Evaluation of Irrigation Scheduling Methods and Nitrogen Fertilization Effect on Corn Production in Alabama

by

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ABSTRACT

The unpredictable rainfall distribution patterns and high spatial variability in soil texture are promoting changes in irrigation and fertilization management. Irrigation systems are helping farmers to achieve consistent yields, regardless of the rainfall conditions, while irrigation scheduling methods are contributing to increase irrigation efficiency. Several studies have looked at the relationship between irrigation application, available water in the soil and N fertilizer uptake as a way to optimize yield and minimize environmental impacts. In Alabama, few studies of this type have been conducted.

Studies were conducted during two growing seasons (2014 and 2015) at two locations in Alabama. The objective of the study conducted at Tennessee Valley Research and Extension Center (TVREC) was to evaluate the interactions between two irrigation scheduling methods (Pan evaporation and Sensor-based) and four N rate applications (0-control, 202, 269 and 336 kg ha^{-1}) on grain yield, aboveground biomass, plant N concentration, N uptake and Nitrogen Use Efficiency (NUE) on corn. The objective of the study conducted at E.V. Smith Research and Extension Center (EVSREC) was to evaluate the advantages and disadvantages of two irrigation scheduling methods (Checkbook and Sensor-based) on corn growing in Central Alabama.

In the TVREC study, irrigation scheduling methods consisted of the Pan evaporation method and Sensor-based method. The Pan evaporation method is based on managing the estimated crop's evapotranspiration (ET) using Pan Evaporation values and the crop's consumptive water use. The Sensor-based irrigation scheduling method is based on soil matric

potential values recorded by soil moisture tension sensors installed in a field. A soil water depletion of 35% of plant available water was set as irrigation threshold for the Sensor-based irrigation treatment, and then each irrigation event was initiated when the soil matric potential reached the soil water depletion threshold. The study located at EVSREC used the same Sensor-based method following a soil water depletion of 35% plant available water as the irrigation threshold. However, it was compared with Checkbook method, which is based on the soil water balance estimated using water lost by evapotranspiration (ET) and its replacement through rainfall or irrigation.

Results obtained in the first study at TVREC showed that 29% more water was applied on average using the Pan evaporation irrigation scheduling method compared to the Sensor-based. However, the amount applied from the two irrigation scheduling methods did not present statistical differences in terms of grain yield, aboveground biomass, or NUE. Also, technical problems with the irrigation pump during silking and grain filling periods may affect the grain yield response to N fertilizer and water application in both years. The growing season of 2014 received 138 mm of irrigation water on the plots under the Pan evaporation irrigation scheduling method and the Sensor-based irrigation scheduling method received 122 mm on the plots fertilized with 202 kg N ha^{-1} and 99 mm on the plots fertilized with 269 and 336 kg N ha^{-}1. The greatest grain yield was 14203 kg ha^{-1} achieved on the plot fertilized with 269 kg ha^{-1}. In 2015, the Pan evaporation plots received 215 mm of irrigation and the Sensor-based plots received 152 mm at 202 and 336 kg N ha^{-1} plots and 127 mm at 269 kg N ha^{-1} plots and the greatest yield was 13809 kg N ha^{-1} achieved on the plot fertilized with 336 kg N ha^{-1}

The results of the second study at EVSREC showed that the Checkbook irrigation scheduling treatment resulted on more water application than Sensor-based treatment during both growing seasons. However, there were not statistically significant grain yield differences with respect to both irrigation scheduling treatments. In contrast, the two irrigation scheduling methods resulted in comparable values for total profit per hectare. In 2014, Checkbook and Sensor-based treatment plots located on zone A showed yield of 10181 kg ha^{-1} and 9696 kg ha^{-1}, respectively. Also, the irrigation application was 193 mm in the Checkbook plots and 60 mm in the Sensor-based plots. In zone B, the Sensor-based and Checkbook treatment plots achieved yield of 9673 kg ha^{-1} and 9584 kg ha^{-1}, respectively. Moreover, the irrigation amount applied in the Sensor-based treatment (91mm) was lower than Checkbook treatment (193 mm). In the growing season of 2015, zone A showed yield of 13597 kg ha^{-1} and 12674 kg ha^{-1} on the Sensor and Checkbook plots, respectively. In zone B, yields were 13417 kg ha^{-1} and 11659 kg ha^{-1} on the Checkbook and Sensor-based plots, respectively. The irrigation amount was the same in both zones, 121 mm applied in the Checkbook plots and 70 mm applied in the Sensor-based plots.

Further studies are necessary to improve the knowledge of sensor technology as a tool for irrigation scheduling method. For example, research addressing the SMP corresponding the FC for the various soils in Alabama would help to determine more accurate values of PAW. In addition, the evaluation of different irrigation threshold values is important, because different threshold values would likely produce different results in terms of crop production.

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I. LITERATURE REVIEW

1. Current World Water Resources and Demand

Water is the essential ingredient of life, which influenced the development of civilizations and how small groups of people formed villages and cities. Sedlak (2014) stated that people started gathering in settlements for trade or mutual protection. Also, the short distance of their drinking water was an important factor. However, settlements grew into cities and increased the necessity of living longer distances from the water source. Living away from the water source resulted in the use of water from wells and subsequently, paying for home delivery.

Nowadays, access to water is still a challenge; however, the distance from a water source is not a problem anymore. In contrast, water quality and availability have become the current challenge to overcome. To illustrate how important this challenge is, let us think of the proportion of liquid freshwater with respect to the world's total water: a spoon of water in about 1 liter of water. This is mainly because almost 97% of the world's water is found in the oceans (Qadir et al., 2003).

The water scarcity situation is serious in some regions on the world, and it is anticipated that this situation will become worse during the first half of the 21st century (Oki et al., 2003). Chauhan et al. (2012) stated that declining availability of fresh water has become a worldwide problem, especially in arid and semi-arid regions where irrigation water is supplied mainly from groundwater. Furthermore, Pereira et al. (2002) states that water scarcity is not only affecting only the arid and drought-prone areas but also regions where precipitation is abundant.

Population and economic growth will continue increasing U.S demand for quality water and the competition for water resources (Schaible and Aillery, 2012). For example, the increase of urban population adds demands for fresh water. Biswas (1992) affirms that world population is the first reason for increasing shortage of water resources. Demands of municipal, industrial, and agricultural water are increasing where water resources are limited, thus competition between agriculture and more valued domestic and industrial water uses is increasing. Typically, agricultural products have lower added values; therefore, the water supply will be prioritized for domestic and industrial uses (Rosegrant and Ringler, 1999). Furthermore, conflicts addressing demands for water resources in the U.S. are expected to intensify due to environmental factors such as instream flow requirements, Native American water rights and the expanding energy sector (Schaible and Aillery, 2012).

1.2 Climate Change

Evidence indicates that global climate is changing and it will impact the agriculture and water resources substantially (IPCC Report, 2007; U.S. CCSP, 2008). Therefore, new precipitation patterns and rising temperatures will influence agriculture in several aspects. In addition, evapotranspiration is positively correlated with temperature. Hence besides the water supply, climate change will also affect plant water demand. Thus, plants will require more irrigation in one scenario of water supply reduction (Schaible and Aillery, 2012).

1.3 Agricultural Water Demand

Agricultural water use is under growing pressure as demands for water are increasing. However, to express the water demand in terms of numbers depends on specific parameters. For example, some countries differ in terms of water availability, irrigation technology, industrial platform and population, and then this variability can influence water demand. At a global level, withdrawal ratios are 70% agricultural, 11% municipal and 19% industrial. Nevertheless, averages of ratios for each country are 59, 23 and 18% for agricultural, municipal and industrial, respectively (FAO, 2015).

Increasing use of global fresh water for agricultural purposes is considered one of the causes of global freshwater scarcity (Jury and Vaux, 2007). Therefore, over the next decades, water supply availability will be under pressure, as a result of the increase in agricultural and industrial production (Ringler et al., 2010). The growing and wealthier population is also requiring more diversified diets, which will demand more water for agriculture (Molden et al, 2007).

2. Irrigation Systems

The definition of irrigation is conventionally expressed as the controlled application of quantities of water to crops in a timely manner (Adams, 1989). According to Coward (1980), irrigation is a complex system where hydrologic, engineering, farming, and irrigation development are interacting in order to supply water to agricultural areas. Irrigation represents the largest investment in the agricultural and rural sector of developing countries (World Bank, 2003). During the 1970s and 1980s, the peak of irrigation implementation, 50% of the irrigation investment was in agriculture. Even today, in several developing countries, the annual investments in irrigation systems are still in the agricultural sector (Backer et al., 1999).

The concern about producing more food to feed the growing population is increasing advances and adoptions of irrigation systems in agriculture. However, climate change is affecting water availability, which may impact both irrigation adoption and advancements (Doll, 2002).

3. How to deal with the water scarcity and inadequate irrigation practices

The cost of irrigation is increasing due to the worldwide shortage of water. Therefore, new methods of irrigation have been developed in order to minimize water use or maximize water use efficiency (WUE). When resources are abundant, pressure to achieve higher water use efficiency is small because it does not affect the economic return of producers. However when the resource becomes scarcer, there is pressure to regulate the property rights over the resource and to guarantee the conscious use (Otsuka and Place, 2001). It is clear that water is becoming scarcer and it is increasing the costs of irrigation, thus the concern to maximize crop production per unit of applied water is stimulating changes in irrigation management.

Wallace and Bachelor (1997) indicated different options for improving water-use efficiency (WUE) in different categories (agronomic, engineering, managerial, and institutional). Options to optimize WUE include: crop management to enhance rainfall harvesting but generally it occurs in small areas; proper irrigation systems and accurate irrigation scheduling to minimize irrigation losses; and selection of varieties with drought-resistant characteristics.

Crop water consumption per unit of area is expected to decrease by 3% and gross crop water use by 16%. The reason for this difference is increased irrigation efficiency because water losses are minimized, consequently reducing water withdrawals per unit of irrigated area (FAO, 2015). Furthermore, precision irrigation has an important role in reducing water waste using irrigation scheduling methods and devices to improve the accuracy of measuring plant water requirements (Jones, 2004).

The WUE determination requires the estimation of several parameters: plant parameters (species, variety, phenological stage); agronomic parameters (fertilization, water quality); and environmental parameters (weather, soil characteristics, climate changes) (Katerji et al., 2008).

Many methods have been proposed to relate WUE and crop-water productivity (WP); however, they are two different terms. Water use efficiency is basically the ratio of crop biomass production to water consumption by the crop (Hsiao et al., 2007; Turner, 2004). Ali and Talukder (2008) stated that WP is the relationship between crop produced and the amount of water involved in the crop production and it is expressed as the amount of crop production per unit volume of water. Even though WUE and WP have different definitions, they have a strong linkage because usually WP increases as WUE increases.

4. Problems related with over-irrigation

Previous studies have shown the negative crop environmental effects of over-irrigation that include nitrate leaching, sediment and nutrient losses by runoff, crop diseases, and higher crop production cost in terms of higher investment in N fertilizer, water, fungicides and energy (Howell, 1996; Tarchitzky and Chen, 2002; Vermillion, 1997) . Nitrate leaching is influenced by soil properties, precipitation, amount of irrigation and specific of nitrogen (N) application (Shepherd, 1992). Runoff caused by over-irrigation will affect several water quality parameters such as pH, total suspended solids, and dissolved oxygen (Winter, 1998). Full irrigation minimizes water stress, however moisture in the canopy is increased and may be conducive to disease associated with high humidity (Cook and Papendick, 1972).

In dry areas the use of low-water for irrigation and not optimum irrigation rate can increase the concentration of mineral salts in the soil (Chapman, 1996; Eldridge, 1963; Sylvester and Seabloom, 1962; Wilcox, 1962). Water used in irrigated areas have potential to contain several tons of dissolved salt per acre-foot (Rhades et al., 1971). The increase in salt concentration occurs with irrigation because plants absorb and transpire water from the soil; however significant amounts of salt are left in the soil profile. The high concentration of salt in the soil solution will harm crop growth but some of the soluble salts must pass through the root zone and be flushed away with excess of water (Edminster and Reave, 1957).

Excess soil moisture can also affect root development, aeration, and temperature of the soil. For instance, if the plant is under high water availability in shallow layers, roots will not be forced to reach the deeper layers of the soil. Also, soil aeration is necessary for supplying oxygen to the roots and for removing carbon dioxide and other toxic substances (Williamson, 1964).

5. Irrigation Scheduling

Irrigation scheduling is an important element to improve WUE. Jensen et al. (1990) defined irrigation scheduling as a decision-making activity the producer is involved in before and during the growing season. Another definition for irrigation scheduling is the process of determining when to irrigate and how much water to apply, based upon measurements or estimates of soil water or water used by the plant (ASABE Standards, 2007).

Irrigation scheduling requires knowledge on several factors: crop water requirements and yield responses to water, conditions and limitations of the irrigation system, the water supply availability, and expected economic return (Pereira et al., 2013). Factors influencing water dynamics in the soil such as infiltration and uniformity of irrigation application in the field must be considered to improve irrigation methods (Hlavek, 1995).The consideration of all these aspects makes irrigation management a complex practice, but proper management may result in increased efficiency.

How much water to apply during an irrigation event depends on the soil water holding capacity, and the amount of plant available water depleted from the soil by evapotranspiration. Rhoads and Yonts (2000) stated that to start an irrigation event depends on crop water use and plant available water in the soil profile. Management allowed depletion is dependent on the type of crop, plant stage, and drought sensitivity. For example, management allowed depletion recommended for vegetable crops is only 20 % during critical stages of development because usually vegetables are not drought tolerant. Gross returns are also typically much higher, which justifies more irrigation usage. On the other hand, depletion for soybeans (*Glycine max*) and cotton (*Gossypium*) may reach 70% (Evans et al., 1996b).

Technological innovations have resulted in a large number of irrigation scheduling tools including procedures to compute crop water requirements and estimate the moisture or plant available water in the soil (Hoffman et al., 1990). However, the majority of farmers do not use irrigation scheduling practices on their farms (Pereira, 1996). Among the benefits of irrigation scheduling practices are increased yields and economical returns, water savings, and reduced environmental impacts (Smith et al., 1997).

5.1 Irrigation Scheduling Methods

There are three main approaches regarding irrigation scheduling methods and these are mainly based on soil water measurements, meteorological data or monitoring plant water stress. Martin et al. (1990) stated that irrigation scheduling has been divided into methods based on soil or plant monitoring and soil water balance estimates. The choice of irrigation scheduling method depends on the irrigation strategies and the irrigation system capabilities. More sophisticated scheduling method techniques may be more accurate, but they require higher investments in precision agriculture tools; nevertheless simpler irrigation systems like flood irrigation can achieve improvements when irrigation scheduling is applied (Jones, 2004).

5.2 Water balance estimates method – Farmer's usual practice

The basic method for irrigation scheduling is referred to as the water balance estimate method, which involves estimation of the soil water balance by measuring the amount of rainfall and/or irrigation and then estimating the water deficit using crop water use and evaporation. Harrison and Lee (2007) found the Checkbook method , the irrigation scheduling based on soil water balance, the simplest and most practical way of irrigation scheduling in corn (*Zea mays*). The Checkbook method provides irrigation directions according to the soil water deficit calculated using water balance data collected by irrigator (Wright and Bergsrud, 1991).

Evans et al. (1996b) compared the Checkbook method with a bank account based on deposits and withdrawals, where the estimation of how much water remained in the soil is the calculation of inputs (rainfall and irrigation) and outputs (evapotranspiration). Furthermore the maximum amount of water that can be held in the "bank account" is equivalent to plant available water (PAW). Water exceeding the water holding capacity is lost to the aquifer below, although the producer can minimize the chances of water excess by keeping the proper water balance in the soil.

Water balance estimates may change from one method to another. However, independent of the method, daily data recording (precipitation, irrigation, and crop water use) is extremely important. Thus, the necessary data includes initial in-field soil water deficit, crop grow stage, daily maximum and minimum temperature, daily crop water use estimation, and precipitation and irrigation amounts. The initial in-field soil water deficit can be estimated using tensiometers or the Feel and Appearance technique. Daily crop water use estimates can be found in agronomy or extension reports; furthermore the closest weather station will provide relevant information in terms of meteorological data.

Ko and Piccinni (2009) conducted a field experiment to investigate grain yield responses of corn under irrigation management based on crop evapotranspiration. Results indicated that irrigation scheduling based on evapotranspiration measurements can be an efficient irrigation method for corn with a 10% reduction of grain yield and consequently increased WUE. Therefore, irrigation scheduling based on water balance measurements is a good management tool when used correctly (Duke et al., 1987; Killen, 1984; Lundstrom and Stegman, 1988; Wright and Bergsrud, 1991).

5.3 Sensor-based irrigation scheduling method

New technologies to minimize water waste and environmental impacts have received significant support from American agricultural agencies, and these tools have been used across different parts of the world. For instance, a U.S. Air Force base located in Afghanistan has taught local farmers how to use Watermark soil water tension sensors since 2006 (Kapinos, 2006).In 2009, the U.S. Department of Agriculture located in Arkansas invested $4.45 million to introduce water monitoring technology and soil water content sensors in irrigated areas of the state (NRCS, 2009). Therefore, all these facts suggested that the advances in soil water content technologies will increase in order to support the demand of tools to guide the farmers to minimize the water use.

Several innovations to increase farming efficiency and improve water management have been developed using different approaches such as sensors capable of monitoring soil moisture content or plant water stress based on key soil/plant parameters (Fereres and Goldhamer, 1990; Goldhamer et al., 1999; Hanson et al., 2000). For instance, crop water status can be measured using soil moisture sensors, which provide the water content in the soil profile, and soil matric potential sensors, which indicate the tension plant roots must exert to uptake soil water. Another method used for irrigation scheduling is the use of remote sensors, either spectral or canopy temperature sensors, to assess plant water stress or plant water use (Sui et al., 2012).

Chanzy et al. (1998a) affirmed that the new technologies and practices of irrigation management can vary in many aspects that include operating and device cost, accuracy, reliability, and risk in terms of functional management. Therefore, there are vast options of tools to conduct irrigation management including neutron scattering, tensiometers, gravimetric measurements, capacitance sensors, time domain reflectometry (TDR), electrical resistivity measurements, heat pulse sensors, and fiber optic sensors (Gardner and Klute, 1986; Leib et al., 2002; Leib et al., 2003; Seyfried, 1993). Based on these technologies, producers have many options to upgrade their irrigation schedule strategy; thus they are able to choose something that fit in their budget and conditions.

6. Variable Rate Irrigation – Right Rate, Right Place, Right Time

There are multiple technologies that can be added to center pivot system in order to improve their performance. For example, variable rate irrigation (VRI) is the application of variable amounts of water along the pivot according to the crop water demand and soil variability (Dukes and Perry, 2006). The VRI enables a center pivot to apply water depending on specific characteristics of different areas within the field (Perry and Pocknee, 2003). Evans et al. (1996a) also expressed the importance of VRI systems in order to supply water and N fertilizer precisely at optimal rates relative to characteristics of each irrigation management zone.

Therefore, VRI system changes the irrigation rate varying the center pivot speed and using the sprinkler capabilities to turn on and off following an irrigation requirements map. The irrigation maps are previously defined and the GPS device is used to determine the pivot position and angle.

Plant available water in the soil and the daily water demand of the crop are important parameters in order to operate the VRI system properly. For this reason, the mutual use of irrigation scheduling methods and VRI is the key to optimize irrigation management. Irrigation scheduling method will define the soil water status using the water balance approach or measuring directly with real-time soil moisture sensors, and then the VRI will provide the correct amount of water at the right time (Sadler et al., 2002).

