceeds the RPT, then its QPF is added to the forecast soil water balance.

3.4 SUMMARY AND CONCLUSIONS

Irrigation scheduling in humid climates, such as the southeastern United States, presents a different set of challenges than in arid climates where the two primary factors governing irrigation decisions are water supply and plant water demand. Midseason rainfall, which is highly variable and often localized, creates scenarios that are conducive to over-irrigation, potentially leading to undue water stress on the crop or nutrient losses to surface or ground water via runoff or leaching. Similarly, growers may be faced with having to subjectively decide whether to forgo an irrigation event due to the potential for an upcoming rainfall – at the risk of unduly stressing the crop if the rain forecast is incorrect – or proceeding with irrigation in an attempt to avoid deficit moisture stress only to see rainfall the next day that would have prevented the stress also.

The IDSS presented in this chapter has been developed to address such challenges by objectively incorporating crop growth stage, real-time soil water status in the root zone, and short-term weather forecast to provide a daily updated irrigation recommendation to the user. The web-based application represents the various components of the soil-plant-atmosphere continuum and predicts daily soil water status from the time the model is run until the next irrigation opportunity based on a forecasted soil water balance.

While observed weather data and weather forecasts are automatically accessed by the model presently, the IDS could be improved by expanding the available sources for such data

beyond the forty-two ECONet locations currently available. Similarly, inclusion of a built-in soil water balance to update the current soil water status using weather data or adding functionality to automatically retrieve readings from field installed soil moisture sensors would further reduce the input demand on the user, thus improving the likelihood of adoption of the tool in day-to-day irrigation management.

Field and modeling studies based on the IDSS will be beneficial in optimizing the irrigation options for different objectives (e.g., minimizing drought stress or maximizing potential rainfall benefit) and management thresholds, such as the MAD and RPT for each growth stage. Successful implementation of the IDSS could not only increase crop yields, but also improve crop water and fertilizer use efficiencies by limiting periods of excess or deficit soil water and by reducing runoff and deep percolation. These results would increase profits for growers, while improving the environmental sustainability of production agriculture in the southeastern United States.

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3.6 FIGURES

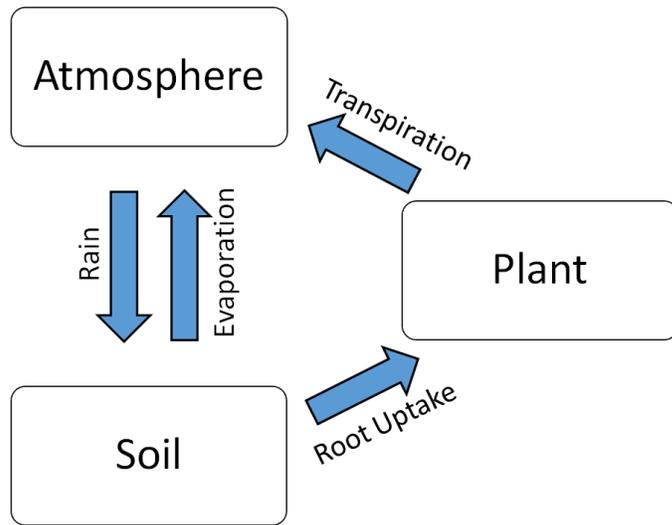


Figure 3.1. Representation of the basic sources, sinks, and mechanisms of water transfer in the soil-plant-atmosphere continuum (SPAC).

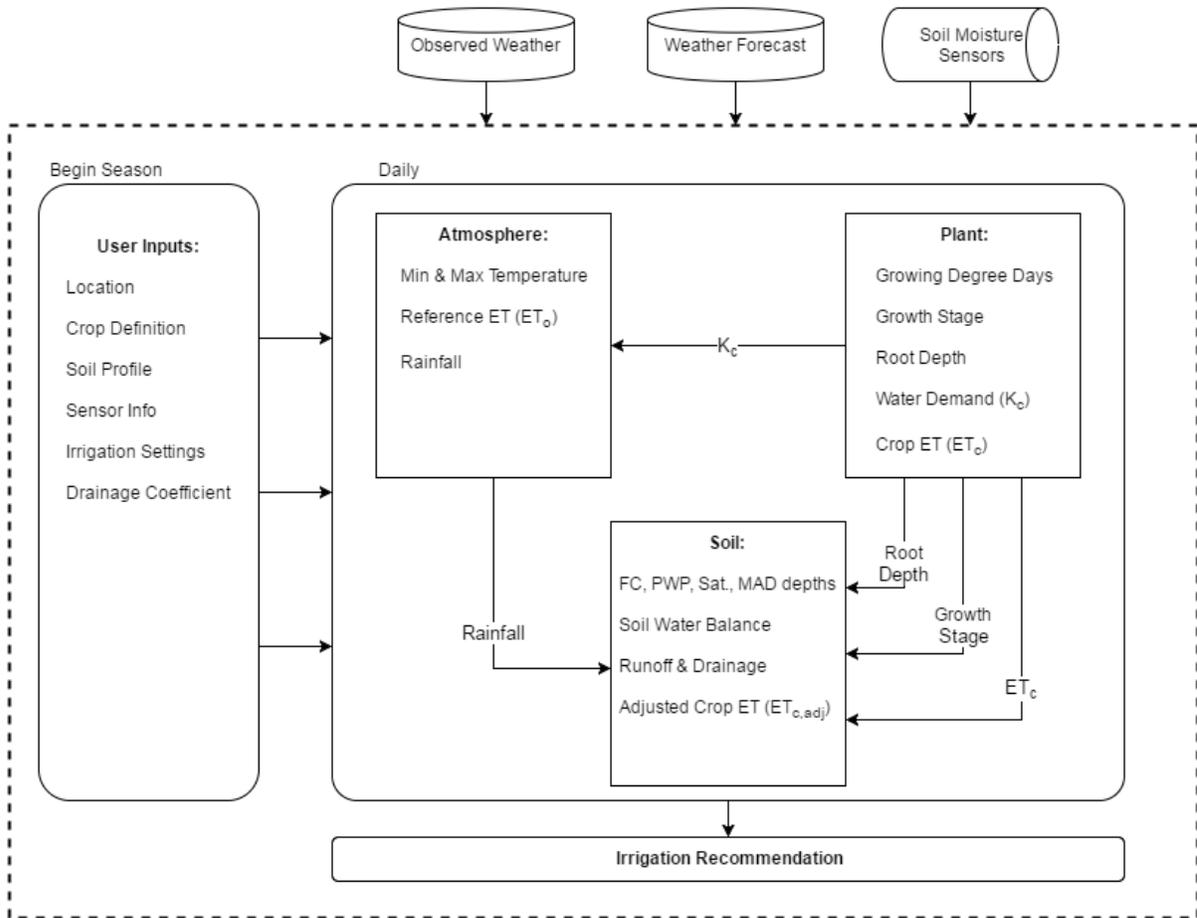


Figure 3.2. High level representation of the IDSS subroutines. (FC = field capacity, PWP = permanent wilting point, Sat. = saturation, and MAD = management allowed depletion)

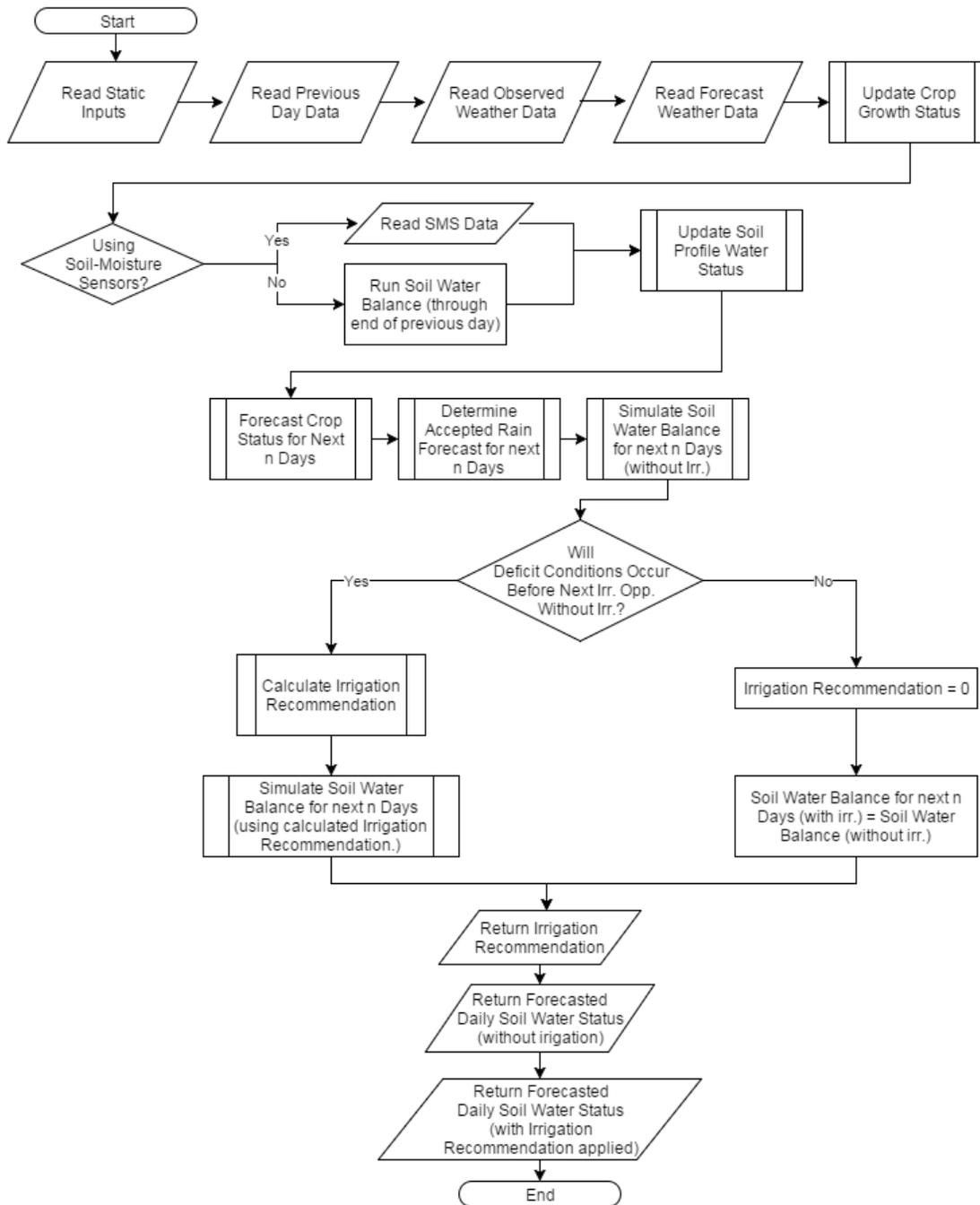


Figure 3.3. Logic diagram for the daily routines of the IDSS.

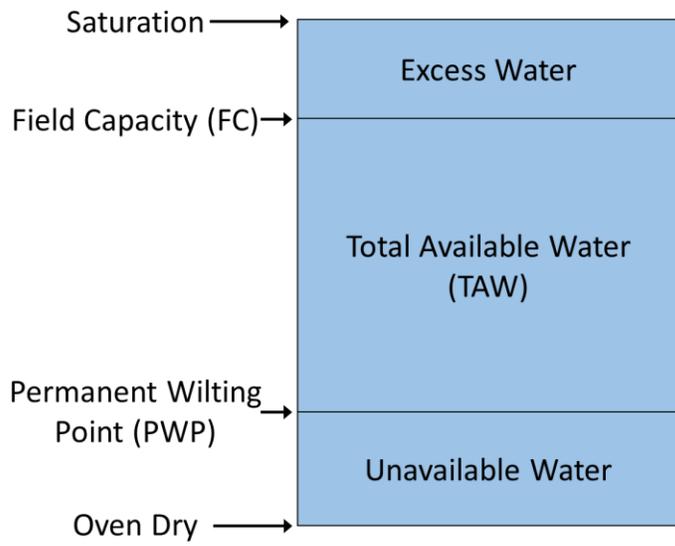


Figure 3.4. Representation of the soil water reservoir (not to scale).

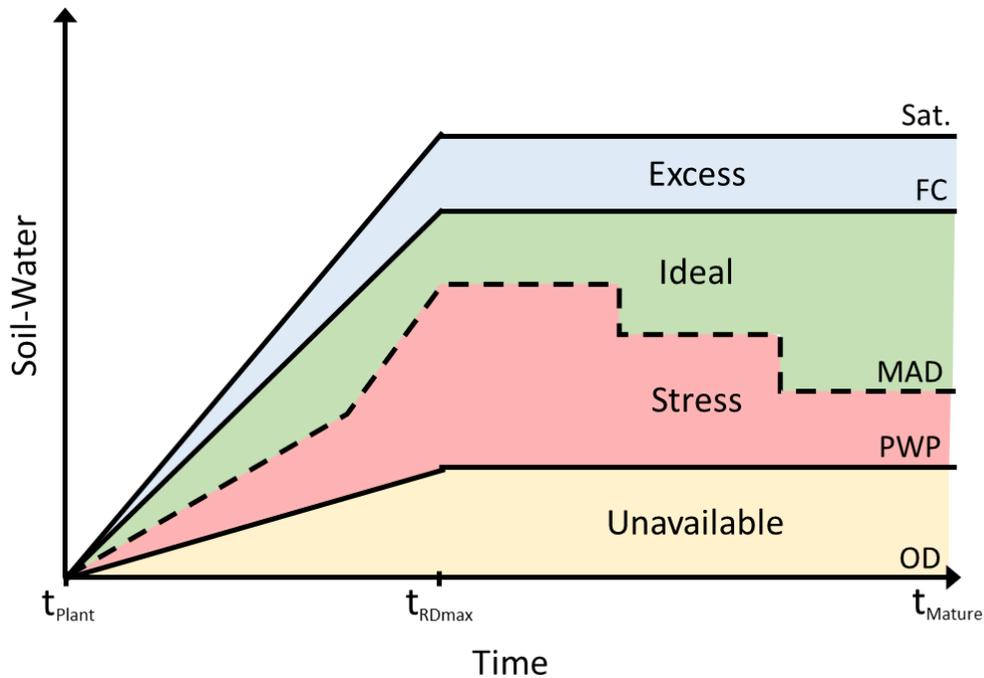


Figure 3.5. Representation of the soil water reservoir over the course of the growing season as calculated by the IDSS. Note the fluctuating management allowed depletion (MAD) line represents how the user can set the IDSS to manage soil water differently at different stages of crop growth. (Sat. = saturation, FC = field capacity, MAD = management allowed depletion, PWP = permanent wilting point, OD = oven dried, t_{Plant} = time of planting, t_{RDmax} = time of when roots reach max depth, t_{Mature} = time of crop maturity)

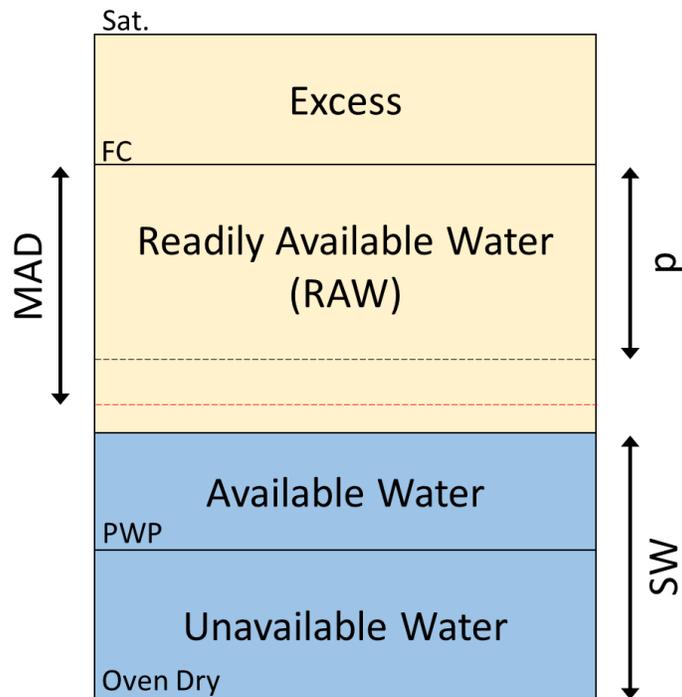


Figure 3.6. Representation of management allowed depletion (MAD) and depletion factor (p) relative to the soil water reservoir (not to scale). Note: MAD and p may change over the course of the season depending on the user's specified values for each in each growth stage.

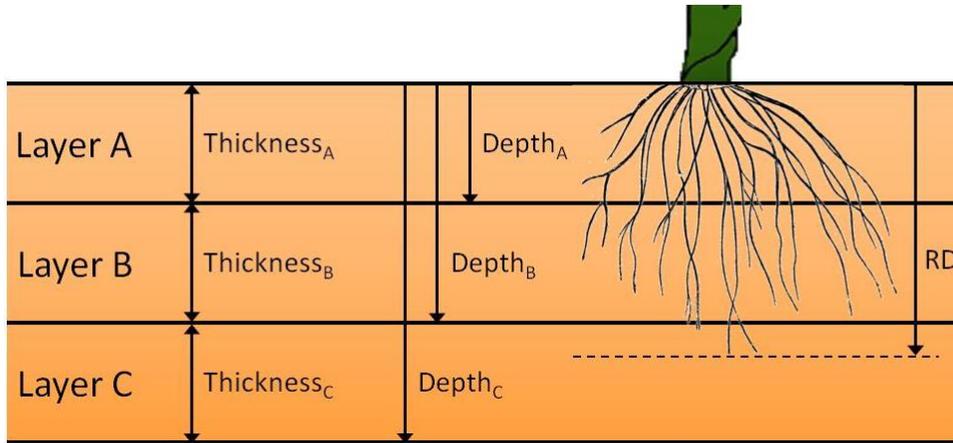


Figure 3.7. Representation of layering within the soil profile as considered by the IDSS. Note: For each defined layer, the user must specify the depth thickness, and volumetric soil water contents corresponding to saturation, field capacity, and permanent wilting point. (RD = root depth)

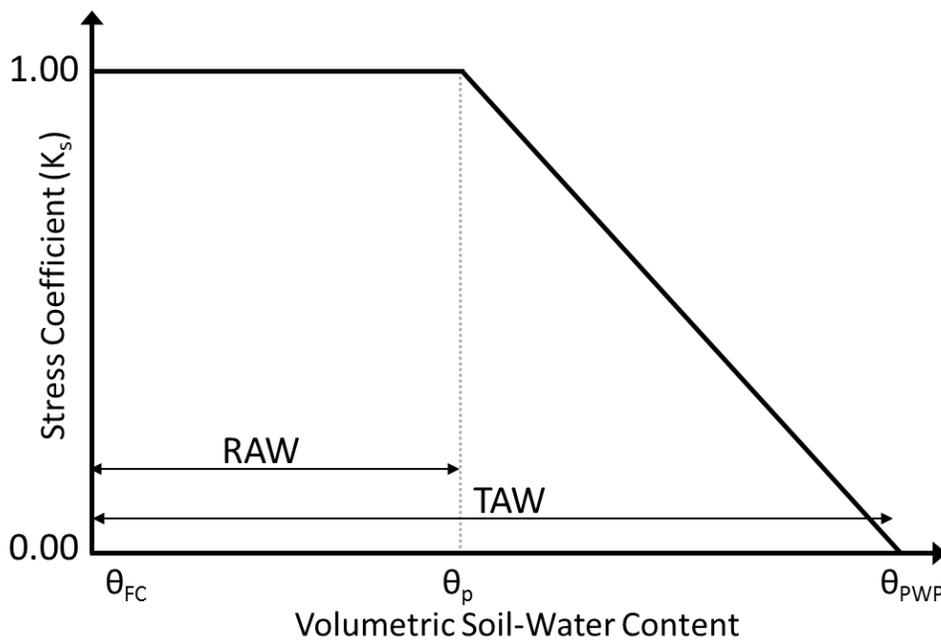


Figure 3.8. Relationship between the calculated crop stress coefficient (K_s) and volumetric soil water content (θ).

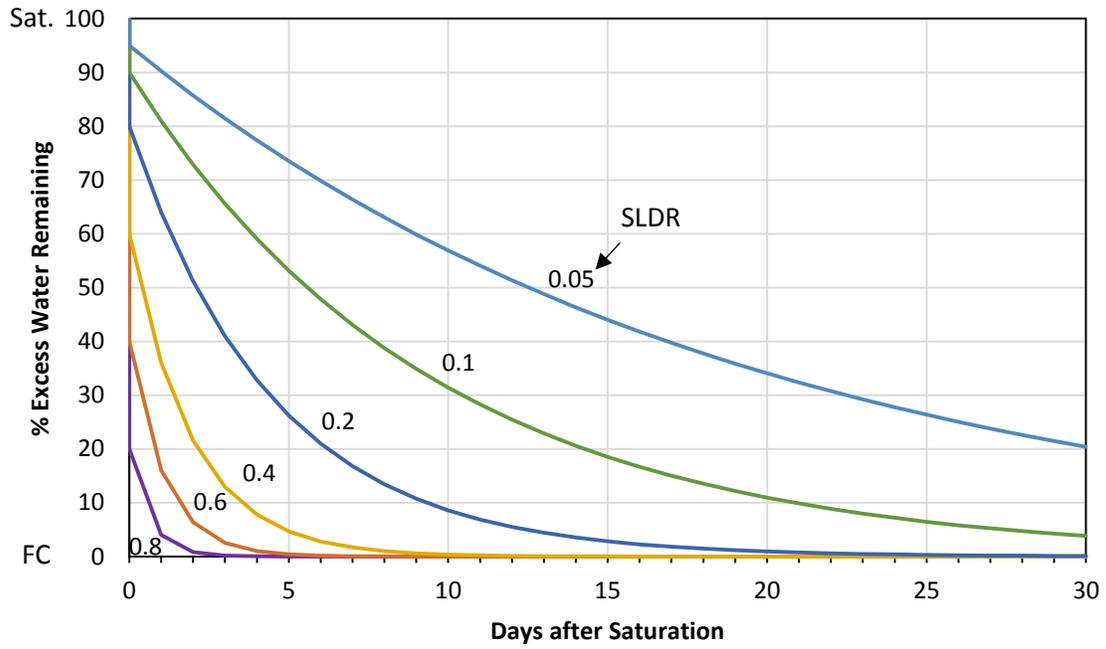


Figure 3.9. Relationship between excess water (defined as water between saturation and field capacity) and days after saturation event assuming no additional inputs (e.g., rainfall) or outputs (e.g., ET) for various soil drainage rates (SLDRs).

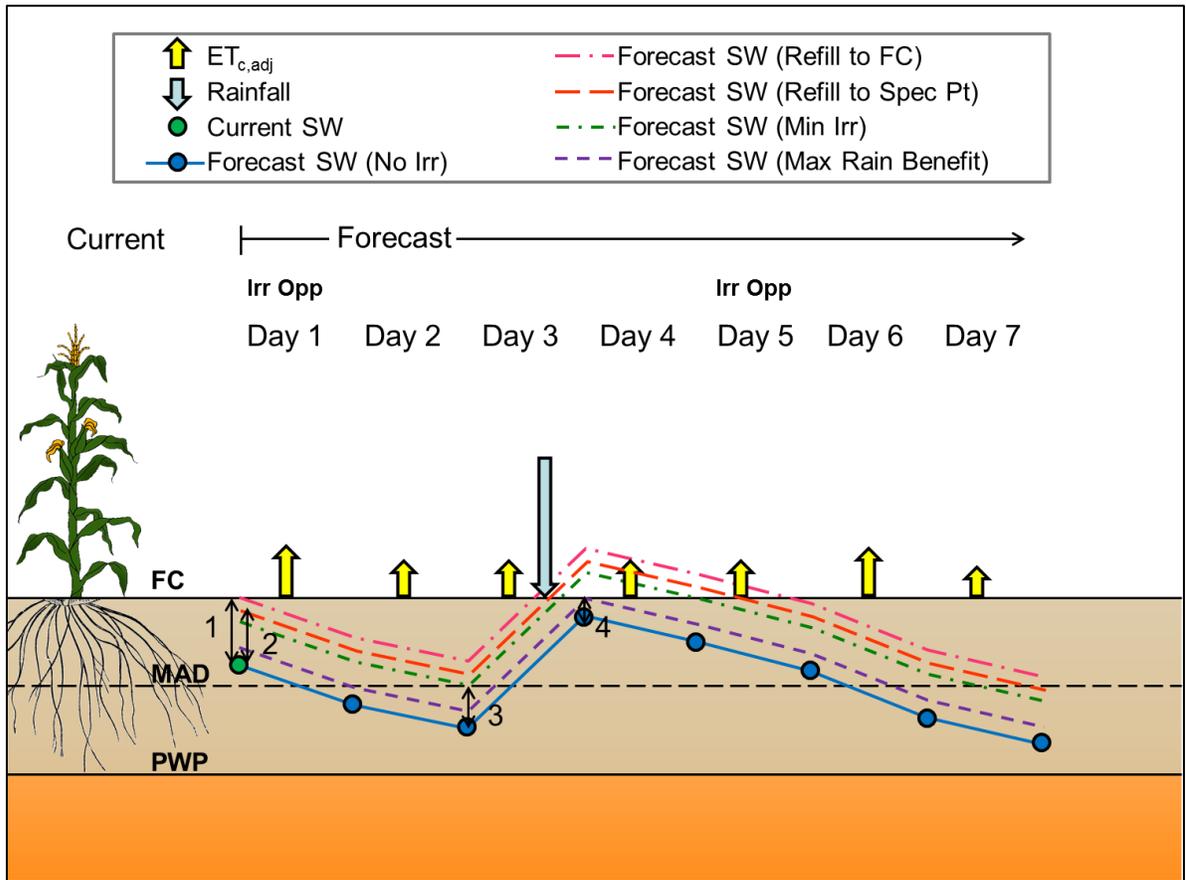


Figure 3.10. Representation of how the IDSS forecasts daily soil water statuses and calculates the irrigation recommendation depending on the irrigation options selected by the user. Note: The first dot represents the current soil water status (as measured by soil moisture sensors or estimated by a concurrent soil water balance) and the subsequent dots represent forecasted daily soil water statuses for next seven days based on forecast $ET_{c,adj}$ and rainfall, without any irrigation. Other lines represent the updated soil water status forecast assuming one of four irrigation options (described in section 3.3.2.8 of text). Options: 1) Refill to FC (pink line), 2) Refill to Specified Point (orange line), 3) Minimal Irrigation (green line), and 4) Maximize potential rainfall benefit (purple line). (FC = field capacity, MAD = management allowed depletion, and PWP = permanent wilting point)

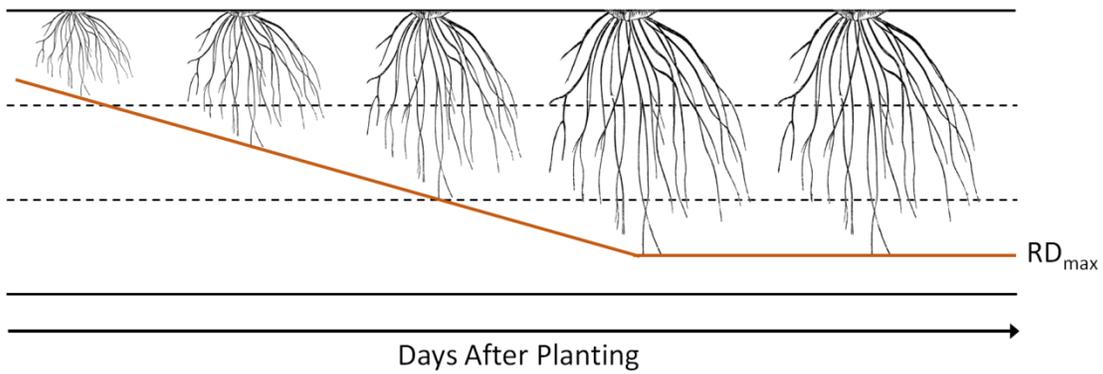


Figure 3.11. Representation of root depth (RD) relative to days after planting as calculated by the IDSS.

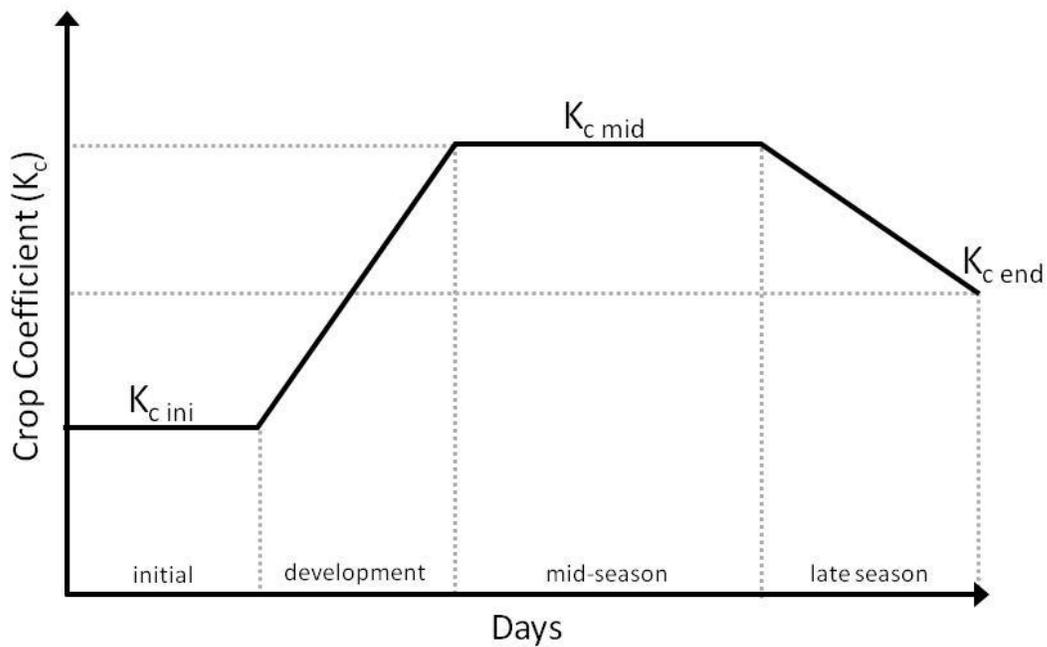


Figure 3.12. Representative crop curve over the course of the growing season.

CHAPTER 4 - IMPLEMENTATION AND EVALUATION OF THE IRRIGATION DECISION SUPPORT SYSTEM ON AN IRRIGATED CORN FIELD IN EASTERN NORTH CAROLINA

4.1 ABSTRACT

A field study was commenced at the Cunningham Research Station in Kinston, NC in 2014 to evaluate the Irrigation Decision Support System (IDSS) described in Chapter 3. The intent was to highly instrument a research field serviced by a linear move irrigation system, retrofitted for variable rate irrigation (VRI) in 2013, in order to test the IDSS compared to non-irrigated and routinely irrigated treatments in the same field. Several challenges hampered the project including irrigation system hardware failures, delays in completing the programming of the IDSS, and inherent variability across the field, including production-limiting compaction and poor drainage. More importantly, the 2014 growing season was the wettest (933 mm of rainfall) among the previous eighteen years of continuous weather data available at the Cunningham Research Station, meaning irrigation was not essentially needed during the study. A total of 16 and 32 mm of irrigation were applied to IDSS and routinely irrigated plots, respectively, before irrigation was ceased entirely. Accordingly, the objectives of the study were modified to focus on evaluating the soil water balance component of the IDSS, used in forecasting the soil water status for coming days, by comparing predicted daily soil water contents based on measured weather data to observed soil water contents in the study field. Soil penetration resistance measurements were taken in multiple locations following harvest in an effort to explain and account for extensive growth and yield variability across and within plots. Plot average yields ranged from 3,680 to 9,506

kg ha⁻¹ and differences were not attributable to irrigation treatments. The IDSS soil water balance was a good predictor of observed root zone soil water contents averaged across all plots (NSE = 0.808, RSME = 9.3 mm), but tended to over predict the magnitude of the effect of rainfall events as well as the drawdown rates during periods of drying. Measurements indicated root impeding penetration resistances as shallow as 50 mm in some areas of the field. There was evidence of a distinct compaction layer between 150 and 300 mm below the soil surface across much of the field. There was also visual evidence that maximum penetration values measured across the field correlated with spatial variability in crop growth and yield. Additional years of field testing, encompassing various locations, soil types, and seasonal rainfall patterns are needed to further evaluate and refine the IDSS, towards the goal of maximizing crop production, while preserving the quantity and quality of fresh water supplies.

4.2 INTRODUCTION

Irrigation in production agriculture in the humid southeastern United States has increased in recent years (USDA-NASS, 2003; 2013) as growers seek to maximize production potential afforded by genetic advancements in seed technology and to reduce the risk of crop failure and substantial yield loss resulting from extreme weather years. Growers in this region are less dependent on irrigation than their counterparts in arid parts of the country, yet they face a different set of scheduling challenges, mainly presented by mid-season rainfall and weather variability (Vories et al., 2009). Season-to-season variability as well as spatial variability in weather patterns within seasons mean that effective irrigation

scheduling must be adaptive in order to account for changes in plant water demand and soil water availability throughout the crop growing season.

Over the years, many irrigation scheduling tools and resources have been developed and made freely available to growers (see Chapter 3 - Section 3.2); however, the adoption and routine use of such tools has remained low (USDA-NASS, 2013) as has the investment in and use of precision irrigation technologies such as variable rate irrigation (VRI) (Evans, et al., 2013). There are multiple contributing factors to the slow adoption of such technologies, including limitations of the scheduling software, gaps in communication between the scheduling resources and the controlling hardware used to implement the irrigation decision, and the time and experience required to run these systems. In short, most growers currently do not consider the potential return on investment worth the costs (e.g., financial, time, and expertise) associated with adopting such technology.

In response to these factors that have limited implementation of smart irrigation systems in agriculture, the IDSS, presented in Chapter 3, was designed as a simple system that requires minimal inputs with the potential for clear and tangible benefits to the grower. The IDSS integrates crop growth stage, real-time soil water status of the root zone, and short-term weather forecast in a daily irrigation recommendation for the user. While the concepts and underlying principles, such as the soil water balance, on which the IDSS is based are well tested and have been proven effective, the unique combination of all of them as proposed in the IDSS has not been field tested. With any proposed decision guidance model for agriculture, there is a need for field studies to validate the tool and evaluate its effectiveness. The experimental study presented in this chapter was designed to field test the

proposed IDSS and its efficacy as an irrigation scheduling resource in the humid southeastern United States. The field testing was carried out during the 2014 growing season by instrumenting a production agriculture field, in a corn-wheat-soybean rotation, with environmental monitoring sensors and a precision controlled, variable rate irrigation system.

The objectives of the study were to: 1) implement and demonstrate the smart irrigation technology represented by the IDSS-scheduled irrigation; 2) evaluate the smart irrigation technology by comparing the IDSS-scheduled irrigation (referred to as smart irrigation) with non-irrigated and routinely irrigated corn on the research field during the 2014 growing season, with respect to yield, water use, and water use efficiency; and 3) assess the efficacy of the IDSS at correctly predicting when and how much irrigation to apply given the real-time soil water status of the root zone, the calculated growth stage of the crop, and short-term, daily weather forecasts.

Achieving the objectives of the study was substantially inhibited by a host of challenges, including delays in configuring a fully operational version of the IDSS; hardware failures with the existing irrigation infrastructure; inferior crop stand (in part due to mismanagement of nutrient application); widespread, inherent variability across the research field; and most significantly, above average rainfall during the growing season, which resulted in minimal need for irrigation and revealed poor drainage in portions of the field.

Accordingly, the proposed objectives, beyond the implementation and demonstration of the smart irrigation technology, were modified to: 1) evaluate the effectiveness of the soil water balance at the core of the IDSS by comparing predicted soil water contents based on observed weather data to measured soil water contents in the field over the course of the

season, and 2) investigate the sources of variation in the field – particularly soil compaction in the shallow soil layers.

4.3 MATERIALS AND METHODS

4.3.1 Site Description

The research field is a relatively flat, 4.4 ha field at the Cunningham Research Station in Kinston, NC (35° 18' 3"N, 77° 34' 8" W). Dominant soil series are Lynchburg sandy loam (Fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults; somewhat poorly drained) and Rains sandy loam (Fine-loamy, siliceous, semiactive, thermic Typic Paleaquults; poorly drained) (USDA-NRCS, 2016) (Figure 4.1). The field is irrigated by three spans of a five-span Valley linear move irrigation system. The source of irrigation water is an onsite pond (located approximately 650 m from the closest point of the field). Irrigation water is supplied via a series of hydrants along the edge of the travel path of the linear move irrigation system.

4.3.2 Variable Rate Irrigation Retrofit

In the spring of 2013, the linear move irrigation system was retrofit to be a variable rate irrigation (VRI) system by Advanced Ag Systems, Inc., Dothan, AL. VRI is a precision agriculture technology that allows users to vary the amount of irrigation applied within different areas of a field to precisely meet the individual water demands of each area (Evans et al., 2013). An onboard global positioning system (GPS) and custom irrigation controller, coupled with user-defined prescription map, determine the spatial variation of irrigation under a VRI system. The VRI kit installed on the study irrigation system divided the linear move into fifteen independently controllable irrigation zones (average width of 18 m), each

of which could be varied in application rate every 11 m along the direction of travel. Prescription maps for the system can be generated by the Irrigation Manager software, provide by Advanced Ag System, Inc. at the time of installation, and loaded onto the VRI controller using a thumb drive. The VRI retrofit was performed to facilitate testing of multiple irrigation strategies on the study field.

4.3.3 Planned Irrigation Treatments

Three water management regimes were planned for the study. The first was a "smart" irrigation schedule (Smart) as determined by the IDDS. The second treatment was a routine irrigation schedule (Routine), intended to mimic irrigation practices currently used by growers that irrigate agronomic crops in North Carolina. The final treatment was a non-irrigated production regime (Rainfed), representative of the still most common practice in North Carolina and much of the southeastern United States.

To reduce labor demands on research station staff and to mimic a realistic limitation that growers may face, irrigation events were restricted to two days per week (Monday and Thursday). Corn is moderately tolerant to water stress during the early vegetative stages (Heiniger et al., 2000), while the greatest water demand and drought susceptibility is during the reproductive stages, particularly between one week prior to tasseling and two weeks after silking (Heiniger et al., 2000). For this reason, many growers that irrigate corn in North Carolina wait until June to start irrigating and cease irrigation by the end of July. Analysis of historical weather data from Kinston, NC and estimates of weekly crop evapotranspiration for non-stressed corn, planted on April 15 (typical planting date for the region) revealed an

average weekly net irrigation requirement of 23 mm week⁻¹ and 22 mm week⁻¹ in June and July, respectively. Using this information, The Routine treatment was scheduled to apply 25 mm week⁻¹, split over two applications, each week during June and July. Weather data used in determining this schedule included historical monthly rainfall and reference evapotranspiration (ET_o) estimates from the Cunningham Research Station weather station, one of forty-two Environment and Climate Observing Network (ECONet) weather stations across the state of North Carolina maintained by the State Climate Office of North Carolina (SCO-NC) (SCO-NC, 2016). Routine irrigation was to be skipped only under the following conditions: 1) a rainfall of 6 mm or greater within 24 hours prior to a scheduled irrigation event, 2) forecast of an imminent rainfall event on the day of or in the days to immediately follow a scheduled irrigation, or 3) standing water in the field. Leeway was given to the station staff in final determination of whether or not to forgo an irrigation event based on their experience and knowledge of the study field.

4.3.4 Experimental Design

The study field was divided into nine plots, with each irrigation treatment replicated three times, in a 3 x 3 randomized block design (Figure 4.2). Each plot was 61 m by 46 m (0.3 ha), with 19 m buffers between plots along the direction of travel of the linear move system (to allow the VRI system to fully transition from one application rate to another between plots) and 8 m buffers between plots within each replication block (where the wheel tracks for the linear move system were able to pass) (Figure 4.3).

4.3.5 Instrumentation

In the spring of 2014, prior to planting, a multi-conductor communication cable was buried between the center plot of each replication and the respective adjoining exterior plots (Figure 4.3). The cable was housed in 2 in. PVC conduit, buried 0.6 m deep to protect it during field cultivation. At the center of each plot, the cable surfaced to a PVC junction box, which served as a protected connection node for multiple field sensors. Tipping bucket rain gauges (Onset Computer Corp., Bourne, MA) and manual rain gauges were mounted 1.8 m above the soil surface in the center of each plot to monitor rainfall and irrigation during the study. Three Decagon 5TM soil moisture and temperature sensors (Decagon Devices, Inc., Pullman, WA) were connected at the junction node in each plot but were not installed in the soil until after planting. Following planting, the soil moisture sensors were installed at depths of 75, 225, and 375 mm in a single vertical trench, offset approximately 300 mm from the plant row near the center of each plot. Readings from these sensors were considered representative of 150 mm thick soil layers at depths of 0, 150, and 300 mm.

A CS451 pressure transducer (Campbell Scientific, Inc., Logan, UT) was wired to each plot junction node for monitoring water table depth, but monitoring wells were not installed until later in the season and the data from them was not used for the analysis presented in this chapter. Both the 5TM and CS451 sensors are SDI-12 compatible, which allowed a single communication cable to be used between these devices. All sensors in each replication were connected to a Campbell CR206x data logger (Campbell Scientific, Inc., Logan, UT), which was housed in a protective enclosure box in the center plot of each replication and powered by a 12volt, 7 amp-hour battery and 10 W solar panel. The data

logger was programmed to take sensor readings every 15 minutes and recorded hourly averages for soil moisture, soil temperature, and water table depth and hourly totals for rainfall. Each CR206x had a built-in radio, which was used to transmit the data collected in each replication back to a base station (Campbell CR800 data logger; Campbell Scientific, Inc., Logan, UT) located in plot 7 and equipped with a Campbell RF 401 900 MHz spread-spectrum radio transmitter (Campbell Scientific, Inc., Logan, UT) and a RavenXTV cellular digital modem (Sierra Wireless, Richmond, British Columbia, Canada). The CR800 collected hourly records from each of the three CR206x data loggers and combined them into common data tables on the base station. Data stored on each of the data loggers was transmitted to an offsite computer, located on the North Carolina State University (NCSU) campus, every four hours using Loggernet data logger support software (Campbell Scientific, Inc., Logan, UT). This data was intended to be an input into the IDSS for real-time scheduling of irrigation during 2014, but was instead used as the check for evaluating the effectiveness of the IDSS soil water balance without irrigation at matching the measured soil water contents in each plot.

4.3.6 Crop Management

In 2013, prior to this research, the study field was planted in no-till wheat followed by no-till soybeans. Following the installation of the communication cable in the spring of 2014, the field was disked on 10 April and 33.6 kg ha⁻¹ of N, 100.8 kg ha⁻¹ of K, and 35.3 kg ha⁻¹ Sulfur (336 kg ha⁻¹ 10-0-30 N-P-K with 10.5% Sulfur) was broadcast on 11 April. On 14 April, a rolling field cultivator was pulled through the field in final preparation for planting.

On the same day, Pioneer P2089YHR field corn was planted at 70,600 seed ha⁻¹ on 97 mm row spacing with 91.5 kg ha⁻¹ N (234 L ha⁻¹ of 30-0-0 N-P-K liquid fertilizer) applied slightly offset from the row center.

Heavy rainfall in the first 10 days after planting (DAP) resulted in water ponding in the field and the development of a hard crust on the soil surface. A rotary hoe was run through the field on 25 April 2014 to loosen the soil surface crust and encourage germination. Germination was observed on 28 April 2014 (14 DAP).

The corn was sprayed with 3.5 L ha⁻¹ Atrazine, 2.3 L ha⁻¹ glyphosate, and 2.3 L 80/20 surfactant per 378.5 L of water on 29 April to control weeds. A follow-up herbicide application of 1.8 L ha⁻¹ glyphosate and 2.3 L ha⁻¹ ammonium sulfate was applied on 12 May. A final herbicide and fertilizer application was made together on 27 May combining 374 L ha⁻¹ of 30% UAN (146 kg ha⁻¹ N), 2.3 L ha⁻¹ Atrazine, and 110 mL ha⁻¹ Steadfast Q (Nicosulfuron – 25.2%; Rimsulfuron – 12.5%). It should be noted that more N was applied during this last application than was intended due to a miscommunication regarding the total N that had been previously applied. The cumulative total N applied in 2014 ended up being 271 kg ha⁻¹, 61% more than the intended total of 168 kg ha⁻¹.

4.3.7 Weather Data

Daily rainfall totals, maximum and minimum temperatures, and ET_o were collected from the Cunningham Research Station weather station, an ECONet station maintained by the SCO-NC. The weather station is located approximately 340 m east of the study field and is one of the stations that users of the IDSS can select as a source for weather data. The data

from all ECONet stations are available via the NC Climate Retrieval and Observations Network of the Southeast (CRONOS) online database managed by the SCO-NC (SCO-NC, 2016). Weather data were used to monitor conditions during the study period and as inputs to the IDSS soil water balance model that was compared to measured soil water contents from the field.

4.3.8 Harvest

4.3.8.1 Plant Sampling

Destructive plant samples were collected from four random locations near the center of each plot on 18 September (157 DAP) to assess the effects of irrigation treatments on yield and for comparison with soil water dynamics monitored in each plot. Each sampling location was chosen within approximately 15 m of the respective plot soil sensors in order to minimize the impact of in-plot spatial variability when relating measured water uptake to plant growth.

At each sampling location, three consecutive plants in the same row were harvested, removing all biomass greater than 75 mm above the soil surface. Individual plants were tagged according to the location from which they were collected, then transported to an offsite location where they were dried for 48 hours at 70 °C prior to processing. Following drying, each plant was partitioned into individual components (i.e. stalk, leaves, sheaves, and ears), which were each weighed, counted, and measured as appropriate. Ears were further subdivided into cobs, kernels, and husks. For the purposes of this chapter, only kernel weights are presented, which were converted to yield per area estimates by dividing the total

kernel weight from the three plants at each sampling locations by the representative area from which they were collected (0.14 m²; based on 70,600 seed ha⁻¹ and 97 mm row spacing).

4.3.8.2 Combine Harvest

All plots were harvested on 23 September (162 DAP) using a commercial, four-row harvester equipped with a Trimble FmX Integrated Display and yield monitor (Trimble Navigation Limited, Sunnyvale, CA). Each of the nine plots was harvested individually so that total kernel weight from each plot could be measured and compared to yield estimates from the plant sampling and the yield monitor. Yield monitor data were imported into Farmworks (Trimble Navigation Limited, Sunnyvale, CA), which was used to generate a point shapefile that could be imported in to ArcMap 10.2 (Esri Inc., Redlands, CA). An interpolated yield map for the entire field was generated using the inverse distance weighting (IDW) feature within the Spatial Analyst toolkit.

4.3.9 Measurement of Soil Penetration Resistance

Over the course of the growing season and particularly during harvest, substantial variability in plant stand, vigor, and yield was apparent across the field and even within plots. Due to significant field traffic during the instrumentation phase of the project, heavy rains that followed cultivation at planting, and visual evidence of limited root depths across the field, it was speculated that much of the field may have been affected by compaction within the normal root zone depth.

Following harvest, but prior to any additional field traffic, a cone penetrometer linked to a tablet computer and modified to mount in the receiver hitch of a full size truck was used to collect penetration resistance readings at depths from 0 to 350 mm across and beyond the study field (Figure 4.4). A total of 51 locations were tested within the study field (5 per plot and 6 sample locations in buffers between plots). Penetrometer readings at each location and depth were imported into ArcMap 10.2 and interpolated penetration resistance maps for 15 layers (from 0 to 350 mm, by increments of 25 mm) were generated using the IDW tool in the Spatial Analyst toolkit. Penetration resistance maps were used to visually assess areas of the field where root growth may have been limited due to compaction or other sources of physical barriers in the shallow soil layers. Evidence of correlation between penetration resistance maps and the yield map were also visually inspected, although no formal test for such was performed.