There are possibilities to upgrade center-pivot systems without VRI capabilities by modifying individual sprinkler controls (Dukes and Perry, 2006; King and Kincaid, 2004). Therefore, older center-pivots systems can convert water applied to yield increases, while minimizing N leaching, runoff and drainage. Water application and yield are strongly linked, thus the proper amount of irrigation applied will be reflected in yield (Allen et al., 1998; Hanks, 1974).

7. Impact of Nitrogen Fertilizer and Different Irrigation Rates

Several studies have been conducted to evaluate the interaction between N and water supply and their effect on crop production (Moser, 2006; Pandey et al., 2000; Shangguan et al., 2000). Therefore, the combination of optimum irrigation and N fertilizer can increasegrain yield more than if only one of these factors is considered (Geerts and Raes, 2009; Rudnick and Irmak, 2013). Furthermore, grain yield is not the only benefit of an optimum interaction of irrigation and N fertilization. Montazar and Azadegan (2012) stated that effective management strategies for irrigation and N fertilizer can maximize crop production profits by decreasing water waste, N leaching, and consequently reducing environmental damage. Excess N application does not necessary affect crop yield increases, but it can considerably increases the N loss by leaching (Hou et al., 2012; Ju et al., 2009a; Matson et al., 1997; Shi et al., 2012). Therefore, to maximize N availability for plants and decrease N leaching, it is important to find the optimal ratio of irrigation application and N rate.

Al-Kaisi and Yin (2003) tested the effects of irrigation and N rate on corn yield and WUE and obtained comparable results for plant N uptake and grain yield in treatments irrigated with 80% and 100% of the estimated evapotranspiration. Irrigation at 60% of evapotranspiration was not competitive for grain yield compared to the other two irrigation methods (80% and 100% of ET). Also they indicated that the N applied at 250 kg N ha^{-1} could be replaced by 140 kg N ha^{-1} because no significant grain yield was obtained, regardless of the irrigation treatment. Ferguson et al. (1991) also stated that a reduction of 50 kg N ha^{-1} did not statistically affect grain yield; however, it can promote significant economic savings and reduce environmental impacts.

Wienhold et al. (1995) found that the decrease in N rate can affect corn yield depending on the growing season temperature. Fertilizer rates equivalent to 100 and 200 kg N ha^{-1} were tested to evaluate grain and dry matter yields, as well as N content and utilization of fertilizer. For the years when the temperatures were below the 30-year average, there were no differences in yield and N content between the two N levels. However, when temperatures were higher than the 30-year average, corn responded to increasing N rate with 60% greater yield and 75% greater N content.

How This Thesis is Organized

The thesis includes an introductory chapter that provides a literature review of current status of irrigation in the southeast, methods of irrigation and irrigation scheduling and impact of nitrogen fertilization on corn production. Two subsequent chapters II and III discuss two independent studies, both conducted in Alabama, at the TVREC and Central Alabama at the EVSREC.

The objectives of the TVREC study were to:

1. Determine the effects of two irrigation scheduling methods, Pan evaporation and Sensor-based scheduling, on N supply on corn yield.
2. Evaluate the interaction of two irrigation scheduling methods and N rates on nitrogen use efficiency (NUE).
3. Assess the impact of different N rates on yield and NUE.

The objectives of the EVSREC study were to:

1. Evaluate the advantages and disadvantages of two irrigation scheduling methods, Checkbook and Sensor-based scheduling in terms of yield impact and water use differences.
2. Evaluate the advantages of using soil sensors as an irrigation scheduling tool.

II. EVALUATION OF TWO IRRIGATION SCHEDULING METHODS AND NITROGEN RATES ON CORN PRODUCTION IN BELLE MINA, ALABAMA

Abstract

Currently, irrigation water availability has been changing due to global climate change and more frequent periods of drought. Additionally, regulations on nutrient application amounts and environmental impacts of fertilizers are promoting advances in agricultural management strategies to optimize irrigation application and N fertilization in corn. Previous studies have found a relationship between irrigation application, available water in the soil, and N fertilizer uptake. The objective of this study was to evaluate interactions between two irrigation scheduling methods and four N rate applications (0-control, 202, 269 and 336 kg ha^{-1}) on grain yield, aboveground biomass, plant N concentration, N uptake and Nitrogen Use Efficiency in corn. The study was conducted at the Tennessee Valley Research and Extension Center (TVREC) during two growing seasons (2014 and 2015). Irrigation scheduling methods consisted of i) the Pan evaporation method, which is based on managing the crop's estimated evapotranspiration (ET) using Pan evaporation values and the crop's consumptive water use, and ii) the Sensor-based irrigation scheduling method based on soil matric potential values recorded by soil moisture tension sensors installed in the field. A soil water depletion of 35% of plant available water was set as the irrigation threshold for the Sensor-based irrigation treatment, and then each irrigation event was initiated when the soil matric potential reached the soil water depletion threshold. Irrigation amounts from both irrigation scheduling methods indicated, less water was applied with the Sensor-based method. The 2014 growing season received 137 mm of irrigation water in the plots under the Pan evaporation irrigation scheduling method and the Sensor-based irrigation scheduling method received 121 mm in the plots fertilized with 202 kg N ha^{-1} and 99 mm in the plots fertilized with 269 and 336 kg N ha^{-1}. In 2015, the Pan evaporation plots received 215 mm of irrigation and the Sensor-based treatments received 152 mm at 202 and

336 kg N ha^{-1} plots and 127 mm at 269 kg N ha^{-1} plots. Different amounts of irrigation applied associated with the two irrigation scheduling methods did not impact grain yield, aboveground biomass and NUE. Also, the grain yield may have been affected by technical problems with the irrigation pump during a period of high corn water demand in both growing seasons. In general, NUEs values decreased with increased N rates, which means that additional N fertilizer added in the soil was not converted to grain yield or/and adsorbed by plants; therefore, more N remained in the soil, increasing the risk for environmental problems.

Introduction

The challenge of making farming profitable and minimizing environmental effects of agriculture have increased adoption of new technologies and practices to increase crop production efficiency. Regarding corn production, two major factors affecting yield are soil water availability and nitrogen (N) fertilization; therefore, irrigation and N application are important management factors for producers. Irrigation is a relevant tool in Alabama and this practice has been increasing among farmers, even though the state enjoys average rainfall amounts of about 1422 mm per year. However, the amount and distribution of rainfall is highly unpredictable because they can vary drastically depending on the year. Rainfed corn production is risky with large variations in yield from one year to the next. In Alabama, even though the number of irrigated harvested acres of cropland increased from 1997 to 2012, only approximately 44 thousand hectares out of the 870 thousand hectares of harvested cropland were irrigated (USDA, NASS 2016). Lack of water from rainfall and/or irrigation can impact the morpho-physiology of corn in terms of cellular and whole-plant effects (Boomsma and Vyn, 2008). Thus, it can result in substantial yield reduction and reasserting the importance of irrigation for consistent corn yields. Meanwhile, N fertilizer is also crucial for corn production and (Qiu et al., 2015) states that N is the most limiting nutrient for agricultural production, and N fertilizer is an important component to maximize the yield of most non-legume crops. Woli et al. (2016) evaluated data of corn hybrids from the 1960 to 2000 and determined that grain yield increased by 65% and total plant biomass by 45% with agronomic optimum N input.

Several approaches, such as improved irrigation technologies that include variable rate irrigation and more efficient irrigation scheduling methods, can be adopted by farmers for more effective use of limited water supplies to maximize water use efficiency (WUE) (Zaman et al., 2001; Kirda, 2002; Pereira et al., 2002; Zeng et al., 2009). The aim of an efficient irrigation scheduling program is to optimize the WUE, replenishing the water deficit within the root zone while minimizing N leaching below this depth (Fares and Alva, 2000). Currently, multiple irrigation scheduling methods have been developed to help producers maintaining adequate soil water content levels in the root zone. Technological advances have improved the devices that continuously monitor changes in soil moisture status. These devices are able to monitor soil moisture during and after irrigation, also it controls the amount of water applied. Phene and Howell (1984) confirmed that irrigation systems can be controlled accurately with sensors that monitor the soil matric potential within the root zone. There are, however, simpler methods to conduct irrigation scheduling. The Pan evaporation method using data from weather stations can be the simplest, cheapest, and most practical meteorological method to measure local atmospheric evaporation demand (Stanhill, 2002). Additionally, values obtained using the Pan evaporation method are important references for water resource assessment and monitoring evaporative climate change (Bruton et al., 2000; Thom et al., 1981). It is recognized that the adoption of appropriate irrigation scheduling practices could increase or maintain yields and maximize profit for producers. Also water savings can reduce the risk of over-irrigation and environmental impacts and consequently improve agricultural sustainability (Pereira, 1999).

Nitrogen fertilization indicates the highest yield increasing effect for corn on different soils occurs when the three macro-elements (NPK) are considered (Fabrizzi et al., 2005; Shaahan et al., 1999). Many physiological processes associated with corn development are enhanced with N fertilization (Eck, 1984). Variation in N application affects crop growth and yield components like potential kernel set (Cox et al., 1993; Greenwood, 1976; McCullough et al., 1994). Numerous studies have shown that N fertilization is highly correlated with corn growth, thus lower N supply can promote reduction of leaf area index (LAI), plant height, crop photosynthetic rate, radiation use efficiency and plant N uptake (Novoa and Loomis, 1981; Pandey et al., 1984; Toth et al., 2002; Uribelarrea et al., 2009).

The integration of effective water and fertilizer management strategies is essential for increasing crop production and maximizing the economic net return, while sustainability is maintained (Djaman et al., 2013; Eck, 1984; Eghball and Maranville, 1993; Liu et al., 2015). Management strategies for water and N can minimize crop production costs and environmental impacts, while maintaining crop performance and economic returns (Montazar and Azadegan, 2012). Efficient N utilization to obtain high yields require adequate water supply for the crop. For instance, a reduction in plant transpiration as a result of water stress can cause decrease in N uptake (Szeles et al., 2012), including reduced development of stem and leaf cells (Lauer, 2003). On the other hand, a surplus of irrigation and N fertilizer can increase residual soil NO_3-N and it may leach or denitrify, reducing the efficiency of applied N. Studies have demonstrated that crop growth and yield response to N fertilization varies under different water management conditions. However, there are few studies addressing interactions between N management strategies and the soil water status in Alabama. Therefore, studies to understand N uptake dynamics and determine the best N management practices under two different irrigation scheduling methods are important to help Alabama producers optimize corn yields and avoid adverse environmental impacts. The objectives of this study were (1) to determine the effects of two irrigation scheduling methods, Pan evaporation and Sensor-based scheduling, on N supply on corn yield and (2) evaluate the interaction of this different Irrigation Scheduling Methods and N on Nitrogen Use Efficiency (NUE) and (3) assess the impact of different N rates on yield and NUE.

MATERIALS AND METHODS

Site Description

The field experiment was conducted at TVREC located in Belle Mina, Alabama (34°39′24″N 86°52′45″W, 183 m above mean sea level) during the 2014 and 2015 growing seasons. The dominant soil series at the research site is a Decatur silty clay loam (fine, kaolinitic, thermic Rhodic Paleudults) with 0% to 10% slope (NRCS Web Soil Survey; http://websoilsurvey.nrcs.usda.gov). Overall, rainfall conditions during both growing seasons (April-August) were below the 30 year average (1971 – 2000). Total rainfall during the 2014 growing season was 11 mm below average and 19 mm below average in 2015. However, in 2014, rainfall distribution per month with respect to the historic average (1971-2000) was higher in April (+39 mm) and June (+42 mm), but rainfall in May (-50 mm), July (-13 mm) and August (-29 mm) was below average. In 2015, above normal rainfall with respect to the 30 year average was observed in in April (+21 mm) and May (+6 mm) contrasting with rainfall in June (-21 mm), July (-1 mm), and August (-24 mm) that was below average.

Experimental Design

A split-plot design with three replications was implemented for this study in which irrigation regime was the main plot and N fertilizer rates were the subplots (Figure 1.1). Two irrigation scheduling methods(Pan evaporation method and Sensor-based irrigation method), and four N rates (0-control, 202, 269 and 336 kg ha^{-1}) were tested for plant N uptake, NUE, and yield differences. Plots consisted of eight rows 11.8m long and 5.3m wide with a row spacing of 76.2 cm and the seeding rate was 89,000 plants ha^{-1}. Urea ammonium nitrate (UAN 32-0-0) was used as the fertilizer source, which was split applied with 1/3 of the total applied at planting and the remainder in a side-dress application at the V6 growth stage. Each eight-row plot was divided in half, 4 rows received 202, 269, or 336 kg N ha^{-1}depending on the randomization and the other adjacent 4 rows did not receive any N which allowed for NUE estimation. Plots received 224.1 kg ha^{-1} in a pre-plant application of P and K. All the cultural practices were performed according to Alabama Cooperative Extension System (ACES) recommendation to maximize corn yield. Each plot was independently irrigated with four overhead sprinkler nozzles located in each corner of the plot.

According to ACES, recommended N rate for irrigated corn in the state is 224.1 kg ha^{-1} in order to achieve 11299 kg ha^{-1}yield. If the yield goal is greater than 12555 kg ha^{-1}, the N recommendation is to apply 1 kg of N per 45.3 kg of anticipated corn yield (Mitchell and Huluka, 2012). The Pioneer 1690YHR corn hybrid was planted on April 4th in 2014 and April 24th in 2015 in single rows and managed with conservation tillage and rye (*Secale cereale*) cover crop. In both growing seasons, the cover crop was planted on 11/21/13 and 11/07/14, respectively. It received 33.6 kg ha^{-1} of N fertilizer (UAN 32-0-0) in both seasons to maximize biomass production.

Water Management Treatments

Two irrigation scheduling methods tested in our study differed from each other in the way to estimate the amount of water stored in the soil during the growing season. The Pan evaporation method was based on calculating the crop's estimated evapotranspiration (ET) using the Pan Evaporation values and the crop's consumptive water use. On the other hand, the Sensor-based irrigation relied on measurements of soil matric potential provided by sensors in order to apply the correct amount of irrigation at the right time. The Water Use Efficiency (WUE) of the two irrigation scheduling methods was included in our evaluation to establish differences in total amount of water applied in the plots.

Pan Evaporation Irrigation Scheduling

Daily Pan evaporation data was reported from the weather station located at the research site (www.awis.com).The daily irrigation requirement, ET, was calculated using the following equation: ET = 0.90 x PAN x CC where evapotranspiration, ET (mm day^{-1}) was calculated from 90% Pan evaporation, PAN (mm day^{-1}) adjusted for fractional canopy cover (CC). Canopy cover was determined weekly by measuring the open canopy distance (cm) between rows with a tape measure. Fractional canopy cover was calculated using the following formula; (row width - open canopy distance)/row width. Canopy closure measurements were a critical component used in this study to determine the daily amount of irrigation water. Rainfall was not accounted for in the equation because calculated Pan Evaporation values on cloudy and rainy days decreased considerably, so this method accounts for rainfall without directly subtracting rainfall from irrigation amounts. Thus irrigation was applied based on the above equation, replacing water lost by evapotranspiration. Soil moisture sensors were not used as a tool to schedule irrigation with Pan evaporation plots. However, some sensors were installed in the Pan evaporation plots in order to monitor soil water dynamics. The irrigation date and amount from the Pan evaporation method is included in the (Appendix 1)

Sensor-based irrigation scheduling

Irrigation events in the Sensor-based irrigation scheduling plots were conducted using information from soil water tension sensors installed between two corn plants in the experimental area. The smart sensor array system used in our research consisted of a centrally located receiver connected to a laptop computer and multiple sensor nodes installed in the field. Each sensor node consisted of sensors (3 soil moisture sensors - Watermark) and thermocouples), a sensor circuit board, and an active transmitter, which transmitted data to the receiver (Vellidis et al., 2007). The smart sensor board acquired sensor values and wirelessly transmitted those values to a centrally located radio frequency receiver, and then via cellphone signal, the data was transmitted to a website. The board of each node was able to read up to three Watermark granular resistive-type soil moisture sensors located at three soil depths (15, 30 and 60 cm) enabling a better assessment of the water availability through the soil profile. In term of water adsorption, these three soil depths corresponded to the most active root zone in corn. A Watermark sensor is a granular matrix device that was used to measure soil water tension, therefore the data obtained from the Watermark sensors is transferred to the data base in Kilopascal units. These soil water tension measuring devices provided a continuous measurement analogous to the force (Soil Matric Potential) necessary for corn plants to extract water from soil and these values were used to schedule irrigation. Watermark sensors have been used to measure soil water status for irrigation management and other purposes for more than two decades (Armstrong et al., 1985; Thomson and Threadgill, 1985; Thomson and Armstrong, 1987; Eldredge et al., 1993; Bausch and Bernard, 1996; Mitchell and Shock, 1996).

Soil Water Dynamics and Irrigation Strategy

Whereas soil moisture sensors provided hourly data of soil matric potential in the field, the next important step was to set the Manageable Allowed Depletion (MAD) which is how much water to decrease from soil before starting irrigation. The MAD represented the level of Plant Available Water (PAW) used by the plant or evaporated before irrigation was applied without exposing the plants to water stress. Several studies have recommended irrigating row crops such as corn or cotton (*Gossypium hirsutum L*) when the MAD approaches 50% (Doorenbos and Pruitt, 1977; Lamm et al, 1994; Evans et al, 1996). On another hand, Irmak et al. (2012) used 35% depletion of PAW in a study testing irrigation strategies based on soil matric potential sensors. Therefore, as it was the first time that this type of experiment was conducted in Alabama, a MAD of 35% was selected as a more conservative approach. Once the MAD in volumetric water content units was identified, it was necessary to identify the soil matric potential that corresponded with the specific MAD value. In order to define this MAD, soil water level, it was necessary to estimate first the Field Capacity (FC), Permanent Wilting Point (PWP), and PAW values, which were important parameters to determine the soil moisture threshold to start irrigation on the Sensor-based irrigation plots. Soil texture data from soil samples collected from the study site was used to calculate a Pedotransfer function which was used to estimate soil water retention curves (SWRC) and subsequently the FC and PWP parameters. Saxton et al. (1986) states that experience have shown that soil texture predominately determines the water-holding characteristics of most agricultural soils.

Disturbed soil samples were collected from three depths (15, 30 and 60 cm) in a representative area of the field. The disturbed soil samples were used to run a soil texture analysis, which allowed estimation of the percentage of sand, silt and clay for each sample. These data were used to estimate the van Genuchten equation parameters using the Retention Curve (RECT) Computer Program. The percent of sand, silt and clay data were inputted in the (RETC) Computer Program, thus this software defined the θ_r, θ_s, α, n values representing the experimental field. All these variables were plugged in the van Genuchten equation. The van Genuchten model has the following form:

$$\theta_h = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n)^m} \quad (1)$$

where θ(h) is the actual soil water content ($cm^3\ cm^{-3}$) at the suction h (cm, taken positive for increasing suctions); θr and θs are the residual and saturated soil water contents ($cm^3\ cm^{-3}$), respectively; α is a parameter related to the inverse of the air entry suction (cm^{-1}); m and n are curve shape parameters (Van Genuchten, 1980). Note that m here characterizes the asymmetry using the constraint m=1- 1/n, therefore the water retention characteristics defined by this equation only contained four unknown parameters, that was, θr, θs, α, and n and these unknown parameters were defined using the (RETC) Computer Program (Table 1.1). The solution of this equation provided enough data to generate the SWRC representing the soil water content according to the soil matric potential, which was essential to set the irrigation threshold (Figure 1.2).

Each SWRC was generated in order to estimate the amount of water retained in a soil (expressed as mass or volume water content) under equilibrium at a given soil matric potential. In practical applications, soil matric potential has a negative sign (i.e., more negative soil matric potential values indicate drier soil), however a positive sign is used in this study as an indicator of soil water tension.