4.3.10 Soil Sampling for Parameterization of the Simulated Soil Water Balance

Three intact soil cores (75 mm diameter by 75 mm height) were collected from within approximately 2 m of the soil moisture sensors in each plot, at depths of 75 mm, 225 mm, and 375 mm (corresponding to the installation depths of the soil moisture sensors). These samples were analyzed to determine representative volumetric soil moisture contents associated with saturation, field capacity, and permanent wilting point to be used in the IDSS soil water balance evaluation. All cores were analyzed intact using a tension-plate assembly (Hillel, 2004) at pressures from 0 to 39 kPa for development of the low-pressure portion of individual soil water release curves. Representative samples from each depth were subjected

to a pressure-plate apparatus (Hillel, 2004) to develop the high-pressure portion of the soil water release curves. Saturation volume was determined based on the total water extracted from the samples over the course of the tension-plate analysis, following initial saturation. Field capacity and permanent wilting point were taken as the volumetric water contents corresponding to 33 and 1500 kPa, respectively.

4.3.11 Evaluation of the IDSS Forecast Soil Water Balance

The accuracy of the soil water balance used by the IDSS for predicting daily soil water status was evaluated using measured soil moisture data collected in study plots throughout the 2014 growing season. Measured volumetric water contents in each layer were converted to a representative daily depth of soil water in the root zone by multiplying the volumetric readings by calculated root depths in each respective layer. A maximum effective rooting depth of 300 mm was assumed to be reached 60 days after planting (i.e., linear growth rate of 5 mm day⁻¹ until 60 DAP; Evans et al., 1996) and the soil drainage rate (SLDR) was set to 0.4 day⁻¹ based on drawdown rates recorded by field installed soil moisture sensors.

Daily estimates of soil water content in the root zone were estimated using measured weather data, soil parameter estimates, and the IDSS soil water balance (section 3.3.2.7; equation 3.4):

$$SW_{\text{end}} = SW_{\text{beg}} + \text{RGW} + I - ET_{\text{c,adj}} + P - \text{RO} - \text{DP} \quad [4.1]$$

where,

SW_{end} = depth of soil water in the root zone at the end of the day (mm)

SW_{beg} = depth of soil water in the root zone at the beginning of the day (equal to SW_{end} for previous day) (mm)

RGW = depth of the soil water added to the root zone due to daily root growth (mm)

I = net irrigation (mm)

$ET_{c,\text{adj}}$ = adjusted crop evapotranspiration (mm)

P = precipitation (mm)

RO = water loss to surface runoff (mm)

DP = water loss to deep percolation below the root zone (mm).

A single composite soil water balance was used to represent the entire field, using average values for saturation, field capacity, and permanent wilting point for each soil layer as determined during the soil water retention analysis (section 4.3.10). Measured rainfall from the onsite weather station was used as an input to the SWB, as was ET_o . Reference ET was calculated using daily recorded minimum and maximum temperatures, solar radiation, wind speed, and relative humidity based on the Food and Agricultural Organization (FAO) 56 Penman-Monteith equation (Allen et al., 1998) and using the Ref-ET Software Version 4.1 (Allen, 2016). ET_o was converted to ET_c using a standard crop curve for corn (Allen et al., 1998). To obtain $ET_{c,\text{adj}}$, ET_c was adjusted using a daily calculated stress coefficient (K_s), as describe in Chapter 3 - Section 3.3.2.7.

The predicted daily soil water status for the field was plotted against soil moisture data from all nine plots as well as the average values between them. Goodness of fit between the predicted soil water contents and those observed in each plot and over all plots were assessed using the FITEVAL software (Ritter and Muñoz-Carpena, 2013), which calculates

the root mean square error (RMSE) and the Nash-Sutcliffe Efficiency coefficient (NSE)

(Nash and Sutcliffe, 1970) as:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (O_i - P_i)^2}{N}} \quad [4.2]$$

and

$$\text{NSE} = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} = 1 - \left(\frac{\text{RMSE}}{\text{SD}}\right)^2 \quad [4.3]$$

where,

O = observed value

P = predicted value

N = sample size

\bar{O} = mean of observed values

SD = the standard deviation of the observed values.

4.4 RESULTS AND DISCUSSION

4.4.1 Challenges Encountered

There were numerous challenges encountered during the 2014 growing season that prevented meeting the original objective of testing the IDSS versus routine irrigation and rainfed conditions. Ranging from unforeseen hardware and software delays with the irrigation system early in the season to extreme rainfall and unexpected poor drainage conditions across the season, each of the challenges led to modifications of the season objectives and overall outcomes.

4.4.1.1 Delays in Implementation of a Fully Functional IDSS

Although the foundational logic of the IDSS was in place at the beginning of the 2014 growing season, the implementation of the logic in a fully functional web application was not. The sources for weather data and weather forecast had been identified, but the subroutines of the IDSS that allow for automated retrieval and processing of the data were not completed. While the IDSS user platform was being completed, the daily weather observations and seven-day weather forecast were collected and stored by a separate web service running on a NCSU managed server. The intent was to later use these data to simulate any irrigation decisions that were missed while the IDSS was being completed; however, an error that was not discovered in the web service until later in the season resulted in much of the weather forecast data being overwritten.

4.4.1.2 Irrigation System Hardware Failure

Testing of the linear move irrigation system and pumping station early in the growing season, prior to need for irrigation, revealed a crack in one of the VRI control manifolds, presumably due to entrapped water that froze during the previous winter. A replacement manifold was ordered and installed by representatives from Advanced Ag Systems on 30 May 2014. During this same time frame, problems were discovered with the guidance system of the linear move, which prevented the system from being able to traverse the entire study field and prevented the VRI controller from functioning correctly. To increase application rates and reduce overall run times, the guidance system was repaired and new irrigation nozzles were installed on the linear move system in mid-June, just prior to the corn entering the critical stage for moisture stress (Evans et al., 1996; Heiniger et al., 2000).

4.4.1.3 Above Normal Rainfall

The 2014 corn growing season (taken as April through August) was the wettest on record (933 mm) among eighteen years of continuous rainfall data at the Cunningham Research Station in Kinston (Figure 4.5) (SCO-NC, 2016). This was 33% more rain than the next wettest growing season (2013), which received 703 mm of rain, and 84% more than the average seasonal rainfall (521 mm).

Not only was the cumulative rainfall total exceedingly high in 2014, rainfall was evenly distributed over the growing season (Figure 4.6). Particularly during the critical moisture growth stages for corn, 60 to 90 days after planting, there was never more than a six-day period without measurable rainfall. The only extended periods without rainfall were between 32 and 52 DAP and 126 and 146 DAP. During the former, the crop did begin to show some signs of moisture stress; however, the hardware failures in the linear move prevented irrigation during this time and the crop was still almost two weeks from tassel appearance (65 DAP) when the dry stress would have been more critical. The latter dry period was after the crop was fully mature and was senescing.

The timing of rainfall events meant there was no real need for irrigation during the 2014 growing season. The magnitude of the events (12 events that exceeded 40 mm from planting to harvest) presented and revealed other challenges in various areas of the field. The 45 mm rainfall event 1 DAP, combined with the traditional tillage that was practiced before planting, resulted in crusting of the soil surface, which delayed, and in some spots may have prevented, emergence. The later, more continuous rainfall events highlighted poor drainage conditions in much of the field, which lead to extended periods of ponding and at-or-near-

saturated conditions in the root zone. This lack of drainage was part of the impetus for measuring the soil penetration resistance across the field following harvest.

4.4.1.4 Field Variability

The drainage issues did not impact all areas of the field equally, which was reflected in growth and yield of the crop across the field. Significant variability was evident from early in the season, when some areas of the field had nearly 100% emergence before other areas had any. Certain plots, such as plot 7 and portions of plot 3, were able to adequately drain the excessive rainfall, producing high yielding plants that were in excess of 2.3 m tall, while other plots, such as 4, 5, and 9, had standing water for extended periods and produced plants that were just over 1.5 m tall. These differences were reflected in plot yields, which are discussed in section 4.4.5. The observed variability was not only from plot to plot, but also within plots, which would have further complicated the identification of any treatment effects had there been a greater need for irrigation. The variability was also apparent in soil moisture sensor data, indicating a need for multiple sensors installed in various representative locations across a field in order to manage irrigation effectively.

4.4.2 Soil Water Holding Characteristics

Average field capacity values for the layers tested ranged from 0.217 to 0.243 mm³ mm⁻³ (Table 4.1) and the average permanent wilting point, considered representative of all three layers, was 0.103 mm³ mm⁻³. This resulted in available water contents for the layers ranging from 0.114 to 0.140, which are consistent with published values for both Lynchburg and Rains sandy loams (USDA-NRCS, 2016). Despite the variability observed in soil water

dynamics across the various plots during the season, there was minimal variation in lab-measured soil water holding characteristics from different locations across the field. This affirms that soil water holding properties are mainly governed by soil texture and may not vary as much spatially as other properties such as bulk density, infiltration rates, and hydraulic conductivities, each of which can also be more locally affected by different management practices (e.g. field traffic that may lead to compaction).

4.4.3 Predicted vs. Observed Soil Water Contents

The soil water balance used in the IDSS satisfactorily predicted observed soil water contents in four of the nine individual plots (Table 4.2; Figure 4.7) and the average soil water content across all plots (Table 4.2; Figure 4.8). The same plots that exhibited poor drainage, low plant stands, or generally reduced growth and vigor (e.g., 1-No, 5-No, 6-Smart, and 9-No), were also plots that had the least amount of fluctuations in observed soil water contents and subsequently were not very well predicted by the model (Figure 4.7). Similarly, plot 7 (Routine), which was the best performing plot across the season with regards to growth and yield, was also the most closely predicted by the model (NSE = 0.884 and RMSE = 8.4 mm; Table 4.2).

In general, soil water contents measured by the soil moisture sensors were less responsive to rainfall and evapotranspiration than those predicted by the IDSS (Figures 4.7 and 4.8). Shallow restrictive layers observed in parts of the field may have prohibited effective root growth from reaching the maximum assumed depth of 300 mm, or prevented infiltration to deeper layers, accounting for some of this lack of responsiveness. Plant stands

were also substantially reduced in several areas across the field, particularly around some of the sensor locations (e.g., plots 1-No, 5-No, and 6-Smart). High field traffic in these locations during instrumentation and logistical challenges in planting near the instrument clusters may have contributed to these reduced plant stands. Full canopy closure never occurred in these locations, which likely lowered actual ET_c , and depressed drawdown rate compared to that predicted by the soil water balance model.

Even so, as a whole the model was able to predict fluctuations in and the relative magnitude of the soil water content across the field within plus or minus one standard deviation of the average values observed across much of the growing season (Figure 4.8). The model accurately predicted that soil water content remained above field capacity for much of the season, which was consistent with field observations that indicated water logging in some cases and even standing water in plot 3 on multiple occasions. This was reflected by the soil water trace in plot 3 (Figure 4.7) that remained near saturation for extended periods in the latter third of the growing season.

The main time when the model did not perform well in all plots was early in the season, when there were twenty consecutive days without rainfall (between 32 and 52 DAP; Figure 4.6) and model-predicted drawdown and plant stress were greater than what was measured by the soil moisture sensors. This could be attributed to model over-prediction of ET_c during the developmental stage of the crop, and possibly could be improved by adjusting the K_c values used in constructing the crop curve.

4.4.4 Irrigation Applications

Due to excessive rainfall during the 2014 growing season and the additional challenges previously discussed (section 4.4.1), minimal irrigation was applied by any of the irrigation treatments (Table 4.3). A test irrigation application of approximately 8 mm was applied on 4 June 2014 to all Smart (2, 6, and 7) and Routine (3, 4, and 8) plots to confirm that the VRI system and all other irrigation system components were functional. Irrigation was also applied on 18 June (13 mm on the Routine plots) and 7 July (11 mm on the Routine plots and 8 mm on the Smart plots); however, there was no evidence of any benefit from these irrigations. Field conditions (particularly how wet much of the soil surface was prior to irrigation and even standing water in places) suggested that these irrigations were not needed.

4.4.5 Yield

Just as there was variability in soil water dynamics and crop growth over the course of the season, so too was there substantial variability in crop yield across the study field (Figures 4.9 – 4.11). Plots that received no irrigation (1, 5, and 9) averaged 35% less yield ($4,277 \text{ kg ha}^{-1}$) than the Smart plots ($6,588 \text{ kg ha}^{-1}$) and 31% less than the Routine plots ($6,229 \text{ kg ha}^{-1}$) (Table 4.3); however, these yield differences were not likely a result of the irrigation treatments. Plants randomly assigned to the No Irrigation plots displayed substantially less vigor and stature in growth very early in the season compared to plants in many of the Smart and Routine plots, well before any irrigation was applied. This weakness persisted through the season and harvest and was most likely due to preexisting soil limitations in these plots, which are discussed further in section 4.4.6 on soil penetration resistance.

Dry yields recorded by the yield monitor ranged from pockets of greater than 13,040 kg ha⁻¹ in plots 7 and 8 to large areas with less than 3,260 kg ha⁻¹ (Figure 4.9). Composite yields from each plot were equally varied (Figure 4.10) and showed the same general spatial trends evidenced on the more detailed yield monitor map. The average yield in plot 7 (9,506 kg ha⁻¹) was more than double the yields for plots 2, 5, and 9 (4,470; 3,906; and 3,680 kg ha⁻¹, respectively). Plot yields in these lower-yielding regions were substantially impacted by weak plant stands and reduced growth that was evident very early in the season and only compounded as the season progressed. Many plants in these plots that lagged behind in growth at the last fertilizer and herbicide application (27 May; 43 DAP) suffered foliar damage from spray drift because of low plant height and never recovered as the season progressed.

Yield estimates from the plant sampling (Figure 4.11) reflected the high yields of plots 7 and 8, but also probably misrepresented the performance of plots 5 (9,561 kg ha⁻¹) and 9 (7,400 kg ha⁻¹). These high yielding, random samples compared to the generally low overall yields of the plots from which they were collected illustrates the within plot variability that was encountered. Essentially every plot had localized areas that yielded well and others that did not, and twelve plants selected from four locations near the center of each plot simply could not fully encompass the magnitude of the variability.

Figure 4.12 shows the distinct variability that was present even in the consecutive plants from within the same row. It should be noted that one reason for the plant sample estimated yields being higher than both other measures of yield is that kernel masses were

converted to mass per area estimates (i.e., kg ha^{-1}) by dividing by the representative area that three consecutive plants would fall in at a seeding rate of $70,600 \text{ seed ha}^{-1}$ and 97 mm row spacing with 100% stand (0.14 m^2), while in reality the stands were much reduced in certain areas of the field.

4.4.6 Soil Penetration Resistance

There was distinct evidence of a restrictive layer in the soil profile at around 250 mm (Figure 4.13). Research has shown that root growth can be completely impeded at penetration resistances as low as 2,000 kPa (Blanchar et al., 1978; Duiker, 2002). Values above this were observed at depths as shallow as 50 mm in some sample locations. While speculative to assume that no roots grew deeper than 50 mm in these locations, it is reasonable to conclude that root growth was likely substantially impeded across much of the field at depths greater than 150 mm with penetration resistances more than double the 2,000 kPa at this depth in many locations. It is also reasonable to conclude that this restrictive layer affected soil water dynamics, particularly drainage from shallow to deeper layers, and may explain the ponding and inundated conditions that were observed in much of the field over the growing season.

The spatial variation of soil penetration resistance at depths ranging from 0 to 350 mm, by increments of 25 mm, are presented in Figure 4.14. Again, it can be seen that penetration resistances across much of the field exceeded 2,000 kPa at depths as shallow as 100 mm (Figure 4.14E). As depth increased beyond 300 mm (Figure 4.14M), penetration resistance quickly dropped across all plots but 6 and 9, indicating that the restrictive layer

was mostly confined to the upper 300 cm of the profile. The spatial variability of penetration resistance values from depths of 225 – 275 mm (Figure 4.14J – L) also closely matched the spatial variability of yield across the field (Figure 4.9). The same was true for the relationship between yield and the maximum penetration resistance measured across the field (Figure 4.15). Penetration resistances in excess of 5,000 kPa were exceeded across much of plots 6 and 9, corresponding to areas where yields were mostly under 4,890 kg ha⁻¹.

4.5 SUMMARY AND CONCLUSIONS

Numerous challenges were encountered in attempting to field test the IDSS against other irrigation strategies, but insightful information was gleaned as well. Hardware failures, delays in the software components of the IDSS, and an exceptionally wet growing season resulted in minimal opportunities and essentially no need to irrigate. Seasons with minimal or no irrigation requirements are common in humid regions, for which the IDSS is intended; thus, the IDSS must be able to not only correctly recommend how much irrigation and when to apply it during dry periods, but also reliably notify the user when no irrigation is needed due to wet conditions. Otherwise, crops could be subjected to undue moisture stress or nutrient leaching from excess water.

The IDSS soil water balance was able to predict with reasonable accuracy the average observed soil water content measured across the research field (NSE = 0.808, RSME = 9.3 mm), except for early in the season when it over predicted soil water stress. It also tended to over predict the rate of drawdown during drying periods and in some cases over predicted refilling following rainfall compared to measured soil water contents; however, the

variability in plant vigor and shallow restrictive layers across the study field may account for these discrepancies in part. Running individual soil water balances for each plot with calibrated root depths and adjusted crop curves to reflect reduced plant stands could improve model predictions; however, it would require more extensive parameterizations than intended for the IDSS.

Much of the variability observed in the study appeared to be closely associated with compaction issues across the field. Penetration resistances in excess of 2,000 kPa, sufficient to severely if not entirely impede root growth, were observed across much of the study field at depths as shallow as 100 mm. The hydraulic properties of this restrictive layer could potentially be improved with appropriately targeted deep-tillage practices (preferably when the soil is dry), reduced field traffic, and reduced surface-tillage.

Despite having to adjust several of the study objectives to accommodate challenges that arose, this study beneficially highlights many of the practical challenges that growers in the southeastern United States face when investing in irrigation. It also reveals several potential future improvements for the IDSS, such as accounting for poor drainage and reduced plant stand, which would make the tool more robust and widely applicable. The real potential benefit of the IDSS will be determined through multiple years of field trials and optimization of inputs, preferably with a mixture of growing conditions, representing various soils and rainfall patterns. Using a modified version of the IDSS in conjunction with existing crop models to conduct simulation studies could be useful in evaluating and optimizing the IDSS, and would help guide future field studies.

4.6 REFERENCES

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4.8 TABLES

Table 4.1. Average soil water holding characteristics used for the IDSS soil water balance for each layer based on soil water retention analysis on intact soil cores.

Depth (mm)	Parameter	Average (mm ³ mm ⁻³)	Standard Deviation (mm ³ mm ⁻³)
0 – 150	Saturation	0.355	0.020
	Field Capacity	0.221	0.015
150 – 300	Saturation	0.314	0.051
	Field Capacity	0.217	0.027
300 – 450	Saturation	0.342	0.032
	Field Capacity	0.243	0.028

Note: Summary statistics calculated using n = 9 samples for upper two layers and n = 8 for the deepest layer. Average permanent wilting point and standard deviation for the four total cores analyzed for such were 0.103 and 0.033 mm³ mm⁻³, respectively.

Table 4.2. Goodness of fit values between predicted and observed soil water contents from each plot and across all.

Plot	NSE ¹	RMSE ² (mm)	Goodness-of-fit
1	0.522	13.2	Unsatisfactory
2	0.647	15.6	Unsatisfactory
3	0.750	13.9	Acceptable
4	0.825	9.7	Good
5	0.578	11.5	Unsatisfactory
6	0.620	11.0	Unsatisfactory
7	0.884	8.4	Good
8	0.653	10.7	Acceptable
9	0.524	12.3	Unsatisfactory
All	0.808	9.3	Good

Note: Goodness-of-fit classification based on default outputs from FITEVAL: Very good (NSE = 0.900 – 1.000), Good (NSE = 0.800 – 0.899), Acceptable (NSE = 0.650 – 0.799), and Unsatisfactory (NSE < 0.650).

¹Nash-Sutcliffe Efficiency coefficient

²Root Mean Square Error

Table 4.3. Average irrigation applied and yield for each irrigation treatment.

Treatment	Irrigation Applied (mm)	Average Yield (kg ha ⁻¹)
No Irrigation	0	4,277
Smart	16	6,588
Routine	32	6,230

4.9 FIGURES

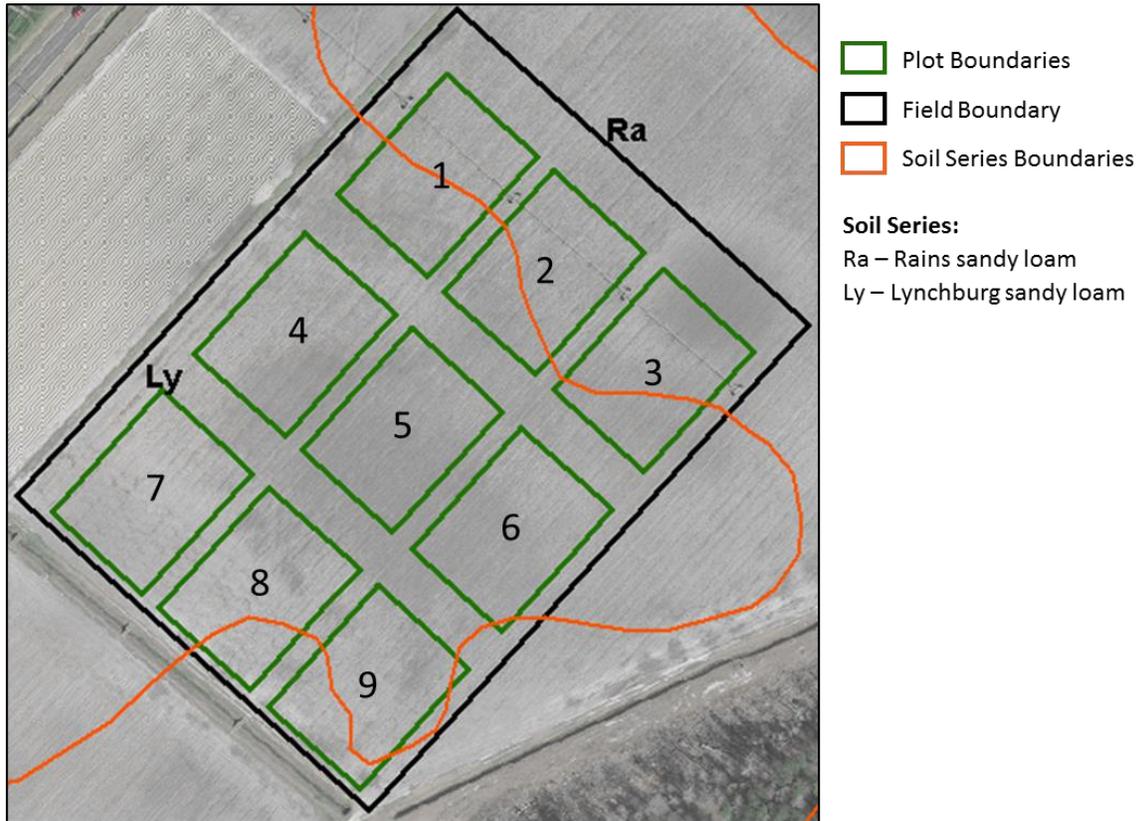


Figure 4.1. Plot diagram overlaid with soil series map.
(Note: Each plot was 61 m x 46 m.)

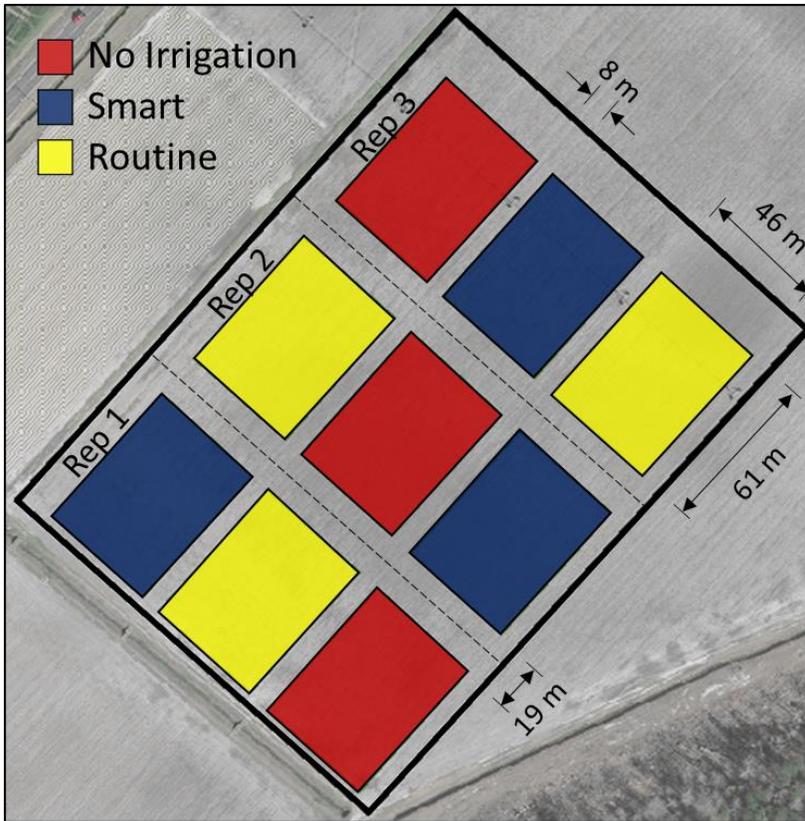


Figure 4.2. Experimental layout of irrigation treatments.



Figure 4.3. Plot diagram overlaid with instrumentation layout.

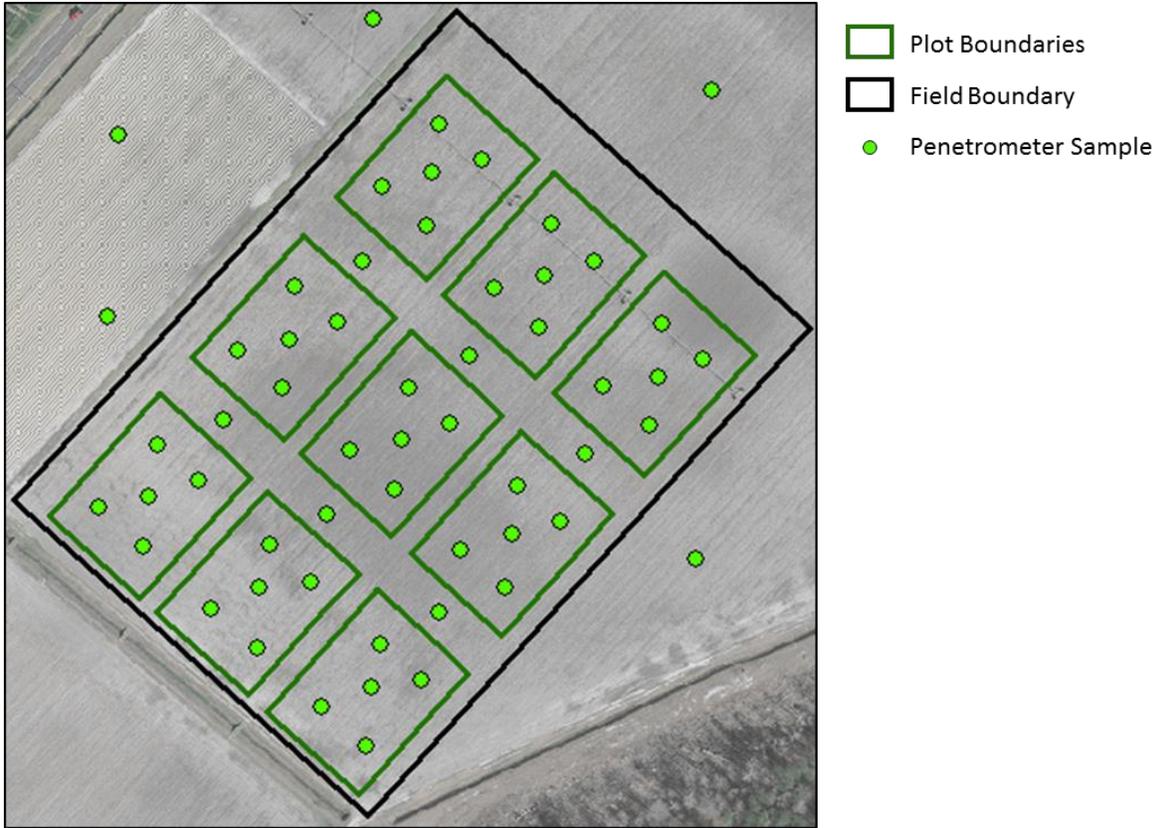


Figure 4.4. Penetrometer sampling points.

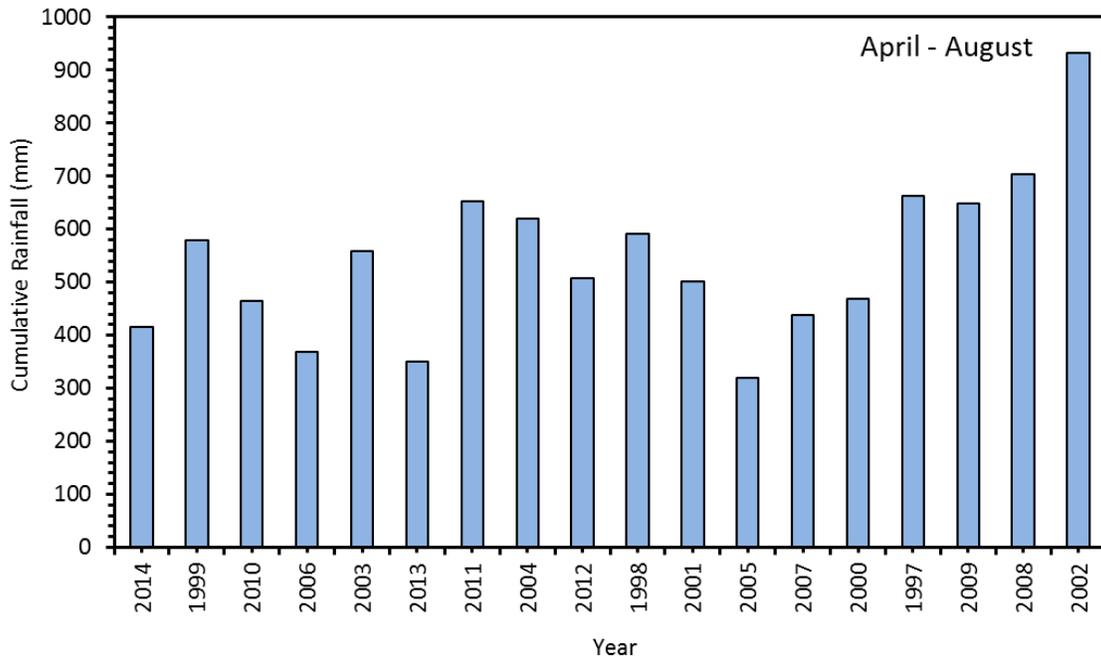


Figure 4.5. Eighteen years of growing season rainfall (taken as April through September) at the Cunningham Research Station in Kinston, NC.

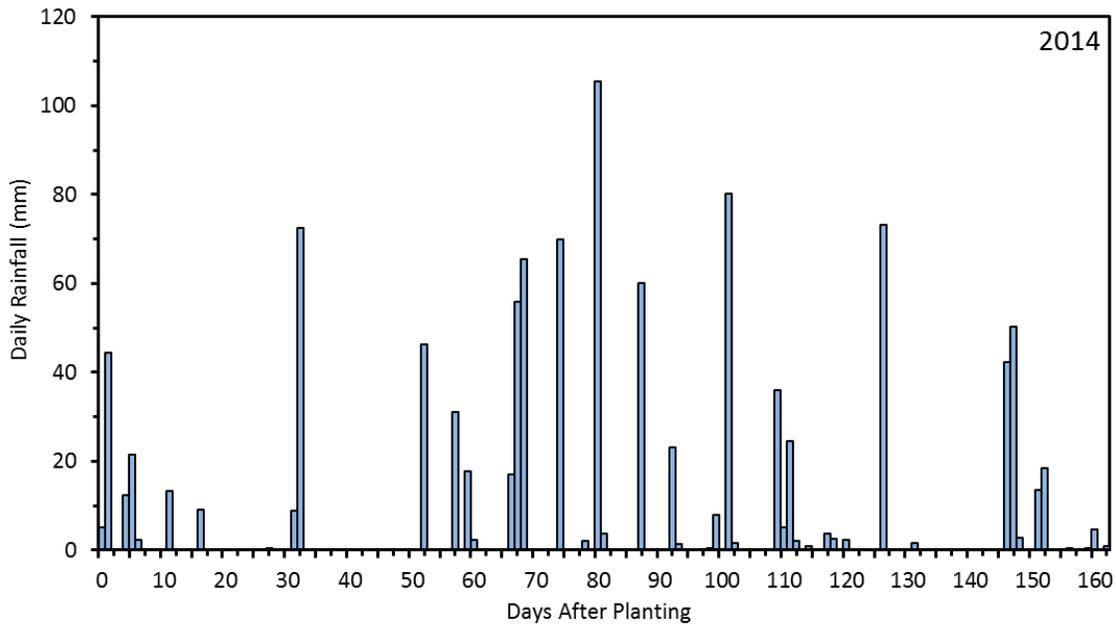


Figure 4.6. Daily rainfall at the Cunningham Research Station in Kinston, NC during the 2014 growing season. Note: Planting date was 14 April, 2014.

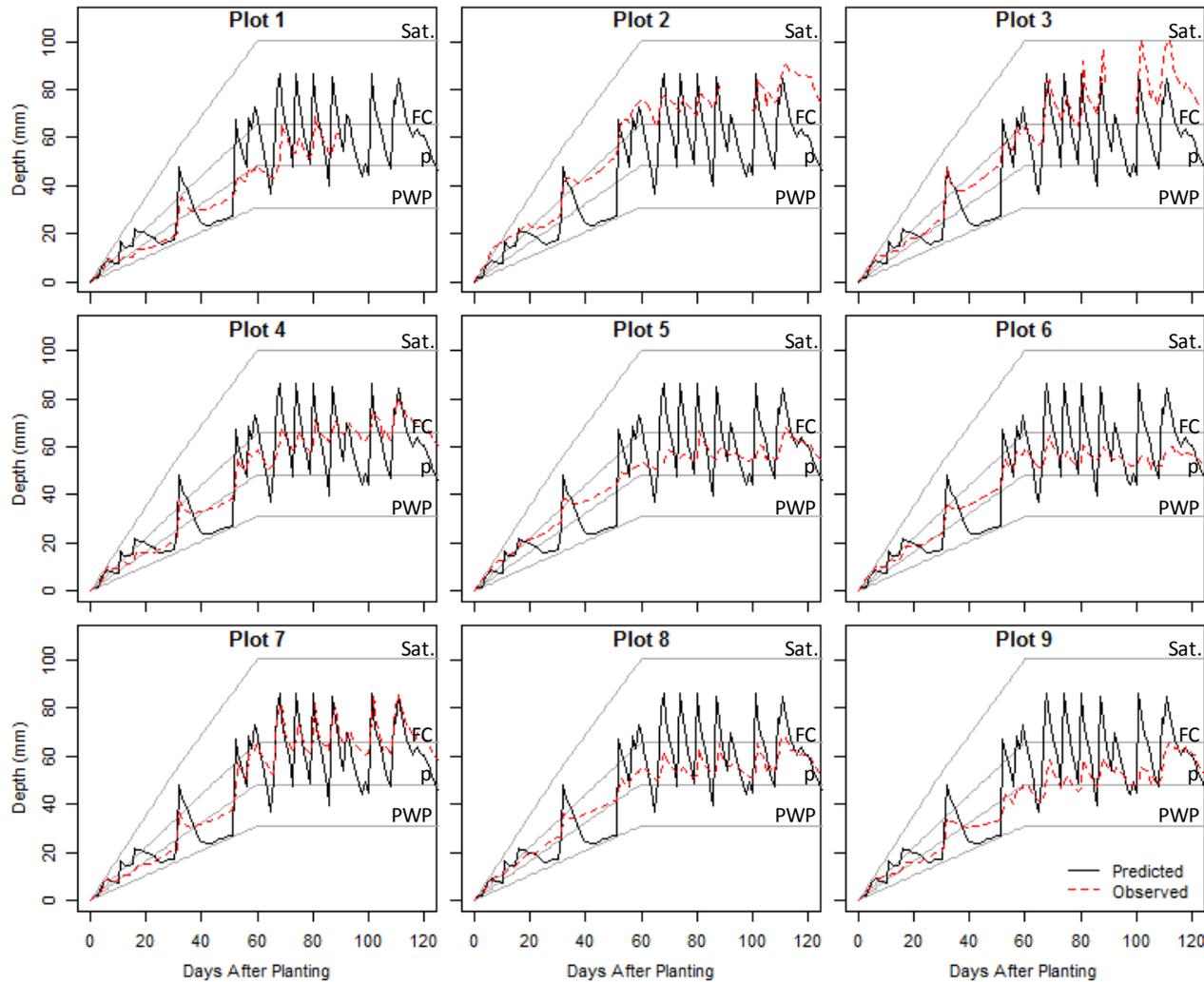


Figure 4.7. Predicted total soil water content in root zone (by the IDSS soil water balance; solid line) vs. observed soil water content in each plot (dashed line). Note: Sat. = saturation, FC = field capacity, p = depletion factor, and PWP = permanent wilting point.

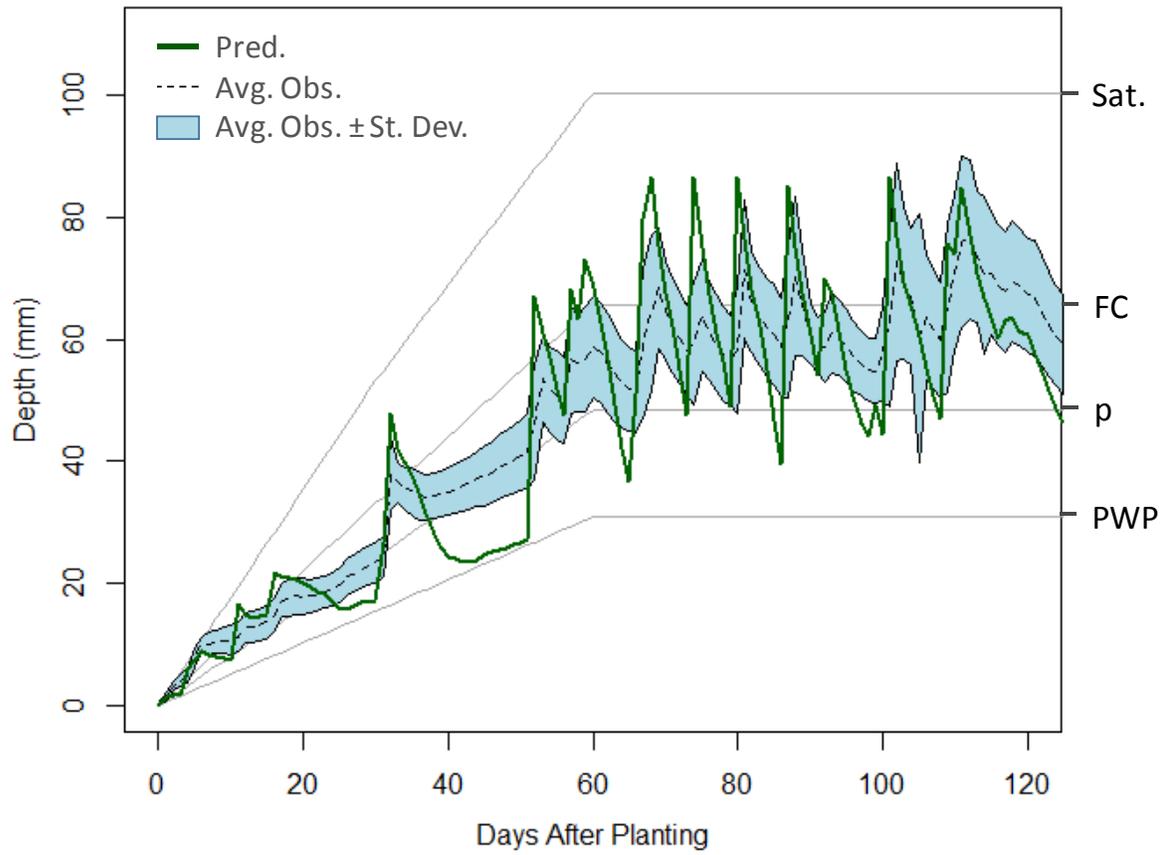


Figure 4.8. Predicted total soil water content in root zone (by the IDSS soil water balance) vs. average observed soil water content across all plots. Note: Sat. = saturation, FC = field capacity, p = depletion factor, and PWP = permanent wilting point.

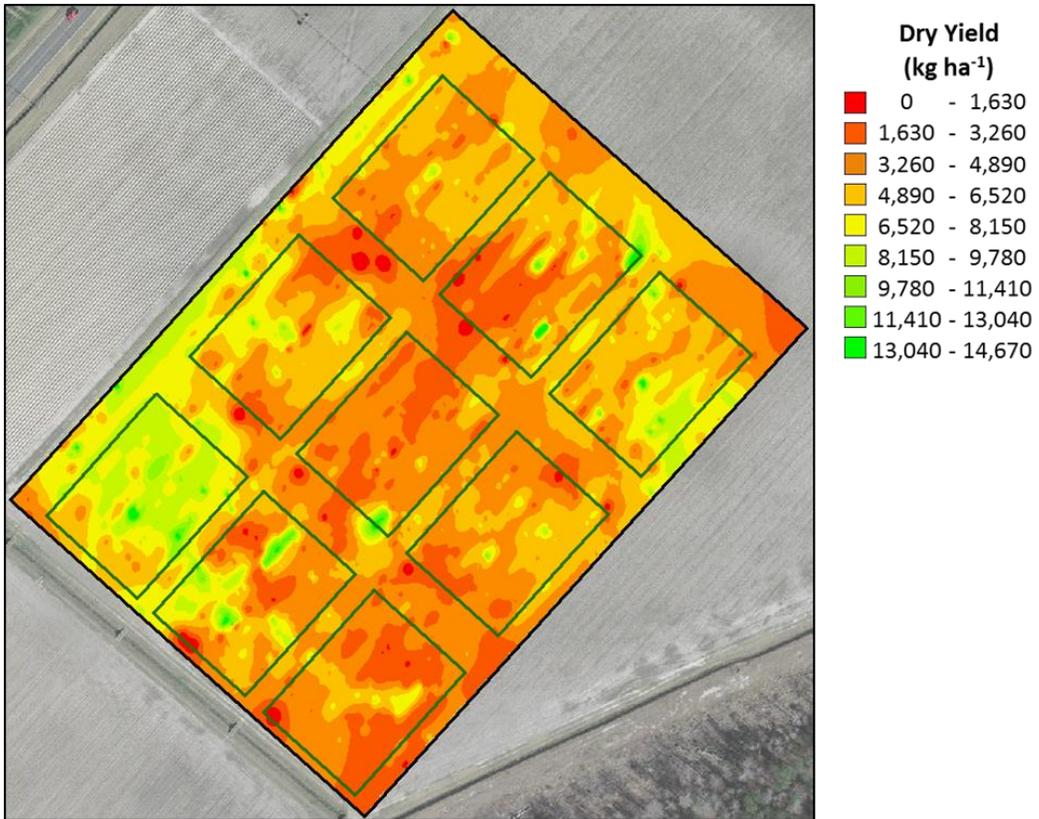


Figure 4.9. 2014 corn yield (yield monitor).

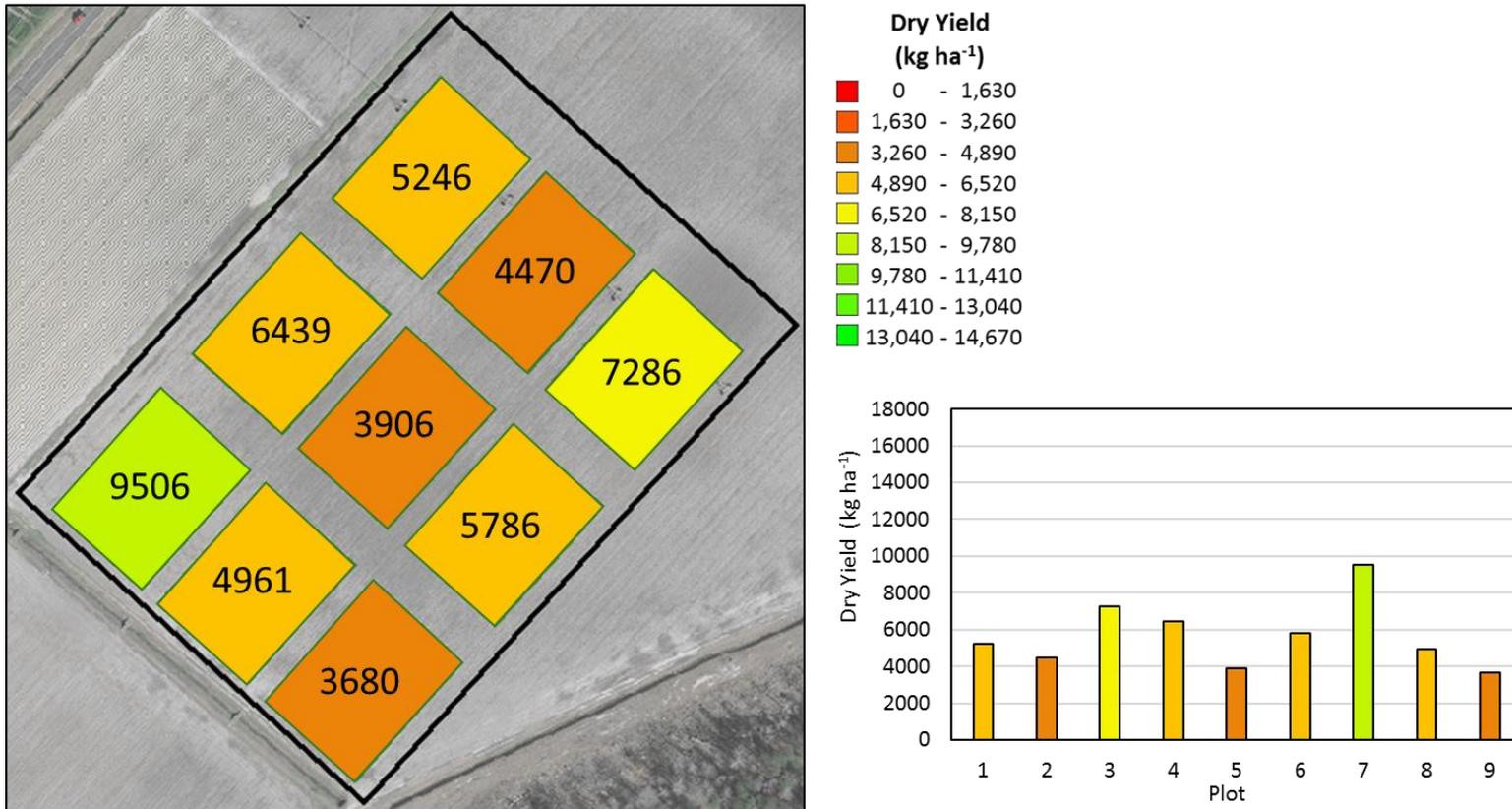


Figure 4.10. 2014 corn yield based on total combine harvest weight by plot.