Once SWRC was generated, the FC and PWP were identified. These parameters are the key for the PAW estimation. Richards and Weaver (1944) found that a coarse-textured soil can reach FC at 10 kPa and a fine-textured soil can reach FC at 33 kPa. The PWP is usually found at a soil matric potential of 1500 kPa. Therefore, for the purpose of this study, soil matric potential values representing FC were selected based on soil texture. In most cases, a FC value at 33 kPa was used in this study when the soil textural class in the experimental field was Silty Clay Loam, Silty Clay or Clay (Table 1.1 and 1.2).

The FC and PWP were established, thus the Plant Available Water (PAW) was calculated using FC minus PWP (Table 1.2). Once PAW was calculated, the irrigation threshold was set using the MAD value of 35%. The specific soil matric potential (tension) representing the irrigation threshold was equal to 76 kPa, which was the average value of the three soil depths (Table 1.2). Every time that the sensors installed on the Sensor-based irrigation plots were approaching 76 kPa, an irrigation event was triggered. A weighted average of the sensor values located at the three different depths was used and it changed according to corn growth stage. At the beginning of the season, the upper sensor (15 cm depth) had more importance as a parameter to schedule irrigation events because corn roots have not reached the deeper layers of the soil. However, as the season progressed, the average of the three sensor tension values was used. Dates and amounts of irrigation events for both Pan evaporation method and Sensor-based irrigation plots were registered; also each irrigation event did not exceed 15 to 25 mm in order to avoid runoff. Sensors located in the Pan evaporation plots were also monitored, however, the irrigation trigger was not based on sensor values but on the method described previously.

Nitrogen Rate Management Treatments

Three N rates (202, 269, and 336 kg N ha^{-1}) and the control (0 kg N ha^{-1}) were evaluated under the two irrigation methods in order to observe the impact of different N rates and irrigation practices including their interaction on corn yield, N uptake, and NUE. Aboveground biomass samples were collected at harvest to determine N concentration in the grain and stover, and then establish the impact of different N rates on NUE.

Field data collection and Data analysis

At maturity, corn plants were harvested from two 1m row sections of each plot. Samples were harvested from rows 1 and 4 because the middle two rows were harvested for yield data using the plot combine. Harvested plants were separated in ears and stover (stem + leaves), then the stover was weighted at the field and a subsample was collected. The ears and stover sub samples were oven-dried at 60^{0}C for one week to reach a constant weight. Also, the ears were shelled prior to N analyses. Posteriorly, the grain, cob and stover were ground through a 2 mm sieve and analyzed for total C and N with the $LECO^{R}$ C/N analyzer (Leco Corp., St.Joseph, MI).

The two center rows were harvested using a plot combine, and the grain yield was based on the data provided by the combine. The stover yield was the sum of cob and stalk yield. Stalk yield was calculated based on the fresh stalk yield harvested in 2 m row and the proportional oven-dried stalk yield in the subsample. Cob yield was calculated based on total weight of oven-dried cobs after the grain was shelled. Grain yield, aboveground biomass, plant N concentration, and plant N uptake are reported on oven-dried basis.

For each plot, the Aboveground N uptake, Recovery Efficiency (RE_n), Nitrogen Agronomic Efficiency (AE_n), Nitrogen Internal Efficiency (IE_n), and Nitrogen Partial Productivity (PFP_n) values were calculated using the following equations:

Aboveground N uptake = (Grain N concentration x Grain yield) + (Stover N concentration x Stover biomass)

$RE_N = (U_N - U_0)/N\ rate \times 100\%$ (2)

$AE_N = (Y_N - Y_0)/N\ rate$ (3)

$IE_N = Y_N/U_N$ (4)

$PFP_N = Y_N/\ N\ rate$ (5)

where U_N and Y_N represented the N uptake by aboveground biomass and grain yield in the fertilized treatments, respectively; U_0 and Y_0 represented the N uptake by aboveground biomass and grain yield in the control treatments, respectively. The N rate was the total amount of N applied during the corn growing season. The NUE was calculated using four different formulas in order to evaluate the interaction between yield and N uptake as N rate change.

Statistical Analysis

Yield, aboveground biomass, grain N concentration, stover N concentration, grain N uptake, aboveground N uptake, RE_n, AE_n, IE_n, and PFP_n differences among N rates were analyzed for both years of the study and for each irrigation scenario (Pan evaporation irrigation scheduling method and Sensor-based irrigation scheduling). The statistical analysis was conducted using the procedure for generalized linear mixed models (PROC GLIMMIX) implemented in SAS 9.1 (SAS for Windows v. 9.1, SAS Institute Inc., Cary, NC). All dependent variables were first analyzed to measure the effect of the Irrigation Scheduling Methods, N rates, and Years as fixed effects. It allowed us to measure the magnitude of Irrigation Method x N rate x Years interactions. Preliminary analyses suggested the need for treating Years as non-fixed effect in order to observe the effects of each year independently and Scheduling Methods and N rates as fixed effects. The mean separation between Irrigation Methods, N rates, Years and all the interactions were obtained by a Tukey’s significant difference test ($P < 0.05$).

Results and Discussion

Climatic conditions and irrigation performance

Monthly average weather variables for the 2013, 2014 and 2015 growing seasons including the long term average values (1971-2000) are summarized in (Table 1.3). Overall, climatic conditions helped explain differences in irrigation amount and grain yield. Differences in rainfall and temperature influence crop evapotranspiration in a given environment. Runge (1968) found that daily temperature and rainfall affect corn yield from 25 days before to 15 days after anthesis. The seasonal average temperature was 22.60 ^{0}C and 23.50 ^{0}C in 2014 and 2015, respectively. The seasonal total rainfall in 2014 and 2015, respectively, were 502 mm (2.1% below normal) and 495 mm (3.7% below normal). The total rainfall was relatively similar across the two years and slightly below the (30 years) normal, which was 513 mm. However, rainfall distribution through the growing season will have greater effect on irrigation amount than total rainfall. Thus, if rainfall is concentrated in the period of high water demand, irrigation requirements will be reduced and if rainfall is concentrated at the beginning and the end of season it will also limit irrigation requirements. In this study, rainfall was distributed differently before and after tasseling in 2014 but evenly in 2015. According to Lee (2011) tasseling is the highest corn water demand period. In 2014 (41% and 58 % of total rainfall) and 2015 (49% and 51% of the total rainfall) were evenly distributed before and after tasseling, respectively.

Irrigation Amounts

Average irrigation amounts applied in the sensor plots were 106 mm and 142 mm in 2014 and 2015, respectively. However, the temporal distribution of rainfall between the two growing seasons was not comparable. Rainfall in the 2014 growing season was concentrated after tasseling, 294 mm, and in 2015, the rainfall distribution was similar before and after tasseling, 246 mm and 248 mm, respectively. Thus, considering that after tasseling corresponds to a period of greater water demand in corn, consequently the 2015 season received more irrigation. The irrigation application dates and amounts during both growing seasons and the two irrigation scheduling methods is provided in the Appendix 1 and 2.

Irrigation amounts for the two irrigation scheduling methods indicated that Sensor-based received less irrigation during both growing seasons. The 2014 growing season received 138 mm of irrigation water on the plots under the Pan evaporation irrigation scheduling method and the Sensor-based irrigation scheduling method received 122 mm in the plots fertilized with 202 kg N ha^{-1} and 99 mm in the plots fertilized with 269 and 336 kg N ha^{-1}. In 2015, the Pan evaporation plots received 215 mm of irrigation and the Sensor-based treatments received 152 mm at 202 and 336 kg N ha^{-1} plots and 127 mm at 269 kg N ha^{-1} plots.

Furthermore, some technical problems with the irrigation system occurred during the two growing seasons. The irrigation pump did not work properly during a period of high corn water demand (from flowering to mid-dough) and it took some weeks to be fixed in 2014 and 2015. During the peak of corn water demand, irrigation timing and amount is key to achieve high yields. Therefore, these unexpected technical problems with the irrigation system in 2014 and 2015 likely limited the crop response to the N applications and also the differences on total irrigation amount applied between both irrigation treatments. The water availability in the soil is strongly linked with the N uptake; therefore the lack of moisture in the soil during the period that the irrigation pump was not working properly might have reduced the N uptake and consequently the crop response to N application.

Figures 1.3 and 1.4 illustrate soil water dynamics in the Pan evaporation and Sensor-based plots during the 2015 growing season, respectively. Daily soil matric potential data was collected from sensors installed in the plots fertilized with 269 kg N ha^{-1}. The figures show how irrigation and rainfall affected soil matric potential values. From the Pan evaporation method was possible to observe that even though a specific irrigation threshold was not set, the soil matric potential was maintained below 76 kPa, at approximately 50 kPa, due to more frequent irrigation events (Figure 1.3). In the Sensor-based approach, irrigation events were applied when the soil matric potential approached the threshold (76 kPa) (Figure 1.4). Therefore, since soil matric potential was maintained at lower values in the Pan evaporation method, it infers that the soil had higher moisture during the growing season. Also, the Sensor-based method depleted more water and faster from the soil for irrigation events scheduled at a higher soil matric potential. After July 22, malfunctions occurred mainly in the sensors located in the 30 and 60 cm depth located in this treatment (Sensor-based irrigation fertilized with 269 kg N ha^{-1}). However, irrigation practices in the Sensor-based irrigation was continued using the shallowest sensor.

Irrigation Scheduling Methods Effects – Pan evaporation and Sensor-based irrigation.

Differences between Pan evaporation and Sensor-based were not significant with respect to all parameters analyzed in this study, except for RE_n (Table 1.4). Therefore, different amounts of irrigation applied using the two irrigation scheduling methods did not result in significant interactions among treatments that include irrigation (I x N, I x Y, and I x N x Y) for examined variables during 2014 and 2015. Again, technical problems in the irrigation system may have affected the performance of both irrigation scheduling methods.

Grain yield is important indicator of profitability for farmers and there were no differences between irrigation methods when these variables were analyzed. During both growing seasons, Pan evaporation irrigation scheduling method on average used 29% more water than Sensor-based irrigation scheduling method. In 2014, the average reduction of water applied was 30 mm and in 2015, the average reduction of water applied was 71 mm without statistically significant differences in grain yield or aboveground biomass within each year (Table 1.5). Based on the 2014 USDA Crop Production Summary, (http://www.usda.gov) the non-irrigated corn yield average in the state of Alabama was 9970 kg ha^{-1} and the average yield obtained from the fertilized treatments of both irrigation methods was 13840 kg ha^{-1} and 13180 kg ha^{-1} during the 2014 and 2015 growing seasons, respectively. Glass et al. (2015) conducted an evaluation of corn hybrids also at the TVREC and the irrigated corn yield average was 13997 kg ha^{-1}.

Effects of N rate on Corn Grain Yield and Aboveground Biomass.

Significant grain yield differences were observed with respect to N rate, Year and interaction between Year x N rate (Table 1.4). In contrast, there was no aboveground biomass differences observed with respect to the same factors (Table 1.4). The lowest grain yield was observed on the control treatment during both years (Table 1.6). In 2014, the greatest grain yield was 14230 kg ha^{-1} achieved in the plot fertilized with 269 kg ha^{-1} and in 2015 the greatest yield was 13809 kg N ha^{-1} achieved in the plot fertilized with 336 kg N ha^{-1} (Table 1.6). In 2014, grain yield differences between the control and fertilized treatments were statistically significant, however no statistical differences were found between the fertilized plots (Table 1.6). In other words, the increase of N rate from 202 to 336 kg N ha^{-1} did not statistically change grain yield. However, the growing season of 2015 the differences between control and fertilized plots were presented. The yield differences during the growing seasons (2014 and 2015) might be explained because of the technical problems with the irrigation pump. Especially in 2014, it took more time to fix the irrigation pump. Therefore, the lack of irrigation during the high period of corn water demand likely limited the corn response to N rate in both growing seasons.

Hagedorn et al. (1997) mentioned that in years with heavy rains the mineral N content in the topsoil decreases by 50-70%, however in low rainfall seasons the pronounced mineralization occurs but mineral N decreases only slightly. Therefore the low rainfall in 2013 may have contributed to the no statistical differences in the fertilized plots in 2014. The 2013 season received 50% less precipitation than the normal of 30 year normal (Table 1.3). Furthermore, residual mineral N may have increase because leaching was limited due to low rainfall in 2013 and it could explain the low corn yield responses to N application observed in 2014. Extra N in 2014 could also explain why control plots in 2014 obtained higher yields than 2015.

The impact of N rate on grain yield is important because of their effect on production profitability. Therefore, if the N fertilizer investment does not translate to a yield increase, then excess N could cause environmental problems. Some studies in this area suggest that increasing N application above optimal rates will lead to only small increases or even decreases in grain yield and aboveground biomass. However it may cause an increase in the energy use and production costs as well as increasing the risk of negative environmental effects such as greenhouse gas emission, soil acidification and nitrate leaching (Ciampitti and Vyn, 2013; Guo et al., 2010; Ju et al., 2009b).

Variation in Corn N Concentration

Grain and stover N concentrations were different between two growing seasons with the N concentration values in 2015 greater than values observed in 2014 (Table 1.7). Overall, grain and stover N concentration increased as N rate increased (Table 1.7). During the two growing seasons, grain N concentration ranged from 8.75 g kg^{-1} to 14.00 g kg^{-1} and the stover N concentration ranged from 0.61 g kg^{-1} to 13.23 g kg^{-1}. Overall, grain and stover N concentration increased as the N rate increased (Table 1.7). Ciampitti and Vyn (2012) reported the N concentration range for the modern corn cultivars was 3.0 g kg^{-1} to 26.8 g kg and 1.2 g kg^{-1} to 21.1 g kg^{-1} for grain and stover, respectively. Setiyono et al. (2010) also reported large variation of N concentration values in corn plants across several studies, therefore this may explain the oscillation of N concentration in 2014 and 2015.

Technical problems with the irrigation system occurred during both growing season might be a reason for the higher values of N concentration values observed in grain and aboveground biomass in 2015. In 2014, yields were higher which indicates that plants were able to use the applied N. Therefore, the N dilution could be occurred because higher yields and more biomass may reduce an equivalent N concentration in the plant in 2014. Moreover, temperature could be another reason of the increase of N concentration in the corn plants. Wienhold et al. (1995) compared N concentration in corn and obtained 75% higher N content values in years when the temperature was above the 30-year average. Therefore, higher temperature in 2015 (Table 1.3) could explain the increase of N concentration for this growing season.

In 2015, grain N concentration differences between the control and fertilized treatments were smaller than differences observed in the 2014 growing season. Therefore in 2015 the corn plants uptake more N from the unfertilized plots, showing the ability of corn to uptake N from the soil N pools even when no N fertilizer is applied (Table 1.7). In 2014, N rate did not affect N concentration in the stover, but in 2015, stover N concentration increased following increment of N fertilizer.

Aboveground N uptake ranged from 125.43 kg N ha^{-1} to 421.64 kg N ha^{-1} during the two growing seasons. Ciampitti and Vyn (2013) reported the mean, minimum and maximum N uptake of modern corn cultivars and the values were 184, 2, and 427 kg N ha^{-1}, respectively. Other numbers reported by Setiyono et al. (2010) showed 239, 7, and 471 kg N ha^{-1} as mean, minimum and maximum respectively. Therefore, the maximum and minimum N uptake values obtained in Alabama's environment in this present study agreed with the range of new era cultivars reported by other authors.

Aboveground N uptake was higher in 2015 when compared to 2014. In 2014, aboveground N uptake between control and fertilized treatments was statistically significant; however considering only the fertilized treatments the N uptake values increased numerically but these differences were not significant (Table 1.7). During the season of 2015, the aboveground N uptake increased significantly with the increase of N rate (Table 1.7). Abbasi et al. (2012) reported that aboveground N uptake increased with N rate, therefore in our study the N uptake increased as the N rate increased but the increment was not significant in all cases.

Setiyono et al. (2010) and Chuan et al. (2013) reported that aboveground N uptake has been closely linked with grain and aboveground biomass. However, we observed that in general grain yield was higher in 2014 but the overall aboveground N uptake was lower when comparing with 2015. Herrmann and Taube (2004) found lower N uptake in higher corn biomass yield and it might be due the N dilution because the N is spread out in the plant tissue.

Furthermore, other studies evidenced that aboveground N uptake is not proportionately linked with grain yield. Jokela and Randall (1989) presented some data from a three year study (1982 – 1984) comparing grain yield and aboveground N uptake and found years with higher yield and lower N uptake or vice-versa. Lambert et. al (2000) compared four highest-yielding commercial corn hybrids in three locations and also found higher yield and lower N uptake, furthermore the in some locations they had a negative N balance or some corn hybrids removed more N than was applied as fertilizer-N. It also occurred in our study in the 2015 growing season (Table 1.7).

Nitrogen Use Efficiency

The Nitrogen Use Efficiency (NUE) increase indicates that most N fertilizer applied in the soil was taken up by plants and converted in grain yield. Therefore, the amount of N that remains in the soil is lower decreasing the potential of leaching and can effectively decrease the potential negative impacts of N fertilizer to the environment (Abbasi et al., 2012; Ciampitti and Vyn, 2011).

The AE_n and PFP_n followed the same trend in 2014 and 2015; higher AE_n and PFP_n were observed for the treatment fertilized with 202 kg N $ha^{-1}$and gradually decreased as N rate increased (Table 1.8). Also the lowest NUE value was observed from the plots fertilized with the highest N rate (336 kg N ha^{-1}). According to Ciampitti and Vyn (2011), it is well accepted the NUEs values are high at low N rates and decrease with increasing N rates. Furthermore, AE_n and PFP_n may be more practical parameters because grain yield and N rate are used in the equation; therefore they are easier parameters to be calculated by farmers. The RE_n and IE_n did not present significant differences during both seasons. Also considering that these parameters use aboveground N uptake in the equation it might be more laborious for the farmers because it is necessary to do the N concentration analysis.

Considering the values obtained in 2014 and 2015 the RE_n decreased from 98.03 to 35.61, AE_n from 36.32 to 16.78 kg kg^{-1}, IE_n from 63.64 to 33.94 kg kg^{-1}, and PFP_n from 67.96 to 39.56 kg kg^{-1} and in the most of the cases the value decreased due increasing N rate. Ciampitti and Vyn (2012) reported that the mean values of RE_n, AE_n, IE_n, and PFP_n for new era hybrid corn were 44%, 22.9, 55.0 and 66.0 kg kg^{-1}, respectively. In general, all NUE parameters from 2014 were similar or comparable to mean values of the new era corn hybrid. However in 2015 RE_n values were high especially in the Pan evaporation treatments and the IE_n values were low (Table 1.8).

High RE_n values in 2015 may be attributed to increased aboveground N uptake; however control treatments had lower N uptake values compared to fertilized treatments (Table 1.8). Therefore, N uptake differences between control and fertilized treatments were higher in 2015; consequently this increased the RE_n values for 2015. Lower IE_n values in 2015 can be explained by the high aboveground N uptake values.

The NUEs equations are simple; however they depend on several parameters, which may or may not be controlled by producers, for example N rate or weather conditions respectively. Therefore, there is potential to improve NUE and minimize negative environmental impacts if optimum practices for soil management, agronomy, ecology, and genetics are adopted with sustainable agriculture (Chen et al., 2011; Ciampitti and Vyn, 2012).