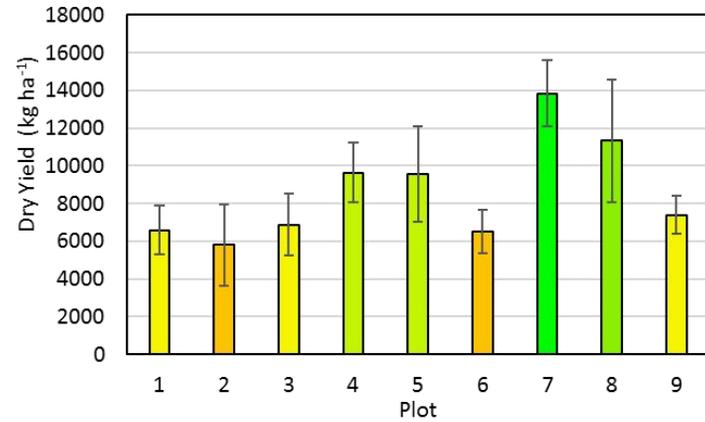
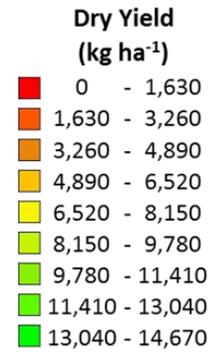


Figure 4.11. 2014 corn yield based on plant sampling by plot.



Figure 4.12. Ears from plant samples collected on 18 September 2014. Note: Samples are ordered by plot from 1 to 9, left to right, top to bottom. (4 sample locations per plot x 3 plants per location)

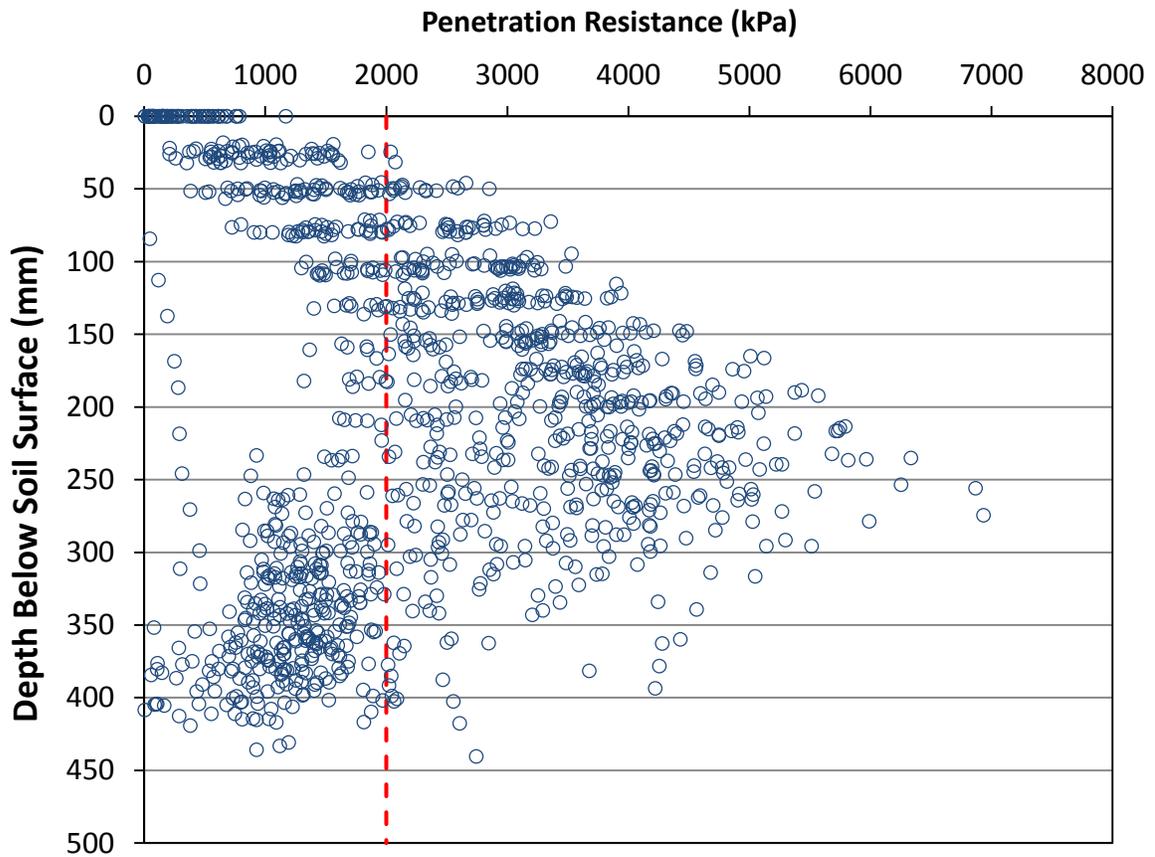


Figure 4.13. Penetration resistance vs. depth below the soil surface. Note: The dashed red line represents the theoretical threshold penetration resistance, above which root growth may be completely impeded (Duiker, 2002).

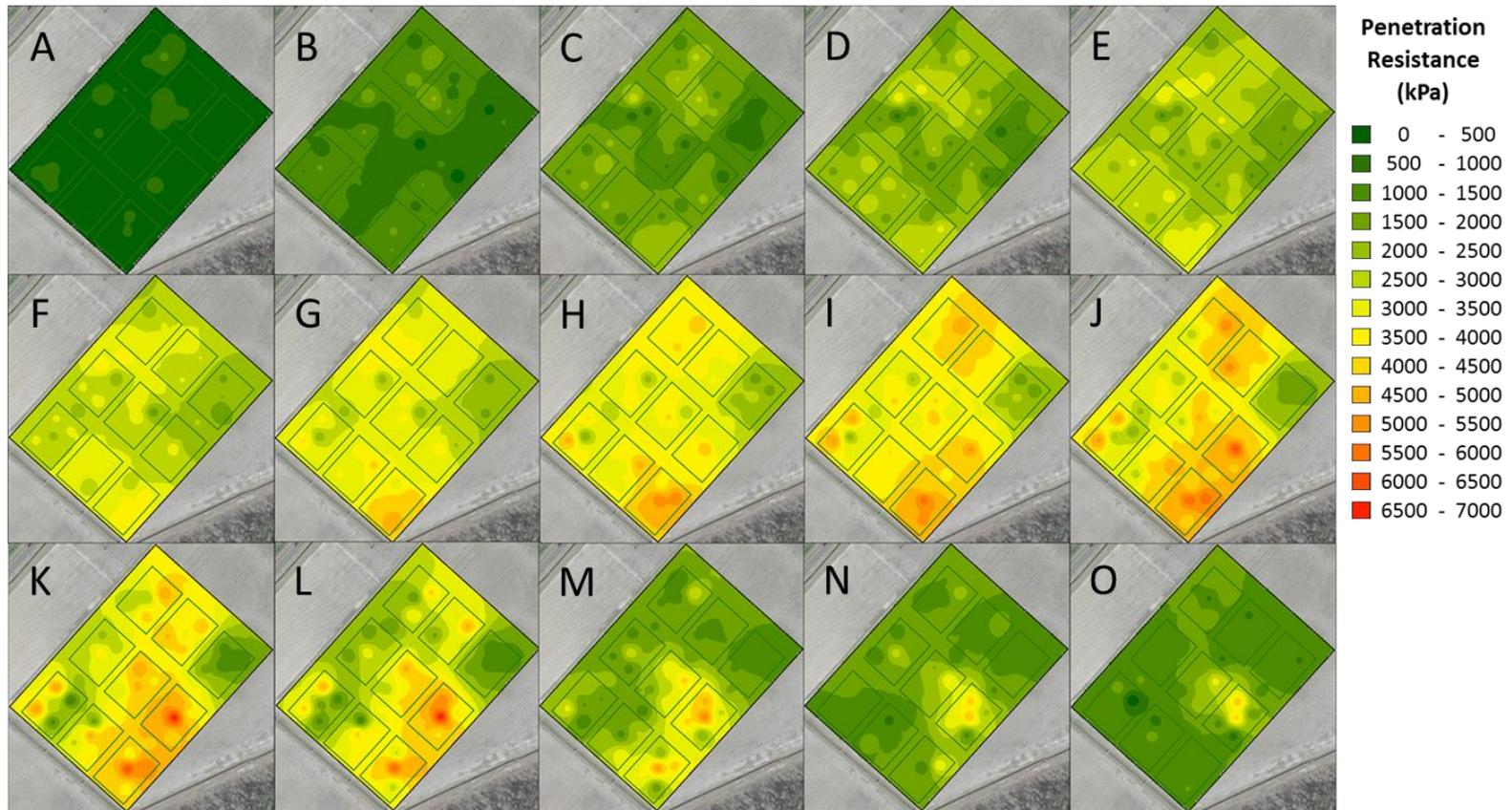


Figure 4.14. Soil penetration resistance measured after harvest at depths of 0 to 350 mm at intervals of 25 mm. Corresponding depths in mm for each map are: A) 0, B) 25, C) 50, D) 75, E) 100, F) 125, G) 150, H) 175, I) 200, J) 225, K) 250, L) 275, M) 300, N) 325, and O) 350.



Figure 4.15. Maximum penetration resistance measured from 0 to 350 mm below the soil surface.

CHAPTER 5 - SENSITIVITY ANALYSIS AND COMPARISON OF IDSS-SCHEDULED IRRIGATION TO NON-IRRIGATED AND ROUTINELY IRRIGATED CORN IN EASTERN NORTH CAROLINA USING DSSAT V4.6

5.1 ABSTRACT

Supplemental irrigation for crops such as corn (*Zea mays* L.) in the humid Coastal Plain of the southeastern United States has increased in recent years as growers seek to capitalize on yield potential of improved varieties and to reduce risk of detrimental yield loss often caused by short-term dry periods during the growing season. Despite seasonal rainfall often matching or exceeding crop water demands in the region, coarse textured soils with low water holding capacities, combined with physical and chemical barriers that tend to limit root growth, mean that even a few days without rainfall can result in yield-reducing stress. This study was conducted to assess the sensitivity to model inputs of a proposed irrigation decision support system (IDSS) that incorporates crop growth stage, current soil water status of the root zone, and short-term weather forecast into calculation of daily irrigation recommendations (Chapter 3) and to evaluate water use and yield effects of implementing IDSS-scheduled irrigation (Smart) compared to non-irrigated (NoIrr) and routine scheduled irrigation (Fixed) in corn. Simulations were conducted across three planting dates (1, 15, and 30 April) using six years (2009 – 2014) of archived daily weather forecasts and historical weather observations from five locations (Kinston, Lewiston, Lumberton, Rocky Mount, and Whiteville) across the Coastal Plain of North Carolina. IDSS outputs were used with the CERES-Maize model in DSSAT to assess water use and yield potential of six irrigation treatments (non-irrigated; three levels of fixed irrigation on a routine schedule; and two

“smart” treatments based on the IDSS, one using actual forecast data [SmAct] and the other based on observed weather data substituted as “perfect” forecasts [SmPerft]). Fixed schedules were based on 100 (Fix100), 77 (Fix77), and 50% (Fix50) of long-term calculated irrigation requirements. Sensitivity indices (S) indicated year ($S = 0.54$) and the interaction between year and location ($S = 0.24$) accounted for most of the variation in seasonal irrigation recommendations across simulated seasons. In regards to variations in IDSS generated irrigation recommendations, accurate representation of the soil water reservoir was more critical in seasons with higher rainfall totals and the timing of rainfall events was more important than the cumulative rainfall total in many cases. There was no difference in average simulated seasonal yields between SmAct ($9,114 \text{ kg ha}^{-1}$) and SmPerf ($9,120 \text{ kg ha}^{-1}$) treatments, which both yielded 4% more than the highest yielding Fixed treatment (Fix100; $8,762 \text{ kg ha}^{-1}$) and 82% more than NoIrr ($5,010 \text{ kg ha}^{-1}$). SmAct and SmPerf also had less variation in yield within and across seasons compared to either Fixed or NoIrr treatments. Seasonal irrigation for both Fix100 (223 mm) and SmAct (222 mm) was about 10% higher than the SmPerf treatment (200 mm); however, SmAct irrigation was much more varied from season-to-season and location-to-location in response to rainfall variations, whereas the Fixed treatments applied essentially the same depths of irrigation for each season and location. Simulation results suggest that IDSS-scheduled irrigation incorporated with improved fertility management could raise corn yields in eastern North Carolina by as much as 168% compared to current production practices.

5.2 INTRODUCTION

The challenges of agricultural water management in the humid, southeastern United States has been well documented (Camp et al., 1988; Sadler et al., 2003; Stone et al., 2008; Stone et al., 2010). Seasonal and spatial variability in rainfall means that growers and their management strategies must be prepared to quickly adapt to changing and localized environmental conditions, be it excess rainfall or drought. Coarse-textured soils with physical and chemical barriers that often limit root growth are typical of much of the agricultural land under production in the southeastern Coast Plain. This means as few as five to seven days without rainfall can result in yield-reducing drought stress (Lambert, 1980), particularly when it occurs at a critical stage of crop development. There is a need to address these challenges with reliable and simply-implemented management strategies that minimize drought risk, maximize crop production, and efficiently use water resources.

Irrigated acreage in the southeastern United States has steadily increased over the past ten to fifteen years, including a 71% increase across Alabama, Georgia, North Carolina, and South Carolina from 2002 to 2012 (USDA-NASS, 2003; 2013). This increase can be attributed to a number of factors, including commodity prices, desire to reduce production risks, and efforts to maximize yields given increased yield potential of improved hybrid varieties. Since 2000, average annual corn yields for the state of North Carolina have ranged from 4,137 kg ha⁻¹ to 7,532 kg ha⁻¹ (overall average of 5, 859 kg ha⁻¹) (USDA-NASS, 2016), with fluctuations reflecting variations in seasonal rainfall. Over the same time span (excluding missing data from 2012), state-wide corn yield contest winners in dryland and irrigated categories averaged 15,475 kg ha⁻¹ and 16,254 kg ha⁻¹, respectively (Heiniger and

Boerema, 2014), evidence that intensive management and well timed rainfall or irrigation can increase yields as much as three-fold. As growers pursue and invest in irrigation, a common dilemma remains: how to manage these systems given dynamic irrigation requirements that change within and across seasons and locations. In other words, growers are continually faced with questions of when and how much irrigation water to apply.

Several field studies have documented the yield effects of irrigation on corn in the southeastern United States, while investigating best management practices for such irrigation. A subsurface drip irrigation (SDI) study conducted in the Piedmont of North Carolina from 2002 to 2005 found no statistical difference in corn yields between drip line spacings of every other row ($13,900 \text{ kg ha}^{-1}$) or every third row ($13,920 \text{ kg ha}^{-1}$) and sprinkler irrigation ($14,910 \text{ kg ha}^{-1}$); however, all irrigation treatments yielded significantly higher than the non-irrigated comparison ($11,880 \text{ kg ha}^{-1}$) (Grabow et al., 2011). Estimated seasonal crop evapotranspiration (ET_c) ranged from 421 to 498 mm and seasonal applied irrigation ranged from 112 to 309 mm in the sprinkler treatment and 134 to 350 mm in the SDI treatments. A similar SDI study near Florence, South Carolina in 2003 and 2004 found no yield benefits from 300 mm of irrigation applied to corn, which had a calculated total seasonal water demand of 620 mm (Stone et al., 2008); however, research at a nearby location from 1999 to 2001 produced averaged yields of $10,300 \text{ kg ha}^{-1}$ and $10,000 \text{ kg ha}^{-1}$ for irrigation applied at 150 and 75% of a calculated irrigation base rate (IBR), respectively, compared to $7,200 \text{ kg ha}^{-1}$ for rainfed corn (Stone et al, 2010). Seasonal irrigations ranged from 134 to 214 mm in the 75% IBR treatment and 252 to 428 mm in the 150% IBR treatment. Two earlier studies, conducted in the 1980s and comparing various levels of irrigation scheduled using

tensiometers, evaporation pans, and a computer-based water balance, found 80% higher yields with irrigation compared to non-irrigated yields of 4,760 kg ha⁻¹ (Camp et al., 1988) and 6,700 kg ha⁻¹ (Camp et al., 1984), but no significant differences in yields among irrigation treatments. Seasonal irrigations ranged from 121 to 333 mm (Camp et al., 1988) and 113 to 448 mm (Camp et al., 1985). The seasonal variations in irrigation requirements reflected in these studies illustrate the challenges of irrigation scheduling in the southeastern United States and that yield benefits from irrigation vary depending on seasonal rainfall. It is interesting to note that none of the studies reported yield differences among irrigation treatments (excluding non-irrigated), despite different levels of water being applied. This suggests the need for improved methods of precisely estimating crop water demands throughout growing seasons, which could result in further reductions in water applied with no negative impacts on yield.

To that end, a real-time irrigation decision support system (IDSS) has been developed (Chapter 3) that incorporates crop growth stage, current water status of the root zone, and short-term weather forecast into daily irrigation recommendations. The web-based scheduling tool was designed with the intent of providing flexibility to the user, while minimizing input requirements, with the hope that it would be robust enough for research applications, but practical enough for day-to-day use in commercial operations. The model functions on a soil water balance (SWB) based on Food and Agriculture Organization (FAO) Irrigation and Drainage Paper Number 56 (FAO-56) (Allen et al., 1998), using daily short-term weather forecasts of temperature, rainfall, and reference evapotranspiration (ET_o) to

predict crop water deficits before they occur, allowing users to irrigate proactively instead of reactively.

A field study was implemented in 2014 on corn grown in Kinston, North Carolina to test the effectiveness of the IDSS with regards to yield and water use compared to routine irrigation and no irrigation (Chapter 4). Limited information was gleaned regarding the IDSS – other than comparing soil water contents estimated by the SWB to those measured using soil moisture sensors – due to abnormally wet growing conditions, unanticipated field drainage problems, as well as hardware and software delays in implementing the complete “smart” irrigation system. These types of challenges are inherent to field work and are some of the reasons that computer-based simulation studies are beneficial in evaluating crop management strategies.

Field studies tend to be expensive, time-consuming, and provide results that are specific to the time and location in which they were conducted, which may not apply to other situations (He et al., 2012). On the other hand, crop models allow for rapid assessment of the effects of various combinations of soil, climate, weather, and crop management factors on crop growth, development, and yield (Ghaffari et al., 2001). Such models cannot replace field experiments entirely and in fact rely upon them for calibration and validation (Monteith, 1996); however, they are ideal for identifying preferred management strategies (Karthikeyan et al., 1996) and significant factors (Sadler et al., 2000), which can then be implemented in field studies to follow.

The Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003; Hoogenboom et al., 2015) is a software application comprised of various crop

simulation models (CSMs) designed for over twenty-eight different crops. One of those models is the Crop Environment Resource Synthesis-Maize model (CERES-Maize) (Jones and Kiniry, 1986), incorporated into DSSAT in a modular form as CSM-CERES-Maize. CERES-Maize has been used to simulate agricultural applications all over the world (Jones et al., 2003), including the effects of different irrigation strategies on corn growth, development, and yield (DeJonge et al., 2010; He et al., 2012; Kisekka et al., 2015; Salazar et al., 2012; Saseendran et al., 2008). Kisekka et al. (2015) used CSM-CERES-Maize in DSSAT v4.6 to determine optimum management allowed depletion (MAD) thresholds for initiating irrigation as well as to assess the effects of soil water depletion at planting and late season termination of irrigation on corn grown in Garden City, Kansas from 2005 to 2012. In their assessment of MAD thresholds, they found initiating irrigation at 50% depletion of plant available water to be the optimum setting to maximize net returns. Similarly, maintaining soil water depletion between 0 and 25% at planting maximized yields and net returns compared to higher levels of depletion at planting, although it also resulted in more extractable soil water at the end of the season (i.e. water not used by the crop). When irrigation was terminated 90 or 95 days after planting (DAP), net returns were maximized and the least amount of extractable soil water remained at physiological maturity among termination dates considered. Saseendran et al. (2008) used CERES-Maize to optimize allocation of limited irrigation between vegetative and reproductive growth stages and to determine depletion levels for triggering such irrigation in Northeastern Colorado. Also in Northeastern Colorado, DeJonge et al. (2010) used CERES-Maize to estimate seasonal

evapotranspiration (ET), crop growth, yield, water use efficiency (WUE), and irrigation use efficiency (IUE) between full and limited irrigation.

CERES-Maize has also been used for irrigation applications in the southeastern United States. He et al. (2012) reported that irrigation frequency had a significant effect on sweet corn yield in North Florida, and that water stress and yield reductions were experienced when MAD exceeded 60%. Salazar et al. (2012) simulated irrigation for 58 years across 88 counties in South Georgia and found seasonal irrigation ranged from 136 to 281 mm, with an average of 227 mm. These results were integrated into a state-wide water plan for sustainable management of Georgia water resources through 2050 (EPD/DNR, 2009), indicating how crop modeling can be a beneficial tool for policy makers in addition to helping growers improve farm management decisions.

The overall goal of this study was to evaluate the potential of the IDSS proposed in Chapter 3 to increase crop production, while managing water resources in an environmentally sustainable manner. Specific objectives were: 1) to assess the sensitivity of the IDSS to uncertainty in input parameters under different weather conditions with regards to seasonal irrigation recommendations for corn grown in Eastern North Carolina and 2) using a multi-year simulation study with CSM-CERES-Maize in DSSAT v4.6, to assess the potential water use and yield impacts of implementing IDSS-scheduled irrigation compared to non-irrigation and fixed irrigation schedules on corn in Eastern North Carolina. A secondary objective was to estimate the potential yield increases that could be achieved if improved fertility management was combined with irrigation.

5.3 MATERIAL AND METHODS

5.3.1 Modification of the Irrigation Decision Support System

The IDSS described in Chapter 3 was modified to allow for simulating past growing seasons, instead of operating in a real-time mode. This modification allows users to simulate a single configuration of the IDSS irrigation settings over multiple soil types, locations, root depths, planting dates, and years in a single run. Additionally, a fixed irrigation option was added to mimic a calendar based irrigation schedule in which a grower would apply a fixed depth of irrigation on predetermined dates during the growing season.

The fixed irrigation option operates independently of the soil water and crop growth statuses estimated by the model and requires four inputs:

1. **Days after planting (DAP) or day of year (DOY) for fixed irrigation to occur:** a list of days during the growing season selected by the user to apply a fixed depth of irrigation.
2. **Fixed irrigation depth:** the amount of irrigation to be applied during each irrigation.
3. **Previous day rain bypass threshold:** minimum depth of rainfall required on the day prior to a scheduled fixed irrigation event to bypass irrigation.
4. **Probability of precipitation (POP) bypass threshold:** minimum forecasted probability of precipitation required on a scheduled fixed irrigation day to bypass irrigation.

The bypass options (3 and 4) were added since it is unlikely that a grower would irrigate the day after a substantial rainfall or on a day when imminent rainfall is forecasted, even when using a fixed schedule.

5.3.1.1 Input Requirements

The input requirements for the modified IDSS remained the same as with the real-time version, with the exception of how observed weather data, daily weather forecasts, and the daily soil water status are obtained. Whereas the real-time IDSS automatically retrieves the most recently observed weather data and the current weather forecasts from online application program interfaces (APIs), simulating past conditions requires obtaining historical weather data and historical forecasts, a feature that is not presently built into the real-time IDSS. Likewise, soil moisture sensor data is unlikely to be available in a simulation scenario – and even if it were available, it would not provide an accurate representation of the soil water status over the course of the season unless the exact same irrigation schedule were used as predicted by the IDSS, in which case a simulation routine would be unnecessary.

Observed weather data and daily weather forecasts are provided to the modified IDSS via comma separated value (CSV) files stored locally on the user's computer. Individual weather and forecast files are required for each location by year simulated. Observed weather files must contain daily observed minimum and maximum temperatures (°C), rainfall (mm) and reference evapotranspiration (ET_o) (mm) for each day of the year, and must be structured as in the example input file provided in Appendix C. Weather forecast files must contain

daily forecasted minimum and maximum temperatures (°C or K; specified by user), forecasted ET_o (mm), forecasted POP (%), and forecasted quantity of precipitation (QOP) (mm) as generated each day of the year for as many days ahead as the user desires for the IDSS to forecast. An example of a weather forecast file when using daily three-day forecasts is provided in Appendix C. The weather forecast file must contain data for at least as many forecast days ahead as the maximum interval between any subsequent irrigation opportunities to prevent errors when the IDSS is calculating irrigation requirements based on the forecasted soil water balance. Missing data in either observed weather or forecast data files can be indicated using a missing data identifier (e.g., “NA”) that the user specifies.

5.3.1.2 Calculations

Weather observations and forecast data are used by the modified IDSS in the same manner as in the real-time IDSS to estimate the crop growth stage and to forecast the soil water status for a user-specified number of days ahead for each simulated day. Whereas the real-time IDSS uses soil moisture sensor data provided by the user to estimate current soil water status in the crop root zone on a daily basis, the modified IDSS relies upon a running soil water balance to estimate this value. The soil water balance model used to estimate daily soil water status throughout the season by the modified IDSS is the same one used in both versions of the IDSS in forecasting the soil water status. The equation for the soil water balance is:

$$SW_{\text{end}} = SW_{\text{beg}} + RGW + I - ET_{\text{c,adj}} + P - RO - DP \quad [5.1]$$

where,

SW_{end} = depth of soil water in the root zone at the end of the day (mm)

SW_{beg} = depth of soil water in the root zone at the beginning of the day (equal to SW_{end} for previous day) (mm)

RGW = depth of the soil water added to the root zone due to daily root growth (mm)

I = net irrigation (mm)

$ET_{\text{c,adj}}$ = adjusted crop evapotranspiration (mm)

P = precipitation (mm)

RO = water loss to runoff (mm)

DP = water loss to deep percolation below the root zone (mm).

Further explanation of the individual components of the soil water balance and how they are calculated is presented in section 3.3.2.7 (Forecasted Soil Water Balance Components). The irrigation term of the daily soil water balance used in the simulation version of the IDSS is assumed equal to the daily irrigation recommendation calculated for that day by the model.

In the event that temperature or ET_o data are missing from the observed weather data, the model assumes the values for the parameters from the previous day for any subsequent calculations for the simulation day. If rainfall data are missing, the rainfall for that day is assumed to be zero. If any forecast variables are missing for a given day of the simulation routine, the forecast soil water balance for the coming days is not generated and the irrigation recommendation for that day is based on the soil water status from the end of the previous day. In such case, if the ending soil water status from the previous day was less than the management allowed depletion (MAD) level for that day and the present day is an irrigation

opportunity, then the model calculates the irrigation recommendation for the present day as the amount of irrigation required to return the soil profile to field capacity (FC).

5.3.1.3 Outputs

The modified IDSS generates a single CSV output file each time the model is run. This file contains inputs and values calculated by the model for each simulation day of every combination of soil type by location by root depth by planting date by year considered in the simulation routine. These data can be used to compare the irrigation use and soil water dynamics between scenarios with the IDSS, or used as inputs to a crop growth model, such as those in DSSAT, to be used in evaluating yield differences between irrigation strategies.

5.3.2 Sites and Simulation Years

Two sets of simulation scenarios were considered for this study. The first was designed to assess the sensitivity of the IDSS for a constant set of irrigation settings to various input variables and weather patterns with regards to irrigation recommended by the model. The second set of simulations was conducted to compare irrigation water use and crop yield, as predicted by CSM-CERES-Maize in DSSAT, among non-irrigated production, fixed irrigation schedules, and “smart” irrigation based on the IDSS. Both sets of simulations were conducted for corn grown in five locations in the Coastal Plain of Eastern North Carolina (Kinston [KINS], Lewiston [LEWI], Lumberton [LUMB], Rocky Mount [ROCK], and Whiteville [WHIT]) (Figure 5.1) over six growing seasons (2009 – 2014). These locations were selected for the following reasons: i) they represent some of the most agriculturally productive areas of North Carolina; ii) observed weather data were readily

available for each of them; iii) and they are close enough to expect similar year-to-year variation in rainfall, yet sufficiently far apart to likely receive different day-to-day rainfall patterns and intensities within any given growing season. Three planting dates (DOY 91, 105, and 120; corresponding to 1 April, 15 April, and 30 April, except in 2012), spanning the month when the majority of corn is planted in North Carolina, were simulated in each year.

5.3.3 Observed Weather Data

Daily observed weather data for each simulation location – including minimum and maximum temperatures, rainfall, solar radiation, dew point, average wind speed, and relative humidity – were retrieved from weather stations within the Climate Retrieval and Observations Network of the Southeast (CRONOS) Database supported by the State Climate Office of North Carolina (SCO-NC) (Table 5.1). Preference was given to data collected from NC Environment and Climate Observing Network (ECONet) and National Weather Service (NWS) Automated Surface Observing System (ASOS) stations; however, in some periods of missing or erroneous data from the preferred stations, rainfall data were replaced using data from nearby NWS Cooperative Observer (Coop) stations, and satellite estimated solar radiation, obtained from the NASA Prediction of Worldwide Energy Resource (POWER) – Climatology Resource for Agroclimatology, was used instead. Daily ET_o estimates were calculated from weather data using the ASCE-EWRI Standardized ET_o method (ASCE-EWRI, 2005) option in the Ref-ET Software v4.1 (Allen, 2015).

5.3.4 Historical Weather Forecast Data

Daily, three-day weather forecasts for each location and simulation year were downloaded from the National Oceanic and Atmospheric Administration (NOAA) National Operational Model Archive and Distribution System (NOMADS) (Rutledge et al., 2006). NOMADS serves as central access portal to national archives of various weather and climate models, including the NWS National Digital Forecast Database (NDFD) (Glahn and Ruth, 2003). NDFD data generated after 5 October 2008 are directly accessible through the NOMADS interface.

Archived NDFD data consisted of three-day forecasts of temperature, QOP, POP, wind speed, percent cloud cover, and dew point temperature for the coordinates of each primary weather station used for the five simulation locations. Temperature, dew point temperature, wind speed, and percent cloud cover forecasts were returned in three-hour increments (i.e., each forecast day had eight temperature forecasts representing three-hour blocks from the beginning to the end of the day), while POP forecasts were in twelve-hour increments and QOP forecasts were in four-hour increments. These sub-daily forecasts were converted to daily forecast values as follows:

1. Forecast average daily dew point temperature, wind speed, and percent cloud cover were calculated as the average of the six three-hour forecast values provided for each day for each parameter.
2. Forecast daily minimum and maximum temperatures were taken as the minimum and maximum three-hour temperature forecasts, respectively.

3. Forecast daily POP was taken as the maximum twelve-hour POP forecast for each forecast day.
4. Forecast daily QOP was calculated as the sum of the four, six-hour QOP forecasts provided for each day.

Forecast daily percent sunshine was estimated by subtracting daily forecast percent cloud cover from 100%. Daily forecast values for minimum and maximum temperatures, percent sunshine, wind speed, and dew point temperature were used to calculate daily forecast ET_o using the ASCE-EWRI Standardized ET_o method (ASCE-EWRI, 2005) option in Ref-ET.

5.3.5 IDSS Sensitivity Analysis

A sensitivity analysis of the IDSS was conducted to assess which input parameters and interactions among them had the most effect on seasonal irrigation recommendations by the model under various weather conditions. Such analysis is beneficial during model development to determine if the model can be simplified, to guide users in knowing which input variables need to be measured or estimated most accurately, and to evaluate the performance of the model under various environmental and climatic conditions (Dzotsi et al., 2013; Monod et al., 2006). It was not the intent of this analysis to evaluate the effects of uncertainties in weather forecasts, variations in crop development parameters (e.g., growth stage versus cumulative growing degree relationship), or various combinations of irrigation settings (e.g. MAD and rainfall probability thresholds [RPT] for each growth stage) on the outputs of the IDSS, although such analysis would be beneficial as the development and

testing of the IDSS is furthered. Rather, the goal was to determine for a given set of irrigation settings and perfect weather forecasts, how other input variables would affect the irrigation recommendations.

5.3.5.1 IDSS Inputs

Seven factors were completely crossed with each other for the sensitivity analysis (Table 5.2). Three soils (representing low, medium, and high available water), five soil drainage rates (SLDR) (ranging from excessively well drained, 1.00, to very poorly drained, 0.05), three maximum effective root depths (RD_{max}) (300, 450, and 600 mm), and three irrigation intervals (1, 2, and 3 days between irrigation opportunities) were simulated across each combination of the three planting dates, five locations, and six year combinations for a total of 12,150 simulation scenarios.

MAD was set at 50% for the entirety of the growing season in the IDSS, the minimum irrigation threshold was set at 10 mm (i.e., calculated irrigation recommendations less than 10 mm were ignored), and the minimal irrigation option was selected (i.e., recommended irrigation depths were calculated as the minimal depth of irrigation required to avoid a forecasted deficit in the days to come, versus irrigating to a set point, such as field capacity). Days to max rooting depth was set independently for each RD_{max} based on a root growth rate of 15 mm d^{-1} . Growing degree requirements used for each growth stage and values used to construct the crop coefficient (K_c) curve are shown in Tables 5.3 and 5.4, respectively. The entire crop curve is presented in Figure 5.2. “Perfect” weather forecast files were created for each location by year using observed weather data so that any

variations in irrigation recommendations would be based on other factors and not forecast uncertainty that could vary from year-to-year or location-to-location.

5.3.5.2 Analysis of Outputs

Main effects of the input variables on seasonal irrigation recommendations were assessed visually using boxplots and statistically using analysis of variance (ANOVA). Simple sensitivity indices were calculated across and within all simulation years for each main effect and all possible interaction effects using the ANOVA procedure described by Monod et al. (2006), such that:

$$S_1 = \frac{SS_1}{SS_T}, S_2 = \frac{SS_2}{SS_T} \quad [5.2]$$

and

$$S_{12} = \frac{SS_{12}}{SS_T} \quad [5.3]$$

where,

S_1 and S_2 = sensitivity indices for main effects 1 and 2

SS_1 and SS_2 = sum of squares attributable to main effects 1 and 2

SS_T = total sum of squares

S_{12} = sensitivity index for interaction effect between factors 1 and 2

SS_{12} = sum of squares attributable to the interaction between factors 1 and 2.

Variations in seasonal rainfall and crop evapotranspiration (ET_c) compared to seasonal irrigation recommendations were evaluated graphically using boxplots and scatter plots. The same procedure was used to assess the relationships among seasonal irrigation

recommendations and calculated ET_c , and measured rainfall from the months of June and July, when corn water demand and drought sensitivity are typically at their peak.

A subset of twelve growing seasons (plant date by year by location) was selected based on seasonal rainfall totals to represent low (four), average (four), and high (four) seasonal rainfall totals. Effects of all RD_{max} and SLDR combinations were explored graphically within these seasons to see how they varied under dry, normal, and wet growing conditions. The daily SWBs predicted by the modified IDSS for these seasons were also investigated to assess the effects of timing and magnitude of individual rainfall events on seasonal irrigation recommendations.

5.3.6 Comparison of Simulated Irrigation Strategies

A second simulation study was conducted using the modified IDSS and CSM-CERES-Maize within DSSAT version 4.6.1.0 (Jones et al., 2003; Hoogenboom et al., 2015) to compare water use and yield differences in corn grown in the Coastal Plain of North Carolina under no irrigation (NoIrr), three fixed irrigation schedules (Fixed), and two “smart” irrigation schedules based on the modified IDSS (Smart). Crop yields were simulated in DSSAT based on fertility levels representative of North Carolina soils and current fertility management practices of North Carolina growers as well as with full fertility levels to estimate the potential combined impact of adding irrigation and improved fertility to corn production in the region.

5.3.6.1 Irrigation Treatments

The six irrigation treatments considered are presented in (Table 5.5). A single non-irrigated treatment represented dryland production, which is still the most common practice used in North Carolina corn production.

Three Fixed irrigation treatments were used and based on average weekly irrigation requirements for the months of June (23 mm) and July (22 mm) calculated using long term precipitation and ET_o data from Kinston, North Carolina. A full irrigation treatment (Fix100) was set to apply 13 mm of irrigation two times per week over the ten-week period beginning 45 days after planting. This depth of irrigation was chosen because it is a common target application depth used with center pivot irrigation systems and applied twice per week it would closely meet the calculated irrigation requirement during this period. The second Fixed treatment (Fix77) was set to apply 10 mm of irrigation two times per week during the same time frame, while the third Fixed treatment (Fix50) was set to apply 13 mm of irrigation once per week during the ten-week period. Fixed treatments were simulated using the modified IDSS, with a previous day rainfall bypass threshold of 13 mm and POP bypass threshold for the scheduled irrigation day of 75%.

Two Smart irrigation treatments were scheduled using the full functionality of the IDSS (i.e., incorporating current soil water status, crop growth stage, and short-term weather forecast into the irrigation recommendation). The difference between the Smart treatments was the type of forecast data used. Forecast files for the first Smart treatment (SmPerf) were based on observed weather data (i.e., “perfect”), while actual three-day forecast data from the NWS was used for the other Smart treatment (SmAct). Irrigation settings for both Smart

treatments were the same as used in the sensitivity analysis (MAD of 50%, minimum irrigation threshold of 10 mm, and irrigation recommendation calculations set to minimal) as were growth calculation parameters (Tables 5.3 and 5.4; Figure 5.2). Irrigation opportunities were set on a three-day interval, beginning at planting and running through crop maturity.

5.3.6.2 Experimental Design

All six irrigation treatments were simulated for two maximum effective rooting depths (300 and 450 mm), representing the range of typical maximum effective rooting depths expected for corn in eastern North Carolina (USDA-NRCS, 2010) and seven different soil types (Table 5.6), representative of typical soils found in the counties of the simulation locations and across the Coastal Plain of North Carolina (Table 5.7). Irrigation simulations were conducted across the same years, locations, and planting dates used for the sensitivity analysis for a total of 1,260 simulated seasons (6 years x 5 locations x 3 planting dates x 2 RD_{\max} x 7 soils) for each irrigation treatment (7,560 total).

Soil survey data from the National Resources Conservation Service's (NRCS) Soil Survey Geographic (SSURGO) database (USDA-NRCS, 2010) were used to create the seven soil profiles used in the simulations (Table 5.6). Permanent wilting point (PWP), field capacity (FC), and saturation water contents, along with saturated hydraulic conductivity (K_{sat}) and bulk density were calculated for each layer based on soil texture using procedures described by Saxton et al. (1986). K_{sat} and bulk density were not needed for the IDSS simulations; however, they were required for generating the soil files used in DSSAT simulations. Additional soil properties required by DSSAT (e.g., runoff curve number [SLRO] and albedo [SALB]) were calculated using the Soil Data Editing Program (Sbuild)

(Wilkens et al., 2004) included with the DSSAT software. Slight adjustments were made to some calculated layer properties based on experience (Dr. Gail Wilkerson, personal communication, 2016) and to better reflect water holding capacities reported in the soil surveys. SLDRs were assigned to each soil based on their reported drainage class as follows: well drained (SLDR = 0.8), moderately well drained (SLDR = 0.6), and poorly drained (SLDR = 0.4). These assignments were made with the assumption that poorly drained soils would necessitate some form of artificial drainage before being used for agricultural production, effectively improving the soil drainage rate. Soil root growth factors (SRGF) were set at 1 or 0 for each layer depending on the RD_{max} for that run. The soil fertility factor (SLPF), which is a general fertility factor representing soil nutrient availability (Hoogenboom et al., 2010), was set to 0.65 in nutrient limited production and 1.00 for non-limited production for each soil. SLPF of 0.65 was selected to reflect current soil fertilities and management practices common in North Carolina, based on calibration routines using average county yields for the simulation years, which is described in the following section.

5.3.6.3 CSM-CERES-Maize Model Description and Calibration

Crop simulations were conducted using CSM-CERES-Maize in DSSAT v4.6 (Jones et al., 2003; Hoogenboom et al., 2015) using the cultivar Novartis N75-T2. Genetic coefficients for Novartis N75-T2 grown in North Carolina were previously estimated and validated using DSSAT v4.0 (Jones et al., 2003) by Yang (2008). Genetic coefficients related to phenological development (P1, P2, P5, and PHINT) and the grain fill rate (G3) were used as reported by Yang (2008) for this study (Table 5.8). The maximum number of kernels per plant (G2) was increased from 600 (Yang, 2008) to 625 to reflect continued

genetic improvements since 2008 and based on recent calibration work using DSSAT v4.6 by Wilkerson and Buol (unpublished manuscript, 2016) using county average yield data from across North Carolina. For these same reasons, the radiation use efficiency (RUE), which directly affects the model calculated conversion of photosynthetically active radiation (PAR) into dry matter (Jones and Kiniry, 1986), was set to 5.4.

Baseline simulations without irrigation were conducted across all simulation locations, years, planting dates, soils, and root depths to confirm that remaining CSM-CERES-Maize settings were properly set for yield predictions in the locations of interest. In the absence of detailed yield data from each location and year, average county yields reported by USDA-NASS (2016) were used for comparison with simulated yields. Adjustments were made to temperature thresholds affecting grain fill and SLPF until a satisfactory fit between modeled and predicted yields was achieved based on visual inspection. The goal of the calibration procedure was to achieve a DSSAT configuration that would provide reasonable estimates of seasonal yields and that was responsive to seasonal fluctuations in moisture availability. Final RUE, grain fill temperature settings, and SLPF selected are presented in Table 5.8.

Three additional baseline scenarios were simulated using the same CSM-CERES-Maize configurations, but 1) assuming no moisture stress (i.e., fully irrigated), 2) assuming an SLPF of 1.00 (i.e., full fertility), but no irrigation, and 3) assuming no moisture stress and an SLPF of 1.00. The scenarios were meant to simulate theoretical maximum yields that could be achieved by adding irrigation only, improving fertility only, and by adding irrigation and improving fertility. The full fertility and fully irrigated simulations were

compared with state wide irrigated corn yield winners from each year (Heiniger and Boerema, 2014) to ensure that such estimates were reasonable.

5.3.6.4 CSM-CERES-Maize Simulations of Irrigation Treatments

Corn yields were predicted using the calibrated CSM-CERES-Maize model for each of the six irrigation treatments across all years, locations, planting dates, soil types, and maximum effective rooting depths listed in section 5.3.6.2 (1,260 simulations) with limited and full soil fertility levels (SLPF = 0.65 and 1.00, respectively), resulting in 15,120 total simulation runs (6 x 1,260 x 2). Individual DSSAT management files (FileXs) were created for each irrigation treatment by year by plant date by root depth combination. Every FileX consisted of thirty-five experimental treatments, one for each irrigation schedule generated by the modified IDSS for every location (n = 5) by soil (n = 7) combination. DSSAT irrigation simulations were conducted in four batch runs, one for each combination of maximum effective rooting depth and SLPF.

5.3.6.5 Statistical Analysis of Irrigation Simulations

Irrigation treatment effects on simulated yield and irrigation were tested using a mixed effect model via PROC MIXED (SAS Version 9.4; SAS Institute, Inc., Cary, NC). Irrigation treatment was modeled as a fixed effect and soil, RDmax, location, year, plant date nested within year, location nested within the interaction between plant date and year, and the interaction between treatment and location nested within the interaction between plant date and year were modeled as random effects. The LSMEANS statement was used to test for treatment mean differences controlling for Type I error rate at $\alpha = 0.05$. Boxplots were

constructed to assess variation in irrigation treatment effects on yield and irrigation within and across simulation seasons.

IDSS simulated daily root zone soil water contents for the SmAct treatment based on observed weather data were compared to estimates based on forecast weather data using linear regression to assess the efficacy of predicting root zone soil water content one, two, and three days in advance. Goodness of fit between simulated soil water contents based on forecast versus observed weather data were assessed using the FITEVAL software (Ritter and Muñoz-Carpena, 2013), which calculates the root mean square error (RMSE) and the Nash-Sutcliffe Efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (O_i - P_i)^2}{N}} \quad [5.4]$$

and

$$NSE = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} = 1 - \left(\frac{RMSE}{SD}\right)^2 \quad [5.5]$$

where,

O = observed value

P = predicted value

N = sample size

\bar{O} = mean of observed values

SD = the standard deviation of the observed values.

5.4 RESULTS AND DISCUSSION

5.4.1 Sensitivity Analysis of IDSS Irrigation Outputs

Year accounted for the greatest proportion of variation in seasonal IDSS recommended irrigation depths ($S = 0.54$) among all seven main factors (year, plant date, location, irrigation opportunity interval, RDmax, SLDR, and available water) and their possible interactions, based on the ANOVA generated sensitivity indices (Figure 5.3). The interaction between year and location ($S = 0.24$), SLDR ($S = 0.07$), and RDmax ($S = 0.03$) had the next highest sensitivity indices, with the remaining factors and interactions combined accounting for only 12% of the variation in seasonal irrigation (no single factor or interaction having an S greater than 0.02).

The prominent effects of year and year by location are most likely attributable to variations in rainfall from year-to-year (Figure 5.4) and within season from location-to-location (evidenced by the tall rainfall boxplots in Figure 5.4). Seasonal ET_c remained relatively constant, compared to rainfall, ranging from 442 mm (2013-WHIT-91; labeling convention is year-location-plant day of year) to 574 mm (2011-LUMB-105) and on average was greater than rainfall during the first three simulated seasons (2009 – 2011) and less than rainfall during the last three simulated seasons (2012 – 2014). Seasonal irrigation depth recommended by the IDSS followed an inverse relationship to seasonal rainfall (Figures 5.4 and Figure 5.5A); however, there was substantial variation within this relationship (Figure 5.5A). For example, there were simulation seasons with 597 mm of rainfall that applied no irrigation for one combination of input factors and over 200 mm of irrigation for another

combination of inputs. This supports the assertion that irrigation scheduling in humid climates is not only dependent on rainfall quantity, but other factors, such as the timing of rainfall events throughout the growing season (Camp et al., 1985; Camp et al., 1988). IDSS recommended seasonal irrigation depths were also inversely related to total rainfall received during the peak water use and drought sensitive months of June and July (Figure 5.5B). This relationship displayed a high degree of variability as well.

The relationships between seasonal irrigation and the six other factors (excluding year) across all simulation seasons are shown in Figure 5.7. Despite visually evident trends – such as decreased average seasonal applied irrigation as maximum effective rooting depth or soil available water increased, increased irrigation as soil drainage rate increased, and decreased irrigation as the planting date was delayed – there were large variations in seasonal irrigation not well accounted for by any of the “non-year” main factors, consistent with the sensitivity indices previously referred to in Figure 5.3. This does not suggest, however, that these factors did not have a substantial effect on irrigation recommendations within individual simulation seasons (i.e., there was evidence of interaction effects between year and some of these factors).

Sensitivity indices within each simulated season (Figure 5.8) reveal how the effects of these non-year factors on irrigation varied from season-to-season, depending largely on the weather within the season. Location accounted for the majority of the variation in seasonal rainfall during the first four simulation seasons, presumably due to varied rainfall patterns at the different simulation locations within those years. While still important, location did not account for as much of the variation in irrigation in 2013 and 2014, in which average rainfall

across all locations and planting dates (419 and 363 mm, in 2013 and 2014, respectively) was greater than in the earlier seasons (Figure 5.9). In these wetter seasons, factors such as SLDR, planting date, and RDmax accounted for substantial portions of the variation in IDSS irrigation recommendations. Similarly, in 2010, the driest simulation year (172 mm rainfall across all locations and planting dates), SLDR ($S = 0.13$), RDmax (0.05), and available water (0.04) accounted for 22% of the total variation in irrigation.

5.4.1.1 Select Simulations Examined More Closely

This varied response of the IDSS to different weather patterns was further evident upon closer examination of twelve of the ninety simulated growing seasons: four representative seasons with low rainfall, four with average rainfall, and four with high rainfall (Table 5.9). Seasons in each rainfall category with similar rainfall totals had drastically different recommended irrigation totals. The 2009-ROCK-91 growing season received 238 mm of rainfall, similar to 2011-KINS-91 (245 mm); however, on average (across all RDmax by SLDR by soil available water by irrigation opportunity interval combinations) the IDSS recommended 24% more irrigation in 2011-KINS-91 (322 mm) than in 2009-ROCK-91 (260 mm). The discrepancy was even greater between two of the seasons with high rainfall totals. Nearly four times as much irrigation (141 mm) was recommended in the 2014-LEWI-91 season (763 mm of rainfall) as in the 2013-WHIT-105 growing season (36 mm of irrigation; 754 mm of rainfall) across all combinations of sensitivity analysis factors.

The differences in irrigation totals between seasons with similar total rainfall were primarily due to the timing and magnitudes of individual rainfall events, as can be seen in the

daily SWBs of the simulation seasons for a given combination of RDmax (450 mm), SLDR (0.60), soil available water ($0.13 \text{ mm}^3 \text{ mm}^{-3}$), and irrigation opportunity interval (3 days) (Figures 5.10 – 5.12). The 2011-KINS-91 growing season received several moderate rainfalls during the first 28 DAP (Figure 5.10B), but only had one day with greater than 10 mm of rainfall between 28 DAP and 72 DAP, just four days before the model predicted tasseling, meaning the crop was near its maximum daily water use rate and susceptibility to dry stresses. On the other hand, the 2009-ROCK-91 season received 125 mm of rainfall over 16 different days during the same time span (Figure 5.10A). Rainfall tapered off after 80 DAP in this simulated season, at the time when the crop water demand was decreasing as well. The 2014-LUMB-91, 2013-WHIT-105, and 2014-LEWI-91 growing seasons, which received three, five, and six rainfall events in excess of 40 mm, respectively (Figures 5.11B, 5.12A, and 5.12B), were examples of how high magnitude rainfall events coupled with the timing of such events can significantly affect the irrigation schedule.

The importance of properly setting model parameters that defined the soil water reservoir (RDmax, SLDR, and available water) during such seasons was highlighted in 2014-LEWI-91, when many of the rainfalls were of high magnitude, yet the time intervals between rainfall events were relatively long. The average irrigation recommended for this season across all three irrigation opportunity intervals ranged from 71 mm (RDmax, SLDR, and available water set to 600 mm, 0.05, and 0.17, respectively) to 217 mm (same parameters set to 300 mm, 1.00, and 0.10, respectively) (Figure 5.13). While these conditions represent extreme opposite ends of the spectrum for how a user could parameterize the model for a site, nonetheless they highlight the importance of accurately setting these values in years with

scattered, high-intensity rainfall events – precisely the type of weather that characterizes much of the humid southeastern United States, particularly during the summer months (SCONC, 2016). These soil water reservoir parameters had less impact on seasonal irrigation during dry seasons, such as 2011-KINS-105 (Figure 5.14), when the irrigation demand was driven almost entirely by the evapotranspiration demand and there was minimal rainfall to store. In such a scenario, the soil parameters may affect frequency of irrigation events needed and their individual magnitudes, but not the overall depth of irrigation for the season. These relationships can be seen in plots of seasonal irrigation depths (Appendix E) and frequencies (Appendix F) across all combinations of RDmax, SLDR, and available water for the twelve locations that were closely examined.

5.4.2 IDDS and DSSAT Simulated Irrigation Treatments

5.4.2.1 DSSAT Calibration and Baseline Scenarios

Simulations using the calibrated CSM-CERES-Maize with no irrigation and an SLPF of 0.65 did not closely match observed annual county average yields (Figure 5.15); however, the overall level of agreement between predicted and observed county yields was deemed acceptable for the scope of this study. The model most closely matched observed yields in Bertie County ($R^2 = 0.70$; $RMSE = 1,473 \text{ kg ha}^{-1}$) (Figure 5.15) and most poorly in Columbus ($R^2 = 0.28$; $RMSE = 1,468 \text{ kg ha}^{-1}$) and Lenoir ($R^2 = 0.55$; $RMSE = 1,833 \text{ kg ha}^{-1}$) counties. There was visual evidence that some points may have been outliers, but such points were not removed due to the limited size of the data set. Stricter calibration standards could have been used had the observed versus predicted data set covered more years and

locations, and if multiple configurations of CSM-CERES-Maize had been considered for individual county locations. For example, simulated yields for the seven soil types, three planting dates, and two maximum rooting depths were weighted equally in calculating predicted yields for each county. These estimates could possibly be improved by considering more or fewer soil types and planting dates in each county, or by weighting average yield predictions based on factors such as occurrence of soil types in the county or recorded percentages of the crop planted by certain dates in the county. It should also be noted that predicted yields were based on weather observations representing a single location within each county, whereas the county yields were a function of weather patterns across the county. A well timed rainfall or extended drought in one portion of a county for a given growing season could significantly skew the average observed county yield for that year (Yang et al., 2008) and unfortunately no measure of variability is provided with the USDA reported county yields (USDA-NASS, 2016).

The goal of the calibration procedure was to configure CSM-CERES-Maize within DSSAT v4.6 such that reasonable yield estimates were predicted and the model was responsive to environmental variations within and across growing seasons, particularly the availability of water (be it from rainfall or irrigation). Figure 5.16A shows that the calibrated, non-irrigated DSSAT model did reflect locational variations in weather within each growing season, and closely reflected the seasonal variations in average observed yields across the simulation counties. Figures 5.16B, 5.16C, and 5.16D reflect the theoretical yields that could have been achieved with full irrigation (irrigated; SLPF = 0.65), full fertility (no irrigation; SLPF = 1.00), and both full irrigation and fertility (irrigated; SLPF = 1.00),

respectively. The simulated yields at full irrigation and fertility were comparable with statewide highest recorded yields of irrigated corn for each of these seasons (Heiniger and Boerema, 2014). Predicted yields in the irrigated scenarios were also much less variable across and within seasons as the dependency on rainfall was reduced. The yields presented in Figure 5.16 represented baselines for the irrigation simulations that followed.

5.4.2.2 Estimated Yields and Water Use Among Irrigation Treatments

Irrigation treatment had a significant effect on simulated yields and seasonal irrigation predicted by the IDSS. Irrigation, of any form, resulted in significantly higher average estimated yields than the NoIrr treatment (5,010 kg ha⁻¹) (Table 5.10 and Figure 5.17), which was comparable to the average reported yields for the simulation counties during the same time span (5,337 kg ha⁻¹) (USDA-NASS, 2016). The SmPerf and SmAct treatments had the highest average seasonal yields (9,120 kg ha⁻¹ and 9,114 kg ha⁻¹, respectively), followed by Fix100 (8,762 kg ha⁻¹) (Table 5.10). Although this yield increase from the Smart treatments compared to the Fix100 treatment was only about 4% averaged across all simulated seasons, the increase was more evident in years with less rainfall (e.g., 8% in 2010 and 2011) and the variation in yields was less in the Smart treatments than in any of the other treatments in each season, with the degree of variation increasing substantially as the level of irrigation decreased progressively from Smart to Fixed to NoIrr (Figure 5.17).

The significance of the reduced variation in yields in the Smart treatments cannot be understated. While the overall mean yields may only suggest a minimal yield benefit from the Smart systems compared particularly to the Fix100 treatment, the distributions of yields among treatments suggest that the risk of substantially reduced yields is much greater for an

individual grower using any of the Fixed systems than with the Smart treatments, as indicated by the minimum bars on the box plots (Figure 5.17) and yield standard deviations presented in Table 5.10. A grower would stand to lose much less yield falling into the lower quartile of the SmAct treatment yields than in that of any of the Fixed or NoIrr treatments.

Within the Smart treatments, there was no evidence of a yield effect between IDSS-scheduled irrigation based on actual forecasts versus observed weather data, substituted as “perfect” forecasts. The SmPerf treatment did however apply on average 22 mm less seasonal irrigation (200 mm) than the SmAct treatment (222 mm) (Table 5.11 and Figure 5.18). Averaged across all seasons, there was no difference in seasonal irrigation for the Fix100 (223 mm) and the SmAct (222 mm) treatments, which applied the greatest amounts of irrigation among all treatments. While this lack of a difference may seem discouraging at face value, it is a product of how the Fix100 schedule was determined and should be expected if considering amply representative irrigation seasons. The Fix100 schedule was based off of the long-term calculated irrigation requirement, while the IDSS seeks to match the irrigation requirement in real-time. They are in principal based on the same theory, but on much different time scales. This nuanced difference is evidenced by the seasonal variation in irrigation among the Fixed and Smart treatments (Figure 5.18). Total irrigation applied by the Fixed treatments did not vary substantially from season-to-season, nor within season, as indicated by the narrow distributions of the respective boxplots. On the other hand, the Smart treatments varied seasonally (Figure 5.18), in response to seasonal rainfall (Figure 5.4), and within season, as indicated by the wide distributions in the Smart irrigation boxplots (Figure 5.18). The within season variation was due to the IDSS accounting for

other simulation factors (e.g. soil and RDmax), not the least of which was presumably weather variations among simulation locations and planting dates.

It should be noted that because the depth of irrigation applied by the Fix100 treatment remained essentially constant across seasons and locations the net result was either under (Figure 5.19) or over-irrigation (Figure 5.20) in many cases. When the latter occurred, particularly on less well drained soils, the soil water content remained at or above field capacity for extended days, which could have led to nutrient leaching and or hypoxic (low oxygen) conditions in portions of the root zone. Boote and Jones (2013) documented that one of the limitations of the DSSAT suite of models is the inability to predict yield depression from excess moisture stress, which in this case means the Fix100 yields may have been over estimated in seasons where over-irrigation occurred. In fairness, if this did occur, then all treatment yields were likely overinflated in 2013 and 2014 when heavy and frequent rainfalls kept the less well drained soils above field capacity for multiple days at time, the difference being this was due to rainfall and not irrigation (Figure 5.20).

Simulated yields by irrigation treatment and year based on assumed full fertility (SLPF = 1.00) are presented in Figure 5.21. The relationship among yields by irrigation treatments was the same under full fertility as for SLPF = 0.65; however, the magnitudes of the yields increased by about 47% for each treatment. These yield estimates under such conditions for the SmAct (13,435 kg ha⁻¹) and SmPerf (13,444 kg ha⁻¹) treatments were similar to the baseline yields estimated during the calibration routine (Figure 5.16D). This suggests that implementing IDSS-based irrigation scheduling along with more intensive fertility management could result in as much as 168% increase in average seasonal yields.

Adding irrigation alone could result in an 82% increase in average seasonal yields, while also reducing seasonal and spatial yield variations.

5.4.2.3 Simulated Soil Water Content Based on Observed vs. Forecast Weather Data

IDSS simulated daily root zone soil water contents based on forecast weather data were similar to those simulated based on observed weather data across all years, locations, planting dates, soil types, maximum effective root depths, and soil drainage rates (Figure 5.22). Root zone soil water contents predicted using forecast weather data from one day in advance (Figure 5.22A) most closely matched soil water contents based on observed weather data (NSE = 0.953, RMSE = 6.389 mm, $R^2 = 0.954$); however, estimates based on two (Figure 5.22B) and three day (Figure 5.22C) in advance forecasts were reasonable also (NSE = 0.906, RMSE = 9.078 mm, $R^2 = 0.914$ and NSE = 0.864, RMSE = 10.895 mm, and $R^2 = 0.892$, respectively). Normalizing across maximum effective root depths (i.e., 300 and 450 mm), RMSE values ranged from 1.4 to 3.6%. As the forecast lead time increased, soil water content predictions tended to slightly under estimate what was calculated based on observed data. This can be attributed to increasing uncertainty as lead time increases, particularly in precipitation forecasts. Nonetheless, these data suggest that three day forecasts can be useful in irrigation scheduling.

5.5 SUMMARY AND CONCLUSIONS

The real-time IDSS proposed in Chapter 3 was modified to operate in a simulation mode, using historical weather observations and archived daily forecasts as inputs. A sensitivity analysis on the effects of seven IDSS inputs (year, location, plant date, RDmax,

SLDR, soil available water, and irrigation opportunity interval) was conducted to assess the effects of each factor and all possible combinations on season irrigation recommendations for corn grown in Eastern North Carolina. A simulation study was also conducted to estimate the yield and water use effects of six irrigation treatments using the CERES-Maize model within DSSAT v4.6, which was calibrated using reported average county corn yields for the simulation locations. All simulations were run across six years (2009 – 2014), three planting dates (1, 15, and 30 April), and five locations from across the Coastal Plain of North Carolina (Kinston, Lewiston, Lumberton, Rocky Mount, and Whiteville).

Year ($S = 0.54$) and the interaction between year and location ($S = 0.24$) accounted for the greatest proportion of variation in seasonal irrigation. Within seasons, location had the highest sensitivity index of any factor in five of the six simulated years. While irrigation generally decreased with seasonal rainfall, the relationship was highly variable, with several seasons having similar cumulative rainfall totals yet differing in seasonal irrigation by as much as 163% (e.g., 2014-LEWI-91 vs. 2013-WHIT-105). In such cases, the timing and magnitude of individual rainfalls was more important than the seasonal rainfall total. This reiterates the well documented challenges that temporal and spatial rainfall variations present to irrigation scheduling in the humid southeastern United States (Sadler et al., 2003).

Factors characterizing the soil water reservoir (e.g., SLDR, RDmax, and soil available water) were more important predictors of irrigation as seasonal rainfall increased (e.g., 2012 – 2014) because they govern the amount of rainfall that can be stored in the soil, and thus the amount that remains available to the plant versus being lost to runoff or drainage. The allowance for soil water storage above field capacity beyond the day of or one day following

a rainfall event is frequently omitted in SWBs; however, this study suggests that accounting for this water, such as with the SLDR term, is important to prevent over-irrigation in soils with even moderately reduced drainage, as is common of many Coastal Plain soils.

The simulation study revealed that irrigation treatment had a significant effect on both average seasonal yield and average seasonal irrigation. At fertility levels representing typical soils and management practices in North Carolina (SLPF = 0.65), both Smart treatments increased average seasonal yields 82% compared to the NoIrr treatment (5,010 kg ha⁻¹) and 4% compared to the highest yielding Fixed treatment (Fix 100; 8,762 kg ha⁻¹). While this yield increase was modest averaged over all seasons, the increase provided by the Smart treatments was more pronounced in drier years. Perhaps even more importantly, the SmAct and SmPerf treatments reduced the variation in simulated yields from year-to-year and within season compared to the other treatments. This suggests that either Smart treatment could reduce the risk of substantial yield loss due to drought compared to the other treatments considered.

There was no difference in yield predictions between IDSS-scheduled irrigation using actual forecasts instead of perfect forecast; however, on average, the SmPerf treatment applied about 10% less irrigation (200 mm) seasonally than the SmAct treatment. There was no difference between the overall average irrigation applied by the Fix100 (223 mm) and SmAct (222 mm) treatments, but the Smart irrigation totals fluctuated from year-to-year and within year, in response to the changes in rainfall, while the Fix100 schedule remained relatively constant from season-to-season and within, causing over-irrigation in some years and under irrigation in others. In a field setting, this over-irrigation could lead to nutrient

leaching and even hypoxia conditions within the root zone. Nutrient leaching was not accounted for in this study and it has been documented that DSSAT does not do a good job of accounting for the effects of excess water stress (Boote and Jones, 2013). Studies have reported the need for improvement in DSSAT estimations of soil water and nitrogen interactions (Garrison et al., 1999; Sadler et al., 2000) and the combined model DRAINMOD-DSSAT has been created specifically for this purpose (Negm et al., 2014). It is plausible that corn yields for the Fix100 treatment were over-predicted in some simulated seasons based on these reasons, which suggests that the yield difference between the Fixed and Smart treatments could be even greater than the 4% reported in this study.

The results also suggest that implementing IDSS-scheduled irrigation in the Coastal Plain of North Carolina could reduce seasonal and locational variations in yields that currently exist due to similar variations in rainfall. Additionally, adopting the system alone could increase yields by 82% from current, non-irrigated production, or by 168% if implemented with intensive, improved fertility management. This study should be beneficial in guiding future simulation and field studies with the IDSS, which are necessary and recommended as the system has displayed promising potential for addressing yield limitations and water management challenges facing growers, particularly in the humid southeastern United States.

A financial analysis at the farm level would be helpful in quantifying net increase in returns versus annualized costs of implementing smart irrigation. Potential regional and state-wide yield increases that could be achieved with widespread transitions from rainfed to rainfed-irrigated, hybrid cropping systems should also be assessed. In addition to

considering any economic impacts, such an analysis should also include an estimate of the water that would be needed to implement such changes and long-term sustainability.

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5.7 TABLES

Table 5.1. Weather stations from which observed weather data was obtained for simulation studies (via CRONOS Database of the State Climate Office of NC).

Simulation Location	Nearby Weather Stations		
	Name (ID)	Network	Coordinates
Lewiston	Peanut Belt Research Station (LEWS)	ECONet	36.132°, -77.176°
Lewiston	Lewiston (314962)	COOP	36.133°, -77.171°
Lumberton	Lumberton Municipal Airport (KLBT)	ASOS	34.610°, -79.059°
Kinston	Cunningham Research Station (KINS)	ECONet	35.303°, -77.573°
Rocky Mount	Upper Coastal Plain Research Station (ROCK)	ECONet	35.893°, -77.680°
Rocky Mount	Tarboro 1 S (318500)	COOP	35.885°, -77.539°
Whiteville	Border Belt Tobacco Research Station (WHIT)	ECONet	34.413°, -78.792°
Whiteville	Whiteville 7 NW (319357)	COOP	34.409°, -78.791°

Note: Preference was given to ECONet and ASOS stations as data sources. COOP stations were used to supplement periods of missing or erroneous data, as were satellite estimates of solar radiation from NASA Prediction of Worldwide Energy Resource (POWER) – Climatology Resource for Agroclimatology.

Table 5.2. Variables and levels used in the sensitivity analysis.

Parameter	Levels
Plant Available Water ($\text{mm}^3 \text{mm}^{-3}$)	0.10, 0.13, 0.17
Soil Drainage Rate (SLDR)	1.00, 0.80, 0.60, 0.40, 0.05
Maximum Effective Root Depth (RD_{max}) (mm)	300, 450, 600
Irrigation Opportunity Interval (days)	1, 2, 3
Plant Date (DOY)	91, 105, 120
Location	KINS, LEWI, LUMB, ROCK, WHIT
Years	2009, 2010, 2011, 2012, 2013, 2014

Table 5.3. Cumulative growing degree day requirements for each growth stage and respective management allowed depletions and rainfall probability thresholds used by the IDSS in the study simulations.

Growth Stage	Stage No.	Cum GDD (°C)
Pre-Emerge	0	0
VE-Emergence	1	56
V1	2	100
V2	3	150
V3	4	200
V4	5	250
V5	6	300
V6	7	350
V7	8	400
V8	9	450
V9	10	500
V10	11	550
V11	12	581
V12	13	611
V13	14	642
V14	15	672
V15	16	703
V16	17	733
V17	18	764
V18	19	792
VT-Tasseling	20	822
R1-Silking	21	836
R2-Blister	22	964
R3-Milk	23	1058
R4-Dough	24	1222
R5 - Dent	25	1389
R6-Phys Maturity	26	1556

Table 5.4. Parameters used to develop the IDSS crop curve.

Parameter	Value
$K_{c\ ini}$	0.3
$K_{c\ mid}$	1.2
$K_{c\ end}$	0.6
L_{ini}	20
L_{dev}	35
L_{mid}	40
L_{late}	30

Note: L_i indicates the length of development stage i in days

Table 5.5. Irrigation treatments considered in the simulation study.

Irrigation Treatment	Description
NoIrr	No irrigation
Fix100 ¹	Fixed irrigation of 13 mm, twice a week over 10-week period beginning 45 DAP
Fix77 ¹	Fixed irrigation of 10 mm, twice a week over 10-week period beginning 45 DAP
Fix50 ¹	Fixed irrigation of 13 mm, 2 x per week over 10-week period beginning 45 DAP
SmPerf ²	Irrigation scheduled by modified IDSS using perfect forecast date (i.e., replaced with observed weather data)
SmAct ²	Irrigation scheduled by modified IDSS using actual three-day weather forecast from the NWS

¹Previous day rainfall bypass threshold of 13 mm and POP bypass threshold for the scheduled irrigation day of 75%.

²MAD of 50% across the growing season.

Table 5.6. Soil physical properties for soil types used in irrigation simulation study.

Soil Series	Layers					
	SLDR	Depth (mm)	Thickness (mm)	θ_{SAT} (mm ³ mm ⁻³)	θ_{FC} (mm ³ mm ⁻³)	θ_{PWP} (mm ³ mm ⁻³)
Rains fine sandy loam (RAFS)	0.40	0	180	0.418	0.237	0.097
		180	270	0.418	0.222	0.097
Goldsboro loamy sand (GOLS)	0.60	0	300	0.364	0.188	0.063
		300	150	0.364	0.148	0.063
Goldsboro sandy loam (GOSL)	0.60	0	300	0.409	0.213	0.088
		300	150	0.409	0.173	0.088
Norfolk loamy sand (NOLS)	0.80	0	450	0.364	0.148	0.063
Pocalla loamy fine sand (PLFS)	0.80	0	450	0.381	0.167	0.072
Roanoke fine sandy loam (ROFS)	0.40	0	300	0.435	0.275	0.105
		300	150	0.507	0.328	0.153
Wagram loamy sand (WALS)	0.80	0	450	0.374	0.161	0.068

Table 5.7. Predominant soil series by county of each simulation location.

County (Sim. Location)	Soil Series	Percent of County Soil Composition (%)
Bertie (LEWI)	Leaf loam	13.6
	Craven fine sandy loam	8.3
	Roanoke fine sandy loam*	6.6
	Goldsboro sandy loam*	5.5
	Rains sandy loam*	5.2
	Lynchburg sandy loam	2.5
Columbus (WHIT)	Lynchburg fine sandy loam	9.4
	Norfolk loamy fine sand*	7.4
	Goldsboro fine sandy loam*	6.3
	Grifton fine sandy loam	6.7
	Rains fine sandy loam*	5.8
Edgecombe (ROCK)	Norfolk loamy sand*	14.3
	Rains fine sandy loam*	10.3
	Roanoke loam*	9.4
	Goldsboro fine sandy loam*	7.6
	Wagram loam sand*	5.4
Lenoir (KINS)	Norfolk loamy sand*	15.2
	Pocalla loamy sand*	10.3
	Rains sandy loam*	7.1
	Goldsboro loamy sand*	5.2
	Lynchburg sandy loam	4.7
	Wagram loamy sand*	4.9
Robeson (LUMB)	Norfolk loamy sand*	13.5
	Johnston soils	12.4
	Rains sandy loam*	11.8
	Wagram loamy sand*	9.6
	Goldsboro loamy sand*	7.6
	Lynchburg sandy loam	5.2
	Pocalla loamy sand*	1.8

*Denotes soil series that was represented in simulation study.

Table 5.8. DSSAT input parameters by file type.

Parameter	Description	Value
<i>Cultivar File (.CUL)</i>		
P1	Degree days from emergence to end of juvenile phase	265.0
P2	Photoperiod sensitivity coefficient (0 – 1.0)	0.450
P5	Degree days from silking to physiological maturity	930.0
PHINT	Degree days between leaf tip appearances (phylochron interval) (base 8 °C)	38.90
G2	Potential kernel number	625.0
G3	Potential kernel growth rate	9.00
<i>Ecotype File (.ECO)</i>		
TBASE	Base temperature below which no development occurs	8.0
TOPT	Temperature at which maximum development rate occurs during vegetative stages	34.0
ROPT	Temperature at which maximum development rate occurs for reproductive stages	34.0
P2O	Daylength below which daylength does not affect development rate	12.5
DJTI	Minimum days from end of juvenile stage to tassel initiation if the cultivar is not photoperiod sensitive	4.0
GDDE	Degree days per cm seed depth required for emergence	6.0
DSGFT	Degree days from silking to effective grain filling period	170
RUE	Radiation use efficiency	5.4
KCAN	Canopy light extinction coefficient for daily PAR	0.85
<i>Species File (.SPE)</i>		
RGFIL – TBASE	Base temperature below which no grain filling occurs	5.5
RGFIL – TOP1	Lower optimum temperature for grain filling rate	16.0
RGFIL – TOP2	Upper optimum temperature for grain filling rate	29.0
RGFIL – TMAX	Maximum temperature above which no grain filling occurs	37.0
<i>Soil File (.SOL)</i>		
SLPF (limited)	Soil fertility factor, (0 – 1.0)	0.65
SLPF (full)	Soil fertility factor, (0 – 1.0)	1.00

Note: All degree days calculated using base of 8 °C

Table 5.9. Season rainfall and irrigation for selected growing seasons with low, average, and high rainfall totals relative to all simulated growing seasons.

Seasonal Rain Category	Year	Location	Plant DOY	Rainfall (mm)	Irrigation (mm)	StDev Irrigation (mm)
Low	2009	ROCK	91	238	260	19
Low	2011	KINS	91	245	322	14
Low	2010	WHIT	91	299	243	25
Low	2011	KINS	105	303	301	15
Avg	2009	WHIT	105	496	94	30
Avg	2014	LUMB	91	507	207	50
Avg	2012	LUMB	91	509	150	46
Avg	2013	LEWI	105	516	93	45
High	2013	WHIT	105	754	36	35
High	2014	LEWI	91	763	141	43
High	2014	KINS	91	850	106	46
High	2014	KINS	105	917	65	45

Abbreviations: Avg = Average, StDev = Standard Deviation

Table 5.10. Means and standard deviations of yield by irrigation treatment and year at limited fertility levels (SLPF = 0.65).

Year	Yield (kg ha ⁻¹)											
	NoIrr		Fix50		Fix77		Fix100		SmAct		SmPerf	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
2009	4,938	1,872	8,220	1,401	9,029	1,021	9,375	827	9,529	821	9,554	825
2010	3,403	1,501	6,283	1,317	7,549	1,226	8,329	965	9,027	595	9,031	595
2011	3,826	1,512	5,606	1,735	6,993	1,336	7,907	1,039	8,581	671	8,588	667
2012	3,622	1,550	6,226	1,656	7,727	1,495	8,442	1,064	8,851	647	8,872	659
2013	6,965	1,031	7,875	727	8,210	581	8,337	530	8,406	509	8,397	490
2014	7,308	2,492	8,982	1,647	9,933	1,064	10,182	814	10,289	737	10,279	738
Overall	5,010 e	2,334	7,199 d	1,900	8,240 c	1,516	8,762 b	1,179	9,114 a	922	9,120 a	922

Note: Overall means with similar letters are not statistically different ($\alpha = 0.05$)

Abbreviations: SLPF = soil fertility factor, Std. Dev. = standard deviation

Table 5.11. Means and standard deviations of seasonal irrigation by irrigation treatment and year at limited fertility levels (SLPF = 0.65).

Year	Seasonal Irrigation (mm)											
	NoIrr		Fix50		Fix77		Fix100		SmAct		SmPerf	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
2009	0	0	115	10	174	20	226	26	205	50	185	55
2010	0	0	116	14	171	20	223	26	289	42	267	44
2011	0	0	117	7	183	9	237	11	284	42	268	49
2012	0	0	112	9	177	10	231	13	216	38	196	38
2013	0	0	109	21	167	17	217	23	148	43	127	41
2014	0	0	91	22	157	15	204	20	194	58	156	54
Overall	0 e	0	110 d	17	171 c	18	223 a	23	222 a	68	200 b	71

Note: Overall means with similar letters are not statistically different ($\alpha = 0.05$)

Abbreviations: SLPF = soil fertility factor, Std. Dev. = standard deviation

5.8 FIGURES

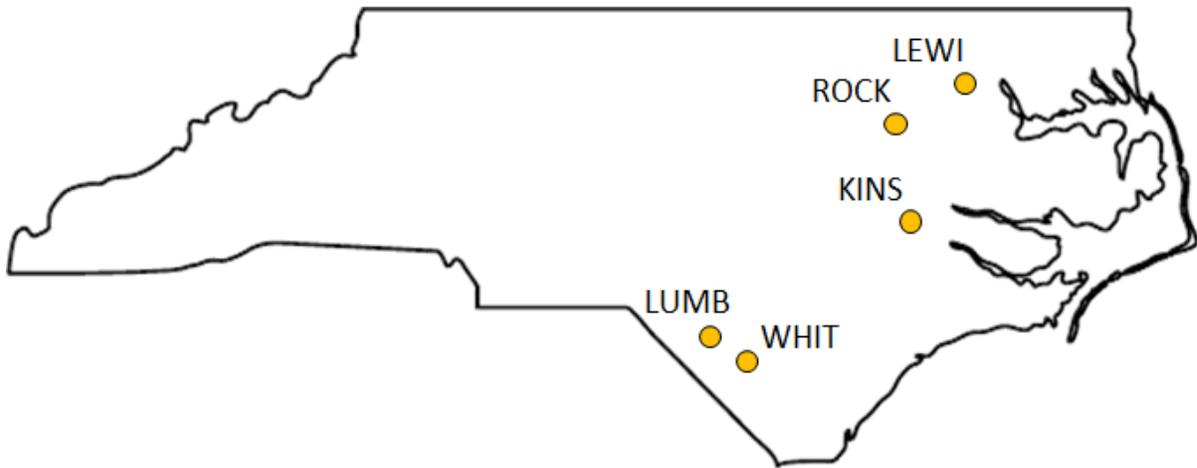


Figure 5.1. Map of locations used in simulation study. Abbreviations are: LEWI (Lewiston), LUMB (Lumberton), KINS (Kinston), ROCK (Rocky Mount), and WHIT (Whiteville).

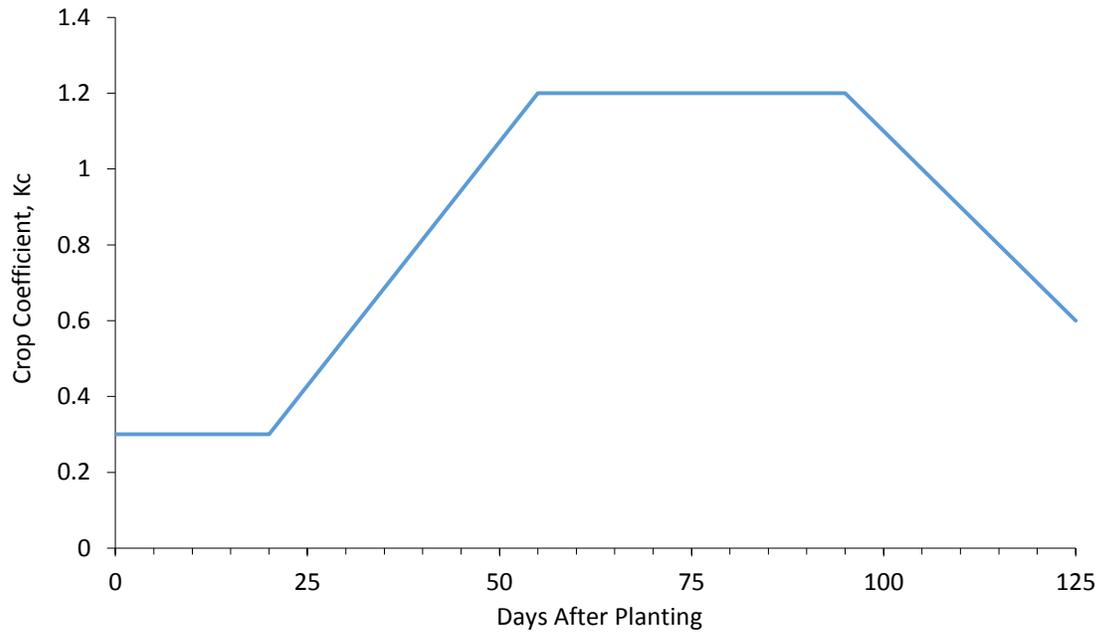


Figure 5.2. Crop curve based on IDSS inputs used in the sensitivity analysis and simulation study.

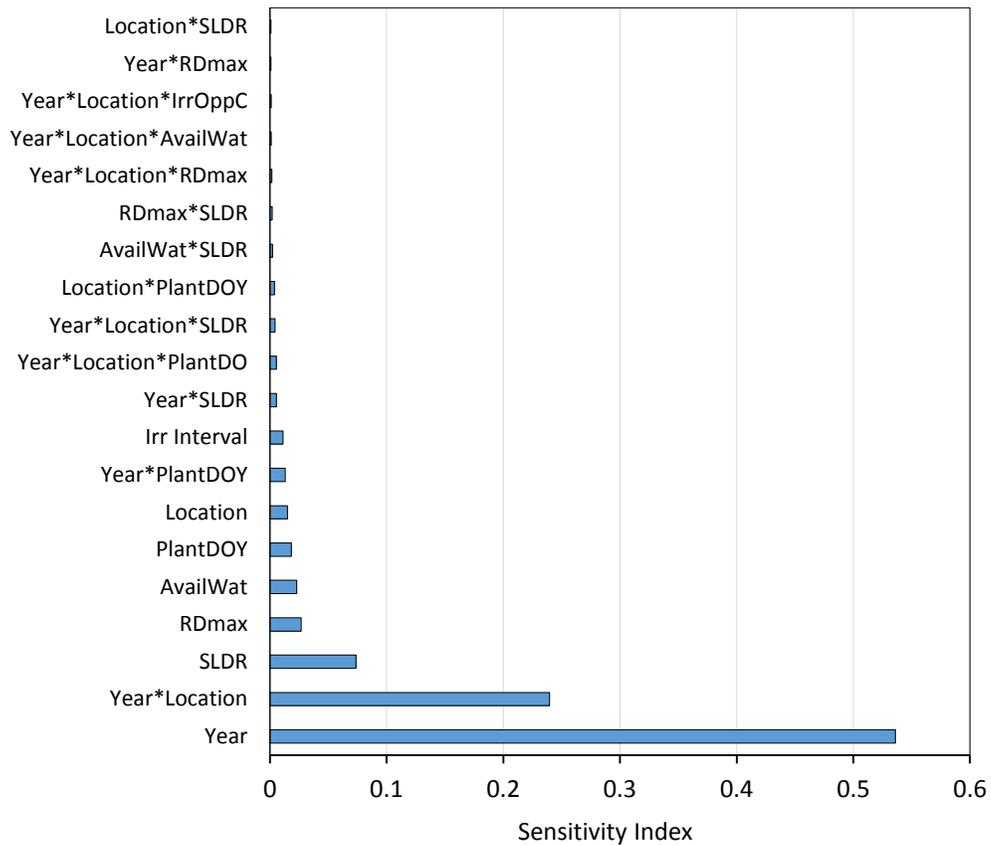


Figure 5.3. ANOVA based main-effect and interaction sensitivity indices for the 12,150 combinations of seven factors considered in the sensitivity analysis. Note: Only the twenty largest sensitivity indices are presented.

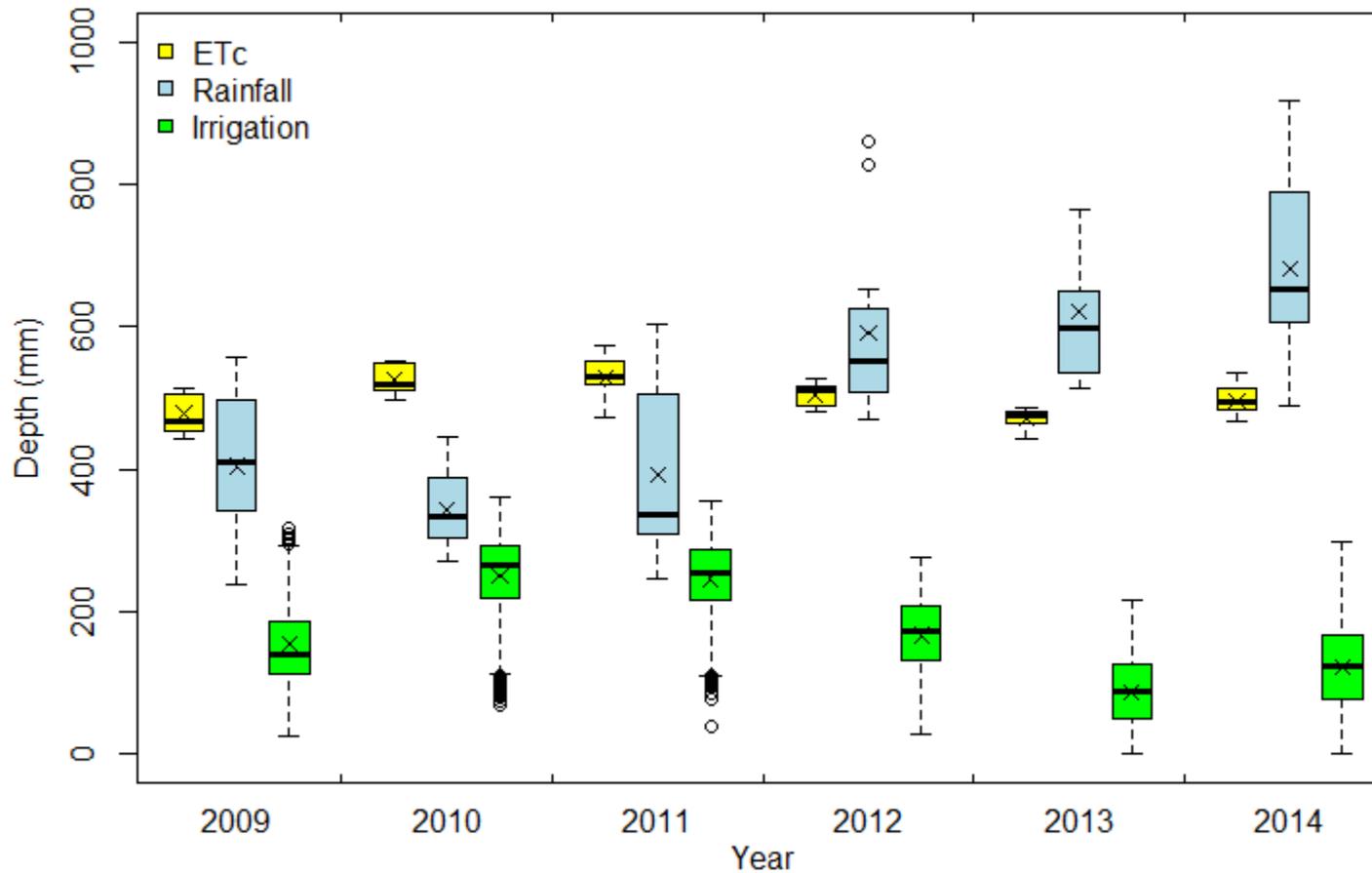


Figure 5.4. Seasonal ET_c, rainfall, and irrigation recommended by the IDSS by year for all 12,150 combinations considered in the sensitivity analysis. Note: × in boxplots denotes mean values; points indicate outliers (values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles).

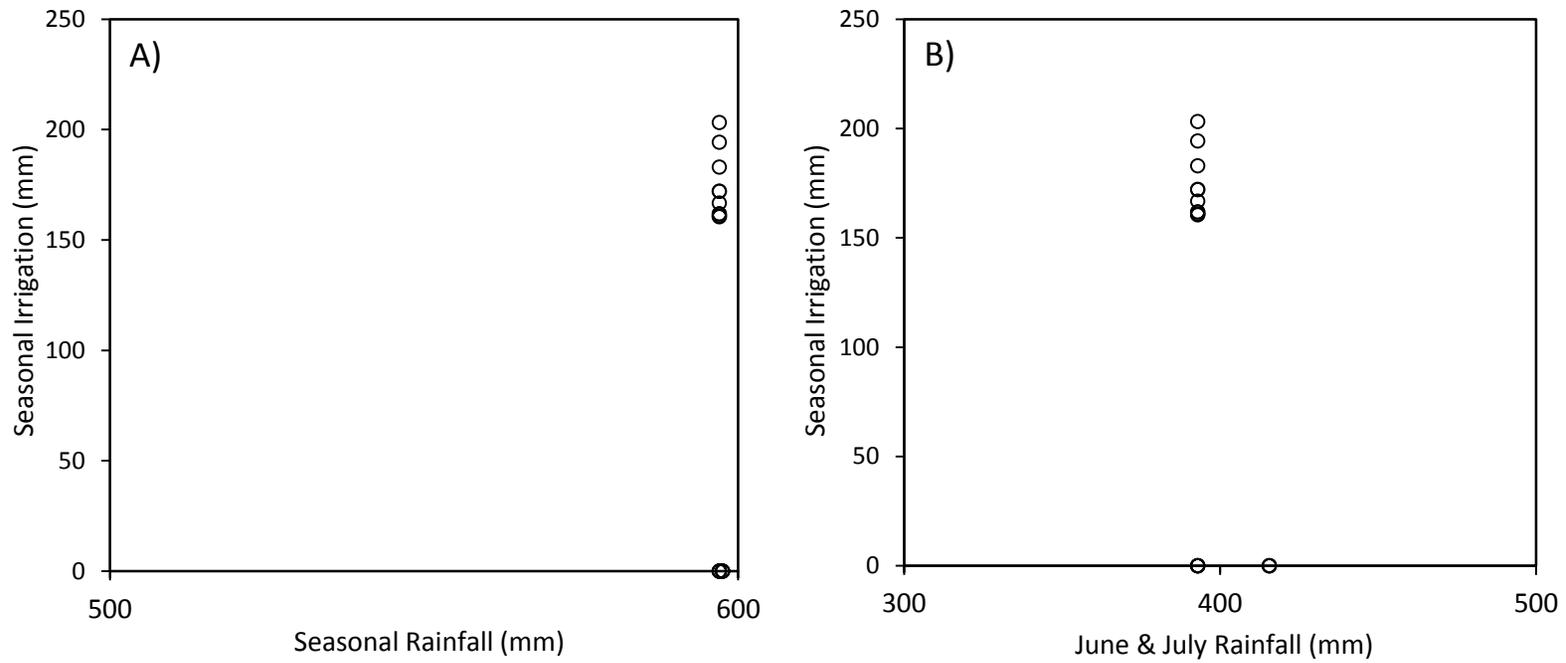


Figure 5.5. A) Seasonal irrigation vs. seasonal rainfall across all seasons simulated for the sensitivity analysis. B) Seasonal irrigation vs. combined rainfall during the months of June and July for all seasons simulated for the sensitivity analysis.

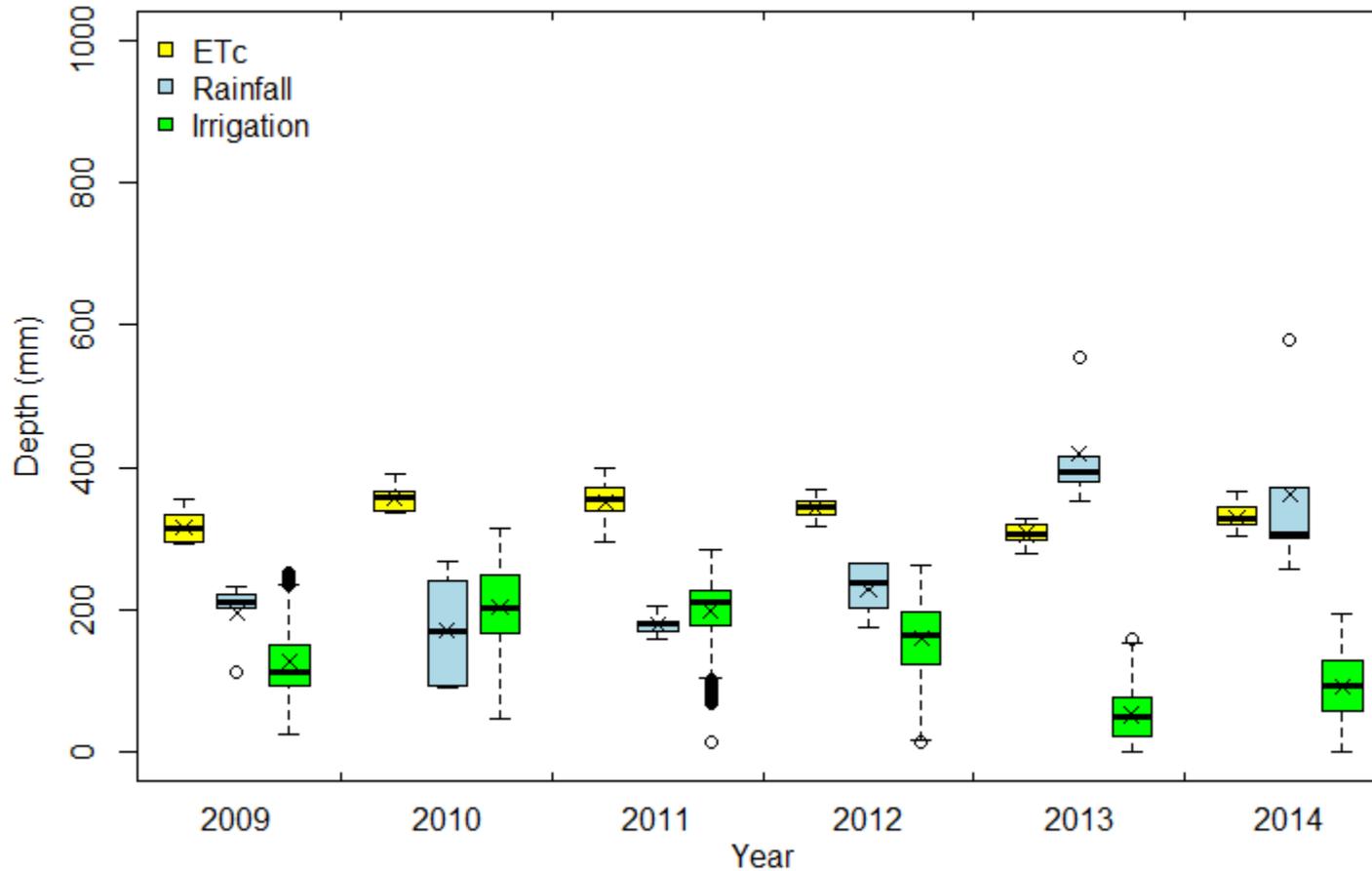


Figure 5.6. ET_c, rainfall, and irrigation recommended by the IDSS during the months of June and July by year for all 12,150 combinations considered in the sensitivity analysis. Note: × in boxplots denotes mean values; points indicate outliers (values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles).

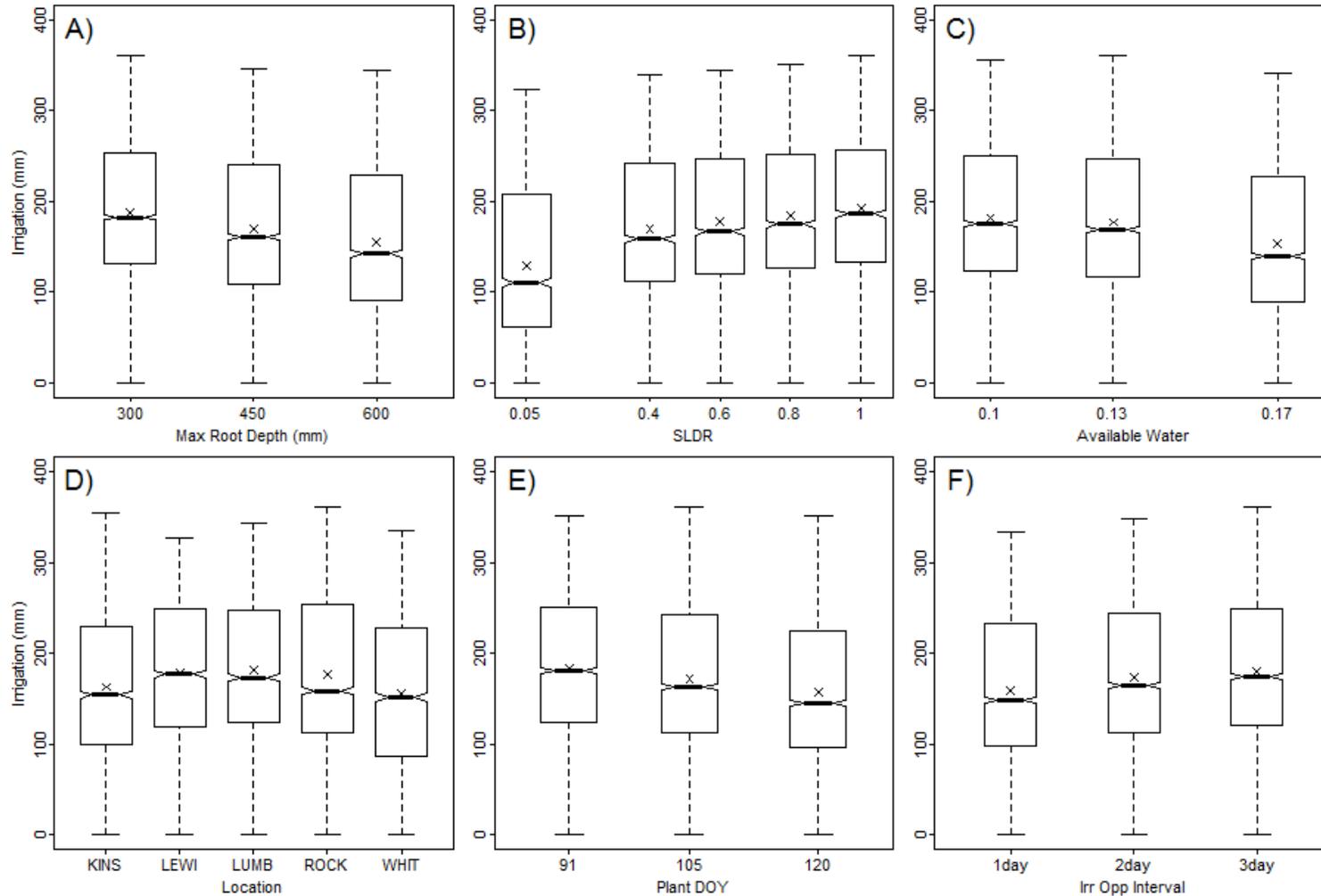


Figure 5.7. Seasonal irrigation by A) RDmax, B) SLDR, C) available water, D) location, E) planting date (DOY), and F) irrigation opportunity interval across all sensitivity analysis combinations. Note: × denotes mean values, cross bars represent median values, and notches represent 95% confidence intervals about median values (Chambers et al., 1983).