Conclusions

The Sensor-based irrigation scheduling method tends to have a better performance during the 2014 and 2015 relative to the Pan evaporation method. Even though less water was applied using the Sensor-based irrigation scheduling method, the differences between the methods might be affected by the lack of irrigation that occurred on both seasons due to the failure of the irrigation pump during the period of high crop water demand. However, results showed that the Sensor-based method was a reliable method to monitor soil water status and provide useful data for producers to manage irrigation scheduling. The Pan evaporation method might be less accurate in terms of soil moisture content monitoring, because it assumes uniform soil conditions and is based on estimations of the soil water balance. When comparing both irrigation scheduling methods, 29% more water was applied on average using the Pan evaporation irrigation scheduling method compared to the Sensor-based method. Despite these differences, there were no significant grain yields or aboveground biomass differences observed between the two irrigation scheduling methods. Moreover, the lack of water application caused by the problems in the irrigation pump may have affected the yield potential of grain and aboveground biomass, thus no significant differences were presented.

The irrigation water differences were not significant enough to impact grain yield. However, the rainfall also has to be accounted in the water differences, thus higher amount of irrigation and rainfall may be required to affect the crop production. The corn hybrid used in this study was somehow tolerant to some level of water stress; therefore the water differences may not promote yield differences.

Nitrogen rates evaluated in this study affected grain yield, aboveground N uptake, and NUE expressed as AE_n and PFP_n. In general, NUEs values decreased with an increase in N rates, which means that extra N fertilizer added to the soil was not converted to grain yield or/and uptake by plants, which might increase the risk of future environmental problems.

Corn yield, N concentration and N uptake are strongly linked with the availability of water. Therefore, technical problems in the irrigation pump occurred in both growing season during the pick of corn water demand likely affected most of the parameters analyzed in this study thereby limiting conclusive comparisons or recommendations.

Table 1.1. van Genuchten equation parameters from 2014, percentage (sand, silt and clay) and soil textural class for three soil depths at the TVREC. The paremeters from 2014 were used during both growing seasons.

Depth (cm)	0 - 15	15 - 30	30 - 60
θr ǂ	0.0808	0.0969	0.1048
θs §	0.4095	0.4779	0.536
α ¶	0.089	0.0132	0.0178
n £	1.4669	1.365	1.3098
m ¤	0.3183	0.2674	0.2365
θs - θr ¥	0.3287	0.381	0.4312
% Sand	16.18	10	9.76
% Silt	51.05	43.45	35.74
% Clay	32.77	46.55	54.5
Textural Class	Silty Clay Loam	Silty Clay	Clay

ǂ Residual soil water content (cm^3 cm^{-3})

§Saturated soil water content (cm^3 cm^{-3})

¶ Parameter related to the inverse of the air entry suction (cm^{-1})

£ n curve shape parameters (empirical parameter)

¤ m= (1-1/n)

¥ θr and θs are the residual and saturated soil water contents (cm^3 cm^{-3})

Table 1.2. Field Capacity, Permanent Wilting Point, Plant Available Water, Water Depletion and 35% depletion of Plant Available Water in water content and soil matric potential units for each soil depth at the TVREC in 2014 . Parameters from 2014 were used during both growing seasons.

Depth (cm)	0 - 15	15 - 30	30 - 60
Field Capacity (FC) ǂ	0.1481	0.3115	0.3478
Permanent Wilting Point (PWP) §	0.0921	0.1517	0.1806
Plant Available Water (PAW) ¶	0.056	0.1598	0.1672
Water Deplet (35%) (cm3/cm3) £	0.0196	0.0559	0.0585
35% of PAW (cm3/cm3) ¤	0.1285	0.2555	0.2892
35 % of PAW (kPa) ¥	70	80	83

ǂ (cm^3 cm^3)

§ (cm^3 cm^3)

¶ PAW = FC – PWP

£ Water Depletion (35%) = PAW * 0.35 – 35% was the soil water depletion selected in the study

¤ 35% of PAW (cm^3 cm^3) = PAW – Water Depletion (35%)

¥ 35% of PAW (kPa) = soil matric potential referred to the depletion of 35% of PAW

Table 1.3. Monthly average climatic conditions, during the 2013, 2014 and 2015 growing seasons and long-term average values (30 years) measured at the research site the TVREC.

Month	Rainfall (mm)	Temperature max (°C)	Temperature min (°C)	Average Temperature (°C)
		2013		
April	48	22.0	10.3	15.9
May	59	25.8	14.5	16.0
June	30	31.5	19.8	25.2
July	106	30.6	20.6	25.2
August	15	30.7	20.1	24.6
Total / Average	259	28.1	17.1	21.4
		2014		
April	147	23.3	10.0	16.9
May	61	27.6	15.2	21.2
June	151	31.0	20.3	25.0
July	93	31.0	19.3	24.9
August	50	32.7	19.8	25.5
Total / Average	502	29.1	16.9	22.6
		2015		
April	129	23.3	11.9	17.9
May	117	27.9	15.6	21.5
June	88	32.3	20.6	26.1
July	105	33.1	22.0	27.2
August	55	31.2	19.8	24.9
Total / Average	494	29.6	17.9	23.5
		Historic average (1971 - 2000)		
April	108	22.2	8.3	15.3
May	111	26.7	13.6	20.1
June	109	30.6	17.9	24.3
July	106	32.4	20.0	26.2
August	79	32.1	18.9	25.5
Total / Average	513	28.8	15.7	22.3

Table 1.4. Summary of ANOVA for grain yield, aboveground biomass, N uptake, and NUE with respect to N rates (0, 202, 269, 336 kg ha^{-1}), irrigation, and years (2014 - 2015) at the TVREC.

Sources of Variation	Grain Yield (kg/ha)	Aboveground Biomass (kg/ha)	Grain N Concentration (g/kg)	Stover N Concentration (g/kg)	Aboveground N Uptake (kg N/ha)	Nitrogen Use Efficiency			
						AEn ǂ	REn §	IEn ¶	PFPn #
Year	<.0001 *	0.655 £	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Irrigation	0.404	0.146	0.265	0.935	0.321	0.137	0.025	0.173	0.752
Y x I	0.405	0.146	0.265	0.935	0.321	0.137	0.025	0.173	0.753
N rate	0.014	0.447	0.241	0.217	0.001	0.044	0.196	0.959	0.029
Y x N	0.014	0.446	0.242	0.217	0.001	0.044	0.196	0.959	0.029
I x N	0.903	0.532	0.076	0.822	0.552	0.324	0.308	0.625	0.997
Y x I x N	0.903	0.532	0.076	0.822	0.552	0.324	0.308	0.625	0.997

*Significant at 0.05 probability level

£ Nonsignificant at 0.05 probability level

ǂ AEn - Nitrogen agronomy efficiency

§ REn – Recovery efficiency

¶ IEn – Nitrogen internal efficiency

PFPn – Nitrogen partial productivity

Table 1.5. Seasonal irrigation on corn under different irrigation scheduling methods and N rates in 2014 and 2015 at the TVREC.

N rate (kg/ha)	Irrigation Amount (mm)	
	2014	2015
	Pan Evaporation	
0	138	215
202	138	215
269	138	215
336	138	215
	Sensor Based	
0	BNIS ǂ	BNIS
202	122	152
269	99	127
336	99	152

ǂ Based on neighboring plot irrigation scheduling (BNIS)

Table 1.6 Grain yield differences between years and N rates (0, 202, 269, 336 kg ha^{-1}) at the TVREC.

N rate (kg/ha)	Grain Yield (kg/ha)			
	2014		2015	
	Mean	SE ǂ	Mean	SE
0	7617 b §	529	5518 c	356
202	13529 a	529	12540 b	356
269	14230 a	529	13224 ba	356
336	13798 a	529	13809 a	356

ǂ Standard error

§ Numbers at the same column followed by the same letter are non-significant at P<0.05

Table 1.7. Grain N, stover N concentrations and grain, aboveground N uptake differences between years and N rates (0, 202, 269, 336 kg ha^{-1}) at the TVREC.

N rate (kg/ha)	Grain N concentration (g/kg)				Stover N concentration (g/kg)				Aboveground N uptake (kg N/ha)			
	2014		2015		2014		2015		2014		2015	
	Mean	SE ǂ	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
0	8.75 b §	0.66	11.70 c	0.21	0.61 a	1.68	8.11 b	0.87	125.43 b	22.03	166.68 c	39.03
202	10.53 a	0.66	12.52 b	0.21	3.05 a	1.68	10.50 ba	0.87	216.55 a	22.03	321.68 b	39.03
269	11.10 a	0.66	13.51 a	0.21	1.15 a	1.68	12.16 a	0.87	230.51 a	22.03	351.36 ba	39.03
336	11.54 a	0.66	14.00 a	0.21	2.45 a	1.68	13.23 a	0.87	241.79 a	22.03	421.64 a	39.03

ǂ Standard error

§ Numbers at the same column followed by the same letter are non-significant at P<0.05

Table 1.8: Nitrogen recovery efficiency (RE_n), nitrogen agronomic efficiency (AE_n), nitrogen internal efficiency (IE_n) and nitrogen partial productivity (PFP_n) at four N rates (0, 202, 269, 280 kg N ha^{-1}) in 2014 and 2015 at the TVREC.

N rate (kg/ha)	REn (%) ǂ				AEn (kg/kg) §				IEn (kg/kg) ¶				PFPn (kg/kg) #			
	2014		2015		2014		2015		2014		2015		2014		2015	
	Mean	SEǂ	Mean	SE	Mean	SE	Mean	SE	Mean	SE ǂ	Mean	SE	Mean	SE	Mean	SE
0	*	*	*	*	*	*	*	*	62.57 a	2.38	35.04 a	2.16	*	*	*	*
202	36.94 a ¥	4.44	98.03 a	16.79	24.96 a	2.79	36.32 a	0.67	63.64 a	2.38	40.38 a	2.16	67.96 a	2.59	62.33 a	1.82
269	43.96 a	4.44	80.27 a	16.79	22.7 a	2.79	28.79 b	0.67	62.76 a	2.38	38.16 a	2.16	52.32 b	2.59	49.32 b	1.82
336	35.61 a	4.44	85.58 a	16.79	16.78 b	2.79	23.62 c	0.67	58.37 a	2.38	33.94 a	2.16	39.56 c	2.59	41.22 c	1.82

ǂ REn - Recovery efficiency

§ AEn Nitrogen agronomy efficiency

¶ IEn – Nitrogen internal efficiency

PFPn – Nitrogen partial productivity

¥ Numbers at the same column followed by the same letter are non-significant at $P<0.05$

*Do not apply

Figure 1.1. Plot layout from 2015 at the TVREC study. In 2014, the plot layout was the same but the N rate randomization was different. The numbers in the top of each rectangle followed by the letter X were the location where the sensors were installed. The numbers in the middle of the rectangle are referred to N rate and the bottom numbers are the identification of each plot.

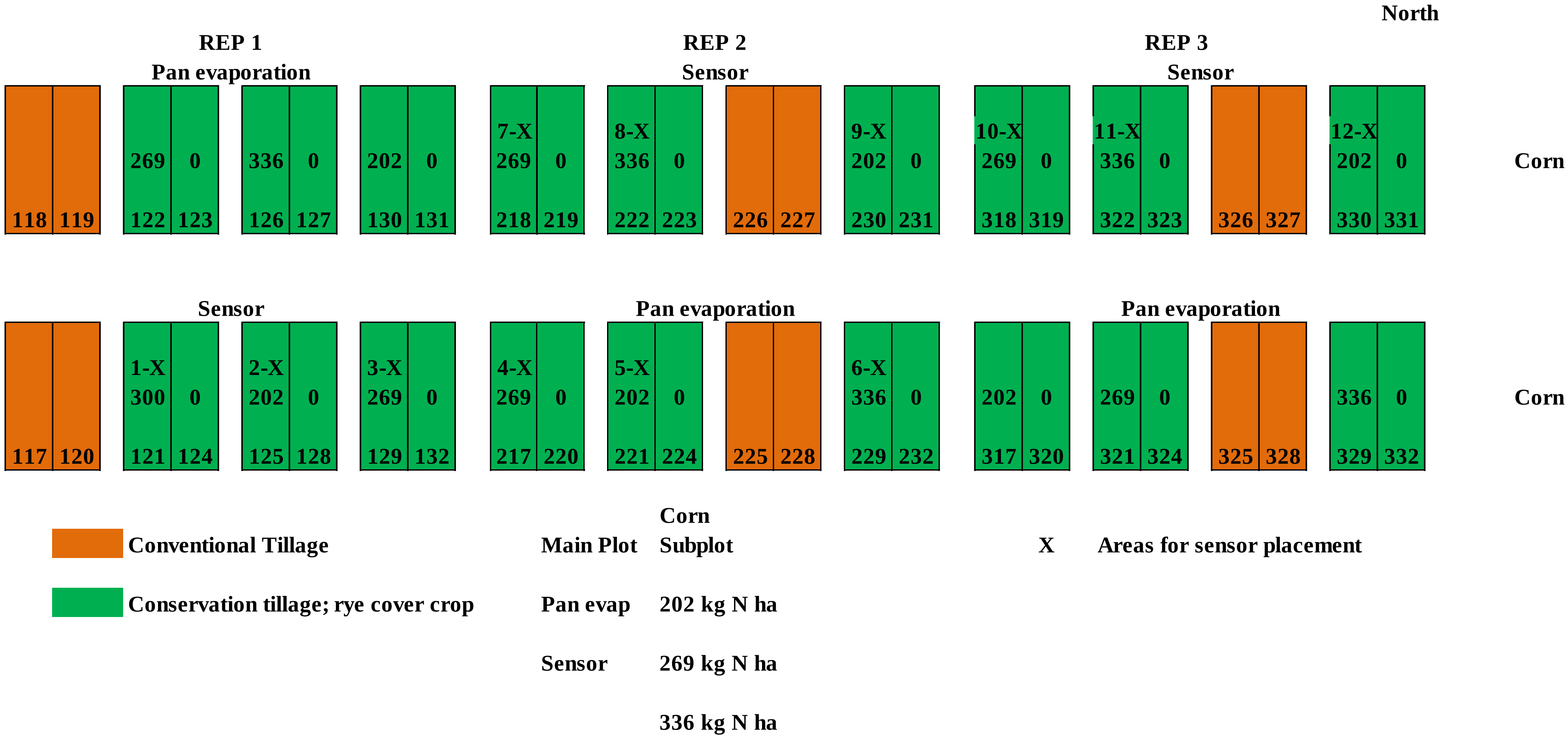


Figure 1.2 Soil water retention curves created using the van Genuchten equation for each depth (15, 30 and 60 cm) to convert soil water content data in soil matric potential in 2014 at the TVREC.

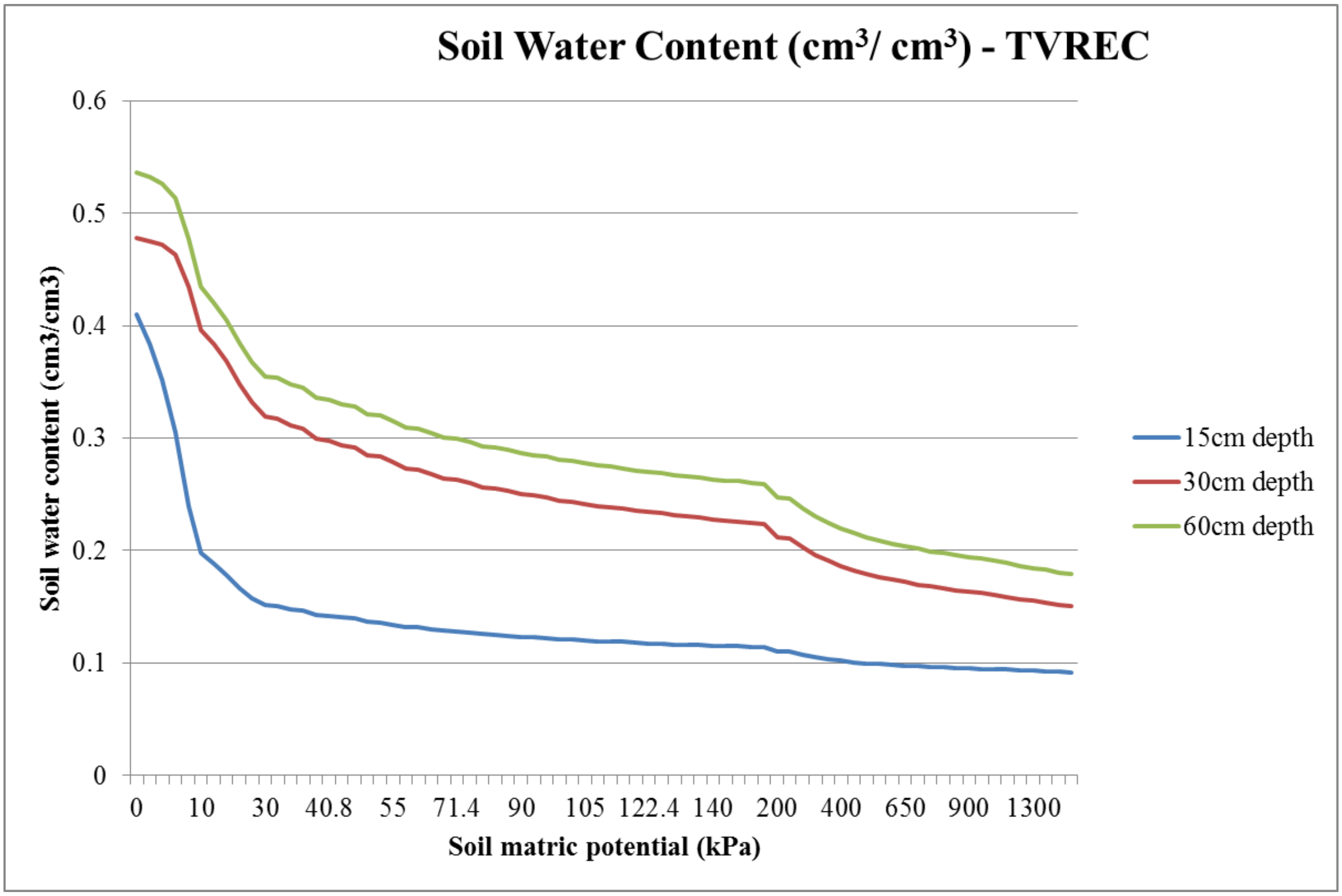


Figure 1.3 Daily soil matric potential in the Pan evaporation plot fertilized with 269 kg N / ha in 2015 at the TVREC. The amounts of irrigation referred in the black arrows were values between 18 and 25 mm to avoid runoff.