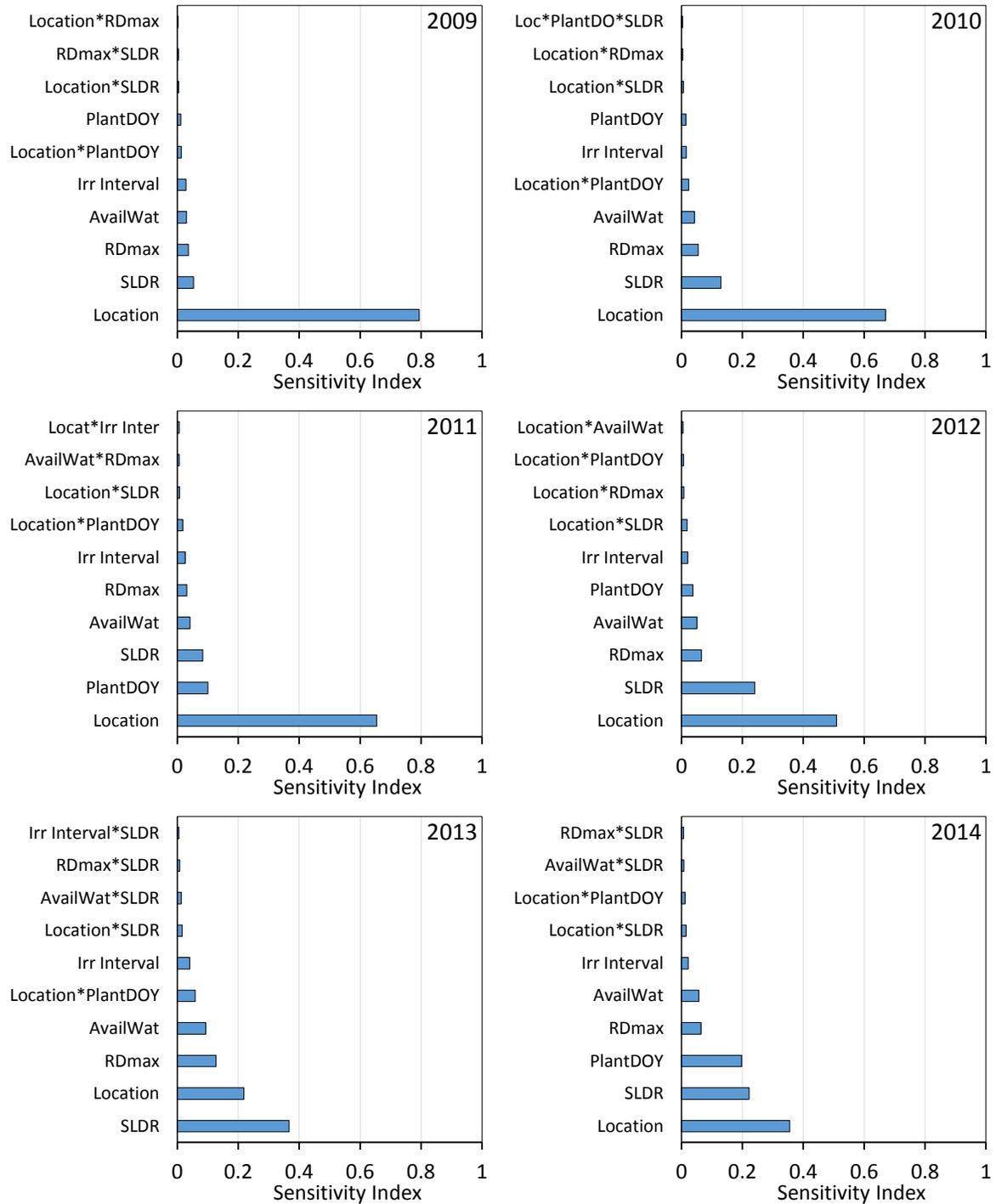


Figure 5.8. ANOVA based main-effect and interaction sensitivity indices for factors considered in the sensitivity analysis within each simulation year. Note: Only the ten largest sensitivity indices are presented for each year.

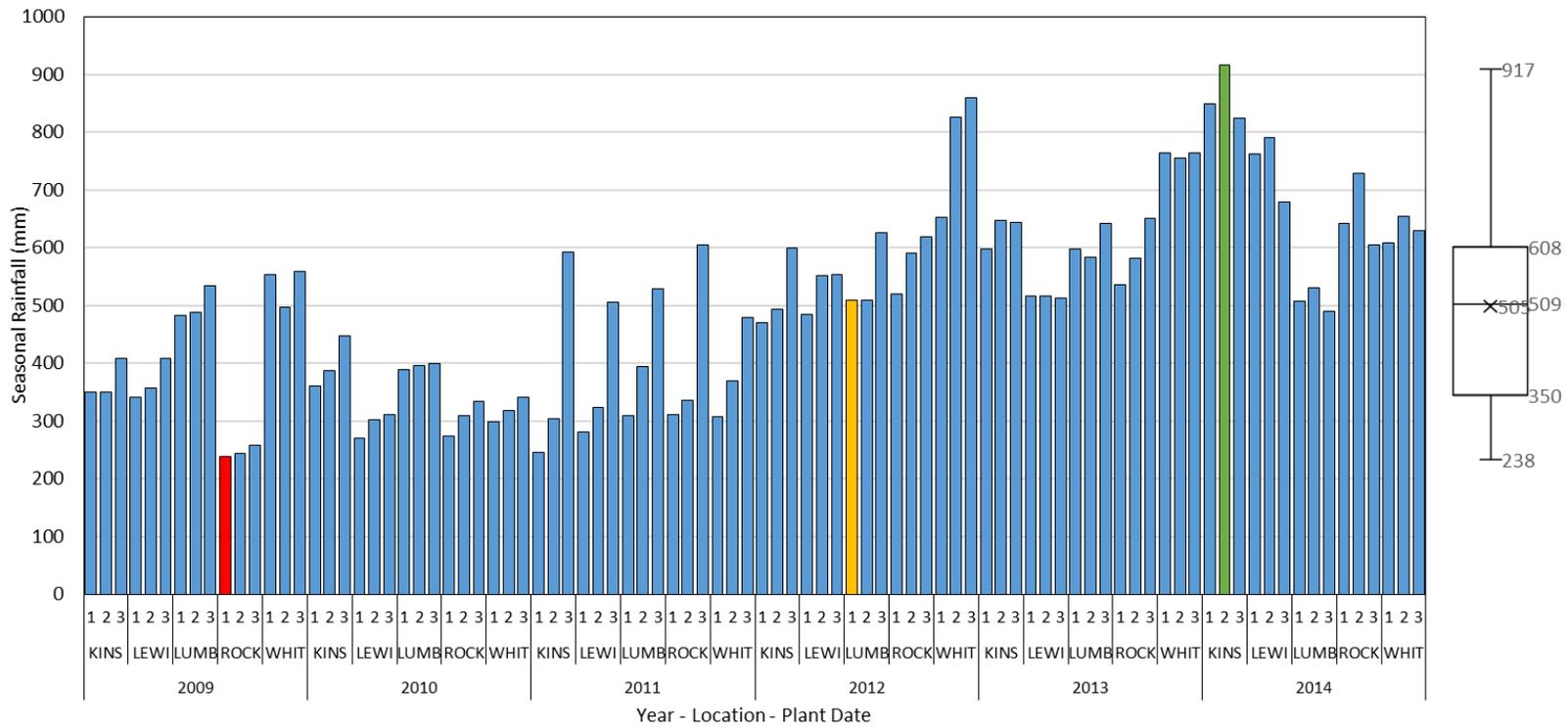


Figure 5.9. Seasonal rainfall for all study years by locations by planting dates used in the sensitivity analysis and the irrigation simulation study. Note: Numbers along x-axis represent planting DOY as follows: 1) 91, 2) 105, and 3) 120; red, yellow, and green indicate minimum, median, and maximum rainfall seasons, respectively.

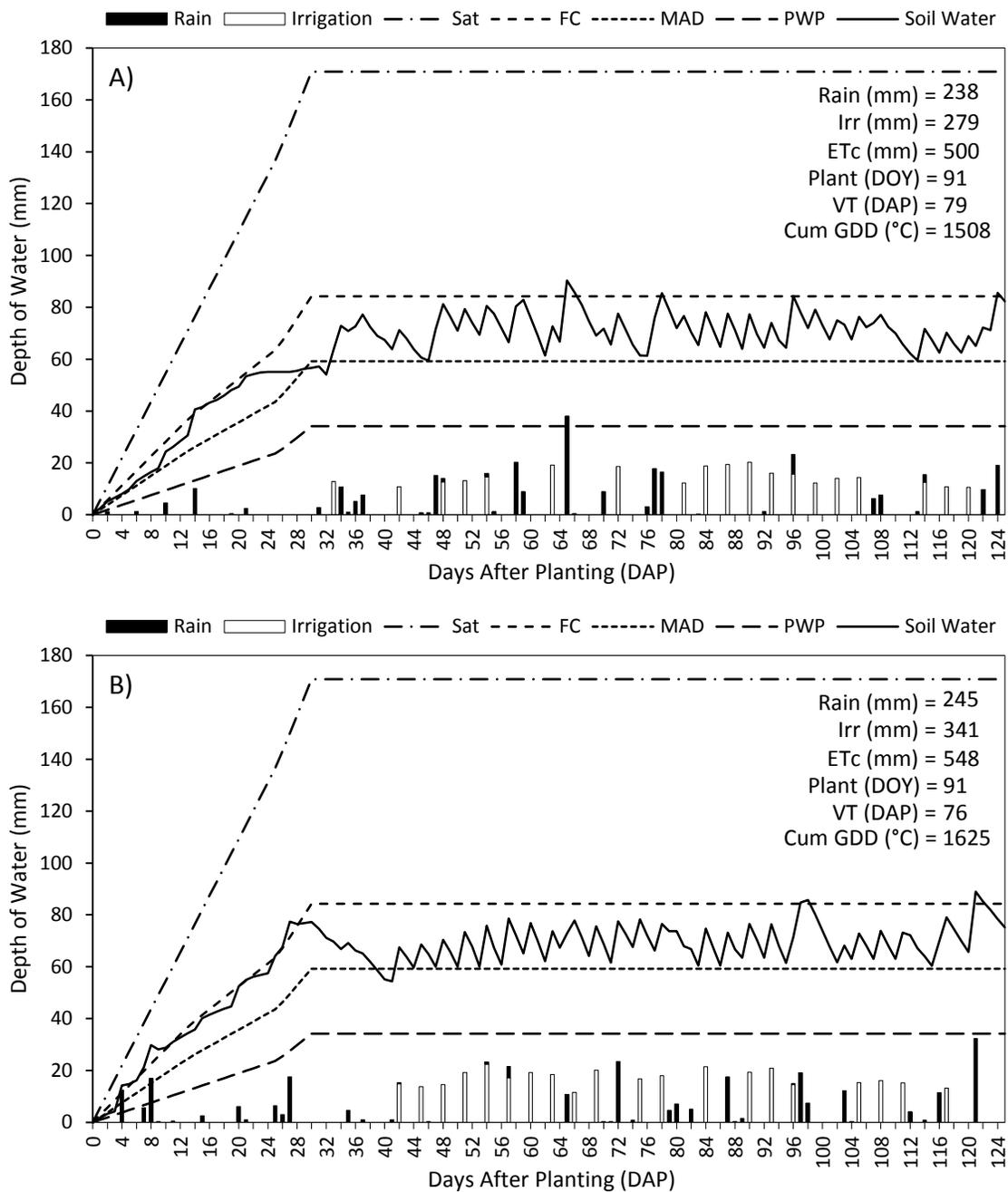


Figure 5.10. Simulated total soil water, rainfall, and irrigation for the A) 2009-ROCK-91 and B) 2011-KINS-91 growing seasons. Note: Scenario based on RDmax = 450 mm, SLDR = 0.60, soil available water = 0.13 mm³ mm⁻³, and irrigation opportunity interval = 3 days.

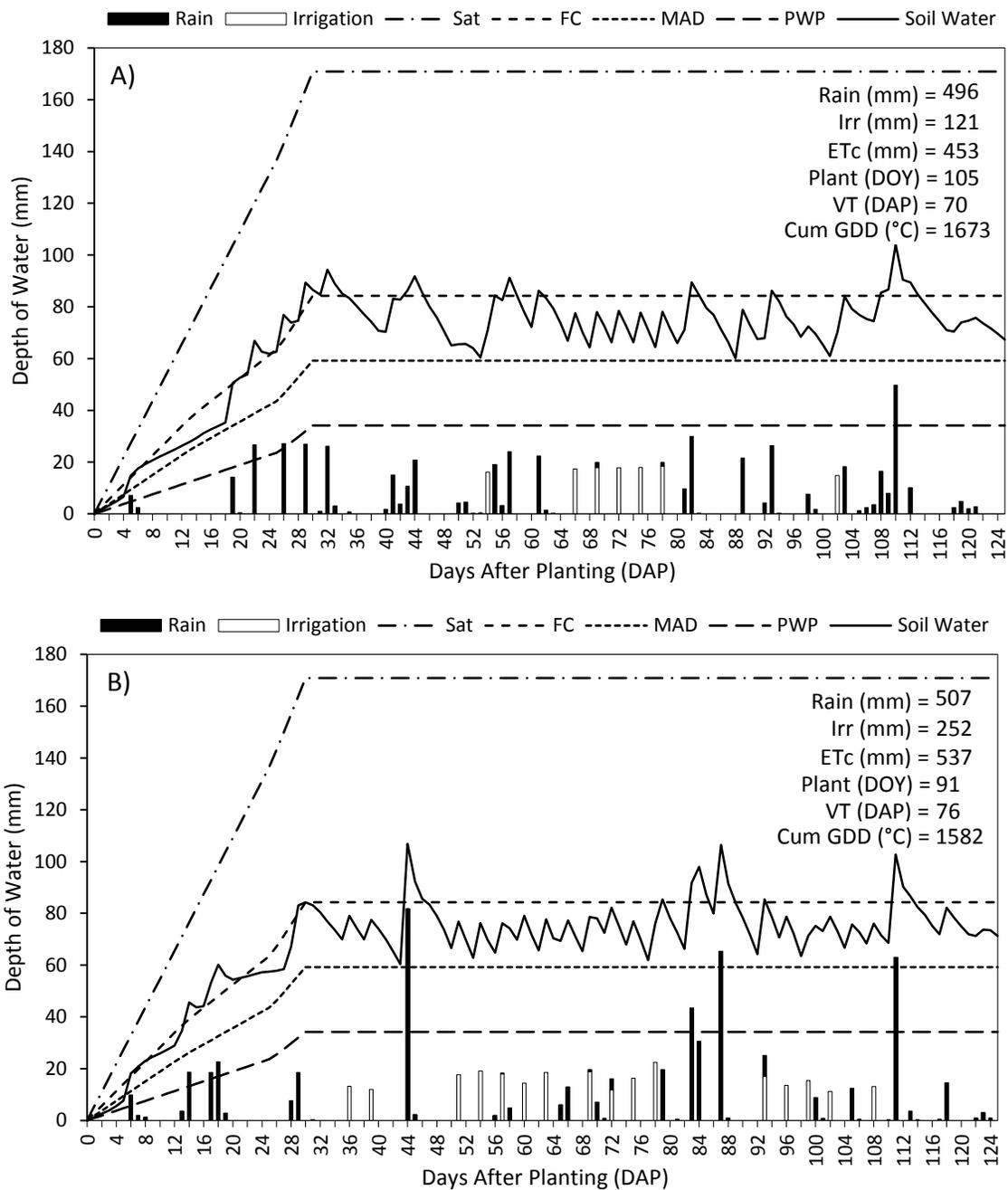


Figure 5.11. Simulated total soil water, rainfall, and irrigation for the A) 2009-WHIT-105 and B) 2014-LUMB-91 growing seasons. Note: Scenario based on RDmax = 450 mm, SLDR = 0.60, soil available water = 0.13 mm³ mm⁻³, and irrigation opportunity interval = 3 days.

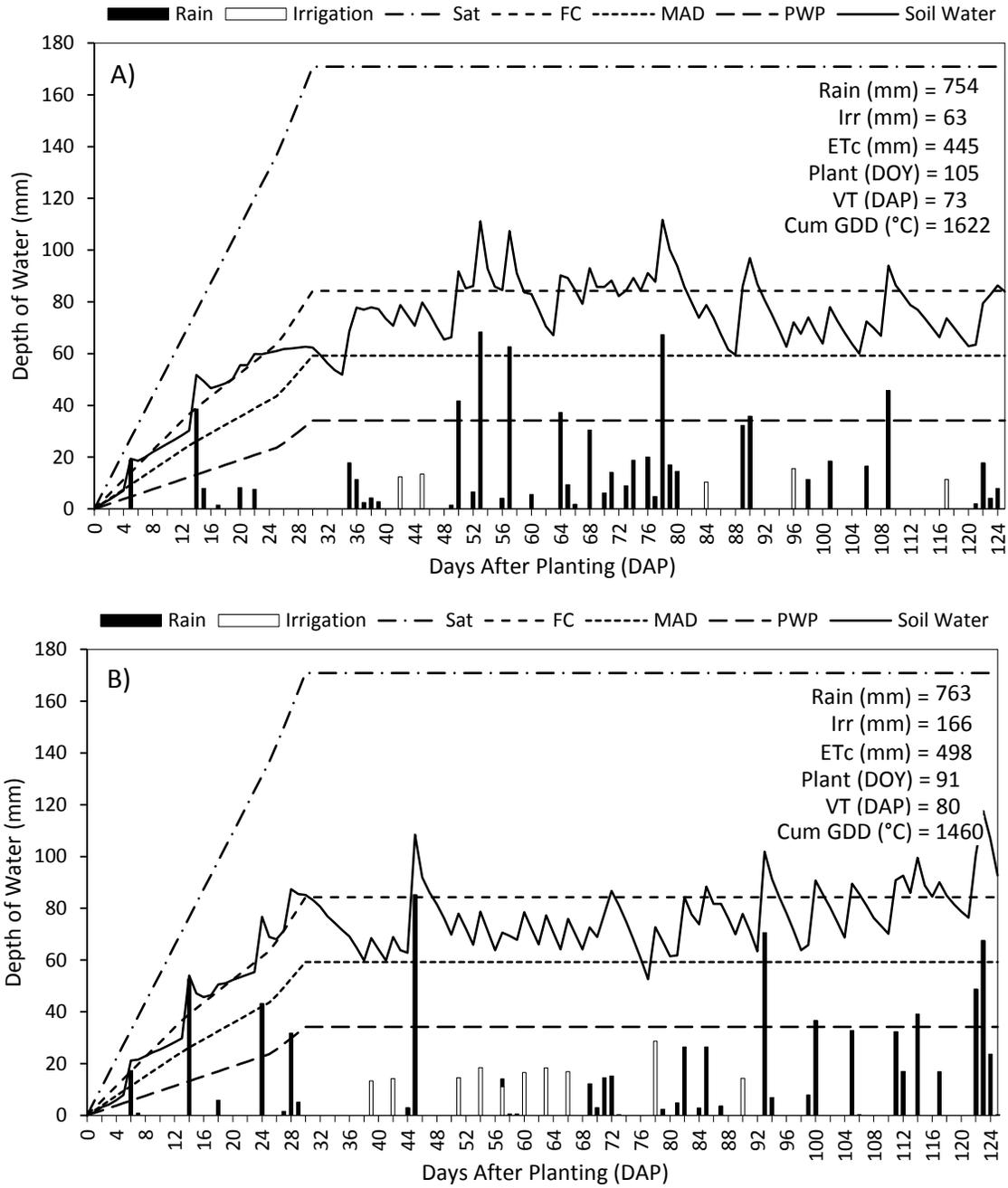


Figure 5.12. Simulated total soil water, rainfall, and irrigation for the A) 2013-WHIT-105 and B) 2014-LEWI-GOLS growing seasons. Note: Scenario based on RDmax = 450 mm, SLDR = 0.60, soil available water = 0.13 mm³ mm⁻³, and irrigation opportunity interval = 3 days.

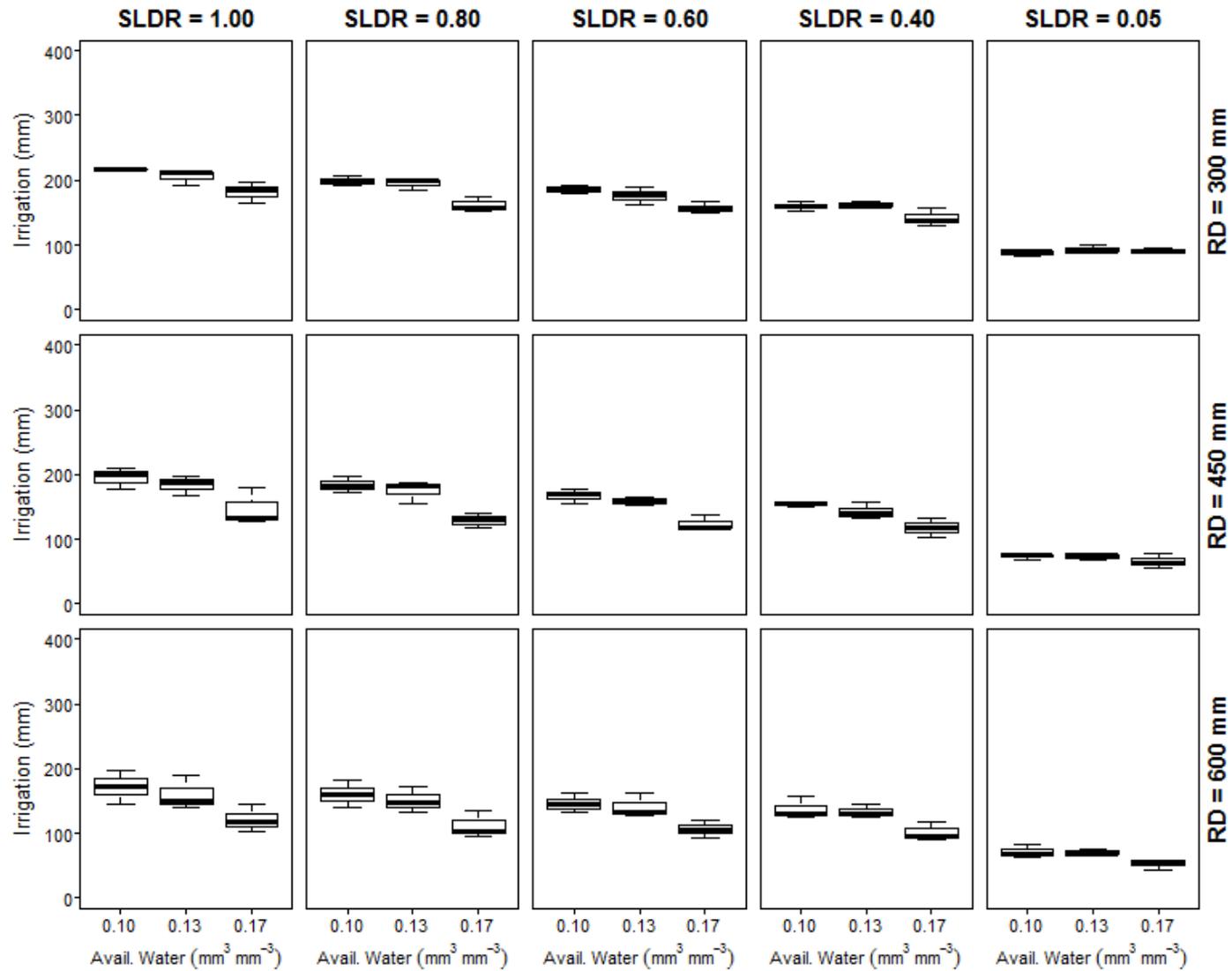


Figure 5.13. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2014-LEWI-91 growing season.

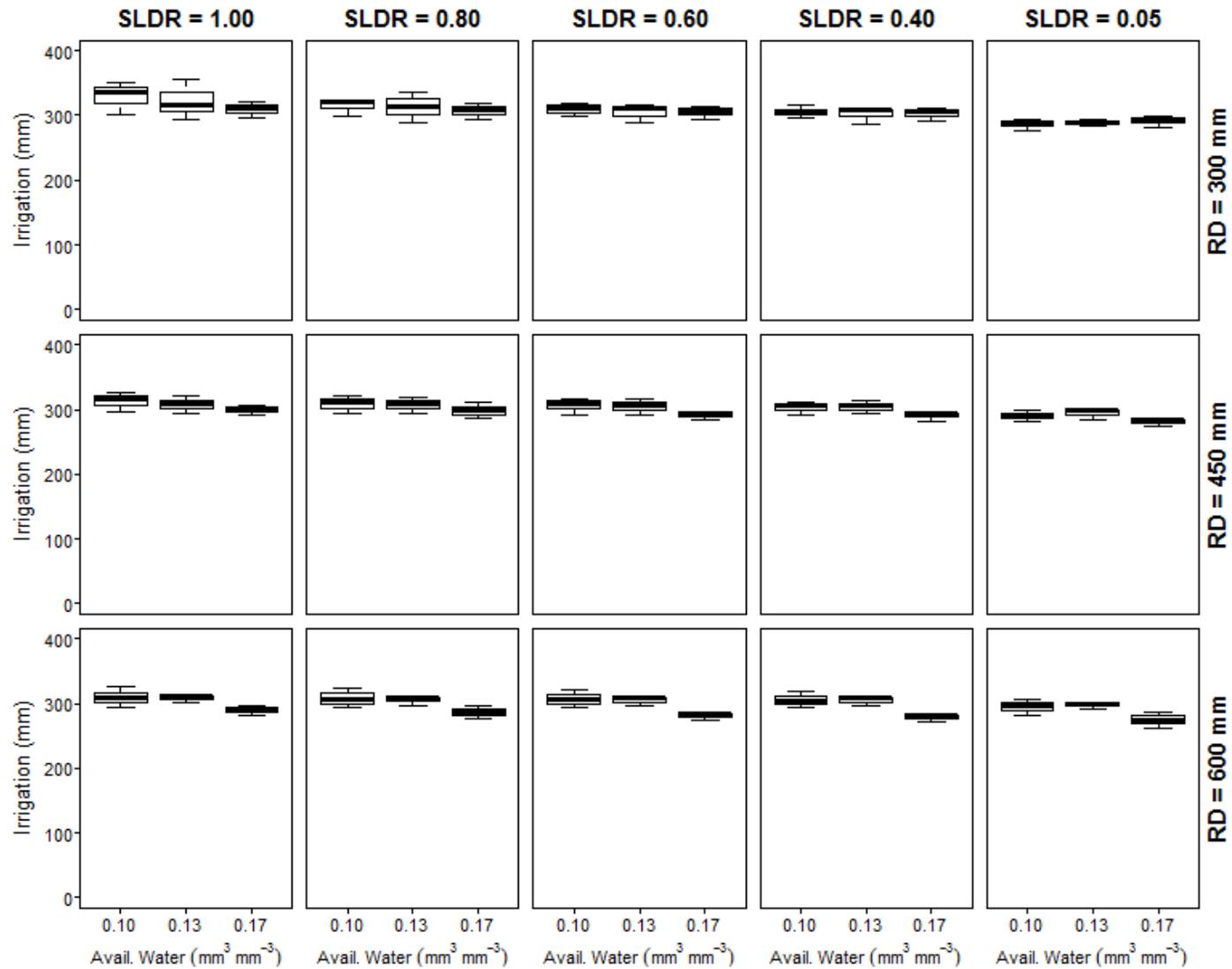


Figure 5.14. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2011-KINS-105 growing season.

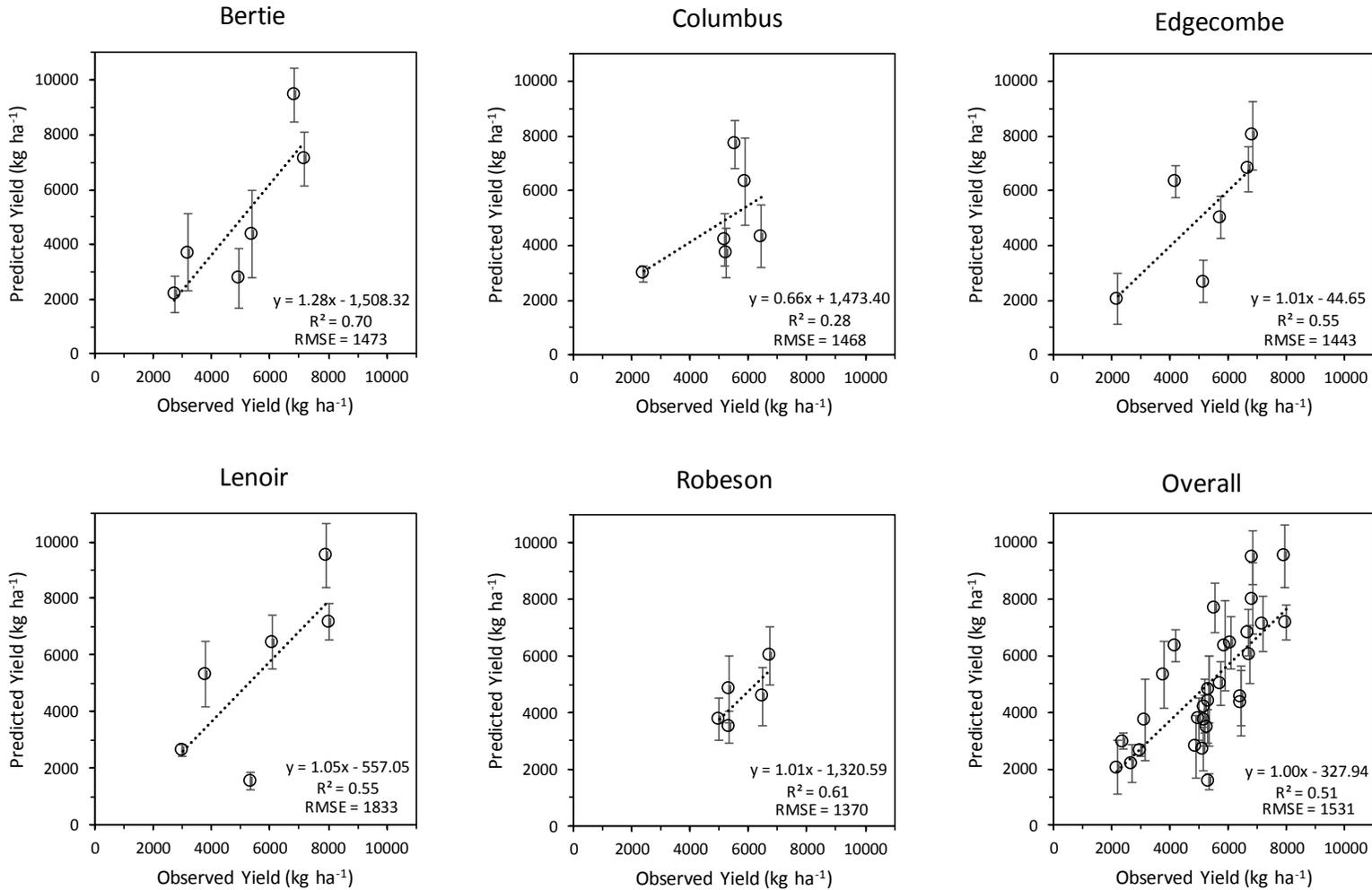


Figure 5.15. Predicted non-irrigated corn yield with SLPF = 0.65 vs. average observed county yields from 2009 to 2014 in Bertie (LEWI), Columbus (WHIT), Edgecombe (ROCK), Lenoir (KINS), and Robeson (LUMB) counties. Note: Error bars represent plus or minus one standard deviation.

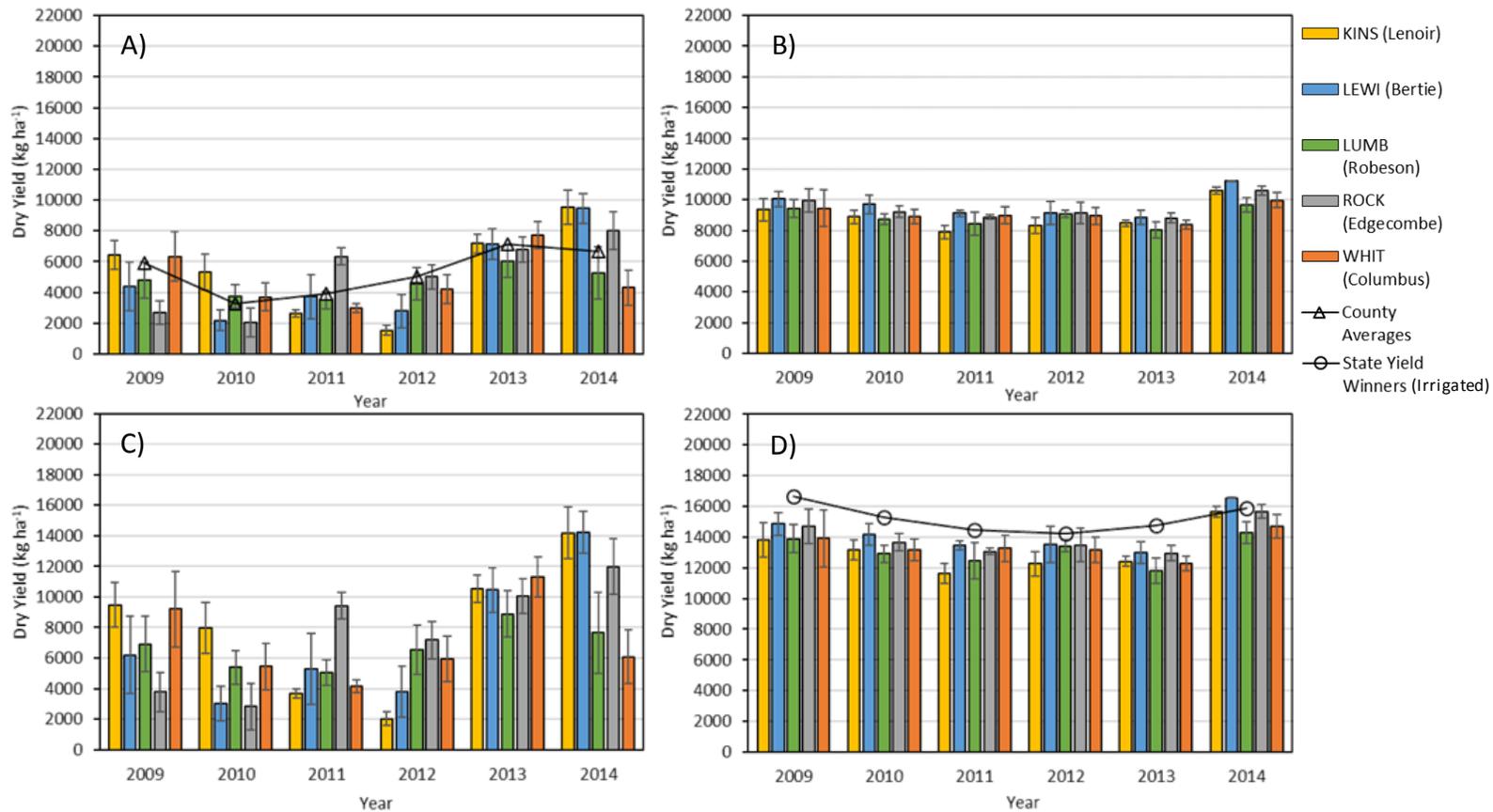


Figure 5.16. DSSAT predicted corn yields for each simulation location assuming: A) no irrigation, SLPF = 0.65; B) no water stress, SLPF = 0.65; C) no irrigation, SLPF = 1.00; and D) no water stress, SLPF = 1.00. Points in plots A and B represent average reported yields across all simulation counties (USDA-NASS, 2016) and statewide, irrigated yield (Heiniger and Boerema, 2014).

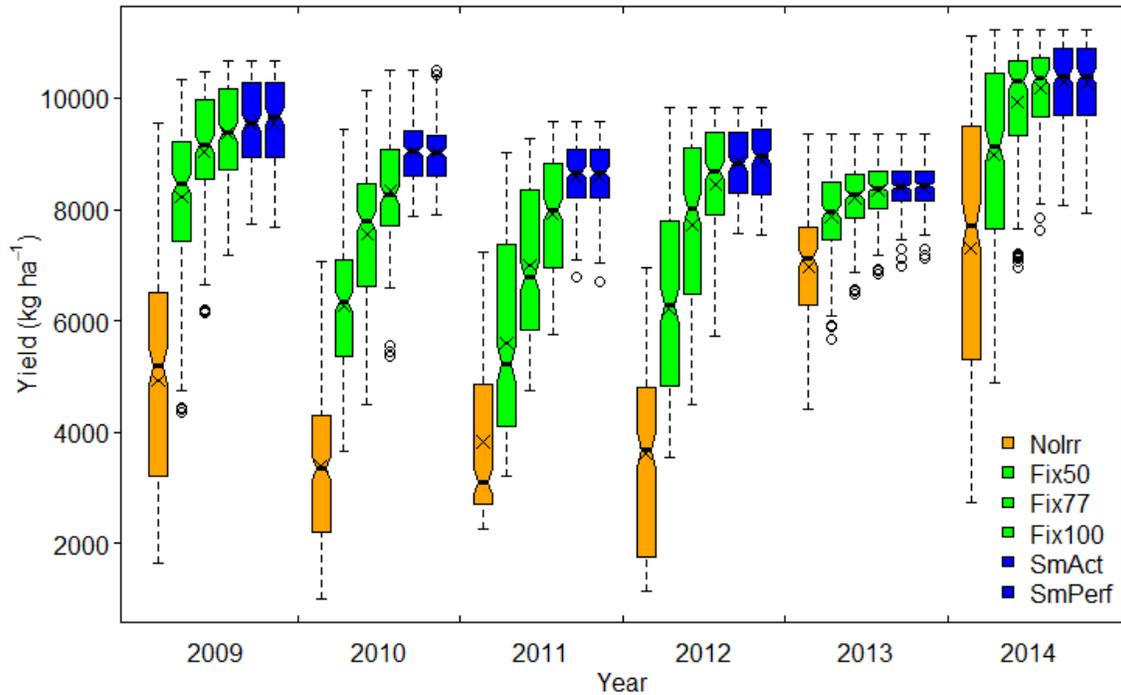


Figure 5.17. DSSAT simulated seasonal yields by irrigation treatment and year across all locations, planting dates, soil types, and maximum effective maximum rooting depths based on limited fertility levels (SLPF = 0.65) calibrated to represent typical North Carolina soils under current management practices. Note: Dots represent outliers (values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles); cross bars within boxes represent median values; Xs represent mean values; notches represent 95% confidence intervals about median values (Chambers et al., 1983).

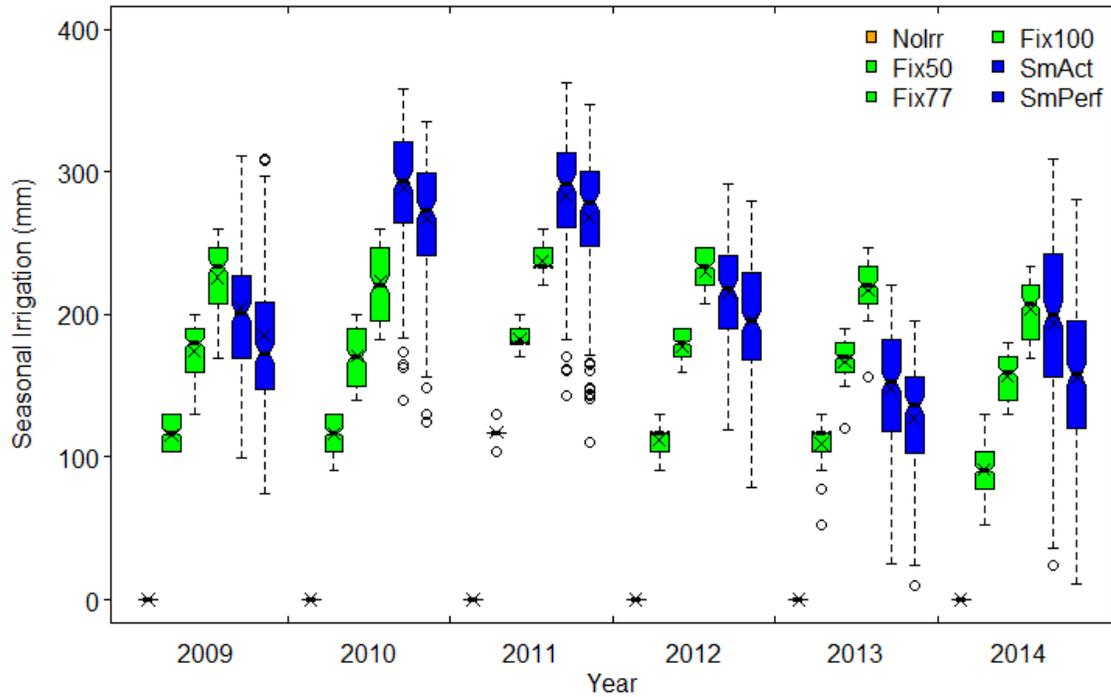


Figure 5.18. Simulated seasonal irrigation by irrigation treatment and year across all locations, planting dates, soil types, and maximum effective maximum rooting depths. Note: * represents NoIrr treatment which applied no irrigation across all factors; dots represent outliers (values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles); cross bars within boxes represent median values; Xs represent mean values; notches represent 95% confidence intervals about median values (Chambers et al., 1983).

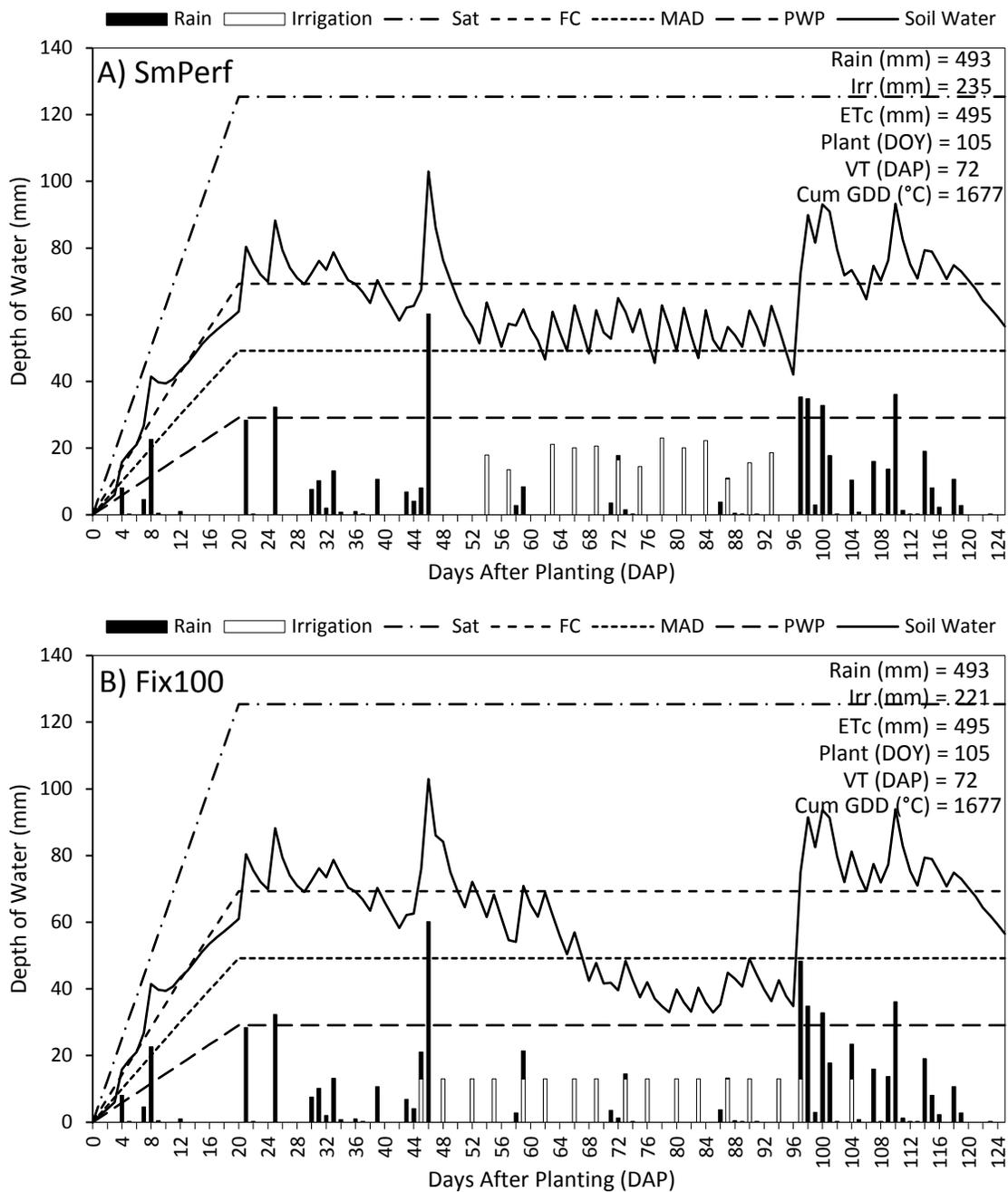


Figure 5.19. Simulated total soil water, rainfall, and irrigation from 2012-KINS-105 on RAFS (RDmax = 300; SLDR = 0.4) for A) SmPerf and B) Fix100. Note: Under irrigation in Fix100 treatment, between 70 (V18) and 97 (R4-Dough) DAP.