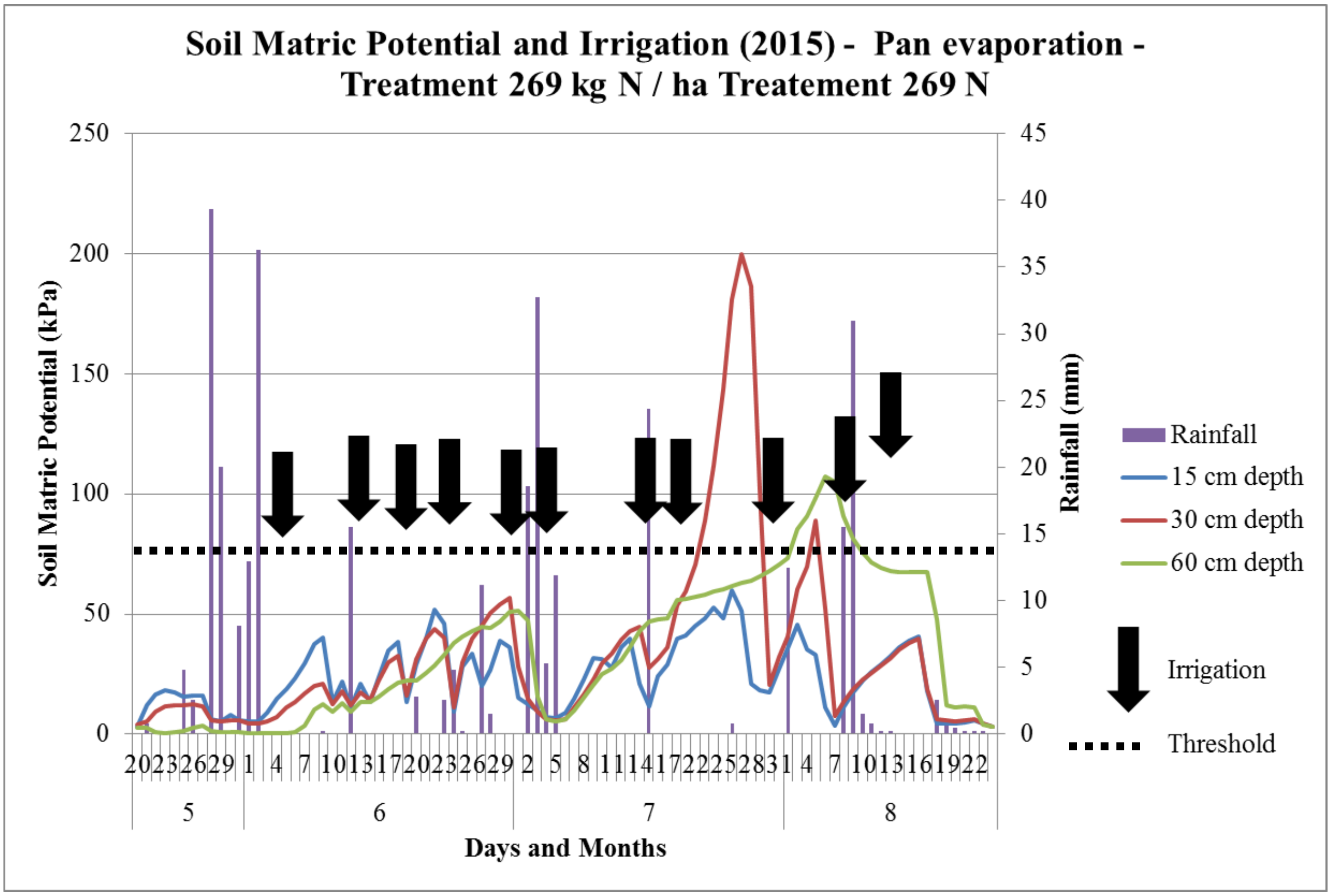
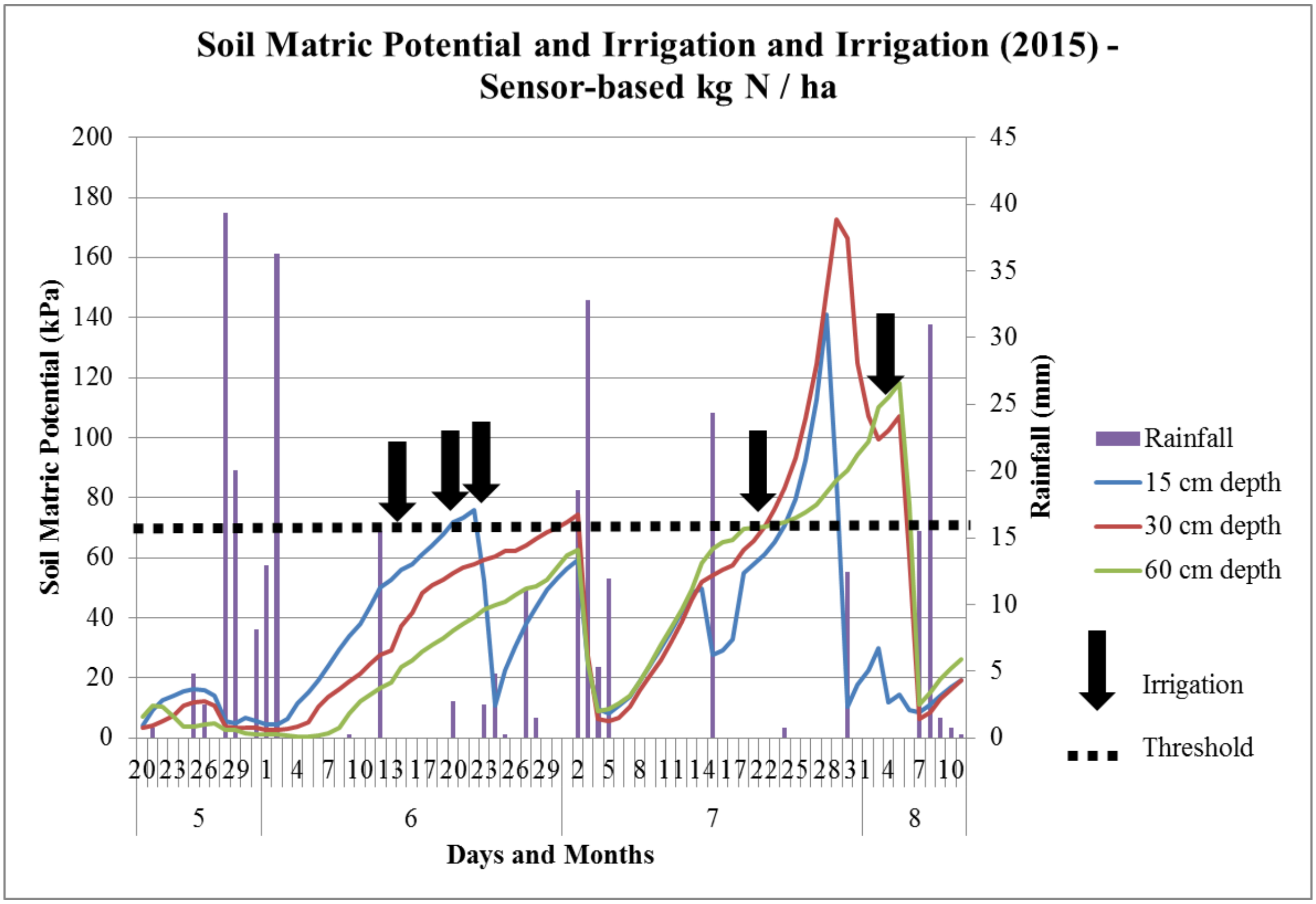


Figure 1.4 Daily soil matric potential in the Senso-based plot fertilized with 269 kg N / ha in 2015 at the TVREC. The amounts of irrigation referred in the black arrows were values of 25 mm to avoid runoff.



III. IRRIGATION SCHEDULING TO PROMOTE CORN PRODUCTIVITY IN CENTRAL ALABAMA

Abstract

Agriculture is the largest consumer of water in the U.S. Results from previous studies have shown that it is possible to substantially reduce irrigation amounts and maintain corn yield. The objectives of this study were to evaluate the advantages and disadvantages of two irrigation scheduling methods for corn production in Alabama. Two irrigation scheduling methods evaluated were: a) Checkbook, which is one of the conventional methods used by farmers that is based on the soil water balance estimated using water lost by evapotranspiration and its replacement through rainfall or irrigation, and b) Sensor-based, which was based on soil matric potential values recorded by soil moisture tension sensors installed in the field. A soil water depletion of 35% plant available water was set as the irrigation threshold for the Sensor-based irrigation treatment, and then each irrigation event was initiated when the soil matric potential reached the soil water depletion threshold. The study was conducted at EVSREC during 2014 and 2015, with different commercial fields utilized for the study each growing season. Each experimental field was divided to two irrigation management zones (zone A and zone B) based on soil properties of each field. Zone A and zone B exhibited lighter and heavier texture characteristics, respectively. Therefore, each zone presented different water holding capacity characteristics, which could have influenced differences in irrigation events such as amount and application times during each season. Variable rate irrigation capability of a center irrigation pivot made this study feasible.

During the 2014 season in zone A, significant grain yield differences were observed between the two irrigation methods. The Checkbook plots exhibited greater yield than Sensor-based plots: 10181 kg ha^{-1} and 9696 kg ha^{-1}, respectively. The greater yield on the Checkbook plots could be associated with higher irrigation rate applied, 133 mm more, compared with the

Sensor-based plots. In zone B, there were no significant yield differences between both irrigation methods; however Sensor-based plots yielded higher than Checkbook plots, with 9673 kg ha^{-1} and 9584 kg ha^{-1}, respectively. Even though the irrigation amount applied in Checkbook located in zone B was higher, 102 mm more, there were no significant yield differences. Therefore, it suggests that the Sensor-based method was a promising irrigation scheduling strategy under the conditions of zone B. In 2015, there were no significant grain yield differences between zone A and zone B when the data from the Checkbook plots was analyzed. However, there were significant grain yield differences between zones. The Sensor-based treatment produced a grain yield of 13597 kg ha^{-1} in zone A and 11659 kg ha^{-1} in zone B, also both zones received the same amount of irrigation. Overall results of both growing seasons indicated that the use of the Sensor-based irrigation scheduling treatment resulted in similar values of total profit per hectare when compared to Checkbook method. The Sensor-based method seems a promising strategy that could result in water savings and indirectly financial results but more research is required.

Introduction

Increases in water demand to support population and economic growth, environmental flows, and the energy-sector have resulted in water shortages for many regions of the world. The lack of appropriate water management practices and integrated water use policies will increase water-related problems in terms of population demand and environmental impacts. Production of agricultural crops could be severely impacted by current and future water shortages. In this scenario, the agricultural sector plays a critical role in terms of water consumption. Worldwide, irrigated agriculture accounts for about 70 percent of total freshwater withdrawals (Molden and Oweis, 2007). In Alabama, even though irrigation adoption is low compared with other states, it should be accompanied with practices that allow farmers to use the water resource effectively and efficiently, while achieving high yields. Based on the 2012 Census of Agriculture, irrigated land in Alabama is small compared with neighboring state – 5.1% of harvested cropland in Alabama is irrigated compared to 30.8% in Georgia. However, the adoption of irrigation, mainly center pivot irrigation systems, has increased from 79,647 acres in 1997 to 113,008 acres in 2012 (USDA, NASS 2013). An estimated 20 percent of the world's cultivated land is irrigated, accounting for 40 percent of total agricultural production (Rosegrant et al., 2009). Recent projections for food and agricultural production assume that the world's population will reach about 9.6 billion people by 2050 (United Nations, 2013), thus higher yields obtained under irrigation systems are helping to feed the growing population. Furthermore, observations of recent growth rates in yields of major crops indicated the need for research incentive and financial investments, in order to continue increasing yields. Currently, the agricultural productivity concern is because the yields increment may not be rising in the same proportion to meet world demands (Ray et al., 2013).

Irrigation is enabling producers to achieve higher yields and at the same time making agriculture feasible in areas with low precipitation. However, the agricultural sector is facing the challenge of creating mechanisms to increase the crop production with less water, consequently increasing crop water productivity (Zwart and Bastiaanssen, 2004). Several possible approaches such as efficient irrigation scheduling methods and improved irrigation technologies may be adopted for more conscious use of limited water resources (Kirda, 2002). Even though several smart-irrigation technologies are available to assist growers in estimating the right rate and the right time to deliver site-specific irrigation rates, adoption is still low. As of 2013, the most recent Farm and Ranch Irrigation Survey indicated that 72% of irrigated U.S. farms still rely either on a fixed schedule or on visual cues of plant stress, such as wilting to schedule irrigation. Among the science-based irrigation scheduling tools adopted, only 10% use soil moisture sensors, 8% use reports on daily crop-water evapotranspiration (ET), and 8% use web-based irrigation scheduling services (USDA, NASS 2014). In Alabama, of the 1022 farms using any method for deciding when to irrigate, 7% use soil moisture sensors and 4% use reports on daily crop-water ET (USDA, NASS 2014).

Furthermore, Variable rate irrigation (VRI) is included as one of the irrigation technology innovations that can make irrigation scheduling feasible and more precise in terms of water application according to within-field variability. Variable rate irrigation is recommended to apply the appropriate amount of water in the right time considering field-level spatiotemporal heterogeneity (Duncan, 2012). Variable rate irrigation is expected to decrease nutrient leaching, but also increase water-use efficiency, productivity, and fuel savings (Pan et al., 2013). As with irrigation scheduling tools, adoption of VRI has also been slow in 2008, of the 175,000 center pivot and linear move sprinkler systems in the U. S., less than 200 had VRI capabilities (USDA, NASS 2007). Therefore, it is important to test and measure advantages and limitations of these technologies to guide producers and increase the implementation of more efficient practices. Variable rate irrigation has obvious potential advances to conserve water use by turning off sprinklers over non-planted areas, farm tracks, drains, etc., as well as varying the timing and amount of irrigation according to different crop and soil types. Several authors have reported on the potential for water conservation that has been observed using VRI systems (Evans et al., 1996b; Hedley and Yule, 2009; Sadler et al., 2005).

Mutual use of VRI and irrigation scheduling as water management strategies can prevent over-application of water and minimize yield losses due to water shortage or drought stress. In general, methods of irrigation scheduling can be classified as plant, soil, climate-based, or combinations. The Checkbook method, the simplest way to conduct irrigation scheduling, gives irrigation directions for crop management according to the soil water deficit calculated from soil water balance data and it can be a good water management tool when used properly (Duke et al., 1987; Killen 1984; Lundstrom and Stegman, 1988; Wright and Bergsrud, 1991). Jones (2004) stated that this method successfully worked for several conditions, however, if the producer does not carefully record water balance data, errors may add up over time. On the other hand, various types of sensing devices have been created and made commercially available to assist the producer with irrigation management. Some of these devices are capable of wirelessly transferring data collected from their sensors. Several types of soil moisture sensors have been evaluated by researchers in terms of accuracy, reliability, and cost (Chanzy et al., 1998b; Evett and Parkin, 2005; Kizito et al., 2008; Seyfried and Murdock, 2004; Yao et al., 2004). Vellidis et al. (2008) developed and evaluated a wireless smart sensor array as a tool to conduct irrigation scheduling. This wireless sensor system can continuously measure soil water tension and soil and air temperature, which offer competitive advantages as a potential irrigation scheduling tool. In the study, the same soil moisture sensor developed by Vellidis et al. (2008) was compared against the Checkbook Irrigation Scheduling Method. Therefore, the objectives of this study were to evaluate, under on-farm conditions, yield and water use differences between these two irrigation scheduling methods for corn production in Alabama.

MATERIALS AND METHODS

Site description

The study was conducted at the EVSREC in Shorter, AL (32°25’43.43”N, 85°53’34.81”W, 69 m above mean sea level), however the test was established on different experimental fields during two growing seasons. In 2014, the site was a 2.4 ha field located at EVS – Plant breeding unit and the dominant soil series was Kalmia loamy sand (Fine-loamy, mixed, semiactive, thermic Aquic Hapludults) with 0% to 3% slope. In 2015, the site was a 6 ha field at EVS - Farm Services unit and the dominant soil series were Altavista silt loam (Fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludults) and Cahaba sandy loam (Fine-loamy, siliceous, semiactive, thermic Typic Hapludults) with 0% to 2% slope (NRCS Web Soil Survey; http://websoilsurvey.nrcs.usda.gov). In general, rainfall during both growing seasons (April-August) was above the historic 20-year average (1971-2000).

Corn was planted in mid-April, and cultural practices were performed according to Alabama Cooperative Extension Service recommendations (ACES, 1994). Each corn field was planted with 0.90 m row spacing and seeding rate of 88,956 seeds ha^{-1}. The crop was fertilized with 280 kg N ha^{-1} as urea ammonium-nitrate (UAN 28-0-0); one third of the total N was applied at planting and the remaining at the V6 growth stage.

Experimental Design

The study in both years was arranged into two management zones (zone A and zone B) delineated according to soil textural properties (Table 2.1 and 2.2). The distinct zones were defined based on soil texture analysis conducted in both growing seasons and a soil electrical conductivity survey.

Two irrigation scheduling strategies were evaluated within each zone: a) Checkbook Irrigation Scheduling Method and b) Sensor-based irrigation scheduling method. A six-row John Deere 9470 grain combine with a yield monitor was used to harvest the test. The system used an AgGPS 132 DGPS receiver with differential correction to calculate the position in the field of the grain combine during harvest.

Soil Electrical Conductivity Mapping

According to Corwin and Lesch (2003), soil EC_a is a function of several soil properties that include soil salinity, soil texture, and water content. The capacity of soil to retain water against gravity depends on soil texture among other characteristics (Aina and Periaswamy, 1985). Therefore, an indirect assessment of within-field soil texture variability allowed the identification of zones with differences in soil water holding capacity, under which irrigation scheduling practices were tested. The Veris 3100 Sensor Cart (Veris Technologies., Salina, KS, USA) was used to map soil electrical conductivity (EC_a). The sensor uses disks with electrodes that once in physical contact with the soil, send an electrical current into the soil and measure the drop in voltage. The soil ECa mapping system uses a sensor cart with a GPS antenna which while pulled through the field with a small tractor, records georeferenced soil ECa values. The sensor collects soil ECa at two soil depths: 0–30 cm (shallow, ECa-s) and 0–90 cm (deep, ECa-d). The correlation of soil ECa with soil properties stems from the fact that sandy soil textures have a low conductivity, silts have a medium conductivity and clays have a high conductivity. Consequently, conductivity measured at low frequencies correlates strongly to soil particle size and texture (Williams and Hoey, 1987). The spatial soil EC_a data collected from each field was imported into a GIS in order to create soil EC_a map. Based on the within field soil EC_a variability, zones with similar values of soil EC_a were identified using the Management Zone

Analyst software (MZA 1.0.1, USDA-ARS, Columbia, Mo., USA). The MZA utilizes the fuzzy *c*-means algorithm and the Euclidean or Mahalanobis distances to separate data into clusters with similar attributes (Fridgen et al., 2004). Evans et al. (2013) stated the importance and critical need to dynamically develop irrigation management zones (MZ) in an accurate and inexpensive manner. After the data was processed through MZA, two management zones were identified/delineated for each field (Figure 2.1 and 2.2).

Zones were delineated based on soil EC_a data with information about how the Ec_a data collection was conducted provided in a subsequent section. Corn was then planted and soil moisture sensor probes were installed in each zone. After the probes were placed in 60 cm holes, a slurry was added in the holes to fill up and promote good contact between soil moisture probes and the ground. Antennas and electronic boards were properly configured and the base station was set in the border of the experimental field.

Soil Water Retention Curve Generation

Disturbed and undisturbed soil samples were collected at three soil depths (15, 30 and 60 cm) at the same locations where soil sensor probes were installed in each zone (A and B). Disturbed soil samples were used for a soil textural analysis, which provided information to describe and verify results obtained from the soil EC_a survey. Also, the percentage of sand, silt and clay obtained from this analysis was used to generate a Soil Water Retention Curves (SWRC) for three soil depths using the Retention Curve (RECT) Computer Program. Undisturbed soil samples were used to generate SWRC in the laboratory as well. Thus, cores collected in the experimental field were set on the bench and the pressure applied was changed every two days. The water remaining in the soil according to pressure applied was documented to generate the SWRC.

The SWRC provides information to relate the amount of water retained in the soil at a given soil matric potential, which is typically reported as negative values, because it represents the force that must be exerted by plants to uptake water from soil. However, because it is implicit, we omitted the negative sign in this study, following the same approach that Irmak et al. (2014) used in an irrigation management study based on soil moisture sensors.

Soil samples, disturbed and undisturbed, were collected at the beginning of each growing season, after zones were delineated and before corn was planted. Textural analysis was conducted after planting. Undisturbed soils were placed on the sorption bench. Both methods were conducted simultaneously in case data from the adsorption bench was not available to start irrigation scheduling. As a result, early season irrigation scheduling was based on the SWRC generated from values estimated using the RETC Computer Program (U.S. Salinity Laboratory, USDA, ARS, Riverside, California). This approach was used because soil texture analysis provided quick results allowing the SWRC to be ready for the beginning of the season. In contrast, generation of the SWRC based on adsorption bench procedures took more than two months to provide data necessary for irrigation threshold calculations. During these two months, corn reached the highest daily water demand for the growing season. Thus the irrigation threshold results obtained from the SWRC generated using the van Genuchten equation was kept throughout the entire season. Furthermore the SWRC generated using the bench procedures presented questionable results, thus the results from Genuchten equation was maintained.