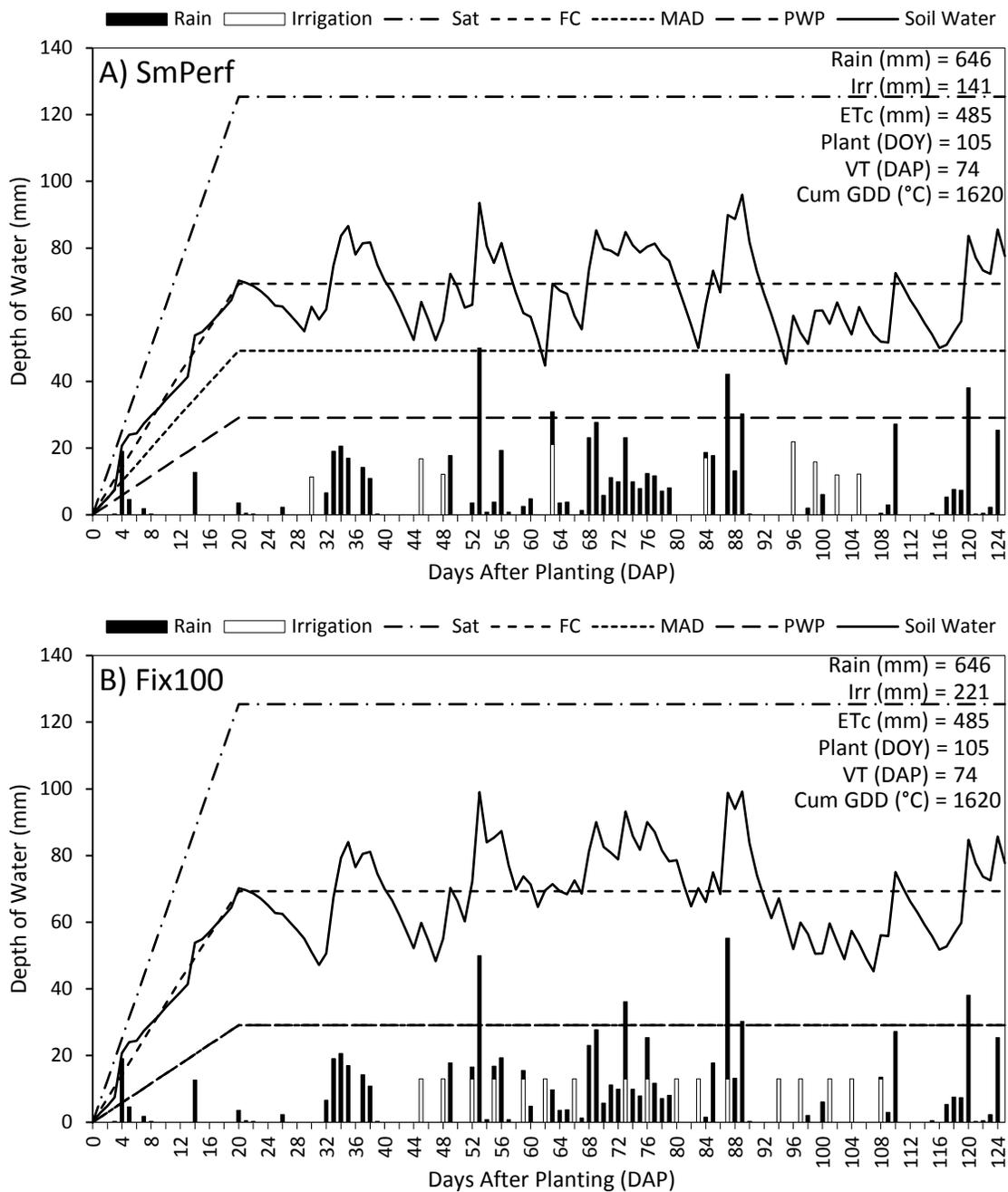


Figure 5.20. Simulated total soil water, rainfall, and irrigation from 2013-KINS-105 on RAFS (RDmax = 300; SLDR = 0.4) for A) SmPerf and B) Fix100. Note: Over-irrigation in Fix100 treatment, between 52 (V9) and 86 (R2-Blister) DAP.

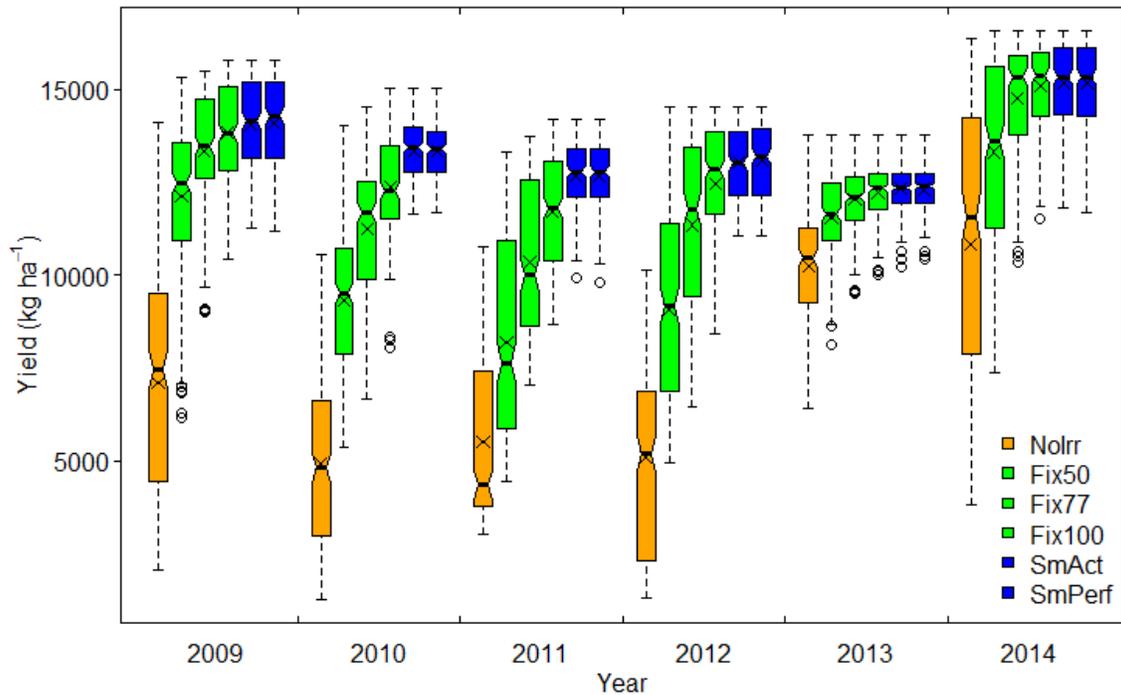


Figure 5.21. DSSAT simulated seasonal yields by irrigation treatment and year across all locations, planting dates, soil types, and maximum effective maximum rooting depths assuming full soil fertility (SLPF = 1.00). Note: Dots represent outliers (values greater than 1.5 interquartile ranges away from the 25th or 75th percentiles); cross bars within boxes represent median values; Xs represent mean values; notches represent 95% confidence intervals about median values (Chambers et al., 1983).

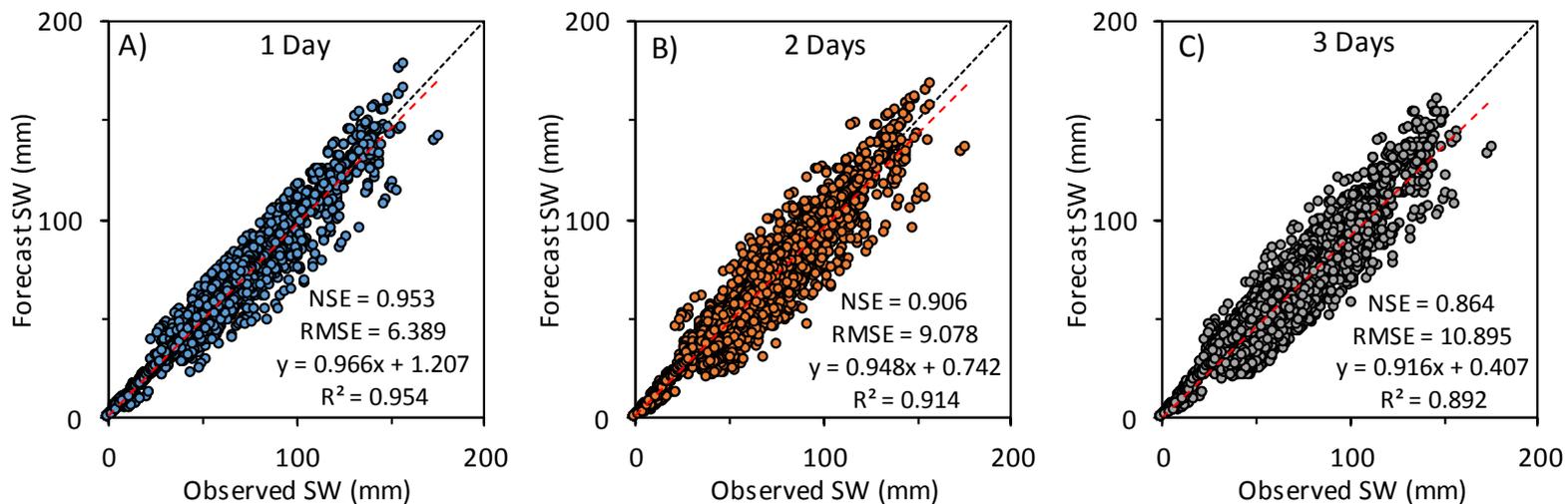


Figure 5.22. IDSS simulated daily root zone soil water contents for the SmAct treatment calculated using observed weather data versus those calculated using forecast weather data from A) 1 day, B) 2 days, and C) 3 days in advance across all simulation years, locations, planting dates, soil types, maximum effective root depths (RDmaxs), and soil drainage rates (SLDRs). Abbreviations: NSE = Nash-Sutcliffe Efficiency, RMSE = Root Mean Square Error

APPENDICES

APPENDIX A – IRRIGATION TREATMENT LAYOUT, DRIP IRRIGATION CONFIGURATION, AND SENSOR PLACEMENT FOR 2013 SWEETPOTATO STUDY

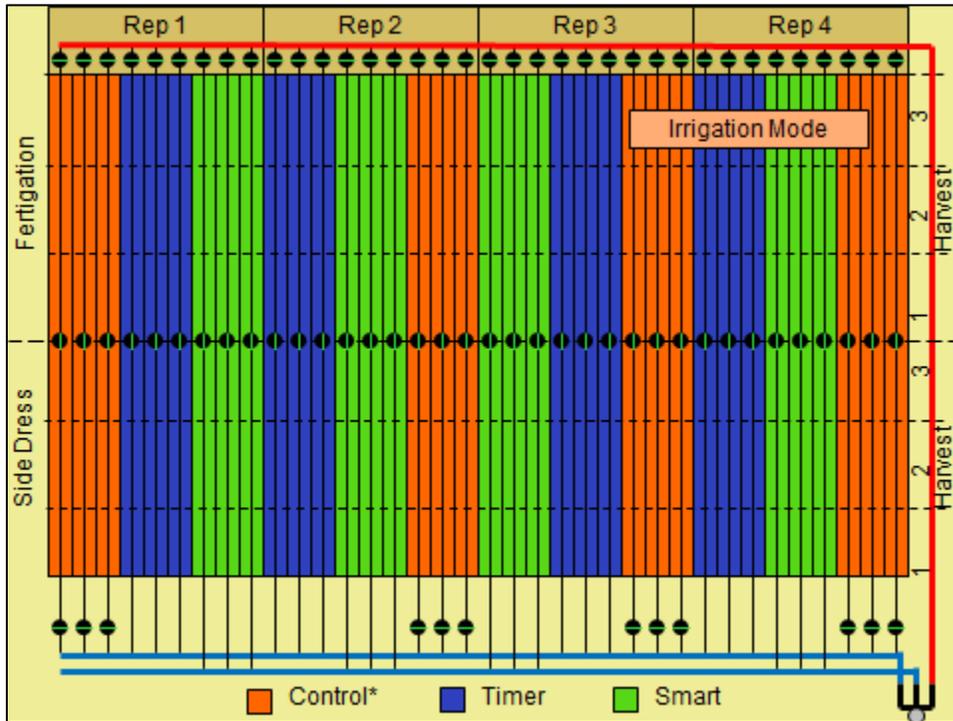


Figure A.1. Plot layout and drip irrigation configuration during normal operation (Irrigation Mode).

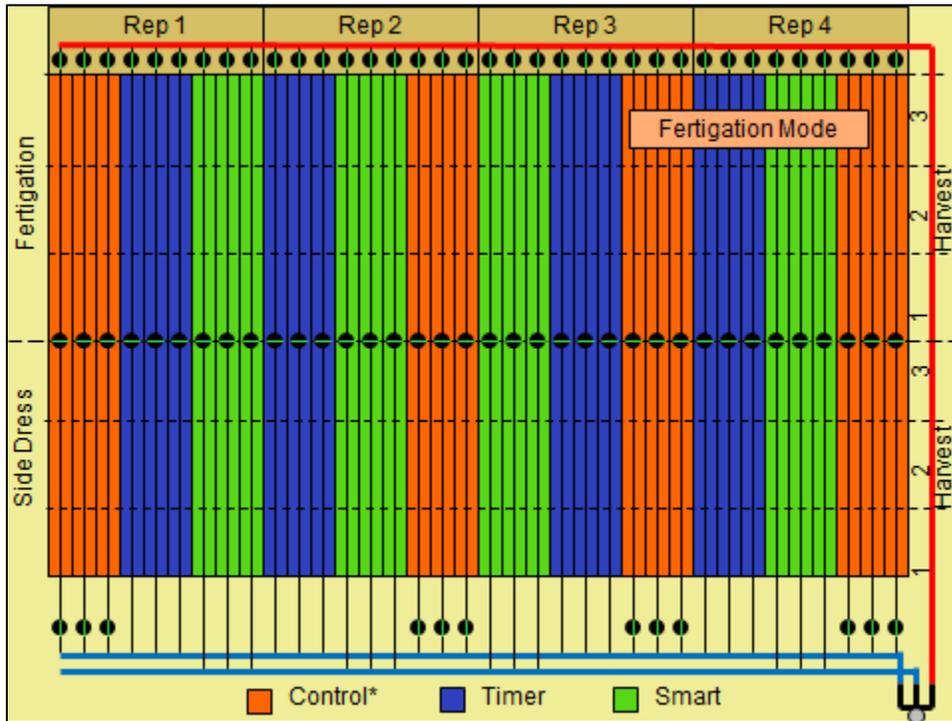


Figure A.2. Plot layout and drip irrigation configuration during fertigation events (Fertigation Mode).

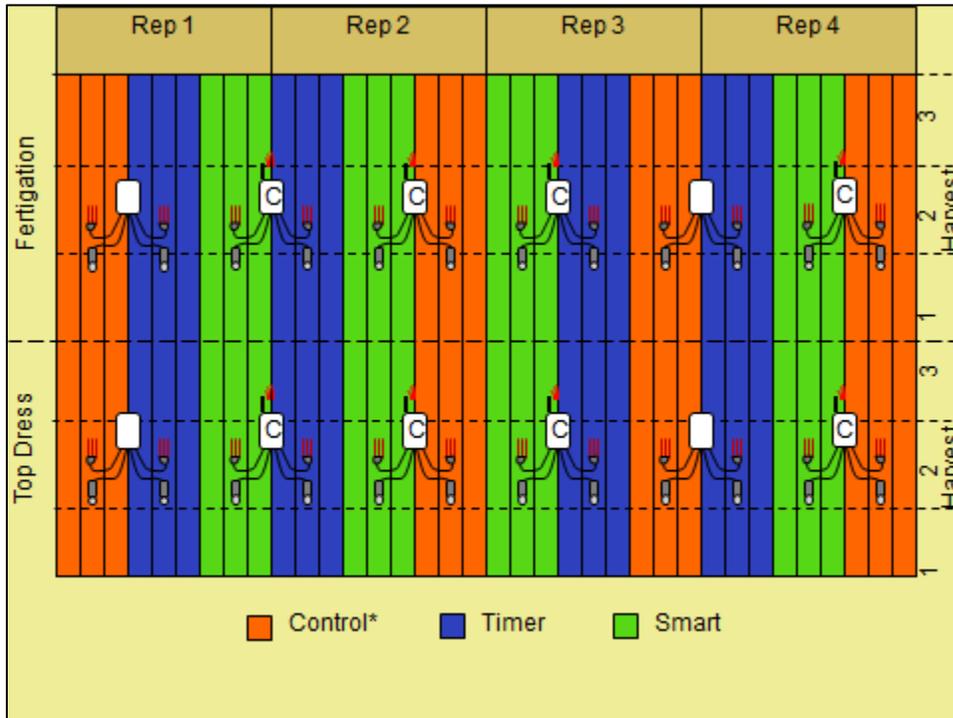


Figure A.3. Treatment layout and sensor placement for 2013.

APPENDIX B – SWEETPOTATO CROP AND IRRIGATION MANAGEMENT RECORDS FOR 2013 AND 2014

2013

Soil:

May 10 – 8 soil cores collected (top of ring @ 6 in.)

Crop:

June 10 – Warhawk (same as Lorsban) applied @ 4 pt/acre

Command applied @ 1.75 pt/acre

Valor applied @ 2.5 oz/acre

- 1) Applied Herbicide
- 2) Cultivated Twice
- 3) Formed Bed
- 4) Spray Valor on Top of Bed

Warhawk: Chlorpyrifos (44.9% AI)

O,O-Diethyl O-(3,5,6-trichloro-2-pyridyl) phosphorothioate

Command: Clomazone (31.1% AI) 2-(2-Chlorophenyl)methyl-4, 4-dimethyl-3-isoxazolidinone)

Valor: Flumioxazin (51% AI)

2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4- benzoxazin-6-yl]- 4,5,6,7-tetrahydro-1H-isoindole- 1,3(2H)-dione

June 12 – Planted G2s from Vick Family Farms

July 8 – Plowed and applied 400 lb/acre of 0 – 15 – 38 (to all)

Aug 23 – Poast applied @ 1.5 pt/ac + 1 qt crop oil/acre to control annual and perennial grasses (not broadleaf or sedge)

Irrigation:

June 13, 17, 18 – Finished installing drip tape, lay flat, valves, sensors, etc.

July 8 – changed rain switch setting from 0.5” to 0.25”

July 8 – I saw timer treatment running... believe I turned it off after a few minutes (presumably wet)

July 11 – Charles turned controller OFF after 3:25 pm (Timer may have been running based on time)

Fertilizer:

Top Dress

July 8 – Plowed and applied 400 lb/acre of 0 – 15 – 38 (to all plots)

July 10 – 105 lb/acre of N (34-0-0)

Fertigated (I think each ran for 1 hr 36 min total unless noted otherwise; lesser minutes equal fert time)

July 16 - First fertigation event (~40 min; 1.4 gal of 19-0-0; 10 lb N/ac)
July 22 - Second fertigation event (~38 min; 2.1 gal of 19-0-0; 15 lb N/ac)
July 29 - Third fertigation event (~67; 2.1 gal of 19-0-0; 15 lb N/ac)
 **Lots of issues (see field notes). Some plots got 1 hr 7 min water, some got 1 hr 16 min, some got both (~2.5 hrs). Prob just use 1:36 again here and go with it.
Aug 5 – Fourth fertigation event (2.8 gal of 19-0-0; 20 lb N/ac) - 2 hrs of water
Aug 12 – Fifth fertigation event (2.1 gal of 19-0-0; 15 lb N/ac) – 1:36
Aug 19 – *Skipped fertigation due to Rain*
Aug 26 – Sixth fertigation event (2.1 gal of 19-0-0; 15 lb N/ac) – 1:36
Sep 3 – Seventh (final) fertigation event (2.1 gal of 19-0-0; 15 lb N/ac) **1 hr run time

Soil and Plant Tissue Samples:

July 16 – Collected first soil and plant tissue samples
Aug 12 – second set collected
Sep 11 – took last set

Harvest:

Sep 11 – First Harvest; Oct 2 – Second Harvest; Oct 21 – Last Harvest

2014

Crop:

June 2 - Warhawk (same as Lorsban) applied @ 4 pt/acre
 Command applied @ 1.75 pt/acre
 Valor applied @ 2.5 oz/acre
 1) Applied Herbicide
 2) Cultivated Twice
 3) Formed Bed
 4) Spray Valor on Top of Bed

June 9 – Planted G2s from Vick Family Farms, installed drip tape, sensors & data loggers
June 25 – Plowed and applied 400 lb/acre of 0 – 15 – 38 (to all)

Irrigation:

July 1 – Wired up controller and irrigation system was functional, ready to go for the first time
July 3 – Charles turned controller OFF in anticipation of Hurricane Arthur
July 7 – Irrigation controller back to ON around 5:30 pm (after fertigation and when “timer” irrigation event would have run)
July 21 – I turned controller OFF after fertigation
July 23 – I turned controller back ON

July 29 – Turned controller back to ON
Aug 18 – Turned controller to OFF
Aug 26 – Controller was in ON position when I arrived

Fertilizer:

Top Dress

July 1 – Applied 105 lb N/ac via 34-0-0 @ 309 lb/ac

Fertigated

*times for 2014 were shorter than 2013; only ran long enough to apply fertilizer

July 7 – First fertigation event (~35 min starting @ 4:15 pm; 1.4 gal of 19-0-0; 10 lb N/ac)

July 14 – Second fertigation (~50 min; Charles ran; 2.1 gal of 19-0-0; 15 lb N/ac)

July 21 – Third fertigation (~30 min run time; 2.1 gal of 19-0-0; “5 inches”; 15 lb N/ac)

July 29 – Fourth fertigation (~30 min run time; 2.8 gal of 19-0-0; 20 lb N/ac)

Aug 5 – Skipped fertigation opp due to wet conditions

Aug 12 – Fifth fertigation (~30 min; 2.1 gal of 19-0-0; 15 lb N/ac)

Aug 18 – Sixth fertigation (~35 min; 2.1 gal of 19-0-0; 15 lb N/ac)

Aug 26 – Seventh and final fertigation (~50 min; 2.1 gal of 19-0-0; 15 lb N/ac)

Soil and Plant Tissue Samples:

July 1 – First set of samples collected

July 21 – Second set of samples collected

Aug 18 – Third set of samples collected

Sep 10 – Fourth/Final set of samples collected

Harvest:

Sep 10 – First Harvest; Sep 29 – Second Harvest; Oct 20 – Last Harvest

APPENDIX C – SAMPLE INPUT FILES FOR IDSS SIMULATIONS

Weather Forecasts File:

Note: Each file contains daily values for one year and one location

```
KINS,35.30288,-77.57306,,,,,,,,,,,,,
Year,DOY,Tmax_0,Tmin_0,ETo_0,POP_0,QOP_0,Tmax_1,Tmin_1,ETo_1,POP_1,QOP_1,Tmax_2,Tm
in_2,ETo_2,POP_2,QOP_2
2009,1,278.7,269.3,1.56,0,0,284.3,272,1.75,7,0,283.1,274.8,1.03,37,0.51
2009,2,284.8,270.4,1.44,0,0.25,286.5,276.5,1.24,26,0.51,287.6,277,1.31,14,0.59
2009,3,286.5,275.4,1.12,8,0,290.4,279.3,1.19,14,0.51,289.8,284.8,1.36,40,0.75
2009,4,287,279.3,0.98,28,3.22,290.9,282.6,1.33,57,3.39,288.1,279.3,1.57,60,7.87
2009,5,290.9,282.6,1.07,14,0,288.1,282.6,1.18,80,11.94,289.8,285.9,1.48,80,1.78
2009,6,289.8,285.9,1.06,80,13.8,292,287,2.02,80,8.89,286.5,279.3,2.52,68,2.03
2009,7,292,288.7,1.98,14,7.87,285.9,279.3,2.41,74,5.33,282.6,271.5,1.63,14,0
2009,8,283.7,278.7,2.31,20,0.25,282.6,272.6,1.71,23,0,288.1,274.8,2.2,13,0
2009,9,281.5,272.1,1.79,5,0,288.7,274.3,2.15,13,0,283.7,279.3,1.15,50,8.89
2009,10,289.3,273.7,1.81,5,0,286.5,283.1,1.98,60,10.16,282.6,273.7,1.13,18,0
2009,11,287,285.4,2.08,79,5.33,282,275.4,1.28,53,0,283.7,274.8,1.43,12,0.13
2009,12,282.6,274.3,1.53,14,0,283.7,272.6,1.2,13,0.76,279.3,271.5,1.61,24,0.76
2009,13,280.4,273.7,0.9,23,6.6,278.7,272,1.25,75,4.32,281.5,272.6,1.66,10,0
2009,14,278.1,272,1.36,28,0.25,279.3,272,1.78,10,0,273.1,266.5,1.5,14,0
2009,15,278.7,272.6,1.75,0,0,273.1,265.9,1.46,0,0,275.9,263.1,0.95,5,0
2009,16,272,265.9,1.46,0,0,273.7,262,0.88,3,0,280.9,268.1,1.5,3,0
2009,17,273.7,263.1,0.86,0,0,280.4,269.3,1.48,0,0,278.7,272.6,1.02,35,0.25
2009,18,280.4,269.3,1.25,0,0,278.7,273.1,1.09,55,5.08,277.6,271.5,1.41,11,0
2009,19,280.4,273.7,0.96,52,0.76,276.5,271.5,1.26,25,0.4,277.6,268.1,1.4,25,0.11
2009,20,274.8,271.5,0.69,90,10.27,274.8,267,1.19,90,3.64,282,268.7,1.6,7,0
... (lines removed for brevity)
2009,365,284.8,276.5,0.92,99,9.9,283.1,279.8,0.94,52,2.28,276.5,272,1.47,31,0
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Observed Weather File:

Note: Each file contains daily values for one year and one location

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KINS,35.303,-77.573,,,
Year,DOY,Tmax,Tmin,Rainfall,ETo
2009,1,3.7,-4.5,0,1.04
2009,2,13.6,-4.7,0.3,0.95
2009,3,14.8,0.3,0,0.72
2009,4,13.3,3.7,2,0.47
2009,5,17.6,11.8,0.3,0.67
2009,6,17.1,10.5,23.9,0.36
2009,7,21.7,8.5,2,3.21
2009,8,12.1,3.8,0,1.99
2009,9,9.1,-1.4,0,1.07
2009,10,17.5,-0.4,0,1.87
2009,11,15.6,7.4,4.8,1.1
2009,12,8.1,0.6,0,1.03
2009,13,5.1,0.7,10.4,0.23
2009,14,5.8,-1,0.3,0.96
2009,15,8.5,-2.9,0,1.54
2009,16,-2.7,-7.4,0,1.24
2009,17,1.2,-10.9,0,1.02
2009,18,5.8,-1.1,9.4,0.6
2009,19,10.8,1,0.3,0.78
2009,20,5.5,-6.6,0.5,0.41
... (lines removed for brevity)
2009,365,10,2.2,18.8,0.42
```

APPENDIX D – SOIL FILES USED IN DSSAT SIMULATIONS FOR EACH ROOT DEPTH AND FERTILITY LEVEL COMBINATION

 !# Rmax = 30 cm SLPF = 0.65 # #####
 #####

!RAFS (Orig. SLDL, SLRO, and SLPF: 1.00, 83, 0.56)
 *NCBE160004 NRCS SALO 135. Rains fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 BE-Bertie C NC Location 35.640 -77.398 fine-loamy, siliceous, semiactive, thermic Typic P
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.40 83. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99 -99
 10. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99 -99
 18. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.7 -99 -99 -99
 30. -99 0.097 0.222 0.418 1.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99 -99
 45. -99 0.097 0.222 0.418 0.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99 -99
 50. -99 0.126 0.281 0.447 0.000 0.786 1.47 0.75 19.0 15.0 -99 -99 5.0 -99 -99 -99
 65. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 5.0 -99 -99 -99
 75. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99 -99
 95. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99 -99
 110. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99 -99
 125. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99 -99
 135. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.7 -99 -99 -99

!GOLS (Orig. SLDL, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160002 NRCS LOSA 165. Goldsboro loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 10. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 20. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 30. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 38. -99 0.063 0.148 0.364 0.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 45. -99 0.063 0.148 0.364 0.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 60. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 75. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 90. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 114. -99 0.146 0.286 0.465 0.000 0.460 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 135. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99 -99
 150. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99 -99
 165. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99 -99

!GOSL (Orig. SLDL, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160001 NRCS SALO 165. Goldsboro sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99 -99
 10. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99 -99
 18. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99 -99
 30. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99 -99
 33. -99 0.088 0.173 0.409 0.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99 -99
 45. -99 0.088 0.173 0.409 0.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 65. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 80. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 102. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99 -99
 120. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99 -99
 135. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99 -99
 150. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99 -99
 165. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99 -99

!NOLS (Orig. SLDL, SLRO, and SLPF: 0.6, 76, 1.00)
 *NCRO160005 NRCS LOSA 178. Norfolk loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, kaolinitic, thermic Typic Kandiodults
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 76. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 10. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 23. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99
 30. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99 -99

36.	-99	0.063	0.148	0.364	0.000	6.360	1.69	1.25	5.0	16.5	-99	-99	-99	-99	-99
45.	-99	0.063	0.148	0.364	0.000	6.360	1.69	1.25	5.0	16.5	-99	-99	-99	-99	-99
50.	-99	0.156	0.296	0.475	0.000	0.385	1.39	-99	26.5	20.0	-99	-99	-99	-99	-99
65.	-99	0.156	0.296	0.475	0.000	0.385	1.39	-99	26.5	20.0	-99	-99	-99	-99	-99
80.	-99	0.156	0.296	0.475	0.000	0.385	1.39	-99	26.5	20.0	-99	-99	-99	-99	-99
97.	-99	0.156	0.296	0.475	0.000	0.390	1.39	-99	26.5	20.0	-99	-99	-99	-99	-99
120.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99
135.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99
150.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99
165.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99
178.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99

!PLFS (Orig. SLDR, SLRO, and SLPF: 0.75, 71, 1.00)
 *NCLE160001 NRCS LOSA 203. Pocalla loamy fine sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 LE-Lenoir C NC Location 35.197 -77.543 loamy, siliceous, subactive, thermic Arenic Plinth

@ SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE						
-99	0.13	3.0	0.80	71.	1.00	0.65	IB001	IB001	IB001						
@ SLB	SLMH	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC SADC
3.	-99	0.072	0.167	0.381	1.000	4.784	1.64	0.50	7.0	12.0	-99	-99	-99	-99	-99
10.	-99	0.072	0.167	0.381	1.000	4.784	1.64	0.50	7.0	12.0	-99	-99	-99	-99	-99
20.	-99	0.072	0.167	0.381	1.000	4.784	1.64	0.50	7.0	12.0	-99	-99	-99	-99	-99
30.	-99	0.072	0.167	0.381	1.000	4.784	1.64	0.50	7.0	12.0	-99	-99	-99	-99	-99
35.	-99	0.072	0.167	0.381	0.000	4.784	1.64	0.50	7.0	12.0	-99	-99	-99	-99	-99
45.	-99	0.072	0.167	0.381	0.000	4.784	1.64	0.50	7.0	12.0	-99	-99	-99	-99	-99
58.	-99	0.072	0.167	0.381	0.000	4.784	1.64	0.50	7.0	12.0	-99	-99	-99	-99	-99
65.	-99	0.121	0.241	0.434	0.000	0.921	1.50	0.50	17.5	5.0	-99	-99	-99	-99	-99
78.	-99	0.121	0.241	0.434	0.000	0.921	1.50	0.50	17.5	5.0	-99	-99	-99	-99	-99
91.	-99	0.121	0.241	0.434	0.000	0.920	1.50	0.50	17.5	5.0	-99	-99	-99	-99	-99
105.	-99	0.064	0.144	0.368	0.000	6.271	1.68	0.50	6.0	6.5	-99	-99	-99	-99	-99
117.	-99	0.064	0.144	0.368	0.000	6.270	1.68	0.50	6.0	6.5	-99	-99	-99	-99	-99
135.	-99	0.140	0.255	0.460	0.000	0.538	1.43	0.50	22.5	16.5	-99	-99	-99	-99	-99
150.	-99	0.140	0.255	0.460	0.000	0.538	1.43	0.50	22.5	16.5	-99	-99	-99	-99	-99
165.	-99	0.140	0.255	0.460	0.000	0.538	1.43	0.50	22.5	16.5	-99	-99	-99	-99	-99
183.	-99	0.140	0.255	0.460	0.000	0.540	1.43	0.50	22.5	16.5	-99	-99	-99	-99	-99
203.	-99	0.140	0.255	0.460	0.000	0.540	1.43	0.50	22.5	16.5	-99	-99	-99	-99	-99

!ROFS (Orig. SLDR, SLRO, and SLPF: 0.05, 84, 1)
 *NCRO160006 NRCS SALO 183. Roanoke fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine, mixed, semiactive, thermic Typic Endoaquults

@ SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE						
-99	0.13	3.0	0.40	84.	1.00	0.65	IB001	IB001	IB001						
@ SLB	SLMH	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC SADC
3.	-99	0.105	0.275	0.435	1.000	1.540	1.50	2.00	14.0	26.0	-99	-99	-99	-99	-99
10.	-99	0.105	0.275	0.435	1.000	1.540	1.50	2.00	14.0	26.0	-99	-99	-99	-99	-99
18.	-99	0.105	0.275	0.435	1.000	1.540	1.50	2.00	14.0	26.0	-99	-99	-99	-99	-99
30.	-99	0.105	0.275	0.435	1.000	1.540	1.50	2.00	14.0	26.0	-99	-99	-99	-99	-99
36.	-99	0.153	0.328	0.507	0.000	0.674	1.31	-99	27.5	60.0	-99	-99	-99	-99	-99
45.	-99	0.153	0.328	0.507	0.000	0.674	1.31	-99	27.5	60.0	-99	-99	-99	-99	-99
50.	-99	0.153	0.298	0.507	0.000	0.674	1.31	-99	27.5	60.0	-99	-99	-99	-99	-99
65.	-99	0.153	0.298	0.507	0.000	0.674	1.31	-99	27.5	60.0	-99	-99	-99	-99	-99
75.	-99	0.153	0.298	0.507	0.000	0.674	1.31	-99	27.5	60.0	-99	-99	-99	-99	-99
90.	-99	0.153	0.298	0.507	0.000	0.670	1.31	-99	27.5	60.0	-99	-99	-99	-99	-99
105.	-99	0.271	0.416	0.531	0.000	0.204	1.24	-99	47.5	32.5	-99	-99	-99	-99	-99
120.	-99	0.271	0.416	0.531	0.000	0.200	1.24	-99	47.5	32.5	-99	-99	-99	-99	-99
137.	-99	0.271	0.416	0.531	0.000	0.200	1.25	-99	47.5	32.5	-99	-99	-99	-99	-99
150.	-99	0.159	0.249	0.481	0.000	0.378	1.38	-99	27.5	25.0	-99	-99	-99	-99	-99
165.	-99	0.159	0.249	0.481	0.000	0.378	1.38	-99	27.5	25.0	-99	-99	-99	-99	-99
183.	-99	0.159	0.249	0.481	0.000	0.380	1.38	-99	27.5	25.0	-99	-99	-99	-99	-99

!WALS (Orig. SLDR, SLRO, and SLPF: 0.6, 68, 1.00)
 !SDUL was 0.133 from Dr. Wilkerson; Raised to 0.161 based on NRCS Data
 *NCRO160003 NRCS LOSA 190. Wagram loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 loamy, kaolinitic, thermic Arenic Kandiuults

@ SCOM	SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE						
-99	0.13	3.0	0.80	68.	1.00	0.65	IB001	IB001	IB001						
@ SLB	SLMH	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC SADC
3.	-99	0.068	0.161	0.374	1.000	5.448	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
10.	-99	0.068	0.161	0.374	1.000	5.448	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
18.	-99	0.068	0.161	0.374	1.000	5.448	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
30.	-99	0.068	0.161	0.374	1.000	5.448	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
36.	-99	0.068	0.161	0.374	0.000	5.448	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
45.	-99	0.068	0.161	0.374	0.000	5.448	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
50.	-99	0.068	0.161	0.374	0.000	5.448	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
61.	-99	0.068	0.161	0.374	0.000	5.450	1.66	1.25	6.0	15.5	-99	-99	-99	-99	-99
75.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99
90.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99
110.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99
130.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99
150.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99
165.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99
180.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99
190.	-99	0.140	0.280	0.461	0.000	0.543	1.43	0.50	22.5	17.5	-99	-99	-99	-99	-99

 !# Rmax = 30 cm SLPF = 1.00 # #####
 !#####

!RAFS (Orig. SLDR, SLRO, and SLPF: 1.00, 83, 0.56)
 *NCBE160004 NRCS SALO 135. Rains fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 BE-Bertie C NC Location 35.640 -77.398 fine-loamy, siliceous, semiactive, thermic Typic P
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.40 83. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99
 10. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99
 18. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.7 -99 -99
 30. -99 0.097 0.222 0.418 1.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99
 45. -99 0.097 0.222 0.418 0.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99
 50. -99 0.126 0.281 0.447 0.000 0.786 1.47 0.75 19.0 15.0 -99 -99 5.0 -99 -99
 65. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 5.0 -99 -99
 75. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 95. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 110. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 125. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 135. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.7 -99 -99

!GOLS (Orig. SLDR, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160002 NRCS LOSA 165. Goldsboro loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 10. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 20. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 30. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 38. -99 0.063 0.148 0.364 0.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 45. -99 0.063 0.148 0.364 0.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 60. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 75. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 90. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 114. -99 0.146 0.286 0.465 0.000 0.460 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 135. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 150. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 165. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99

!GOSL (Orig. SLDR, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160001 NRCS SALO 165. Goldsboro sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 10. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 18. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 30. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 33. -99 0.088 0.173 0.409 0.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 45. -99 0.088 0.173 0.409 0.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 65. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 80. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 102. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 120. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 135. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 150. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 165. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99

!NOLS (Orig. SLDR, SLRO, and SLPF: 0.6, 76, 1.00)
 *NCRO160005 NRCS LOSA 178. Norfolk loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, kaolinitic, thermic Typic Kandiuults
 @ SCOM SALB SLU1 SLDL SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 76. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 10. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 23. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 30. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 36. -99 0.063 0.148 0.364 0.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 45. -99 0.063 0.148 0.364 0.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 50. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 65. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 80. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 97. -99 0.156 0.296 0.475 0.000 0.390 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99

120.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
135.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
150.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
165.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
178.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99

!PLFS (Orig. SLDR, SLRO, and SLPF: 0.75, 71, 1.00)
 *NCLE160001 NRCS LOSA 203. Pocalla loamy fine sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 LE-Lenoir C NC Location 35.197 -77.543 loamy, siliceous, subactive, thermic Arenic Plinth
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 71. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 10. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 20. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 30. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 35. -99 0.072 0.167 0.381 0.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 45. -99 0.072 0.167 0.381 0.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 58. -99 0.072 0.167 0.381 0.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 65. -99 0.121 0.241 0.434 0.000 0.921 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 78. -99 0.121 0.241 0.434 0.000 0.921 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 91. -99 0.121 0.241 0.434 0.000 0.920 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 105. -99 0.064 0.144 0.368 0.000 6.271 1.68 0.50 6.0 6.5 -99 -99 -99 -99 -99 -99
 117. -99 0.064 0.144 0.368 0.000 6.270 1.68 0.50 6.0 6.5 -99 -99 -99 -99 -99 -99
 135. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 150. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 165. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 183. -99 0.140 0.255 0.460 0.000 0.540 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 203. -99 0.140 0.255 0.460 0.000 0.540 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99

!ROFS (Orig. SLDR, SLRO, and SLPF: 0.05, 84, 1)
 *NCRO160006 NRCS SALO 183. Roanoke fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine, mixed, semiaactive, thermic Typic Endoaquults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.40 84. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 10. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 18. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 30. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 36. -99 0.153 0.328 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 45. -99 0.153 0.328 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 50. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 65. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 75. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 90. -99 0.153 0.298 0.507 0.000 0.670 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 105. -99 0.271 0.416 0.531 0.000 0.204 1.24 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 120. -99 0.271 0.416 0.531 0.000 0.200 1.24 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 137. -99 0.271 0.416 0.531 0.000 0.200 1.25 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 150. -99 0.159 0.249 0.481 0.000 0.378 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99
 165. -99 0.159 0.249 0.481 0.000 0.378 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99
 183. -99 0.159 0.249 0.481 0.000 0.380 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99

!WALS (Orig. SLDR, SLRO, and SLPF: 0.6, 68, 1.00)
 !SDUL was 0.133 from Dr. Wilkerson; Raised to 0.161 based on NRCS Data
 *NCRO160003 NRCS LOSA 190. Wagram loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 loamy, kaolinitic, thermic Arenic Kandiuults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 68. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 10. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 18. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 30. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 36. -99 0.068 0.161 0.374 0.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 45. -99 0.068 0.161 0.374 0.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 50. -99 0.068 0.161 0.374 0.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 61. -99 0.068 0.161 0.374 0.000 5.450 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 75. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 90. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 110. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 130. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 150. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 165. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 180. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 190. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99

 !# Rmax = 45 cm SLPF = 0.65 # #####
 !#####

!RAFS (Orig. SLDR, SLRO, and SLPF: 1.00, 83, 0.56)
 *NCBE160004 NRCS SALO 135. Rains fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 BE-Bertie C NC Location 35.640 -77.398 fine-loamy, siliceous, semiactive, thermic Typic P
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.40 83. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99
 10. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99
 18. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.7 -99 -99
 30. -99 0.097 0.222 0.418 1.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99
 45. -99 0.097 0.222 0.418 1.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99
 50. -99 0.126 0.281 0.447 0.000 0.786 1.47 0.75 19.0 15.0 -99 -99 5.0 -99 -99
 65. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 5.0 -99 -99
 75. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 95. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 110. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 125. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 135. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.7 -99 -99

!GOLS (Orig. SLDR, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160002 NRCS LOSA 165. Goldsboro loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 10. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 20. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 30. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 38. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 45. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 60. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 75. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 90. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 114. -99 0.146 0.286 0.465 0.000 0.460 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 135. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 150. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 165. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99

!GOSL (Orig. SLDR, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160001 NRCS SALO 165. Goldsboro sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 10. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 18. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 30. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 33. -99 0.088 0.173 0.409 1.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 45. -99 0.088 0.173 0.409 1.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 65. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 80. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 102. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 120. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 135. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 150. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 165. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99

!NOLS (Orig. SLDR, SLRO, and SLPF: 0.6, 76, 1.00)
 *NCRO160005 NRCS LOSA 178. Norfolk loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, kaolinitic, thermic Typic Kandiuults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 76. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 10. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 23. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 30. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 36. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 45. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 50. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 65. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 80. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 97. -99 0.156 0.296 0.475 0.000 0.390 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99

120.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
135.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
150.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
165.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
178.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99

!PLFS (Orig. SLDR, SLRO, and SLPF: 0.75, 71, 1.00)
 *NCLE160001 NRCS LOSA 203. Pocalla loamy fine sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 LE-Lenoir C NC Location 35.197 -77.543 loamy, siliceous, subactive, thermic Arenic Plinth
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 71. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 10. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 20. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 30. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 35. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 45. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 58. -99 0.072 0.167 0.381 0.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 65. -99 0.121 0.241 0.434 0.000 0.921 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 78. -99 0.121 0.241 0.434 0.000 0.921 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 91. -99 0.121 0.241 0.434 0.000 0.920 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 105. -99 0.064 0.144 0.368 0.000 6.271 1.68 0.50 6.0 6.5 -99 -99 -99 -99 -99 -99
 117. -99 0.064 0.144 0.368 0.000 6.270 1.68 0.50 6.0 6.5 -99 -99 -99 -99 -99 -99
 135. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 150. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 165. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 183. -99 0.140 0.255 0.460 0.000 0.540 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 203. -99 0.140 0.255 0.460 0.000 0.540 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99

!ROFS (Orig. SLDR, SLRO, and SLPF: 0.05, 84, 1)
 *NCRO160006 NRCS SALO 183. Roanoke fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine, mixed, semiaactive, thermic Typic Endoaquults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.40 84. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 10. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 18. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 30. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 36. -99 0.153 0.328 0.507 1.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 45. -99 0.153 0.328 0.507 1.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 50. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 65. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 75. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 90. -99 0.153 0.298 0.507 0.000 0.670 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 105. -99 0.271 0.416 0.531 0.000 0.204 1.24 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 120. -99 0.271 0.416 0.531 0.000 0.200 1.24 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 137. -99 0.271 0.416 0.531 0.000 0.200 1.25 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 150. -99 0.159 0.249 0.481 0.000 0.378 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99
 165. -99 0.159 0.249 0.481 0.000 0.378 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99
 183. -99 0.159 0.249 0.481 0.000 0.380 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99

!WALS (Orig. SLDR, SLRO, and SLPF: 0.6, 68, 1.00)
 !SDUL was 0.133 from Dr. Wilkerson; Raised to 0.161 based on NRCS Data
 *NCRO160003 NRCS LOSA 190. Wagram loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 loamy, kaolinitic, thermic Arenic Kandiuults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 68. 1.00 0.65 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 10. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 18. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 30. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 36. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 45. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 50. -99 0.068 0.161 0.374 0.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 61. -99 0.068 0.161 0.374 0.000 5.450 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 75. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 90. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 110. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 130. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 150. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 165. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 180. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 190. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99

 !# Rmax = 45 cm SLPF = 1.00 # #####
 !#####

!RAFS (Orig. SLDR, SLRO, and SLPF: 1.00, 83, 0.56)
 *NCBE160004 NRCS SALO 135. Rains fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 BE-Bertie C NC Location 35.640 -77.398 fine-loamy, siliceous, semiactive, thermic Typic P
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.40 83. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99
 10. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.8 -99 -99
 18. -99 0.097 0.237 0.418 1.000 2.028 1.54 3.50 12.0 17.0 -99 -99 5.7 -99 -99
 30. -99 0.097 0.222 0.418 1.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99
 45. -99 0.097 0.222 0.418 1.000 2.028 1.54 0.75 12.0 17.0 -99 -99 5.6 -99 -99
 50. -99 0.126 0.281 0.447 0.000 0.786 1.47 0.75 19.0 15.0 -99 -99 5.0 -99 -99
 65. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 5.0 -99 -99
 75. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 95. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 110. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 125. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.8 -99 -99
 135. -99 0.167 0.337 0.479 0.000 0.304 1.38 0.75 29.0 17.0 -99 -99 4.7 -99 -99

!GOLS (Orig. SLDR, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160002 NRCS LOSA 165. Goldsboro loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 10. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 20. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 30. -99 0.063 0.188 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 38. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 45. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 60. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 75. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 90. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 114. -99 0.146 0.286 0.465 0.000 0.460 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 135. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 150. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 165. -99 0.157 0.274 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99

!GOSL (Orig. SLDR, SLRO, and SLPF: 0.4, 76, 1.00)
 *NCRO160001 NRCS SALO 165. Goldsboro sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, siliceous, subactive, thermic Aquic Pa
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.60 76. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 10. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 18. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 30. -99 0.088 0.213 0.409 1.000 2.723 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 33. -99 0.088 0.173 0.409 1.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 45. -99 0.088 0.173 0.409 1.000 2.720 1.57 1.25 10.0 20.0 -99 -99 -99 -99 -99
 50. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 65. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 80. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 102. -99 0.146 0.286 0.465 0.000 0.462 1.42 -99 24.0 16.0 -99 -99 -99 -99 -99
 120. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 135. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 150. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99
 165. -99 0.157 0.312 0.481 0.000 0.398 1.38 -99 27.0 26.0 -99 -99 -99 -99 -99

!NOLS (Orig. SLDR, SLRO, and SLPF: 0.6, 76, 1.00)
 *NCRO160005 NRCS LOSA 178. Norfolk loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine-loamy, kaolinitic, thermic Typic kandiuults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 76. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 10. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 23. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 30. -99 0.063 0.148 0.364 1.000 6.358 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 36. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 45. -99 0.063 0.148 0.364 1.000 6.360 1.69 1.25 5.0 16.5 -99 -99 -99 -99 -99
 50. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 65. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 80. -99 0.156 0.296 0.475 0.000 0.385 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99
 97. -99 0.156 0.296 0.475 0.000 0.390 1.39 -99 26.5 20.0 -99 -99 -99 -99 -99