Soil texture analysis provided the percent of sand, silt and clay values and these data were input in the RETC Computer Program, which calculates the van Genuchten equation parameters: θ_r, θ_s, α, and n (Table 2.1 and 2.2). The van Genuchten equation is often used to describe the SWRC function in unsaturated soil. The van Genuchten model has the following form:

$$\theta_h = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n)^m} \quad (6)$$

where θ(h) is the actual soil water content ($cm^3\ cm^{-3}$) at the suction h (cm, taken positive for increasing suctions); θr and θs are residual and saturated soil water contents ($cm^3\ cm^{-3}$), respectively; α is a parameter related to the inverse of the air entry suction (cm^{-1}); m and n are curve shape parameters (Van Genuchten, 1980). The "m" parameter on this equation characterizes the asymmetry and it can be calculated as m=1- 1/n. The solution of this equation provided enough data to generate the SWRC for three soil depths and allows the estimation of the soil water content at different soil matric potential levels (Figure 2.3, 2.4, 2.5 and 2.6).

Plant Available Water and Manageable Allowed Depletion (Irrigation Threshold)

Once the SWRCs were generated, the field capacity and permanent wilting point values at soil depths of 15, 30, and 60 cm for various locations within each field were identified. These parameters are key for estimation of Plant available water (PAW). Several studies have found that field capacity does not correspond to a fixed soil matric potential value; in contrast, it changes with soil texture. Richards and Weaver (1944) found that a coarse-textured soil can reach field capacity at 10 kPa and a fine-textured soil can reach field capacity at 33 kPa. The permanent wilting point is usually found at a soil matric potential of 1500 kPa. Therefore, for the purposes of this study soil matric potential values representing field capacity were selected based on soil texture determined for each management zone.

Once field capacity and permanent wilting point were established, the PAW was calculated using field capacity minus permanent wilting point (Table 2.3 and 2.4). After PAW was calculated, the irrigation threshold was determined. The Manageable Water Depletion (MAD) is described as how much water to reduce from PAW before initiating an irrigation event. In this study, the irrigation threshold or MAD was set based on 35% depletion of PAW found in and similar studies (Table 2.3 and 2.4). Irmak et al. (2012) used 35% depletion of PAW in a study testing irrigation strategies based on soil moisture sensors. The 35% to 38% depletion of PAW was used to conduct an agricultural water management demonstration network and the threshold point was lower than the traditional strategy of irrigation at 50% depletion of PAW because it accounted for the time it takes a center pivot system to make one full circle (Irmak et al., 2010) Usually, a center pivot takes between 3 to 5 days, depending on system hydraulic design, center pivot conditions, and other factors.

The matric potential value (kPa) associated with water content retained in the soil was important because soil moisture sensors provide data in matric potential units (kPa). The most useful soil matric potential values correspond to 35% depletion of PAW, because these values indicate the threshold to start irrigation events using the Sensor-based irrigation scheduling method. The soil matric potential values that corresponded to the 35% depletion from PAW at various soil sensing locations within each zone were established. An average soil matric potential value per zone was determined for each field-season (Table 2.3 and 2.4).

During both growing seasons, there were some differences in how soil matric potential corresponded to the irrigation threshold was. In 2014, for growth stages before flowering, the soil matric potential representing the 35% depletion of PAW (irrigation threshold) corresponded to the average of soil matric potential values at the 0-15 cm and 15-30 cm soil depth. After flowering, the average of soil matric potential corresponded to the average of the three soil depths (0-15, 15-30, and 30-60 cm). This procedure was conducted separately for data values that corresponded to zone A and Zone B. Thus, the irrigation threshold in 2014 was 23 kPa and 76 kPa for the zones A and B, respectively (Table 2.3). In 2015, the soil matric potential values representing the irrigation threshold were 32 kPa and 93 kPa for the zones A and B, respectively (Table 2.4). The irrigation threshold values were indirectly influenced by field capacity values that in some cases were selected based on a matric potential at 10kPa and in other cases at 33kPa. Even though protocols established for this project were to select the value of matric potential of 10kPa to determine field capacity of areas characterized by higher percent sand content than clay, the soil texture of our soils was neither sandy nor clay but something in between. Therefore, the irrigation thresholds values were slightly modified, increased or decreased, depending on the situation and observations of soil differences during field visits and soil sampling campaigns. As a result of these analyses, in 2014 the final irrigation threshold values were set to 25 kPa and 60kPa for zones A and B, respectively to reflect soil characteristics that were neither sand nor clay. A similar process was followed with the 2015 data; the final irrigation threshold values were set to 55 kPa and 80 kPa for zones A and B, respectively.

Irrigation Scheduling Strategies

Both irrigation scheduling methods tested in this study differed from each other in the way the amount of water stored in the soil during the growing season is calculated. The Checkbook Irrigation Scheduling Method was based on managing the estimated crop's evapotranspiration (ET) using meteorological parameters and replacing the consumptive water use. On the other hand, the Sensor-based irrigation scheduling method relied on values of soil water tension sensors to determine irrigation times.

Checkbook Irrigation Scheduling Method

The Checkbook method was evaluated daily accounting for crop water demand and water input from rainfall and irrigation. Therefore, parameters such as growth of the crop, maximum air temperature of each day, daily ET estimation from the crop water use table, rainfall, and/or irrigation applied to the field were monitored. Rainfall and maximum temperature were frequently checked from E. V. Smith weather stations linked to the AWIS Weather Service (www.awis.com). Every irrigation event, amount and date was recorded and used in the calculations. Weekly plant water demand was determined using University of Georgia Extension recommendations for Corn (Lee, 2011). The soil water deficit balance was calculated by taking into account how much water the soil was able to hold and the amount of water added and removed from the soil. Each day, the estimated crop water use was added to the previous day's soil water deficit, and any rainfall or irrigation amounts were subtracted from this deficit. The daily water demand balance was summarized every week and irrigation (if necessary) was applied. If a weekly balance of rainfall or irrigation minus weekly crop water use was greater than the current deficit, most of the excess was considered lost due to deep percolation below the rooting zone, and the new deficit balance was generally set to zero. The dates and amount of water applied using the Checkbook method is included in the (Appendix 3 and 4)

Sensor-based irrigation scheduling method

Irrigation events from the Sensor-based irrigation scheduling method were determined using information from sensors probes properly installed between two corn plants in the experimental area. Sensors probes recording soil water tension data were part of a smart sensor array system. The smart sensor array system used in this study consisted of a centrally located receiver connected to a laptop computer (base station) with multiple sensor nodes installed in the field. Sensor nodes consisted of sensors (3 soil moisture sensors (Watermark) and thermocouples, a sensor circuit board, and an active transmitter, which transmitted data to the receiver (Vellidis et al., 2007). The smart sensor board acquired sensor values and wirelessly transmitted those values to a centrally located radio frequency receiver (base station), and then via cellphone signal, the data was sent to a website. The board of each node was able to read up to three Watermark soil water tension sensors located at three different soil depths (15, 30 and 60 cm) enabling a better view of the water availability in the root zone. Each Watermark sensor is a granular matrix device used to measure soil water tension, therefore all data obtained from the Watermarks sensors was transferred to the database in kilopascal (kPa) units. Watermark sensors provided continuous data analogous to the force (soil matric potential) that corn roots must exert to extract water from the soil and these values were used to schedule irrigation. Watermark sensors have been used to measure soil water status for irrigation management and other purposes for more than two decades (Armstrong et al., 1985; Thomson and Threadgill, 1985; Thomson and Armstrong, 1987; Eldredge et al., 1993; Bausch and Bernard, 1996; Mitchell and Shock, 1996).

Therefore, soil moisture sensors provide soil matric potential values for the irrigation threshold using (kPa) units. As mentioned above, the irrigation threshold was 23 kPa for zone A and 62 kPa for zone B in the 2014 growing season. In 2015, the irrigation threshold was 55 kPa and 80 kPa for zone A and B, respectively. Thus, an irrigation event was initiated when soil matric potential reached the irrigation threshold. Weather conditions were also considered before initiating irrigation. For instance, if the irrigation threshold was reached, but the weather forecast indicated a high probability of rain for the following days, irrigation was postponed or the irrigation amount was decreased. However, when no chance or low chance of rain was predicted, irrigation was applied to bring the soils to field capacity. Figure 2 illustrates how soil matric potential values were monitored and how irrigation events were set. When the corn reached the black layer (physiological maturity), irrigation was discontinued and the soil probes were removed before harvest time.

Variable Rate Irrigation

The irrigation system at the experimental site (EVS) included variable rate irrigation technology. The variable rate irrigation was essential because soil texture zones reached the irrigation threshold at different times during the growing season and water was applied independently for each zone. For instance, if zone A reached the irrigation threshold but the tension values in zone B were not close to the threshold, the irrigation pivot was initiated and sprinklers were applying water only over zone A. Therefore, the variable rate irrigation was required to split irrigation amounts over the plots. Also this technology minimized water waste because of the capability to turn off the sprinklers when the pivot is crossed the gravel road or non-planted areas.

Water Productivity and Economic Analysis

Average water productivity is estimated by dividing crop yield by total applied water (rainfall plus irrigation) (Molden, 1997). Water productivity was analyzed by growing season to evaluate grain yield and water use between irrigation scheduling methods within each management zone. The relationship between crop production and water received is a crop water production function. According to Vaux and Pruitt (1983), this function can be categorized into three groups depending on a desirable level of water use: (1) agronomists and other production-oriented scientists trying to identify the level of water input necessary to achieve maximum yield per unit land, (2) irrigation engineers trying to maximise water use efficiency, and (3) economists trying to establish the water level that is equivalent to the revenue obtained as a result of its application.

The economic analysis was conducted using total income per hectare referred to as the total grain yield per hectare multiplied by the current price of corn grain. The corn grain price fluctuated around $3.60 per bushel during the second half of June 2015. The $3.60 per bushel was referred as $3.60 per 25.4 kg of corn grain or $0.14 per kg of corn grain. Furthermore, the total income did not consider other crop management spending (i.e., seed price, mineral fertilizers, pest control and harvesting) because the objective of this study was to compare irrigation performance (Table 2.8 and 2.9).

Irrigation cost methodology was based on a 24 ha Pivot Cost Analysis conducted by the Department of Biosystems Engineering of Auburn University (Tyson and Curtis, 2008). The initial cost of the irrigation system was not considered in this study because this cost can be depreciated through years and growing seasons. Therefore, only the annual cost of the irrigation system was taken into account reflect the irrigation investment for one growing season. The annual ownership cost and the annual operating cost per acre-inch of water applied were equivalent at $19.78 per acre-inch. One acre-inch corresponds to 62.78 mm per hectare which was used to define the price of irrigation in mm per hectare. Total irrigation during the season was multiplied per $0.32 per mm-ha in order to define total cost of irrigation (Table 2.8 and 2.9). Total profit per acre was calculated using the total income per ha minus the total cost of irrigation per ha. Furthermore, the cost of sensors was not included based on life cycle use of the sensor system longer than two years, similar to the center pivot which has an even longer design life. Thus, the cost of the sensors system can be depreciated through several growing seasons.

The economic calculation was addressed in this study to illustrate the impact of potential water saving and/or yield increase to the producer. For instance, grain yield differences could be considered statistically significant; however sometimes these differences do not impact the producer's profitability. Because in order to obtain higher yield, the cost of crop production also increases and sometimes the economical return do not worth the higher investment. Also the economic returns eventually are not worth it when a disadvantage such as environmental harm is considered.

Statistical Analysis

Spatial analysis of yield monitor data was conducted using ArcMap vr. 10.3.1 (ESRI). In 2014, a paired t-test was used to compare the effect of irrigation scheduling methods on grain yield within each soil-textural zone and differences in grain yield due to irrigation scheduling methods within each zone were tested using a t-test (PROC TTEST) implemented in SAS 9.1 (SAS for Windows v. 9.1, SAS Institute Inc., Cary, NC). As indicated by the two tales significance probability (P values < 0.0001), there is evidence that the variances for the two irrigation levels are unequal. Thus, the Satterthwaite method was used. In 2015, a split plot completely randomized design was implemented with soil-textural zones as main plot and irrigation scheduling methods as subplots and grain yield differences due to irrigation scheduling within and between zones were tested using generalized linear mixed models (PROC GLIMMIX) implemented in SAS 9.1 (SAS for Windows v. 9.1, SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Precipitation and Irrigation

The 2014 growing season exhibited above normal rainfall (30-year average) in April (+104 mm) and May (+17 mm), but below average in June (-0.5 mm), July (-46 mm) and August (-17 mm). In 2015, rainfall above the historic average (30 year average) was observed in April (+18 mm) and May (+96 mm) but below average in June (-20 mm), July (-17 mm), and August (-11 mm). The total rainfall during the growing season was above average in 2014 (+56 mm) and 2015 (+66 mm) (Table 2.5). The long-term average temperature (30 year average) of the entire growing season (April-August) was 23°C and in average temperature in 2014 and 2015 was 22°C and 23°C, respectively.

The study was conducted on different experimental fields in 2014 and 2015; however, the fields were located at the same research station and less than 5 km from each other. The 2014 seasonal total rainfall (April-August) was 613 mm and 623 mm in 2015 (Table 2.5). Total rainfall was similar across years and above the historic average, which was 556 mm. Total seasonal rainfall above the historic average could minimize the effect of irrigation on grain yield. However, rainfall distribution throughout the growing season has an impact on irrigation frequency and, consequently, on grain yield. Thus, if rainfall is concentrated during the period of high water demand, irrigation frequency and amount will decrease, but if rainfall is concentrated at the beginning or end of season; it does not have much impact on irrigation. Irmak et al. (2012) tested irrigation management strategies in large-scale farms with two growing seasons that had similar total rainfall, however the irrigation amount was lower in the second season because the rainfall distribution was different. Tasseling is the highest daily water demand for corn according to Corn Production Guide in Georgia (Lee, 2011). In 2014, corn plants received 22 mm and 25 mm of rain in the two weeks before and after tasseling, respectively. In 2015, rainfall amounts were 46 mm and 84 mm in the two weeks before and after tasseling respectively. Although total rainfall was similar, rainfall distribution could influence the differences of irrigation amounts in both growing seasons.

During the 2014 season, in zone A, the Checkbook method used 148 mm more water than the Sensor-based method. In zone B, the Checkbook method used 102 mm more water than the Sensor-based irrigation method. When the Sensor-based method was compared between both zones, 30 mm more water was applied in zone B compared to zone A. This result is interesting because zone B should have higher water holding capacity than zone A based on soil texture information (Table 2.3). Results from 2014 suggest that other factors (i.e. runoff) not examined in this study may have a stronger influence on PAW in this experimental field.

During the 2015 season, zone A and zone B did not exhibit irrigation differences between the Sensor-based irrigation plots. In this case, soil texture in the topsoil was different; however, deeper layers presented similar soil texture, which could minimize the differences in PAW between zones. Furthermore, when the irrigation threshold was adjusted, the irrigation threshold values were more similar. For example, difference between 55 kPa and 80 kPa was much smaller than between 32 kPa and 93 kPa. This increased the chances of similar sensor threshold occurring simultaneously in both zone and starting an irrigation event at the same time. The Checkbook method used more water than Sensor-based irrigation (51 mm) as it was expected (Table 2.5). The irrigation dates and amounts of two irrigation scheduling methods during both season is documented in the (Appendix 3 and 4)

Seasonal changes in soil matric potential, soil water, and irrigation management

Daily soil matric potential (SMP) changes at the 15, 30 and 60 cm soil depth from the Sensor-based irrigation plots during the 2014 and 2015 seasons are presented in the figures 2.3; 2.4; 2.5; 2.6. In 2014, sensors 1 and 6 were used to represent of the daily SMP changes in zone A and B, respectively. In 2015, sensors 8 and 4 were used to represent of the variation in SMP during the growing season for zone A and B, respectively. The same data was collected by eight sensor probes, four from each zone. However, seasonal patterns of SMP during both growing seasons for the previously mentioned sensors were representative of the major features of soil water dynamics in the Sensor-based method.

In 2014 the sensor installed in zone A indicated that irrigation was initiated when SPM values of at least one depth approached the threshold (23 kPa) (Figure 2.7). In zone B, the first irrigation event occurred when the irrigation threshold (62 kPa) was reached, but even though water was applied through irrigation, the SMP values continued increasing especially in the 15 and 30 cm soil depths. Subsequent irrigation events were not sufficient to decrease tension in the 15 and 30 cm depths, indicating that water uptake was very high in this period. The middle of June and beginning of July is a period of high daily water demand (Silks emerging and Blister stage). Therefore, corn plants were using mainly the root zone between 0 to 30 cm to uptake water and irrigation applied was taken up very rapidly because soil water tension did not significantly decrease. However, after middle July, rainfall plus irrigation brought the tension down and no more irrigation was required because the SMP did not approach the threshold (Figure 2.8).

During the 2015 growing season, sensors placed in zone A indicated that irrigation event was initiated when one or all depths approached the threshold (55 kPa). In some cases for instance in July 27th the threshold was approached however the irrigation was not necessary because the rainfall brought the tension to low values. Furthermore at the end of July the sensor located in the 60 cm depth started to malfunction because values were increasing quickly and it did not follow the trend of the others depths (15 and 30 cm) (Figure 2.9). In zone B, irrigation was triggered when SMP approached the irrigation threshold (80 kPa). At the end of July sensors indicated high SMP and irrigation was not enough to decrease it. However, a period of frequent and high amount of rain decreased the values (Figure 2.10).

Grain yield differences between irrigation strategies

Grain yield was analyzed differently for each growing season because of the different experimental design used each year. In 2014, grain yield from the two irrigation methods, Checkbook and Sensor-based, was analyzed independently by zone. In zone A, there were statistically significant grain yield differences between the two irrigation methods, with Checkbook plots exhibiting higher yield than Sensor-based plots: 10181 kg ha^{-1} and 9696 kg ha^{-1}, respectively (Table 2.6). The higher yield for the Checkbook plots could be associated with higher irrigation rate applied, 133 mm more, compared with the Sensor-based plots in zone A.

On the other hand, grain yield differences in zone B were not significant between irrigation methods. However, Sensor-based plots yielded higher than checkbook plots, with 9673 kg ha^{-1} and 9584 kg ha^{-1}, respectively. Even though irrigation amount applied in the Sensor-based (91mm) was lower than Checkbook (193 mm), there were not significant yield differences. Therefore, it suggests that the Sensor-based method was a promising strategy for this zone.

In 2015, the Type III test of fixed effects indicated that grain yield was significant different for Irrigation and Interaction (Zone x Irrigation) (Table 2.7). The Sensor-based method in zone A and Checkbook method in zone B exhibited the highest grain yield: 13597 kg ha^{-1} and

13417 kg ha^{-1}, respectively. The lowest grain yield, 11659 kg ha^{-1}, was recorded in the Sensor-based plots located in zone B (Table 2.8). There were no significant grain yield differences between zone A and zone B when data from the Checkbook plots was analyzed. In contrast, with the Checkbook method, there were significant grain yield differences between zones when data from the Sensor-based irrigation plots were analyzed. The Sensor-based method produced a grain yield of 13597 kg ha^{-1} in zone A and 11659 kg ha^{-1} in zone B, although both zones received the same amount of irrigation. However, zone B should have held more water because this zone had a higher clay percentage. Therefore, applying the same amount of irrigation to both zones could oversaturate the soil in zone B, decreasing yield. Ponnamperuma (1984) stated that oversaturated areas are usually characterized by the absence of O_2 and a lower amount of fertilizer. Therefore, the over-irrigation may occur in this zone and it could affect the grain yield. In zone A during 2015 growing season the implementation of the Sensor-based irrigation method showed positive results in terms of grain yield and water savings because when compared with the Checkbook method, the irrigation amount was lower but the yield was higher.

Water Productivity

Increasing productivity of water in corn can be achieved by producing more corn yield with the same amount of water resources or decrease the amount of water and maintain the corn yield. In 2014, greater water productivity (WP) values were recorded for the Sensor-based irrigation plots, 1.37 kg m^3 and 1.44 kg m^3 in zones A and B, respectively. The use of the Checkbook method resulted on WP values of 1.26 kg m^3 and 1.19 kg m^3 for zone A and B, respectively (Table 2.6). Several irrigation experiments involving different irrigation levels showed that deficit irrigation can produce higher WP than full irrigation (Ali et al., 2007; Sarwar and Perry, 2002). In this study the Sensor-based irrigation treatment could be considered as deficit irrigation because the irrigation trigger was set based on a percent depletion of plant available water, 35% depletion, and then, received less water during the growing season. For instance, irrigation studies found that 2/3 of full irrigation can increase water productivity by 19% in wheat crop and 8% for corn (Howell et al., 1997; Schneider and Howell, 1997). In the case of the 2014 growing season, the lowest WP value occurred when the Checkbook method was implemented in zone B. As of the Checkbook method, the same irrigation amount was applied on both zones; therefore, the differences in WP were associated with the crop (grain yield) response to irrigation and soil water holding characteristics between zones. The Sensor-based treatment tested on zone A, the zone with much greater sand content than zone B, showed greater water savings and increase of WP, 69% and 21%, respectively. These values showed that sensors performed well in this zone because the Checkbook method did not result in water savings (Table 2.6).

In 2015 , the greatest WP value was observed when the Sensor-based irrigation treatment was tested on zone A, the zone with a lighter soil texture in the shallow layers compared to zone B, which can be explained by less irrigation water applied (Table 2.8). Contrasting with the results in zone A, application of this method on zone B resulted in the lowest WP. This can be explained because of the low yield recorded where this method was implemented compared to yield from the Checkbook plots Overall, water savings of 42% were recorded on both zones when the Sensor-based method was tested (Table 2.8).

Economic Analysis

In 2014, the greatest total profit per ha, $1382, was observed when the Checkbook treatment was implemented on zone A, the zone with much lighter soil texture compared to zone

B (Table 2.9). When the same irrigation scheduling method was evaluated on zone B, a zone with much heavier soil texture with respect to zone A, the lowest total profit value was recorded. When the average for profit by irrigation method was calculated, a profit of $1348 resulted from use of the Sensor-based treatment compared to a lower profit, $1339, from the use of the checkbook method. In general, total profit differences were relatively small (0.6%).

In 2015, the greatest total profit per ha, $1905, was observed when the Sensor-based treatment was implemented on zone A, the zone with much lighter soil texture compared to zone B. Similar to the results from 2014 , when the Sensor-based treatment was evaluated on zone B, the lowest total profit ($1630) was observed (Table 2.10). When the average profit by irrigation method was calculated, a profit of $1810 resulted from the use of the Checkbook method compared $1767, from use of the Sensor-based method which corresponds to 2.4% profit increase from using the Checkbook method over the Sensor-based method.

Conclusion

This on-farm study conducted over two growing seasons provided a representation of weather, soil and management conditions under which corn is produced in Alabama. Since this study was conducted on commercial-scale fields, the microclimate, soil water balance, and management components differed substantially from small-plot studies. Grain yield in 2014 ranged from 9584 kg ha^{-1} to 10180 kg ha^{-1}; however, in 2015, grain yield ranged from 11659 kg ha^{-1} to 13597 kg ha^{-1}. Furthermore, the 2014 season might have presented yield values lower than the 2015 season because southern corn rust disease infested a large area of corn fields planted in the state and it caused yield losses during the 2014 growing season.

Some difficulties were faced during the growing seasons in order to conduct the two irrigation scheduling methods. The rainfall values inputted into the calculations of Checkbook method were collected from a rain gauge not located in the study site and this might influence the results because usually there is great spatial variability of rainfall. Also, the Checkbook method was based on corn water use curve derived in Georgia several years ago and they might have used a hybrid with different genetics than the hybrids used today. Thus, the response of the crop production to water might be different. Furthermore, due the size of the pivot, sometimes the irrigation was applied in both treatments at the same time even though one of them did not fully reach the threshold. Therefore, the irrigation applications were grouped to be more efficient in terms of labor and power consumption. The response of the crop to water might change with the soil type and Checkbook method does not consider it. Moreover, sensor malfunctions or bad contact with the soil could influence the sensor readings.

The results from this study suggest potential water savings and economic return when the Sensor-based method is implemented. However, additional studies under different weather and soil conditions are necessary to fully evaluate the potential of this technology.

Recommendation for Future Research

Further research addressing the SMP corresponding to the FC for the various soils in Alabama is required because a minor change in this tension can cause a great difference in the PAW values. Therefore, more accurate values of PAW will represent a more realistic volumetric water content available for plants. Consequently, the water depletion selected as irrigation threshold will be more trustful. Moreover, the evaluation of different irrigation threshold values is important. We selected 35% of PAW, but higher or lower, threshold values would likely produce different results. Additional years of research can potentially improve the experience to manage soil moisture sensors and increase long-term impacts while incorporating regional soil, climate, and precipitation differences.

Furthermore, any study addressing irrigation scheduling method requires good data records in terms of irrigation procedures and unexpected problems faced during the growing season. Therefore, detailed reports of each irrigation event with explanations why certain irrigation events did not occur are crucial to answer and justify results of the research.

Table 2.1 van Genuchten equation parameters and soil texture properties for three soil depths of the management zones delineated in 2014 at the EVSREC.

Depth (cm)	0 - 15		15 - 30		30 - 60	
Zone	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B
θr ǂ	0.0422	0.0555	0.04	0.0644	0.0515	0.0823
θs §	0.3837	0.3944	0.3857	0.4011	0.3788	0.4424
α ¶	0.0382	0.0149	0.0373	0.0162	0.0325	0.0112
n £	1.5215	1.4404	1.4526	1.4122	1.429	1.4286
m ¤	0.3428	0.3057	0.3116	0.2919	0.3002	0.3000
$\theta s - \theta r$ ¥	0.3415	0.3389	0.3457	0.3367	0.3273	0.3601
% Sand	75.83	49.17	71.67	47.5	73.33	29.17
% Silt	15.83	34.16	20	30.83	12.5	38.33
% Clay	8.34	16.67	8.33	21.67	14.17	32.5
Textural Class	Sand Loam	Loam	Sand Loam	Loam	Sand Loam	Clay Loam

ǂ Residual soil water content (cm^3 cm^{-3})

§Saturated soil water content (cm^3 cm^{-3})

¶ Parameter related to the inverse of the air entry suction (cm^{-1})

£ n curve shape parameter (empirical parameters)

¤ m= (1-1/n)

¥ θr and θs are the residual and saturated soil water contents (cm^3 cm^{-3})

Table 2.2 van Genuchten equation parameters and soil texture properties for three soil depths of the management zones delineated in 2015 at the EVSREC.

Depth (cm)	0 - 15		15 - 30		30 - 60	
Zone	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B
θr ǂ	0.0652	0.0972	0.0887	0.1036	0.0891	0.0967
θs §	0.3829	0.4887	0.4493	0.513	0.4423	0.4837
α ¶	0.0274	0.012	0.0182	0.0179	0.023	0.0199
n £	1.3149	1.3904	1.29	1.2394	1.244	1.225
m ¤	0.2395	0.2808	0.2248	0.1932	0.1961	0.1837
$\theta s - \theta r$ ¥	0.3177	0.3915	0.3606	0.4094	0.3532	0.387
% Sand	62.5	11.89	30.63	6.88	35	20
% Silt	13.13	45.68	26.25	31.25	19.38	23.13
% Clay	24.38	42.43	43.12	61.87	45.62	56.87
Textural Class	Sand Clay Loam	Silty Clay	Clay	Clay	Clay	Clay

ǂ Residual soil water content (cm^3 cm^{-3})

§Saturated soil water content (cm^3 cm^{-3})

¶ Parameter related to the inverse of the air entry suction (cm^{-1})

£ n curve shape parameter (empirical parameters)

¤ m= (1-1/n)

¥ θr and θs are the residual and saturated soil water contents (cm^3 cm^{-3})

Table 2.3 Soil hydraulic properties - Field Capacity, Permanent Wilting Point, Plant Available Water - and soil moisute and matric potential at 35% soil water depletion for three soil depths of the management zones delineated in 2014 at the EVSREC.

Depth (cm)	0 - 15		15 - 30		30 - 60	
Zone	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B
Field Capacity (FC) ǂ	0.2049	0.218	0.2225	0.2281	0.239	0.2785
Permanent Wilting Point (PWP) §	0.0545	0.087	0.0595	0.099	0.0743	0.1219
Plant Available Water (PAW) ¶	0.1504	0.132	0.163	0.1291	0.1647	0.1566
Water Depletion(35%) (cm3/cm3) £	0.0526	0.046	0.057	0.0451	0.0576	0.0548
35% of PAW (cm3/cm3) ¤	0.1523	0.1719	0.1654	0.1829	0.1813	0.2236
35 % of PAW (kPa) ¥	20	74	24	78	25	78

ǂ (cm^3 cm^3)

§ (cm^3 cm^3)

¶ PAW = FC – PWP

£ Water Depletion (35%) = PAW * 0.35 – 35% was the soil water depletion selected in the study

¤ 35% of PAW (cm^3 cm^3) = PAW – Water Depletion (35%)

¥ 35% of PAW (kPa) = soil matric potential referred to the depletion of 35% of PAW

Table 2.4 Soil hydraulic properties - Field Capacity, Permanent Wilting Point, Plant Available Water - and soil moisute and matric potential at 35% soil water depletion for three soil depths of the management zones delineated in 2015 at the EVSREC.

Depth (cm)	0 - 15		15 - 30		30 - 60	
Zone	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B
Field Capacity (FC) ǂ	0.2838	0.3129	0.367	0.3564	0.361	0.3427
Permanent Wilting Point (PWP) §	0.1126	0.1483	0.1591	0.2103	0.174	0.2035
Plant Available Water (PAW) ¶	0.1712	0.1646	0.2079	0.1461	0.187	0.1392
Water Depletion (35%) (cm3/cm3) £	0.599	0.0576	0.0727	0.0511	0.065	0.0487
35% of PAW (cm3/cm3) ¤	0.2239	0.2553	0.2942	0.3052	0.2951	0.2939
35 % of PAW (kPa) ¥	30	80	31	100	35	99

ǂ (cm^3 cm^3)

§ (cm^3 cm^3)

¶ PAW = FC – PWP

£ Water Depletion (35%) = PAW * 0.35 – 35% was the soil water depletion selected in the study

¤ 35% of PAW (cm^3 cm^3) = PAW – Water Depletion (35%)

¥ 35% of PAW (kPa) = soil matric potential referred to the depletion of 35% of PAW

Table 2.5 Climatic conditions, including rainfall (mm), average temperature(C^0), long-term (30 years) average values and irrigation amount (mm) during the 2014 and 2015 growing seasons and measured at the research site in the EVSREC.

Month	Rainfall (mm)	Temperature (°C)	Checkbook (mm)	Sensor - Zone A (mm)	Sensor - Zone B (mm)
			2014		
March	148	11.11	NI ǂ	NI	NI
April	223	16.67	NI	NI	NI
May	113	20.56	NI	NI	NI
June	112	24.44	30	15	30
July	89	24.44	163	30	61
August	75	24.44	NI	NI	NI
Total / Average	612	22.11	193	45	91
			2015		
March	51	14.44	NI	NI	NI
April	138	18.33	NI	NI	NI
May	192	21.11	13	13	13
June	93	25.00	57	38	38
July	118	26.11	51	19	19
August	82	25.56	NI	NI	NI
Total / Average	622	23.22	121	70	70
			Historic average (1971 - 2000)		
March	165	12.61	NA §	NA	NA
April	120	16.22	NA	NA	NA
May	96	20.50	NA	NA	NA
June	113	24.44	NA	NA	NA
July	135	26.28	NA	NA	NA
August	93	25.89	NA	NA	NA
Total / Average	556	22.67	NA	NA	NA

ǂ NI – No irrigation
§ NA – Not applicable

Table 2.6 Grain yield, irrigation water applied, rainfall, water savings, water productivity and increase of water productivity during the growing season of 2014 at the EVSREC.

Zone	Treatment	Grain yield (kg/ha) ǂ	Irrigation water applied		Rainfall		Water save		Water Productivity	Increase of Water Productivity (%)
			(mm)	(m^3/ha)	(mm)	(m^3/ha)	(mm)	(%)	(kg/m^3) §	
A	Checkbook	10180 a	193	1930	613	6130	0	0	1.26	6.22
	Sensor	9696 b	60	600	613	6130	133	69	1.44	21.16
B	Checkbook	9584 a	193	1930	613	6130	0	0	1.19	0.00
	Sensor	9674 a	91	910	613	6130	102	53	1.37	15.56

ǂ Statistical analysis (t-test) compared the two treatments (Checkbook and Sensor) within zone and not between zones

§Water Productivity = Grain yield / Total water applied (Irrigation + Rainfall)

Table 2.7 Type III test of fixed effects of grain yield during the growing season of 2015 at the EVSREC.

Sources of Variance	Grain Yield
Zone	0.30
Irrigation	<.0001*
Zone x Irrigation	<.0001

*Significant at 0.05 probability level

Table 2.8 Grain yield, irrigation water applied, rainfall, water saving, water productivity and increase of water productivity during the growing season of 2015 at the EVSREC.

Zone	Treatment	Grain yield (kg/ha)ǂ	Irrigation water applied		Rainfall		Water save		Water Productivity	Increase of Water Productivity (%)
			(mm)	(m^3/ha)	(mm)	(m^3/ha)	(mm)	(%)	(kg/m^3) §	
A	Checkbook	12674 bc	121	1210	623	6230	0	0	1.70	1.25
	Sensor	13597 a	70	700	623	6230	51	42	1.96	16.62
B	Checkbook	13417 ba	121	1210	623	6230	0	0	1.80	7.19
	Sensor	11659 c	70	700	623	6230	51	42	1.68	0

ǂ Statistical analysis compared the two treatments (Checkbook and Sensor) within zone and between zones

§Water Productivity = Grain yield / Total water applied (Irrigation + Rainfall)

Table 2.9 Grain yield, total income per hectare, total irrigation water applied, total irrigation cost, total profit per hectare and profit difference during the 2014 growing season at the EVSREC.

Zone	Treatement	Grain yield (kg/ha)	Total Income per ha ($) ǂ	Total Irrigation water applied (mm)	Total Irrigation Cost ($ per mm-ha) §	Total Profit per ha ($) ¶	Profit Difference (%)
A	Checkbook	10180	1442.8	193	60.8	1382.0	6.5
	Sensor	9696	1374.2	60	18.9	1355.3	4.5
B	Checkbook	9584	1358.4	193	60.8	1297.5	0.0
	Sensor	9674	1371.1	91	28.7	1342.4	3.5

ǂ Total income per ha = grain yield / 25.4 * $3.60 (corn grain price (bu).

§ Total irrigation cost = total irrigation water applied * $0.3151 (price of 1 mm per ha in Alabama).

¶ Total Profit per ha = total income per ha – total irrigation cost

Table 2.10 Grain yield, total income per hectare, total irrigation water applied, total irrigation cost, total profit per hectare and profit difference during the 2015 growing season at the EVSREC.

Zone	Treatement	Grain yield (kg/ha)	Total Income per ha ($) ǂ	Total Irrigation water applied (mm)	Total Irrigation Cost ($ per mm-ha) §	Total Profit per ha ($) ¶	Profit Difference (%)
A	Checkbook	12674	1796.3	121	38.1	1758.2	7.8
	Sensor	13597	1927.1	70	22.1	1905.1	16.8
B	Checkbook	13417	1901.6	121	38.1	1863.5	14.3
	Sensor	11659	1652.5	70	22.1	1630.4	0.0

ǂ Total income per ha = grain yield / 25.4 * $3.60 (corn grain price (bu).

§ Total irrigation cost = total irrigation water applied * $0.3151 (price of 1 mm per ha in Alabama).

¶ Total Profit per ha = total income per ha – total irrigation cost

Figure 2.1 Irrigation managment zones in 2014 at the EVSREC, the green polygons represent the Sensor-based plots and the white polygons the Checkbook plots. The blue triangles represent where the sensors were installed.

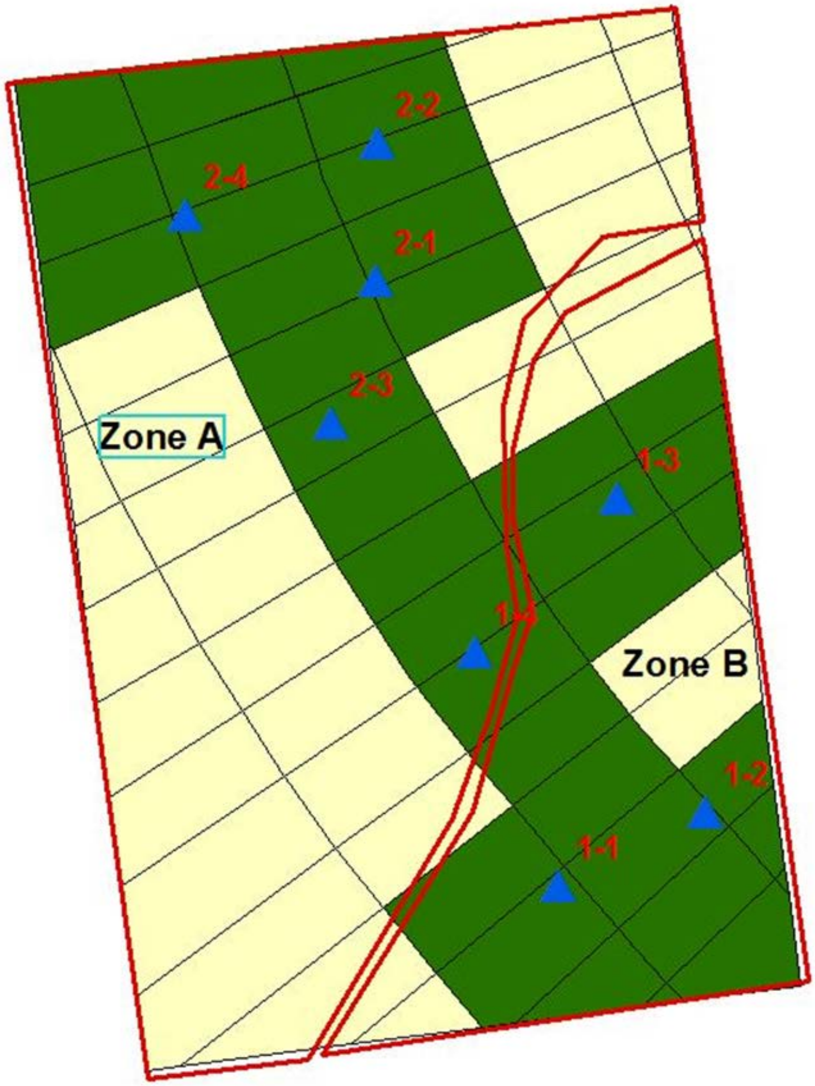


Figure 2.2 – Irrigation Management Zones in 2015 at the EVSREC, the green polygons represent the Sensor-based plots and the blue polygons represent the checkbook plots. The black cirlcles and numbers represent where the sensors were installed. The retangles represent the plot unit.