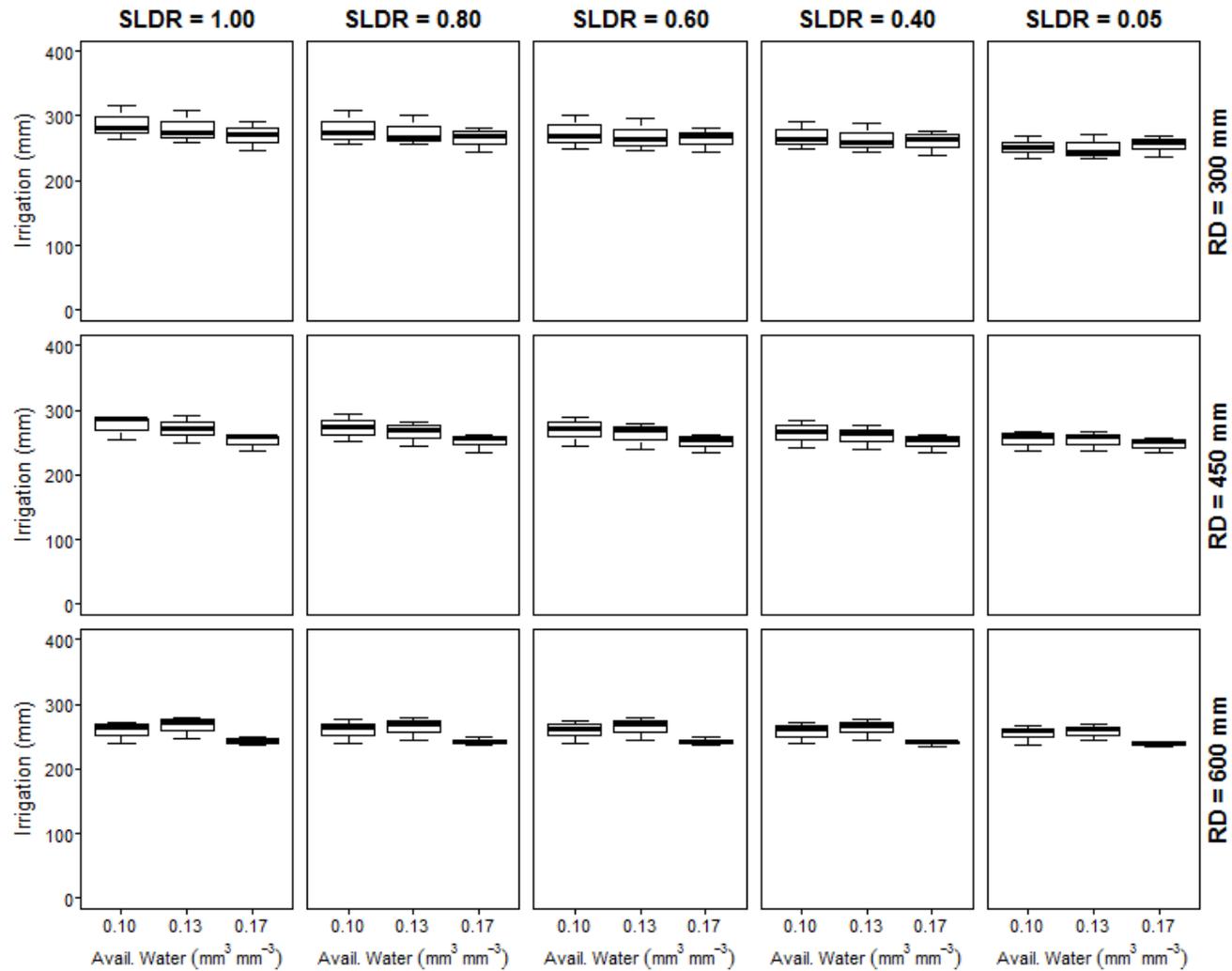
120.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
135.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
150.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
165.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99
178.	-99	0.178	0.318	0.490	0.000	0.277	1.35	-99	31.5	22.5	-99	-99	-99	-99	-99	-99

!PLFS (Orig. SLDR, SLRO, and SLPF: 0.75, 71, 1.00)
 *NCLE160001 NRCS LOSA 203. Pocalla loamy fine sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 LE-Lenoir C NC Location 35.197 -77.543 loamy, siliceous, subactive, thermic Arenic Plinth
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 71. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 10. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 20. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 30. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 35. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 45. -99 0.072 0.167 0.381 1.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 58. -99 0.072 0.167 0.381 0.000 4.784 1.64 0.50 7.0 12.0 -99 -99 -99 -99 -99 -99
 65. -99 0.121 0.241 0.434 0.000 0.921 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 78. -99 0.121 0.241 0.434 0.000 0.921 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 91. -99 0.121 0.241 0.434 0.000 0.920 1.50 0.50 17.5 5.0 -99 -99 -99 -99 -99 -99
 105. -99 0.064 0.144 0.368 0.000 6.271 1.68 0.50 6.0 6.5 -99 -99 -99 -99 -99 -99
 117. -99 0.064 0.144 0.368 0.000 6.270 1.68 0.50 6.0 6.5 -99 -99 -99 -99 -99 -99
 135. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 150. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 165. -99 0.140 0.255 0.460 0.000 0.538 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 183. -99 0.140 0.255 0.460 0.000 0.540 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99
 203. -99 0.140 0.255 0.460 0.000 0.540 1.43 0.50 22.5 16.5 -99 -99 -99 -99 -99 -99

!ROFS (Orig. SLDR, SLRO, and SLPF: 0.05, 84, 1)
 *NCRO160006 NRCS SALO 183. Roanoke fine sandy loam, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 fine, mixed, semiaactive, thermic Typic Endoaquults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.40 84. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 10. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 18. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 30. -99 0.105 0.275 0.435 1.000 1.540 1.50 2.00 14.0 26.0 -99 -99 -99 -99 -99 -99
 36. -99 0.153 0.328 0.507 1.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 45. -99 0.153 0.328 0.507 1.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 50. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 65. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 75. -99 0.153 0.298 0.507 0.000 0.674 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 90. -99 0.153 0.298 0.507 0.000 0.670 1.31 -99 27.5 60.0 -99 -99 -99 -99 -99 -99
 105. -99 0.271 0.416 0.531 0.000 0.204 1.24 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 120. -99 0.271 0.416 0.531 0.000 0.200 1.24 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 137. -99 0.271 0.416 0.531 0.000 0.200 1.25 -99 47.5 32.5 -99 -99 -99 -99 -99 -99
 150. -99 0.159 0.249 0.481 0.000 0.378 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99
 165. -99 0.159 0.249 0.481 0.000 0.378 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99
 183. -99 0.159 0.249 0.481 0.000 0.380 1.38 -99 27.5 25.0 -99 -99 -99 -99 -99 -99

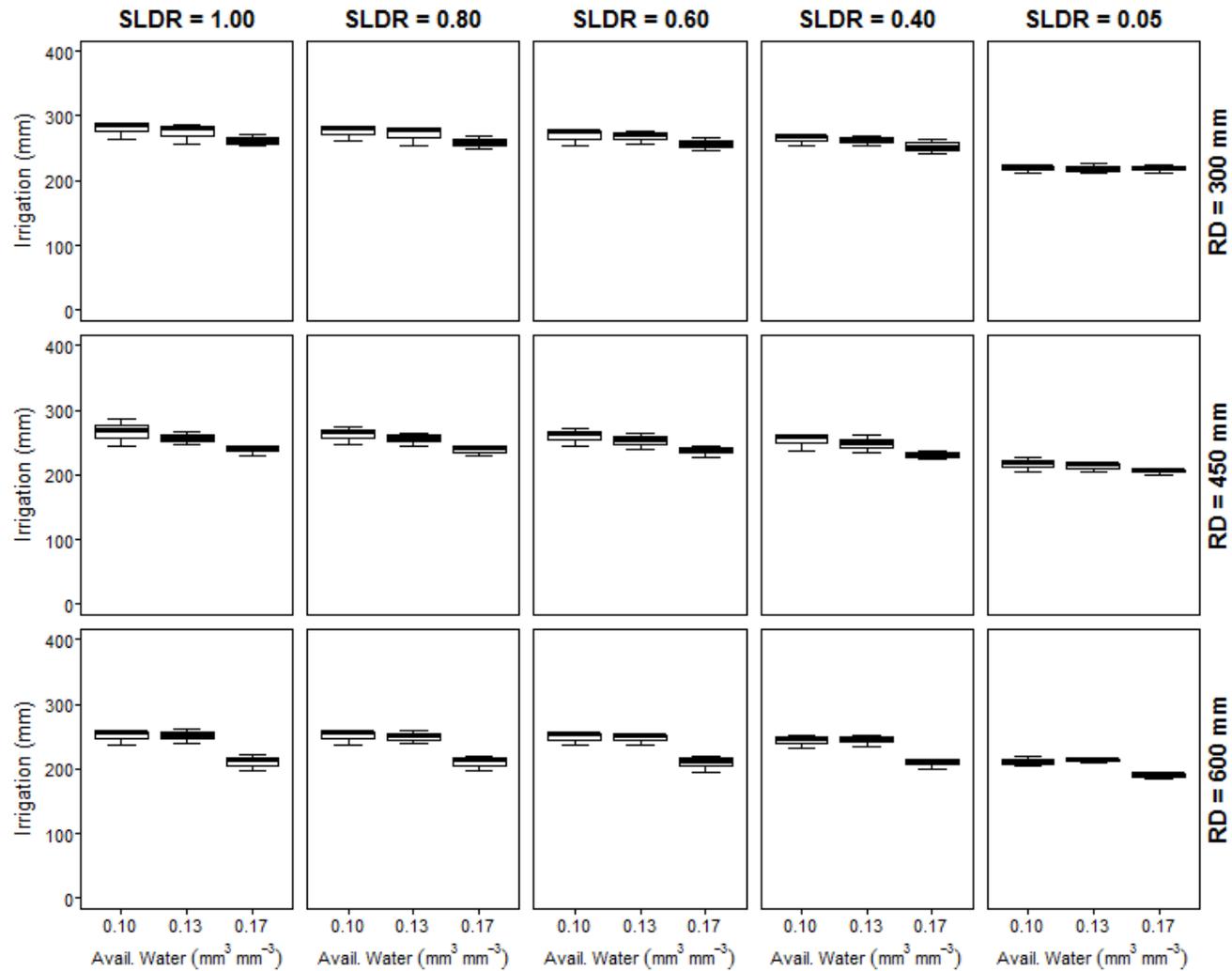
!WALS (Orig. SLDR, SLRO, and SLPF: 0.6, 68, 1.00)
 !SDUL was 0.133 from Dr. Wilkerson; Raised to 0.161 based on NRCS Data
 *NCRO160003 NRCS LOSA 190. Wagram loamy sand, Bobby
 @SITE..... COUNTRY.... LAT LONG SCSFAMILY.....
 RO-Robeson NC Location 34.627 -79.025 loamy, kaolinitic, thermic Arenic Kandiidults
 @ SCOM SALB SLU1 SLDR SLRO SLNF SLPF SMHB SMPX SMKE
 -99 0.13 3.0 0.80 68. 1.00 1.00 IB001 IB001 IB001
 @ SLB SLMH SLLL SDUL SSAT SRGF SSKS SBDM SLOC SLCL SLSI SLCF SLNI SLHW SLHB SCEC SADC
 3. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 10. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 18. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 30. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 36. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 45. -99 0.068 0.161 0.374 1.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 50. -99 0.068 0.161 0.374 0.000 5.448 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 61. -99 0.068 0.161 0.374 0.000 5.450 1.66 1.25 6.0 15.5 -99 -99 -99 -99 -99 -99
 75. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 90. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 110. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 130. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 150. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 165. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 180. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99
 190. -99 0.140 0.280 0.461 0.000 0.543 1.43 0.50 22.5 17.5 -99 -99 -99 -99 -99 -99

**APPENDIX E – BOXPLOTS OF AVERAGE SEASONAL IRRIGATION FOR SELECT LOCATIONS FROM IDSS
SENSITIVITY ANALYSIS ACROSS SLDR, RDMAX, AND AVAILABLE WATER VALUES**



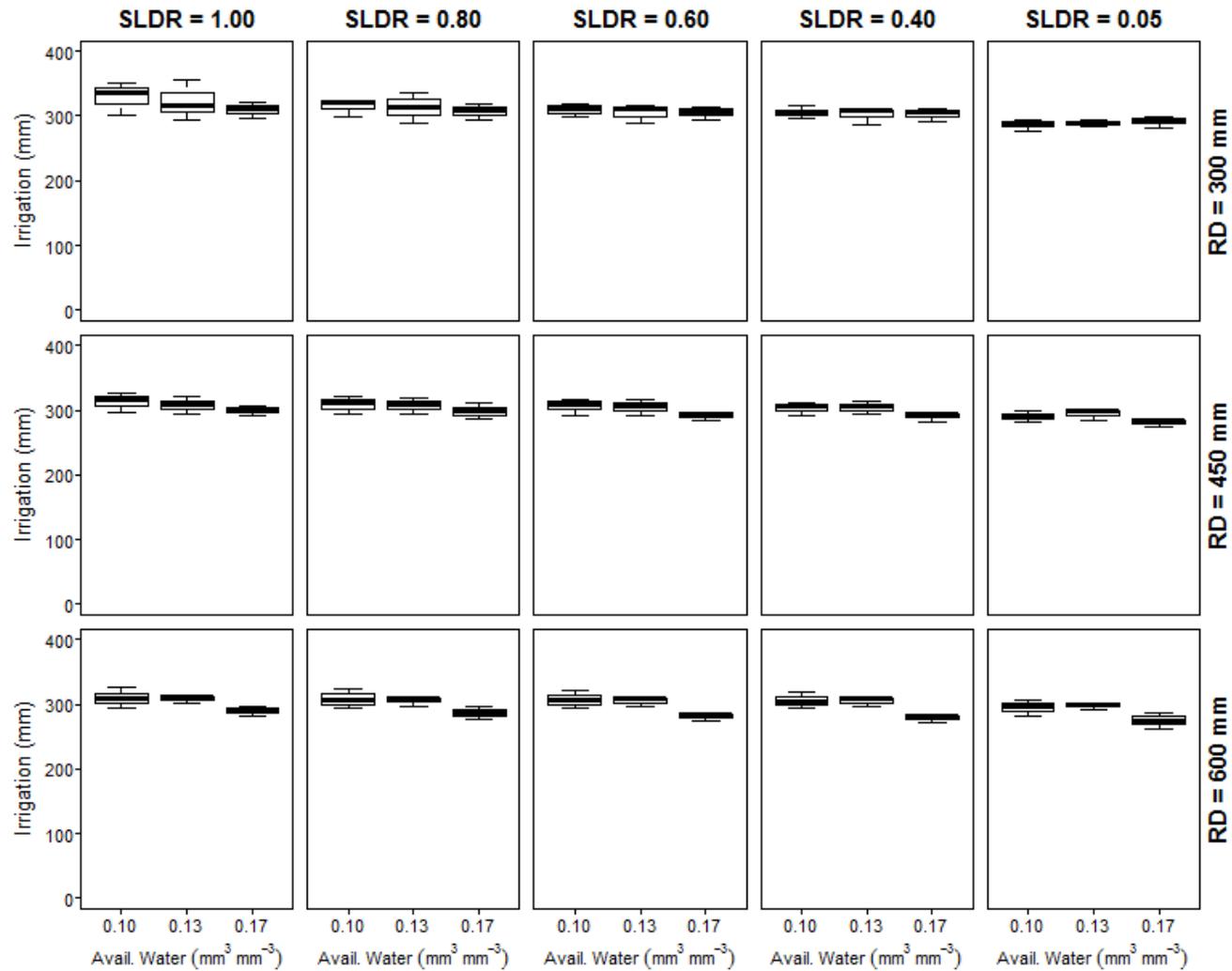
2009-ROCK-91

Figure E.1. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2009-ROCK-91 growing season.



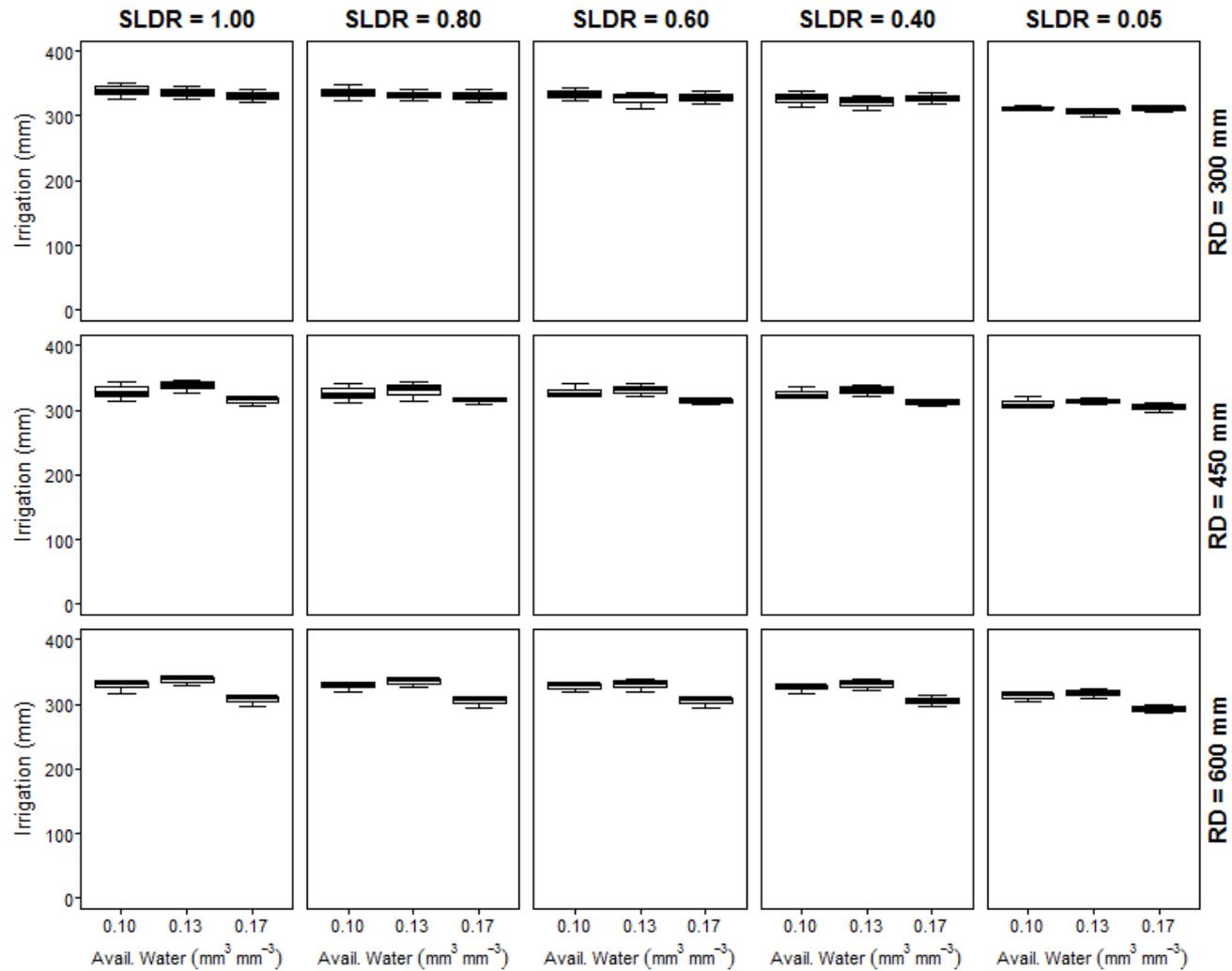
2010-WHIT-91

Figure E.2. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2010-WHIT-91 growing season.



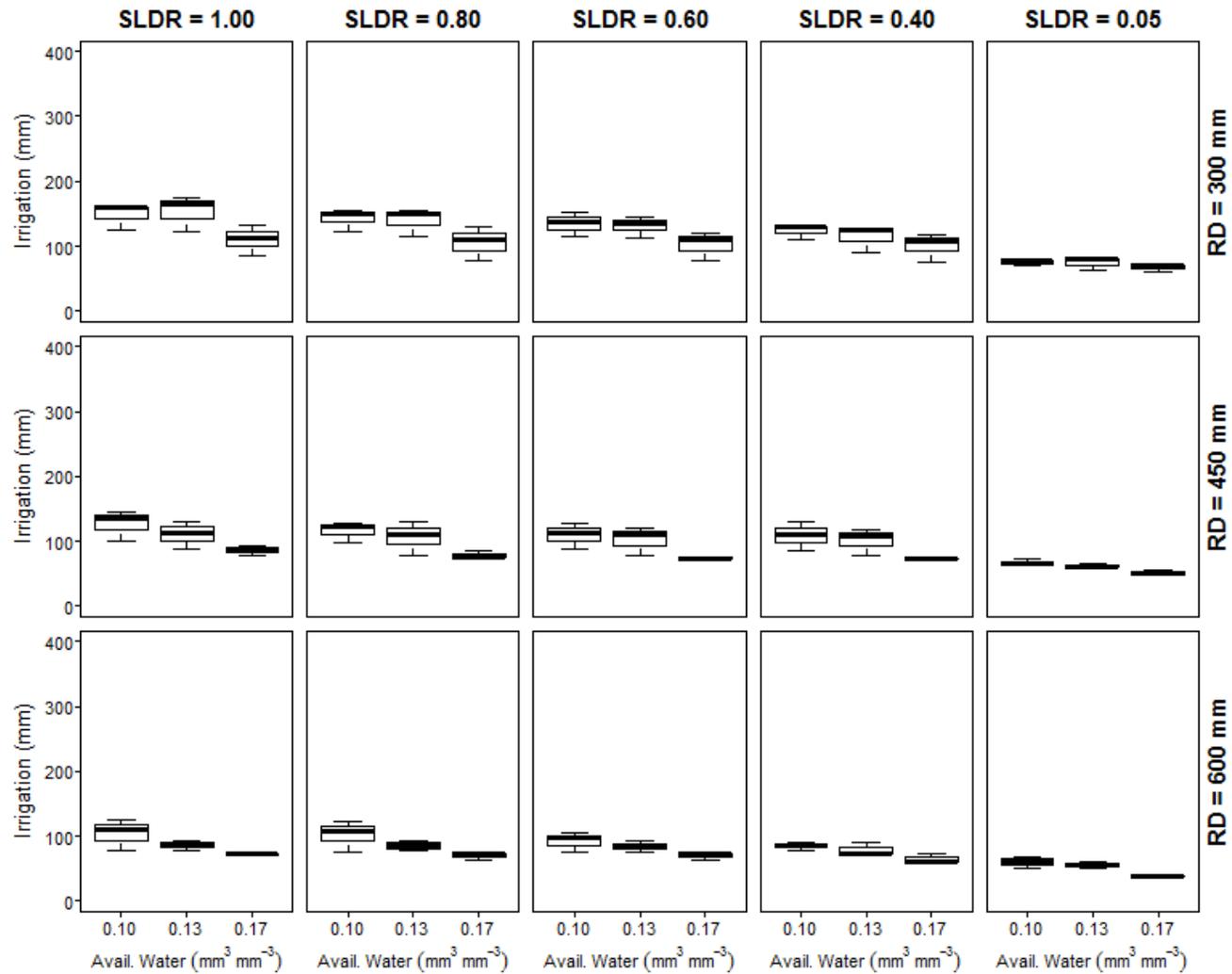
2011-KINS-105

Figure E.3. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2011-KINS-105 growing season.



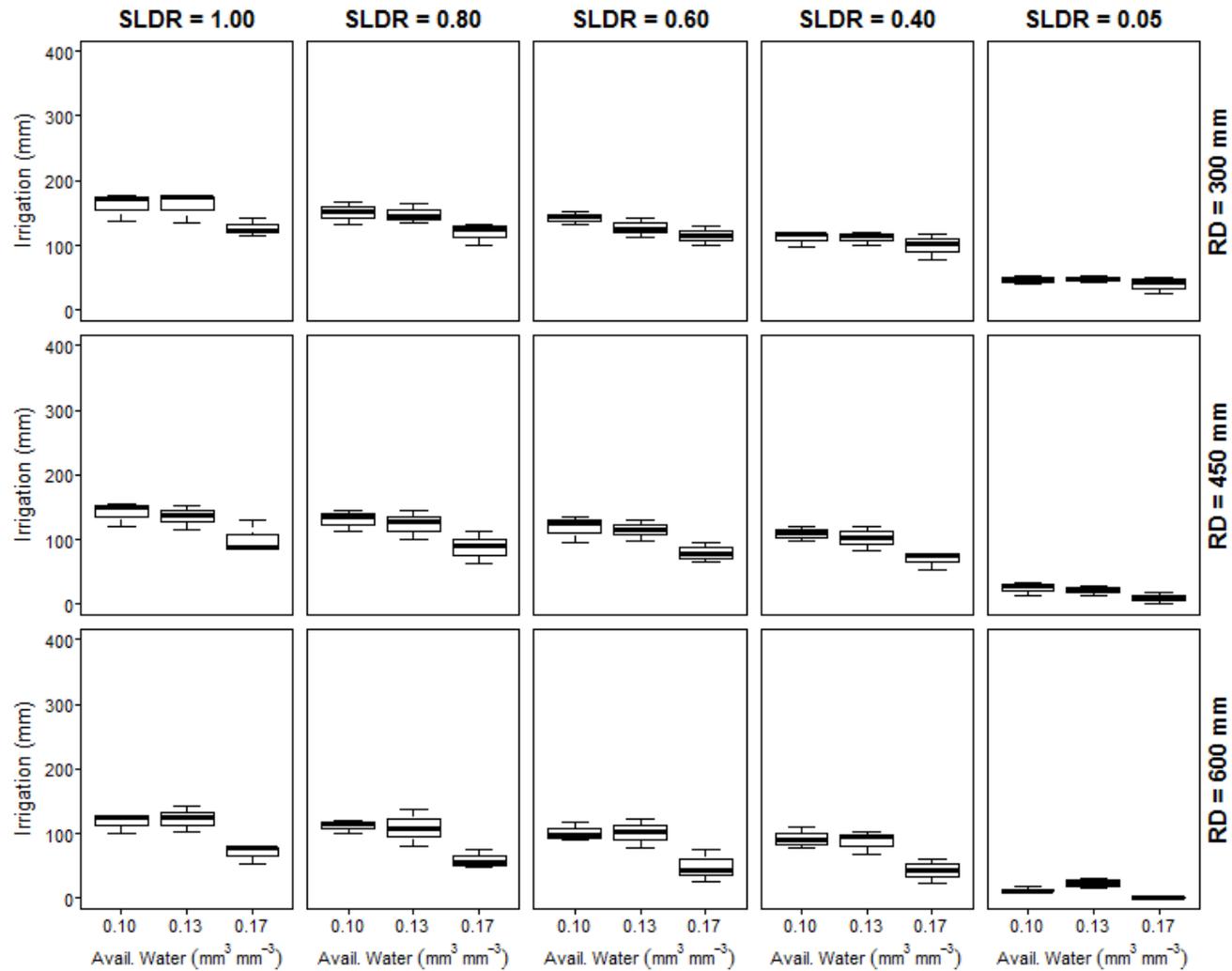
2011-KINS-91

Figure E.4. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2011-KINS-91 growing season.



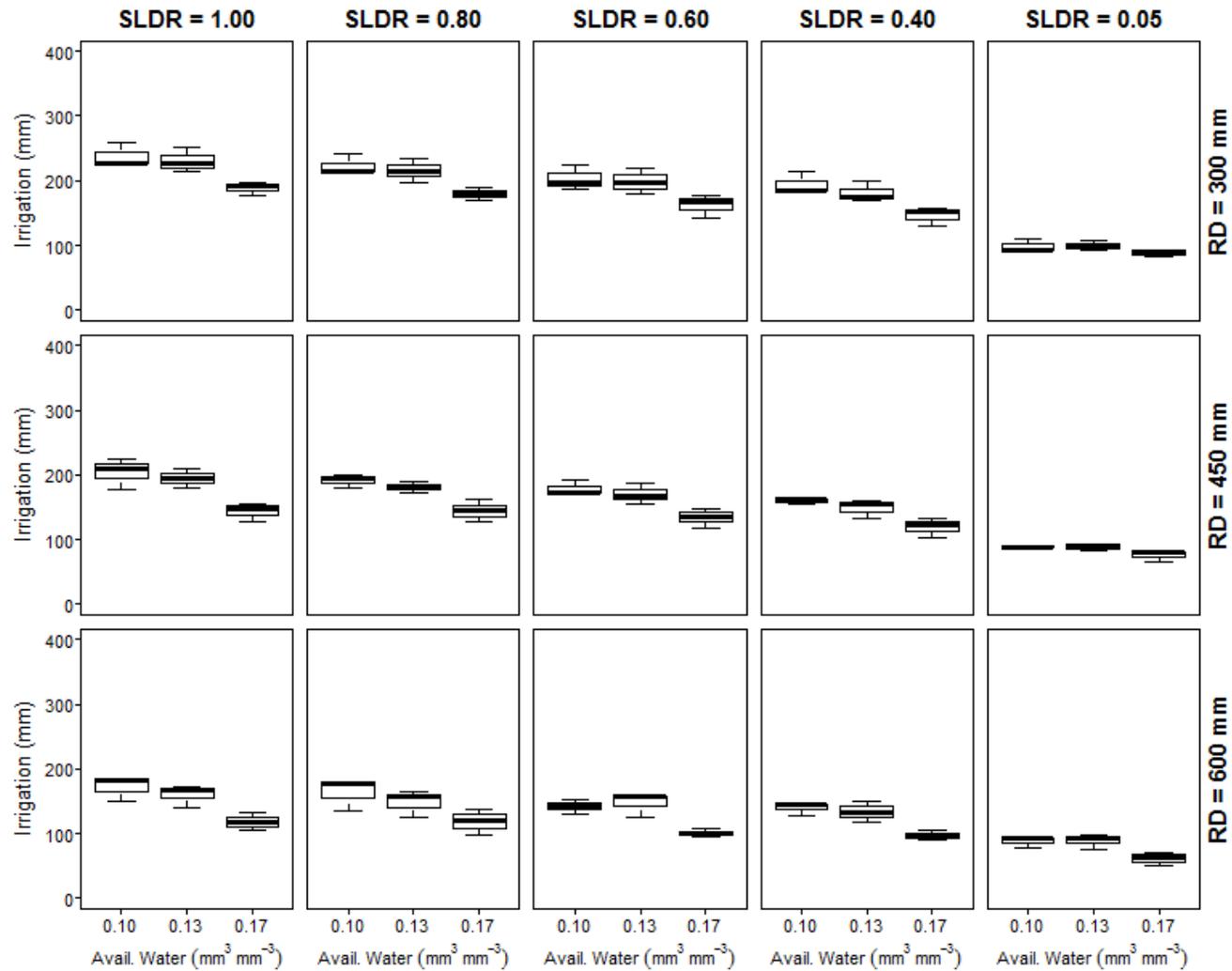
2009-WHIT-105

Figure E.5. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RD_{max}, and available water for the 2009-WHIT-105 growing season.



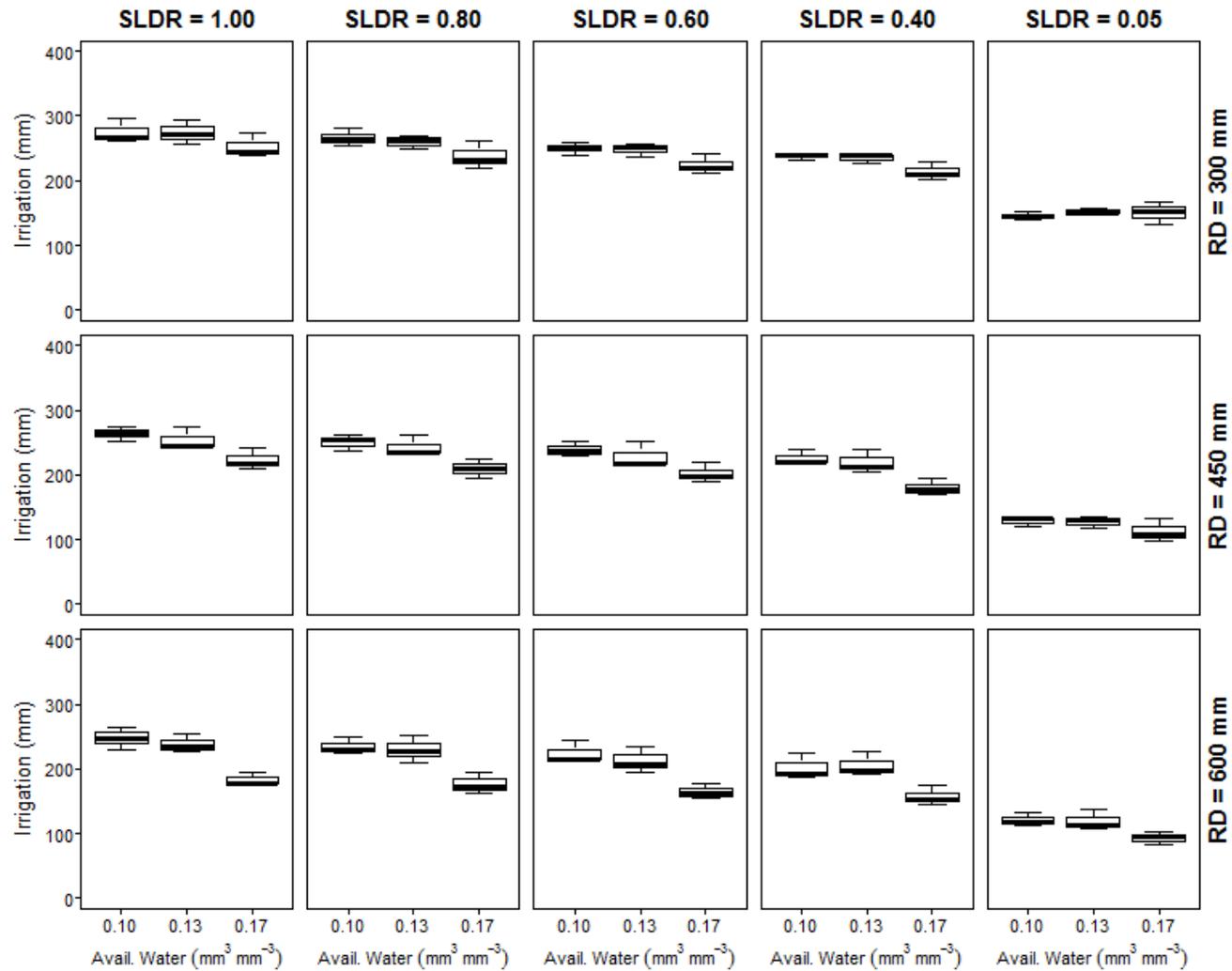
2013-LEWI-105

Figure E.6. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2013-LEWI-105 growing season.



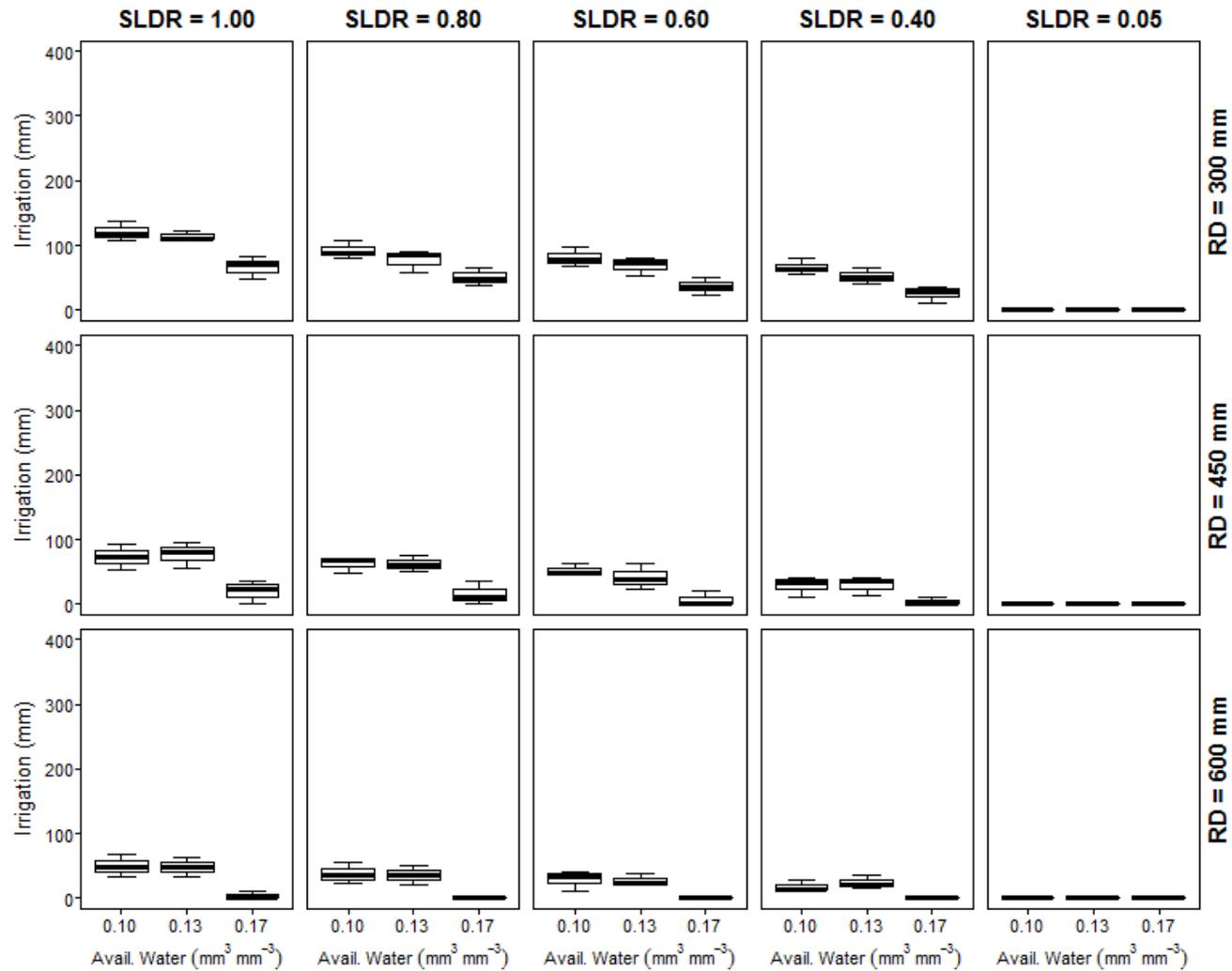
2012-LUMB-91

Figure E.7. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RD_{max}, and available water for the 2012-LUMB-91 growing season.



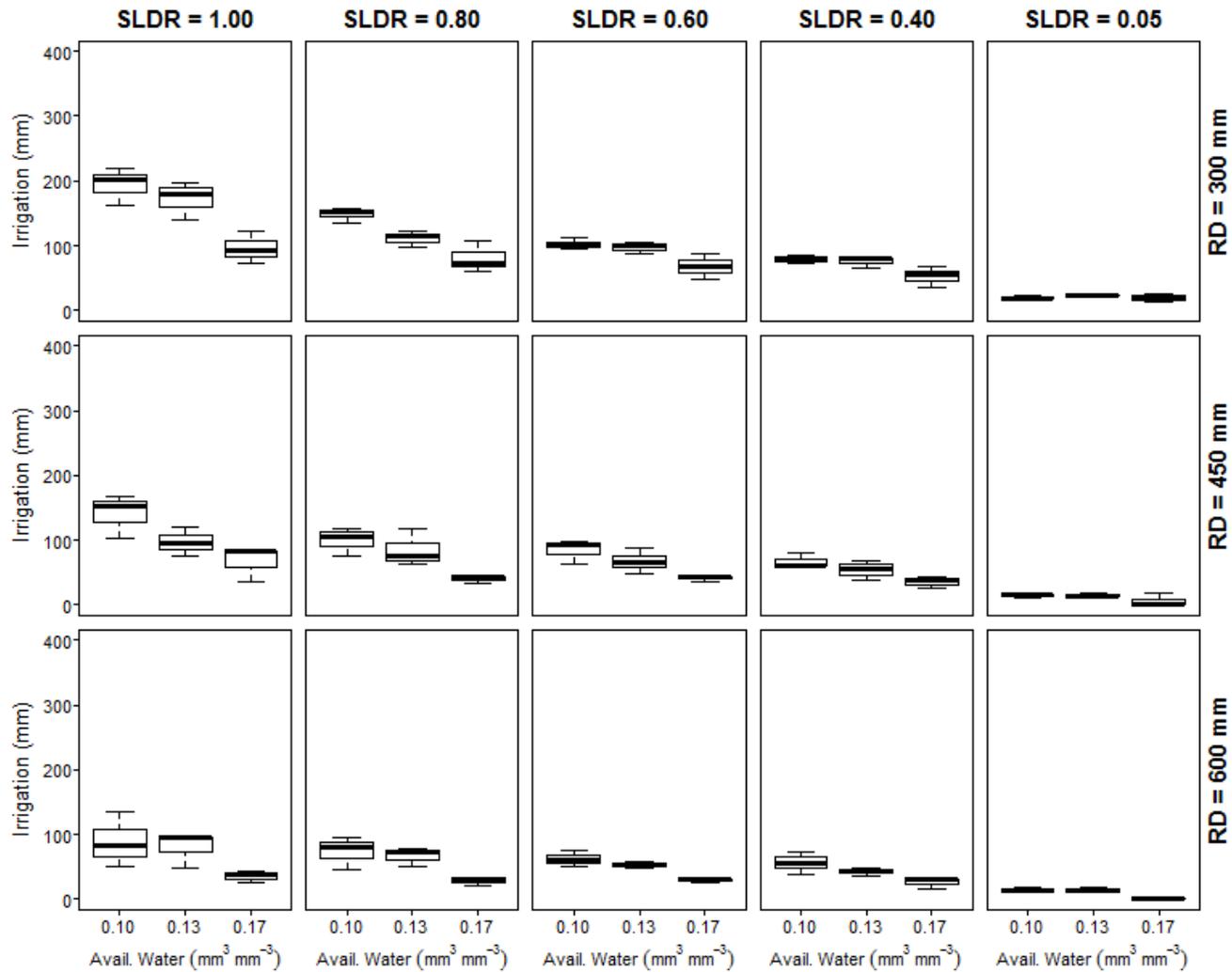
2014-LUMB-91

Figure E.8. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2014-LUMB-91 growing season.



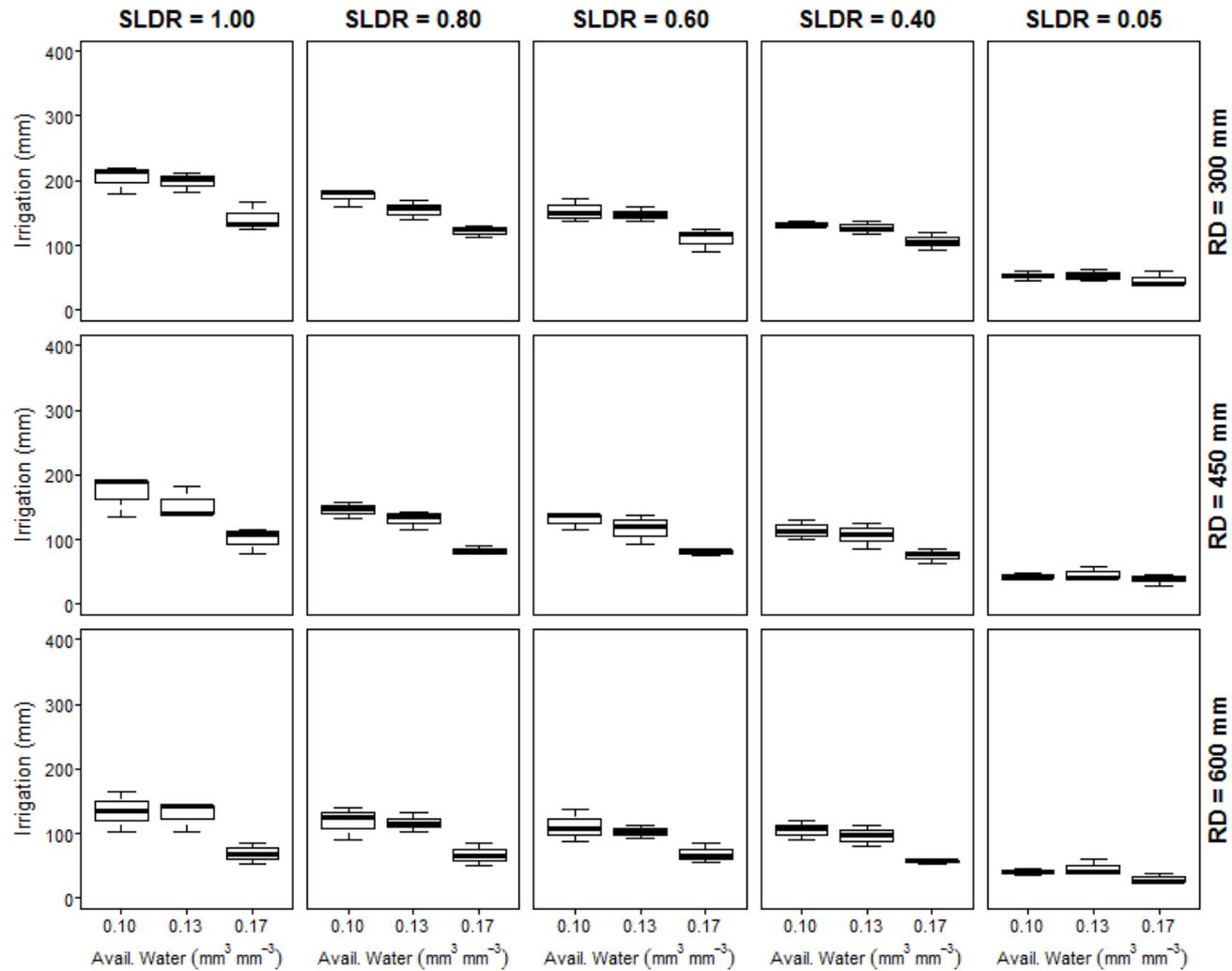
2013-WHIT-105

Figure E.9. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2013-WHIT-105 growing season.



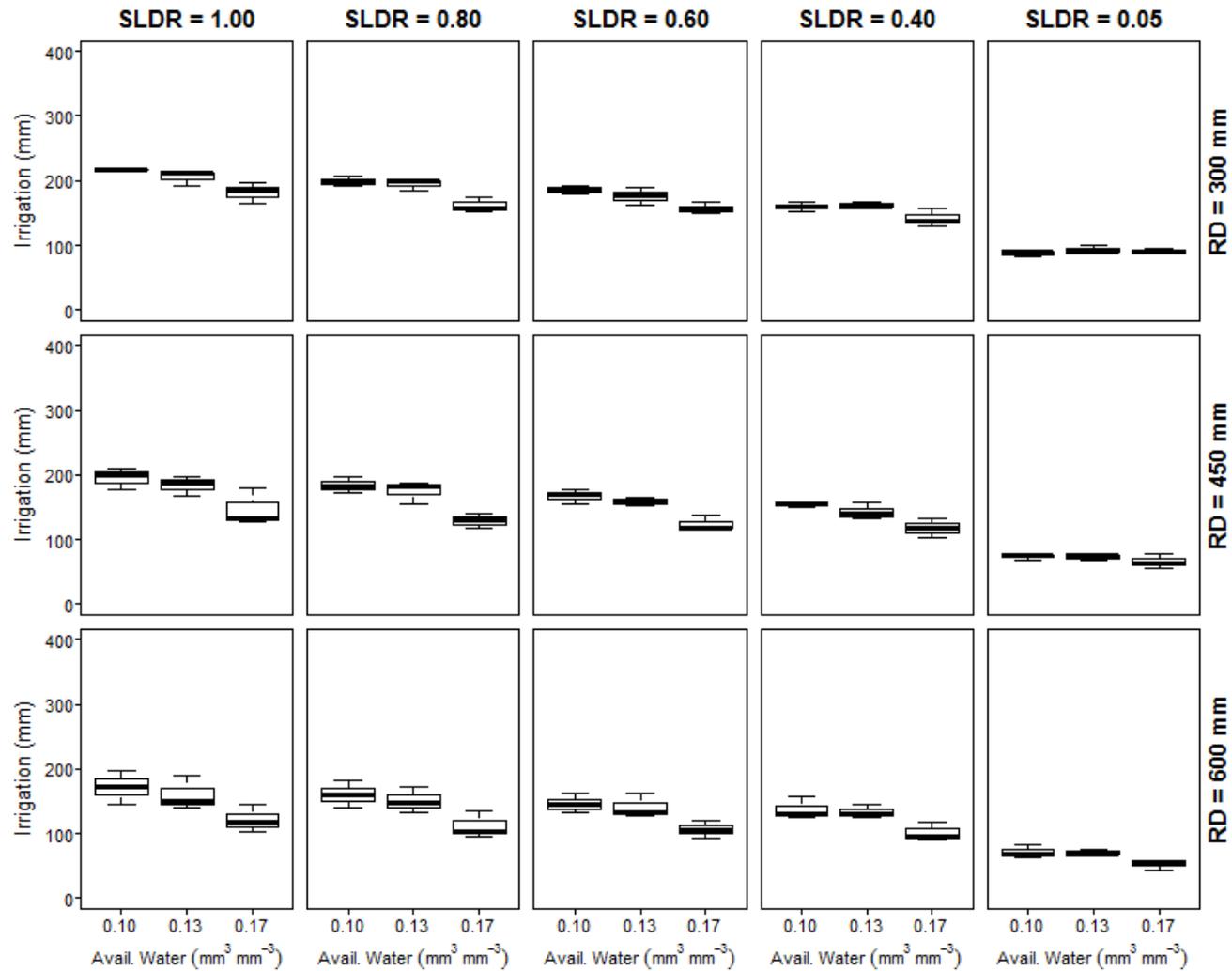
2014-KINS-105

Figure E.10. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2014-KINS-105 growing season.



2014-KINS-91

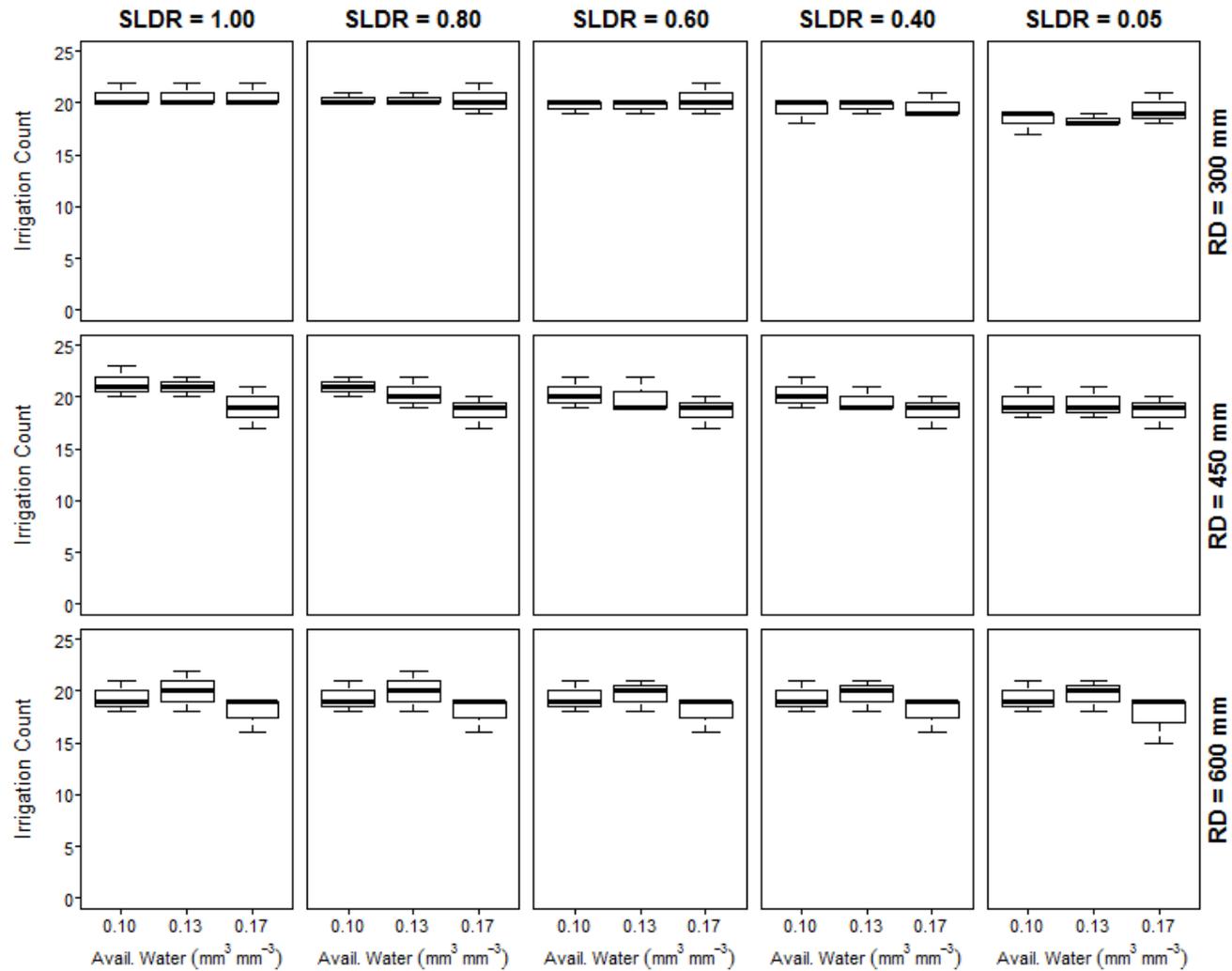
Figure E.11. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RD_{max}, and available water for the 2014-KINS-91 growing season.



2014-LEWI-91

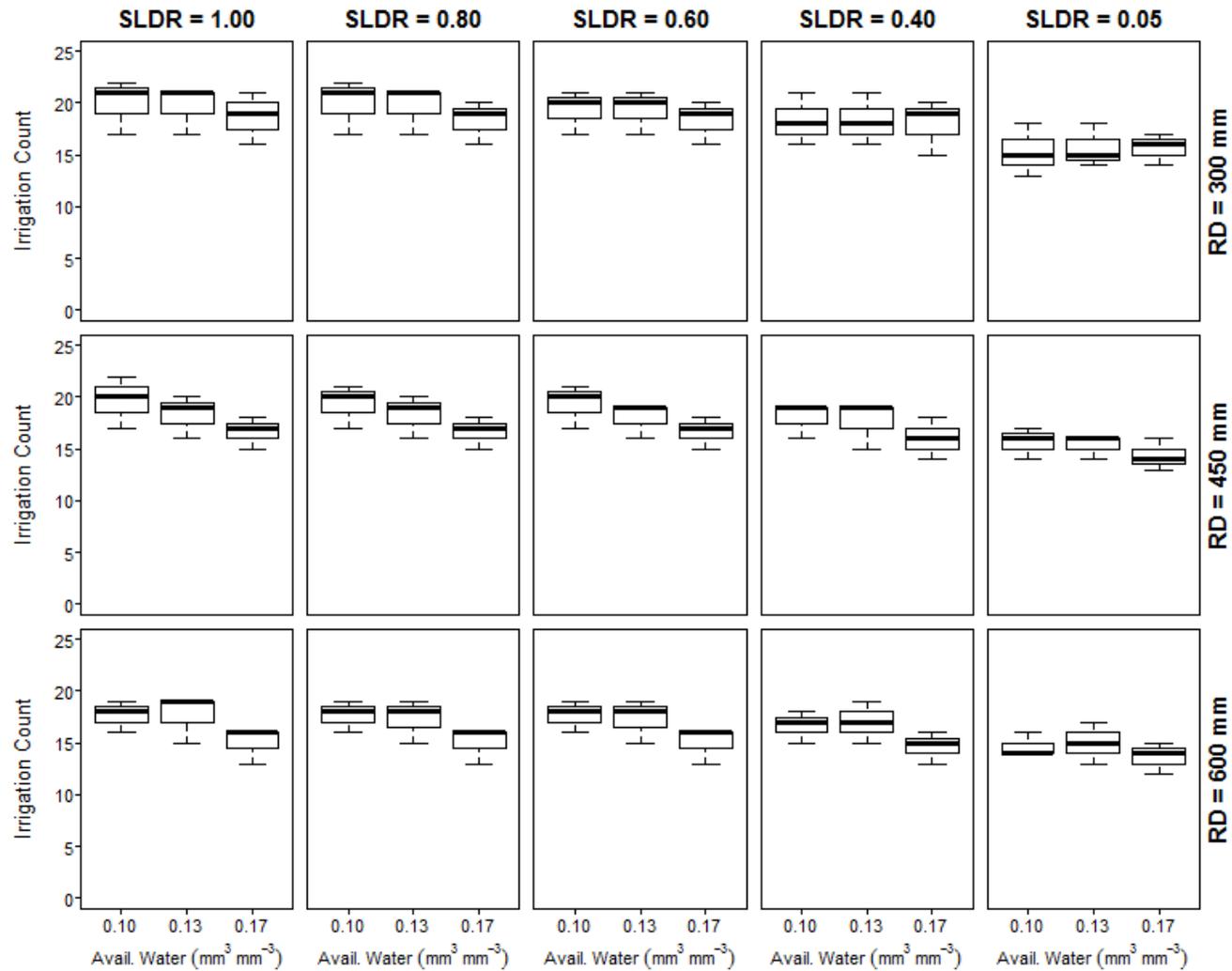
Figure E.12. Average seasonal irrigation recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RD_{max}, and available water for the 2014-LEWI-91 growing season.

APPENDIX F – BOXPLOTS OF AVERAGE NUMBER OF IRRIGATIONS RECOMMENDED PER SEASON FOR SELECT LOCATIONS FROM IDSS SENSITIVITY ANALYSIS ACROSS SLDR, RDMAX, AND AVAILABLE WATER VALUES



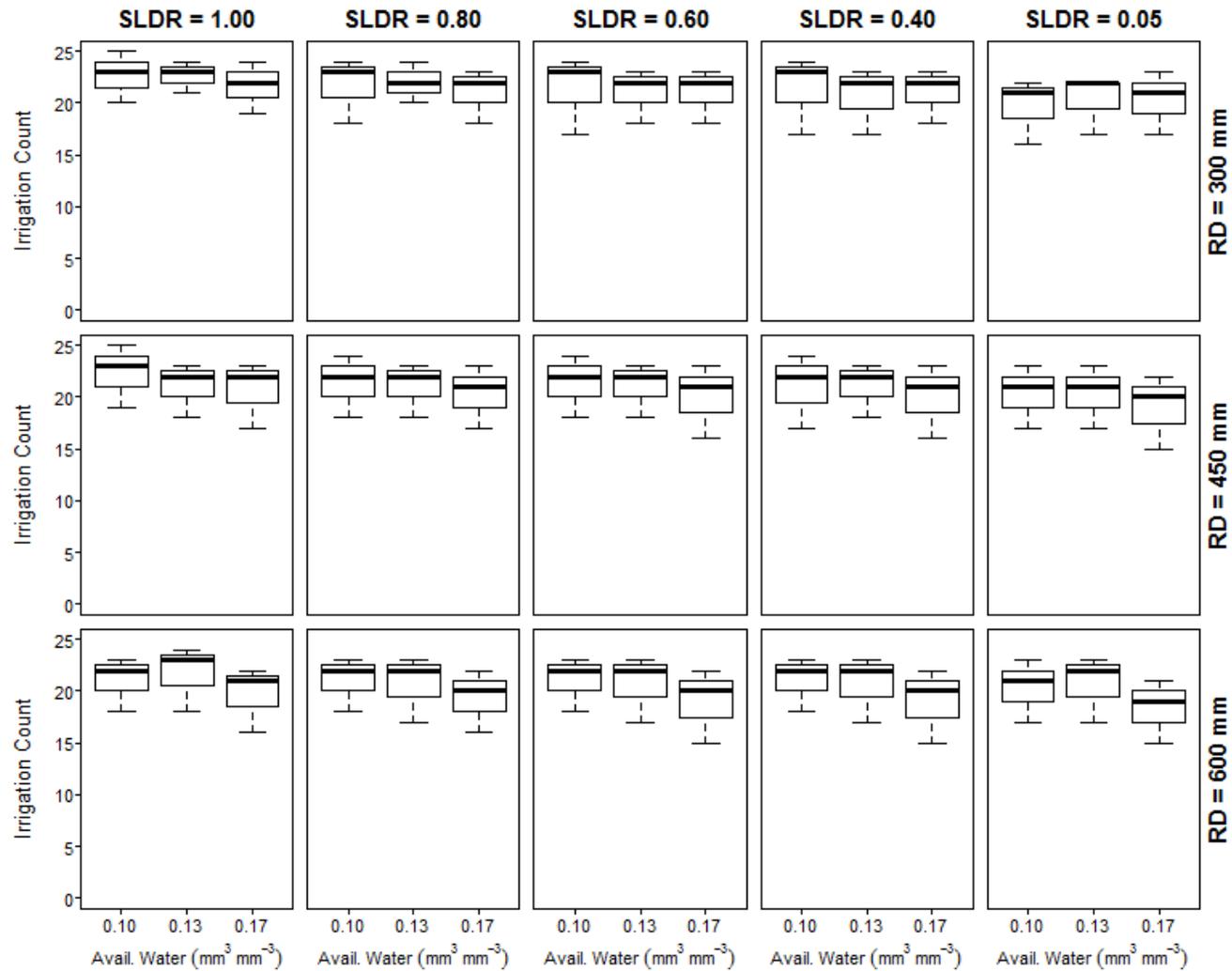
2009-ROCK-91

Figure F.1. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2009-ROCK-91 growing season.



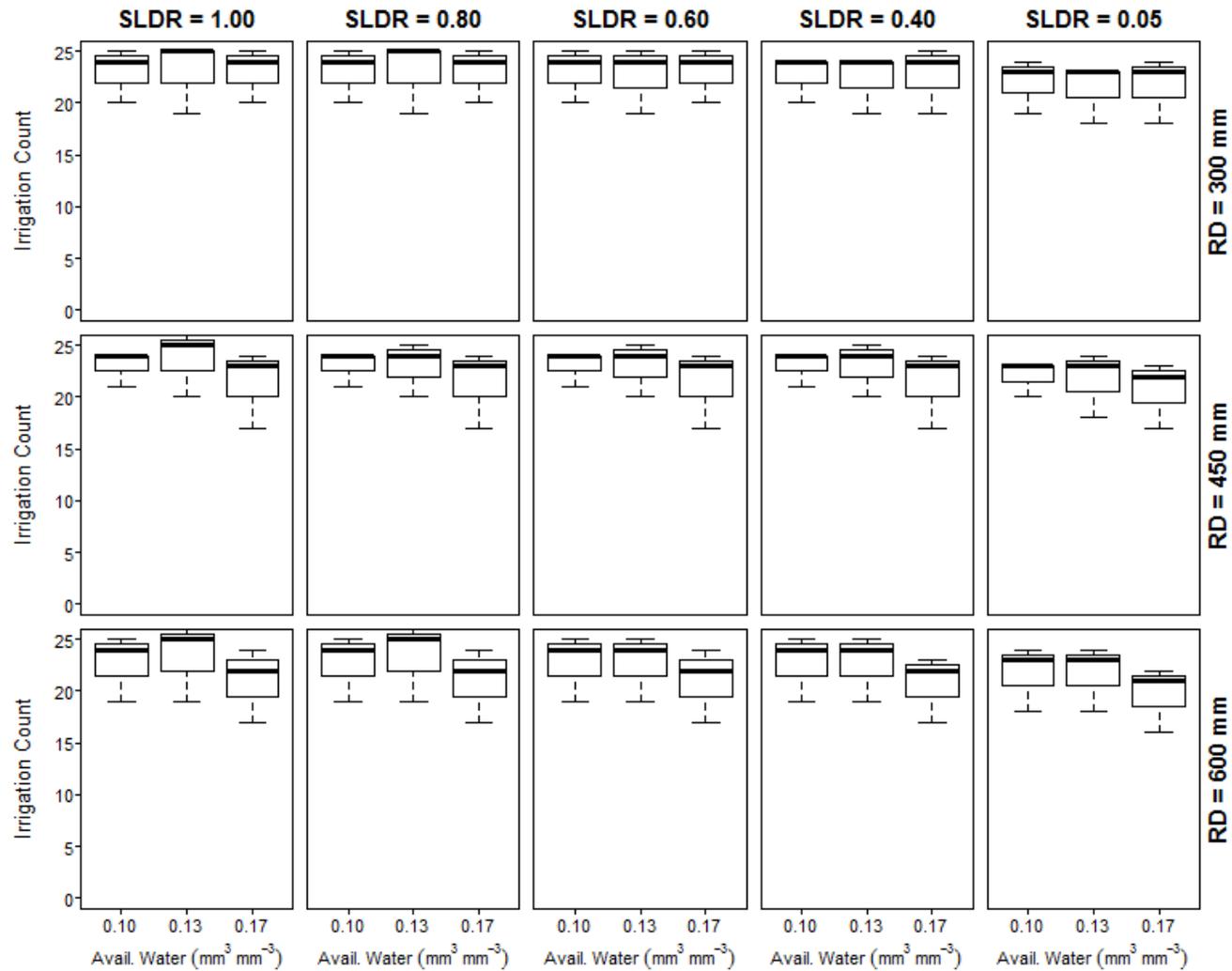
2010-WHIT-91

Figure F.2. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2010-WHIT-91 growing season.



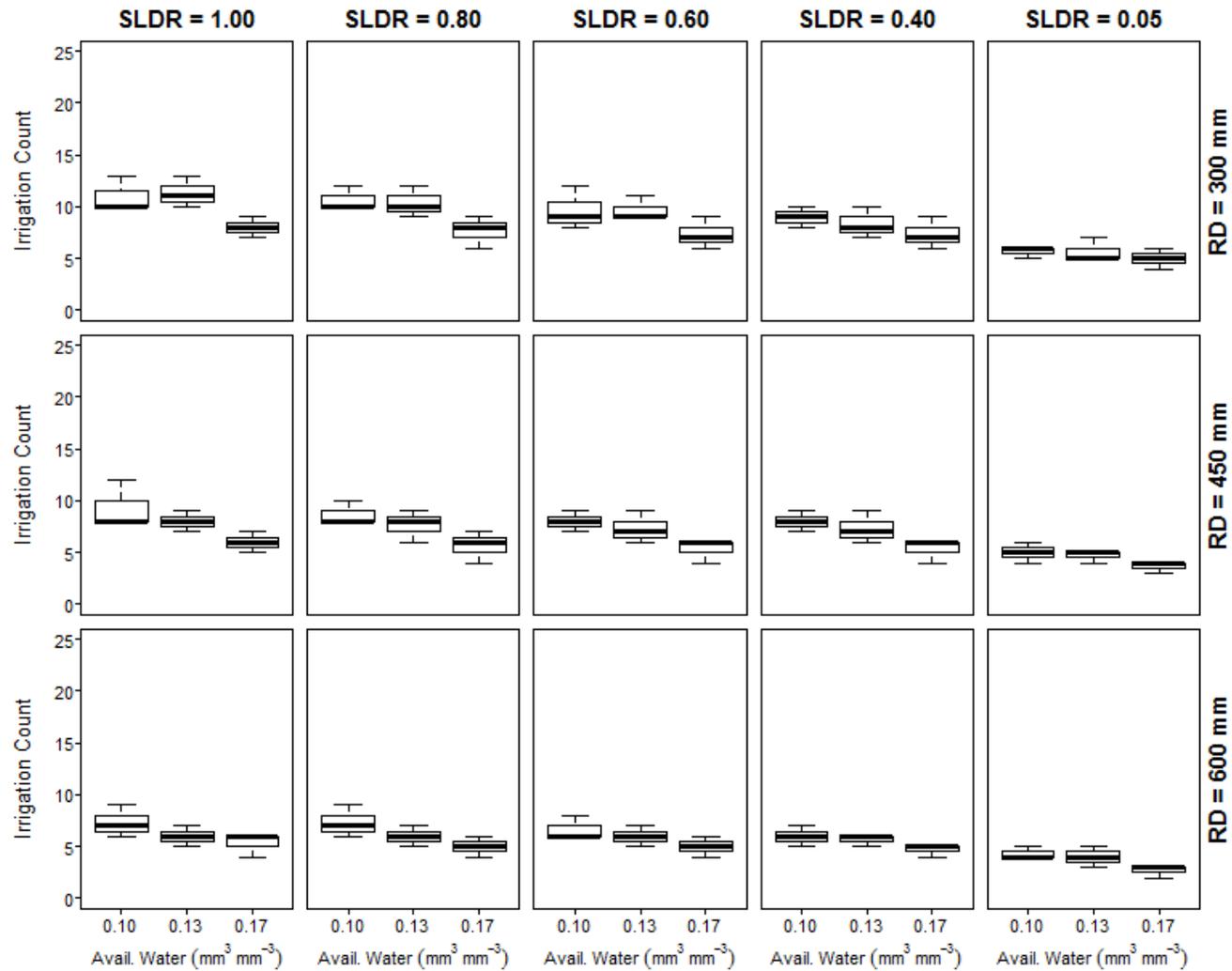
2011-KINS-105

Figure F.3. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2011-KINS-105 growing season.



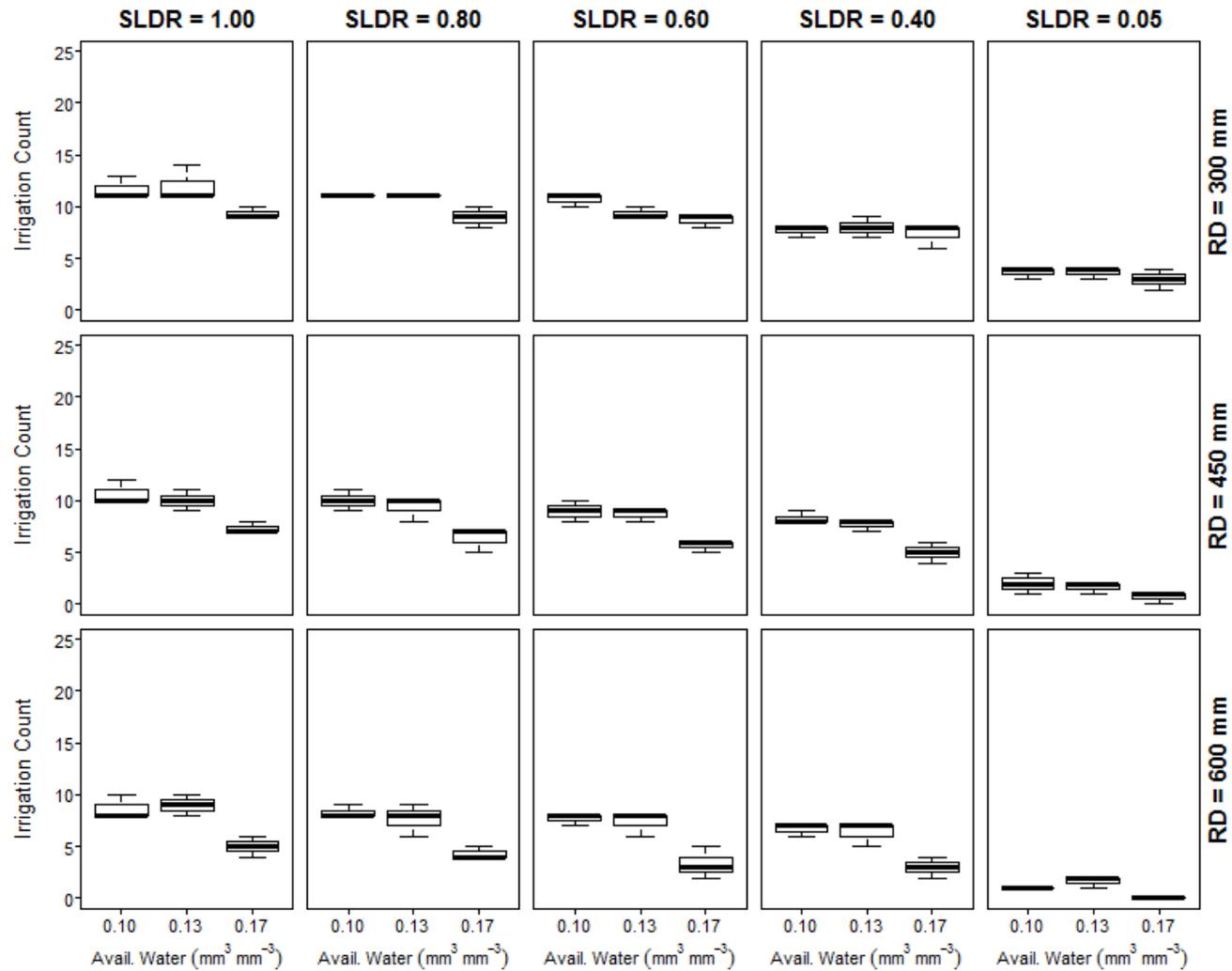
2011-KINS-91

Figure F.4. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2011-KINS-91 growing season.



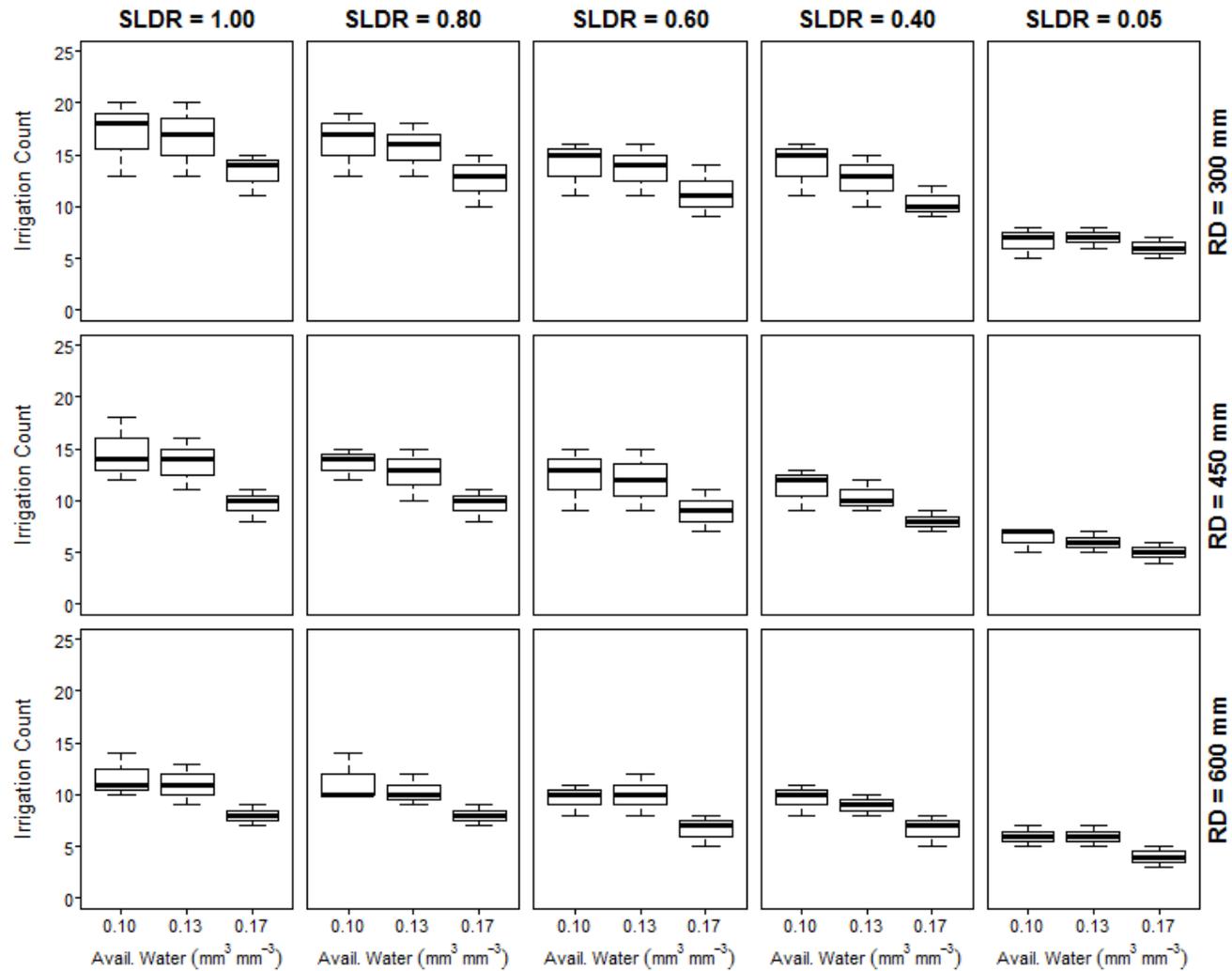
2009-WHIT-105

Figure F.5. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2009-WHIT-105 growing season.



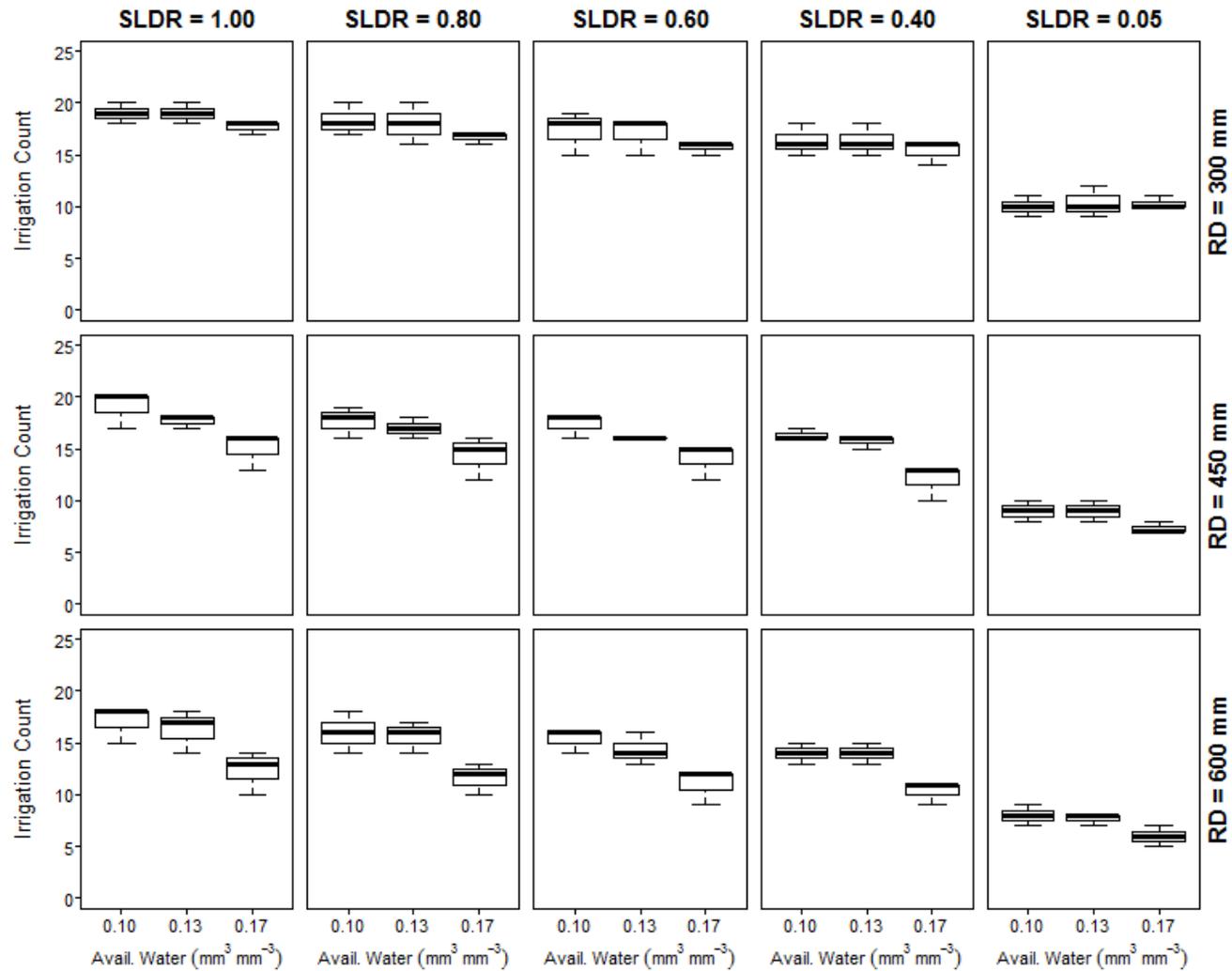
2013-LEWI-105

Figure F.6. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2013-LEWI-105 growing season.



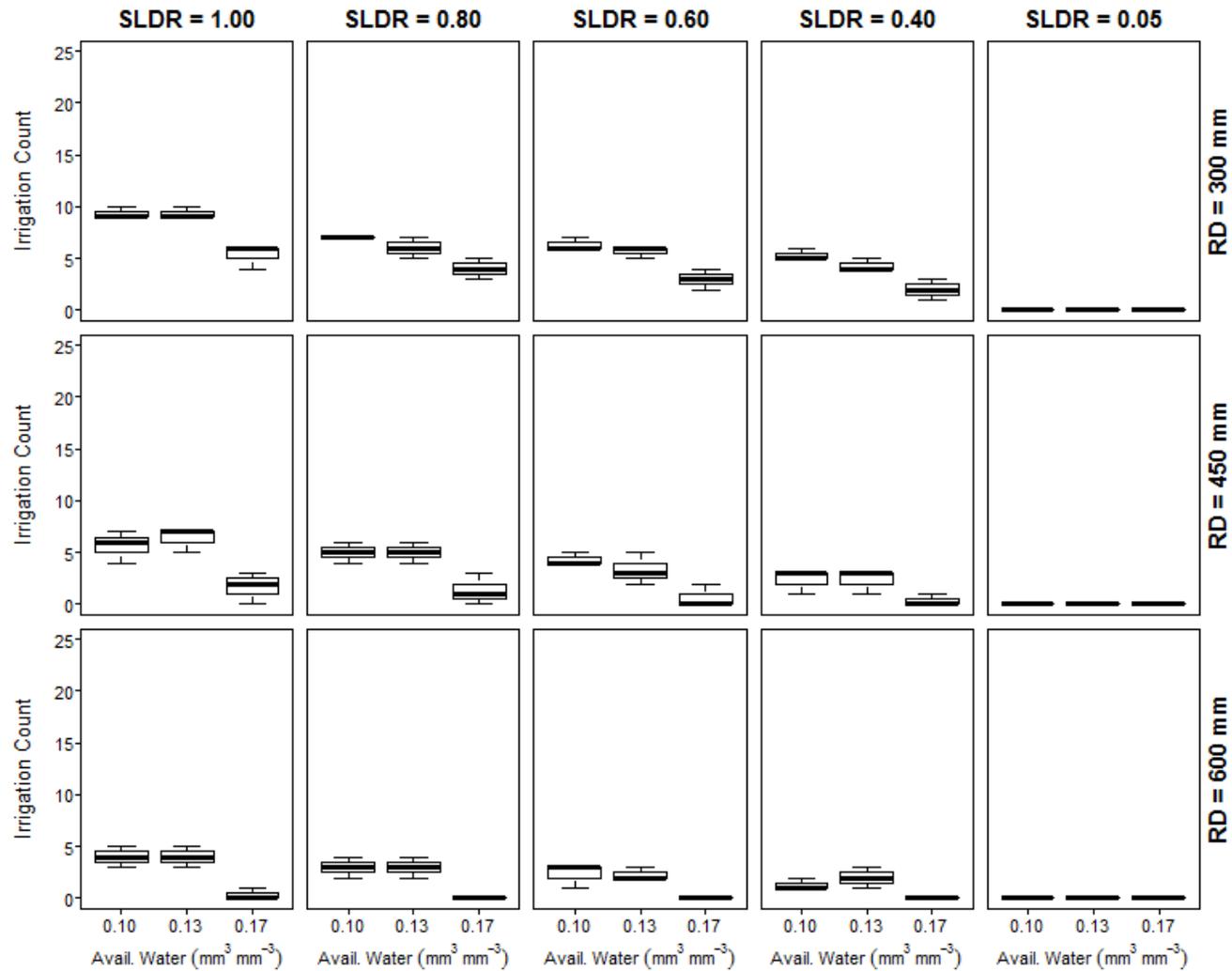
2012-LUMB-91

Figure F.7. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2012-LUMB-91 growing season.



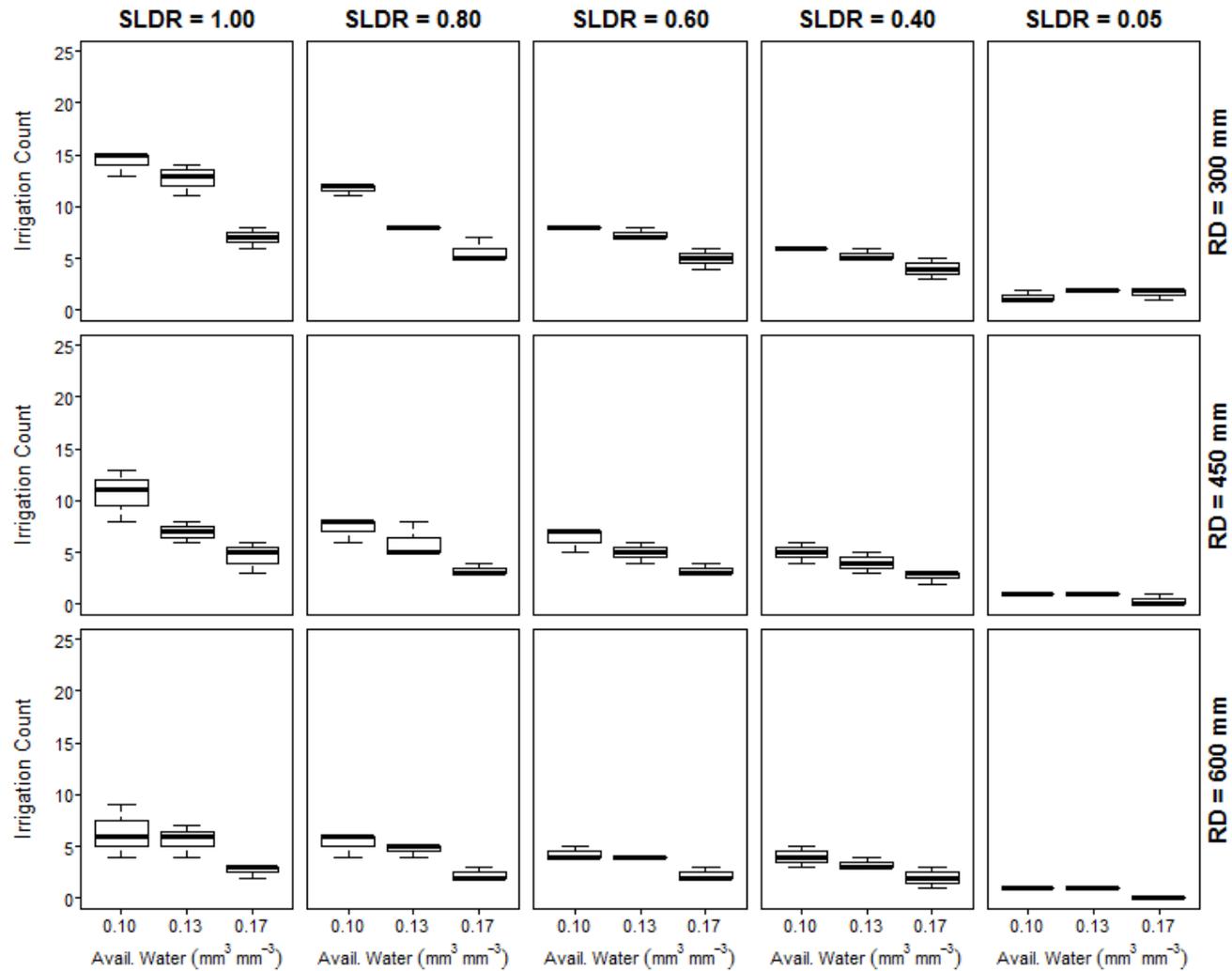
2014-LUMB-91

Figure F.8. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RD_{max}, and available water for the 2014-LUMB-91 growing season.



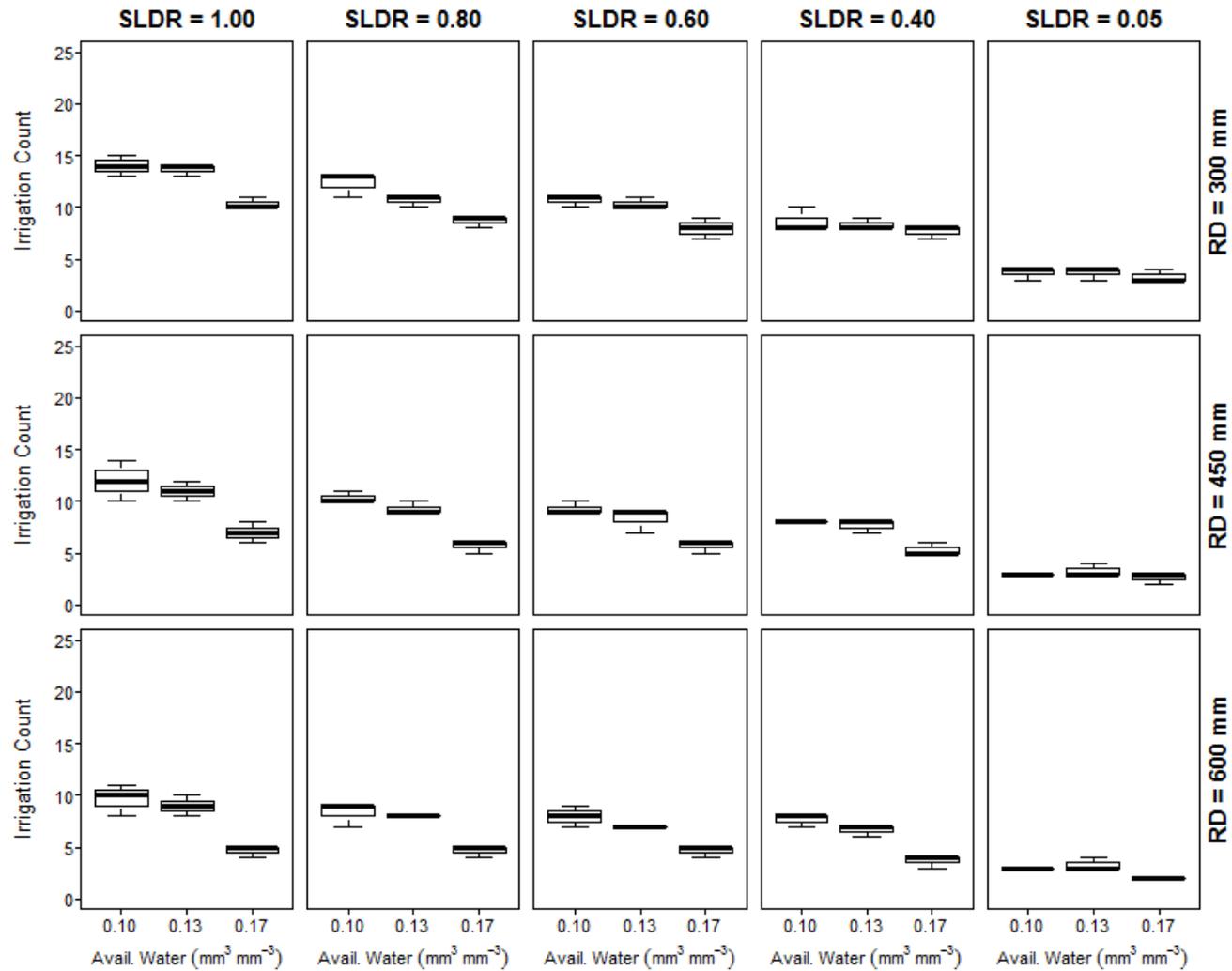
2013-WHIT-105

Figure F.9. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2013-WHIT-105 growing season.



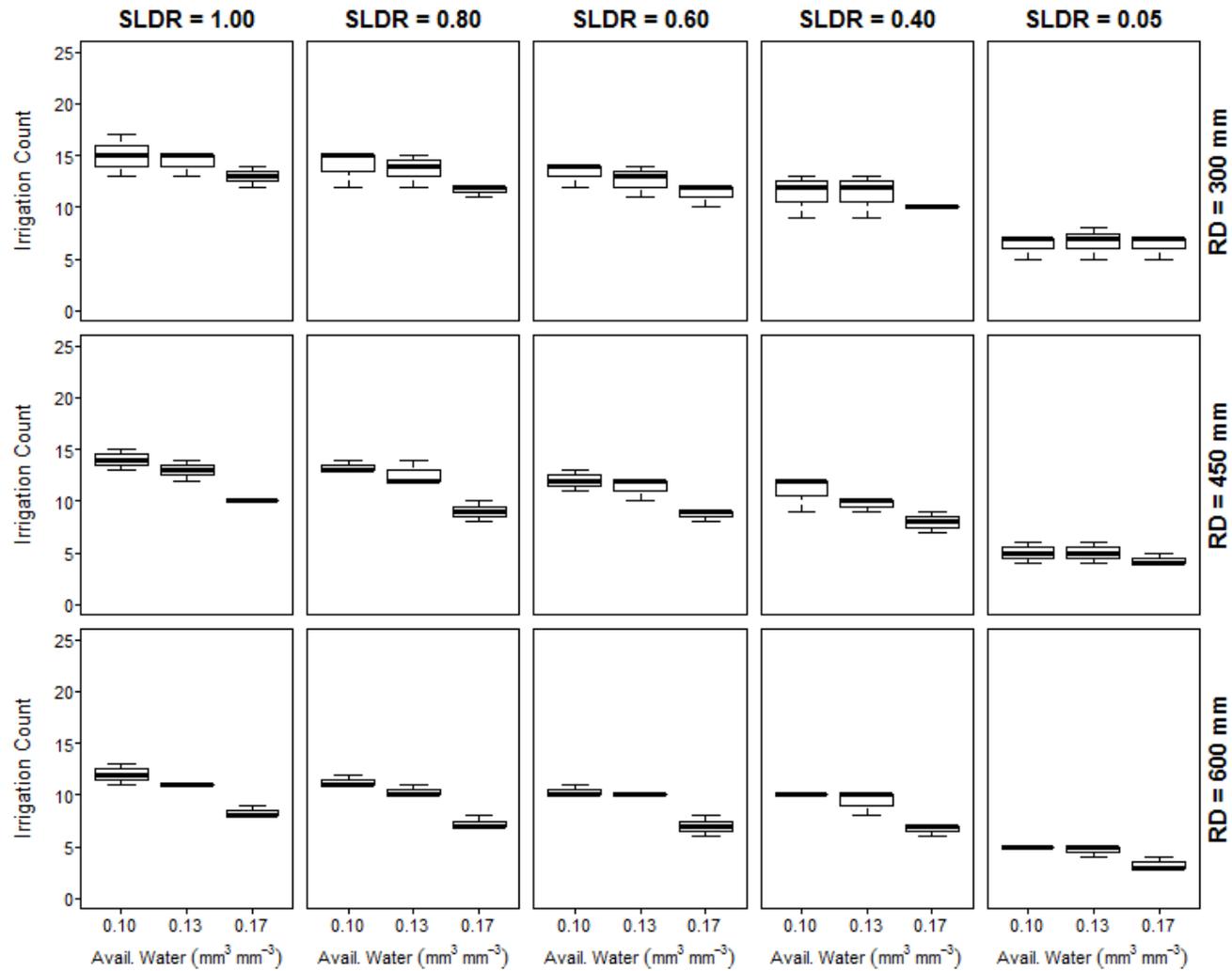
2014-KINS-105

Figure F.10. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2014-KINS-105 growing season.



2014-KINS-91

Figure F.11. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2014-KINS-91 growing season.



2014-LEWI-91

Figure F.12. Average number of irrigations recommended by the IDSS across all irrigation opportunity intervals for each combination of SLDR, RDmax, and available water for the 2014-LEWI-91 growing season.