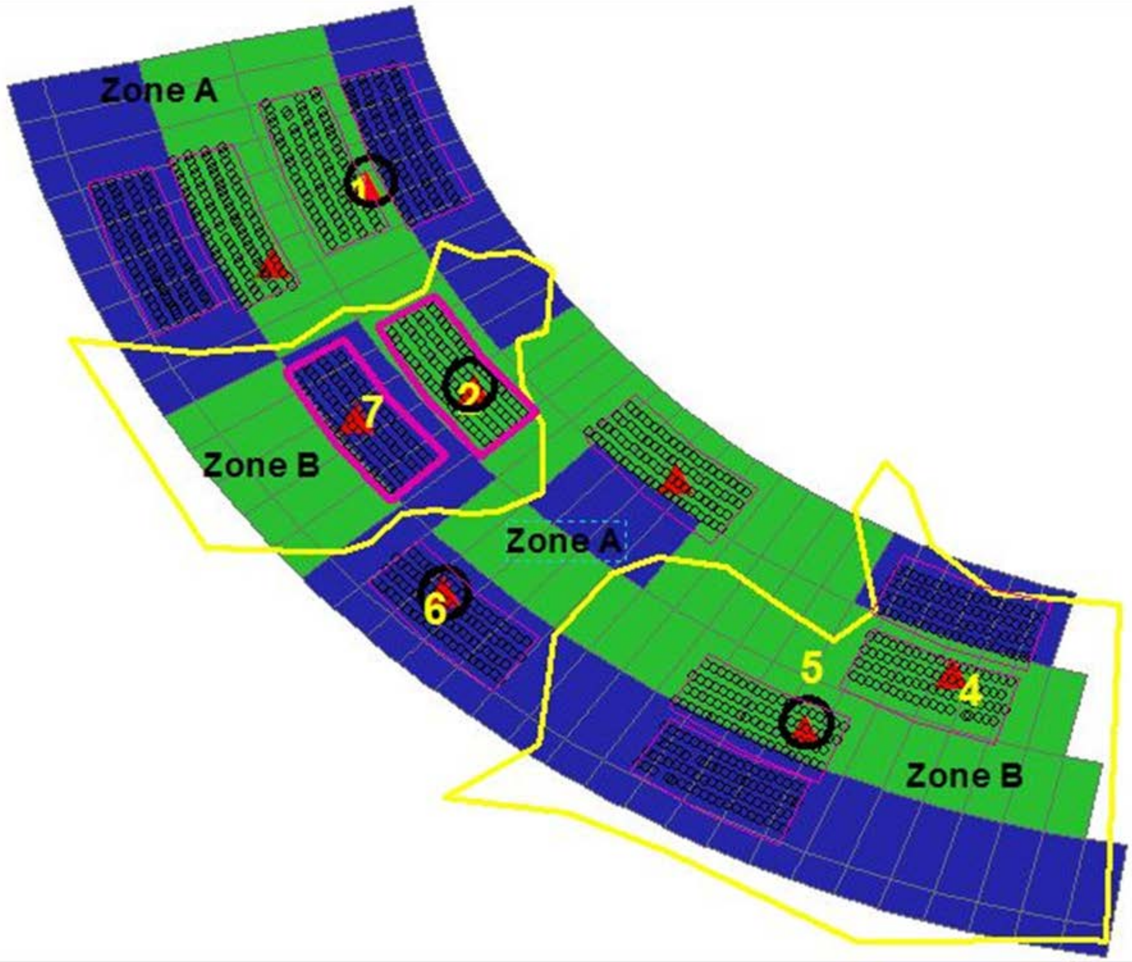


Figure 2.3 Soil water retention curves of the zone A created using the van Genuchten equation for each depth (15, 30 and 60 cm) to convert soil water content data in soil matric potential in 2014 at the EVSREC.

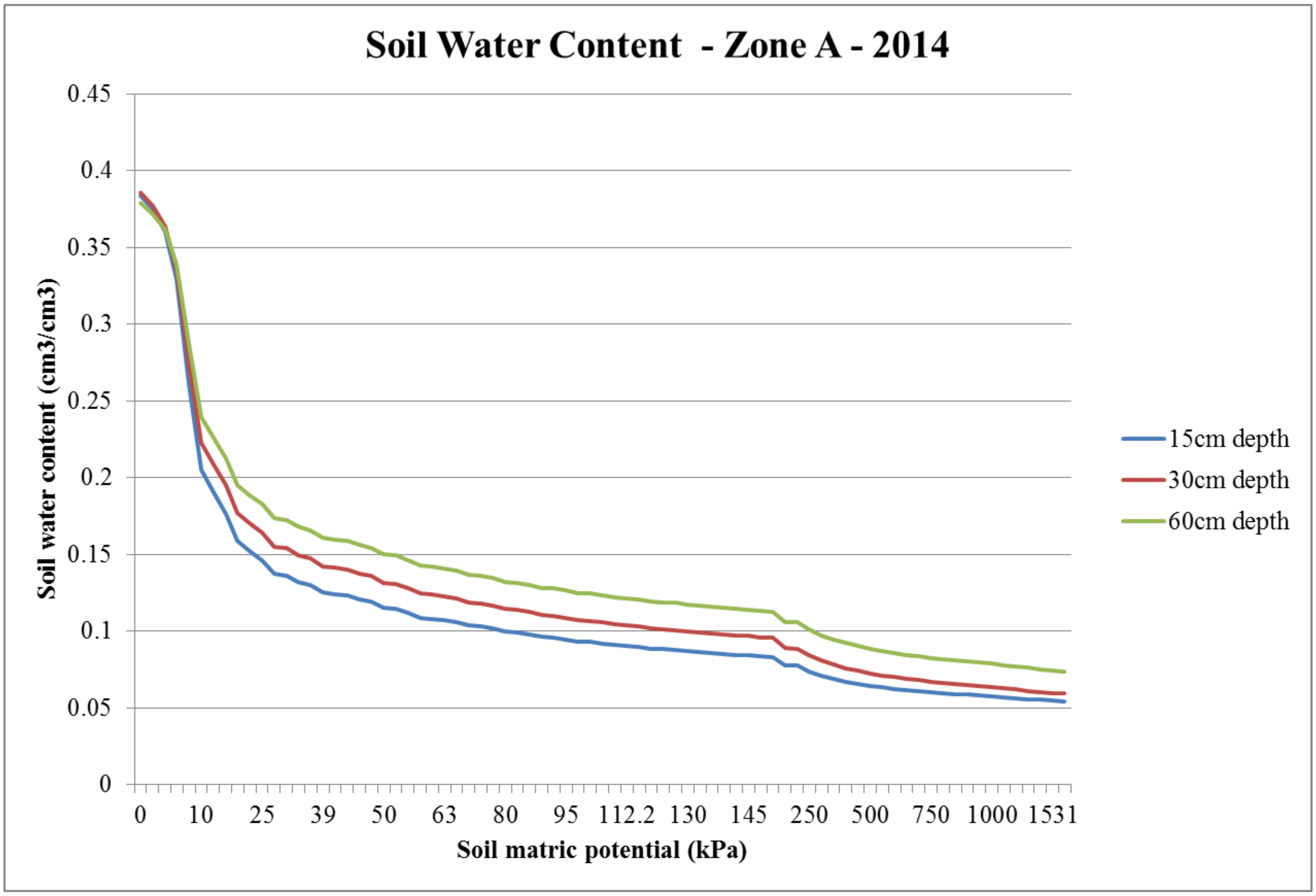


Figure 2.4 Soil water retention curves of the zone B created using the van Genuchten equation for each depth (15, 30 and 60 cm) to convert soil water content data in soil matric potential in 2014 at the EVSREC.

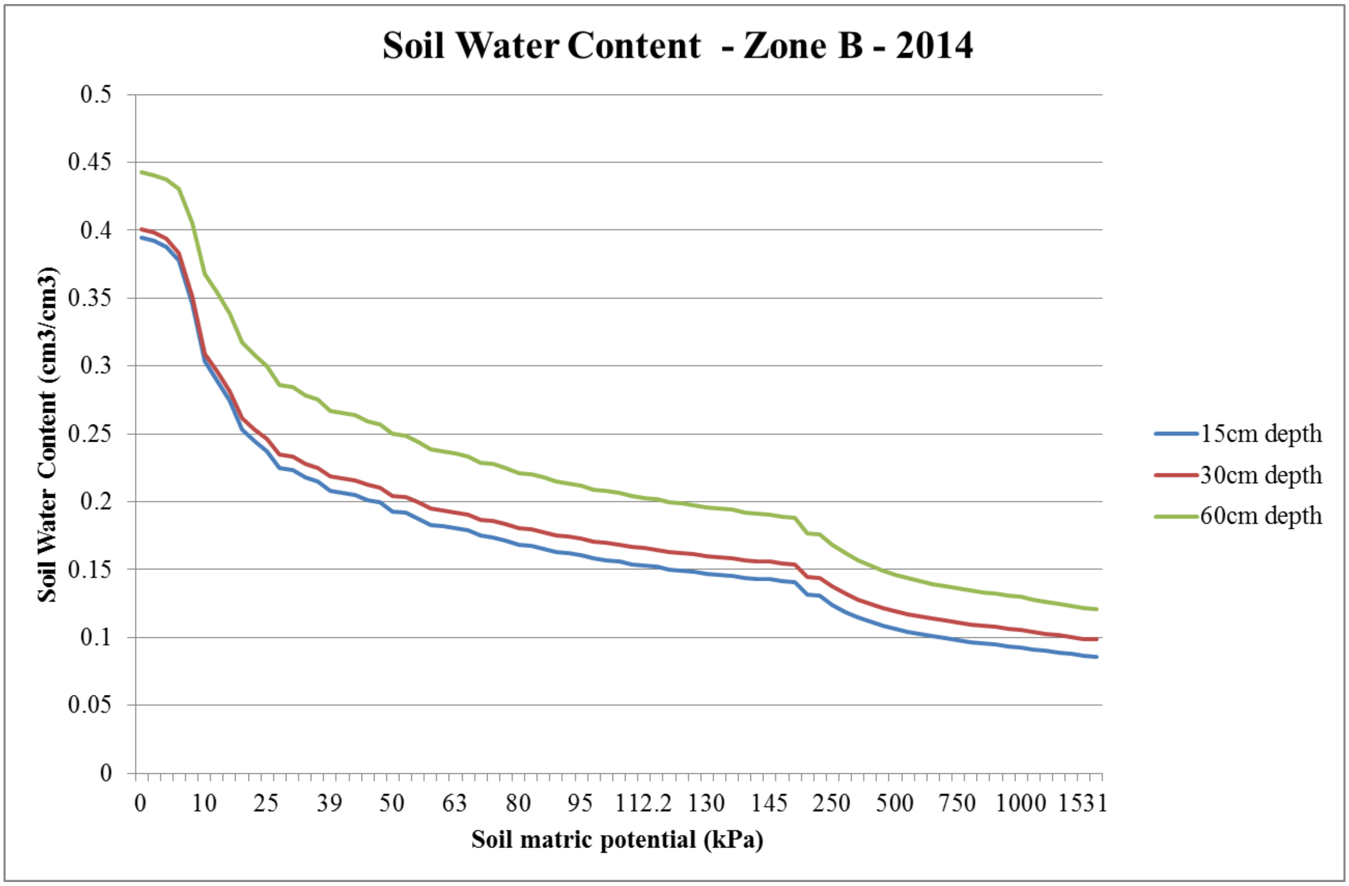


Figure 2.5 Soil water retention curves of the zone A created using the van Genuchten equation for each depth (15, 30 and 60 cm) to convert soil water content data in soil matric potential in 2015 at the EVSREC.

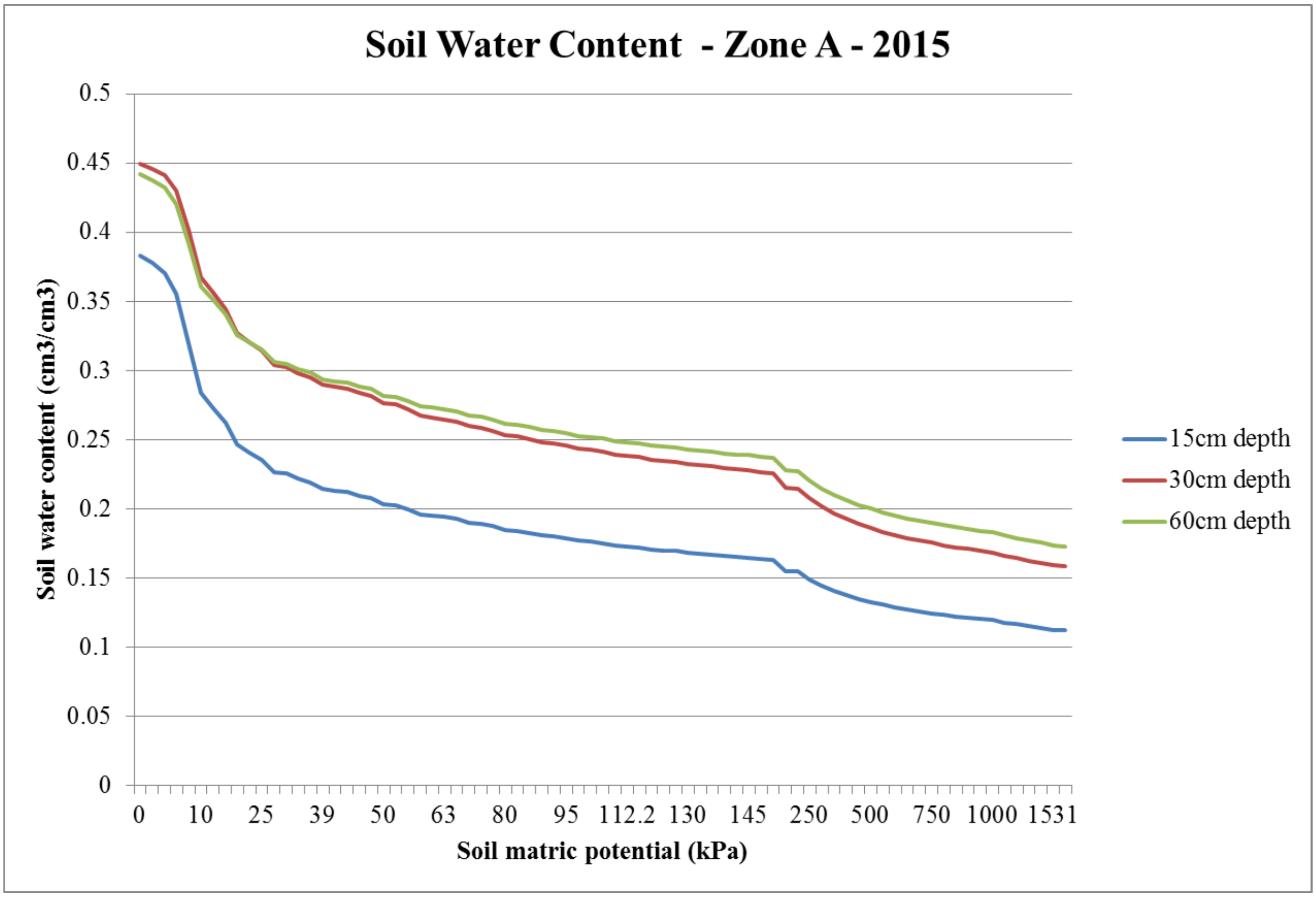


Figure 2.6 Soil water retention curves of the fine-textured zone created using the van Genuchten equation for each depth (15, 30 and 60 cm) to convert soil water content data in soil matric potential in 2015 at the EVSREC.

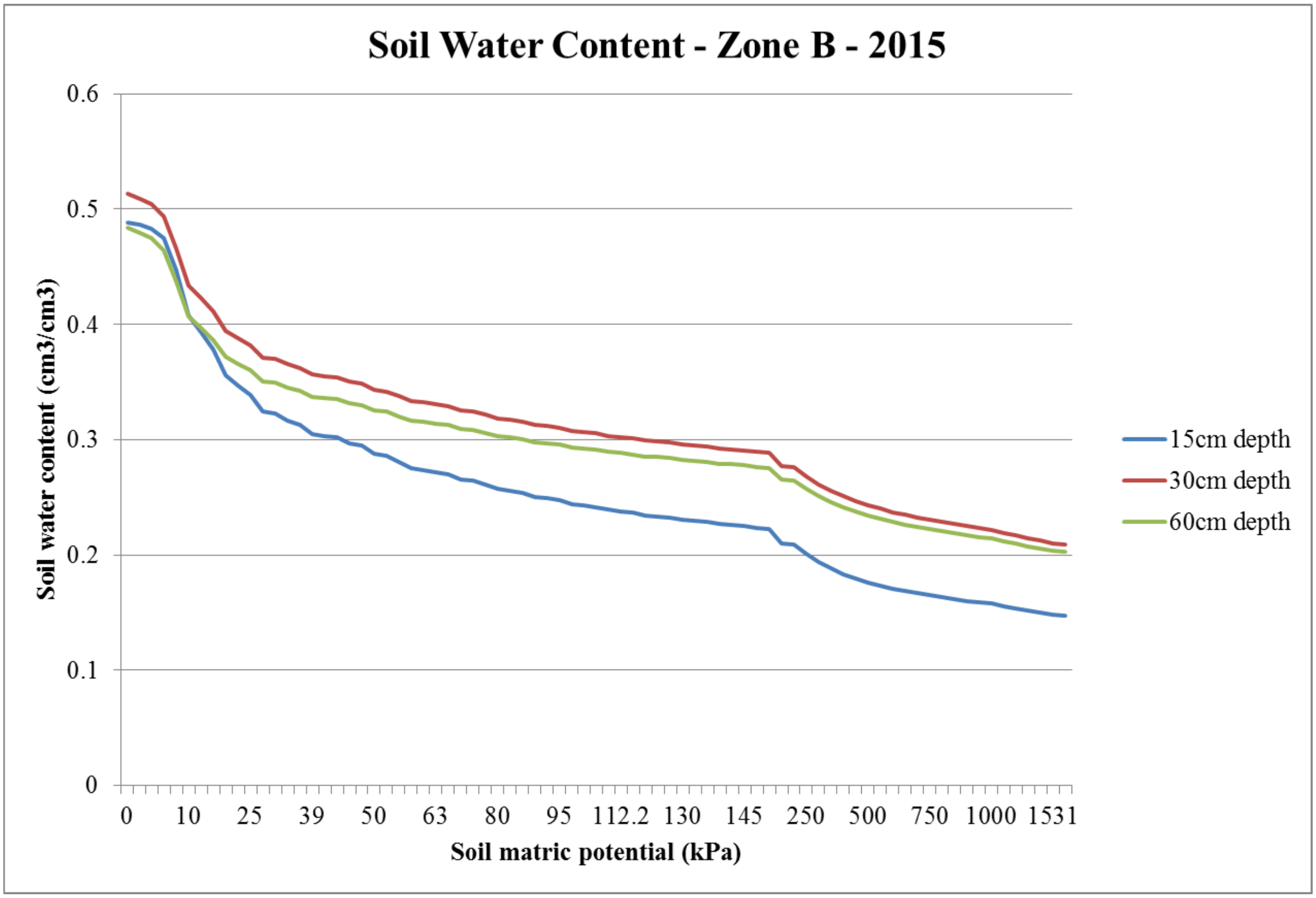


Figure 2.7 Changes in soil water potential provided by sensor 1 installed in zone A during the growing season of 2014 at the EVSREC. The amounts of irrigation referred in the black arrows were values of 15 mm to avoid runoff.

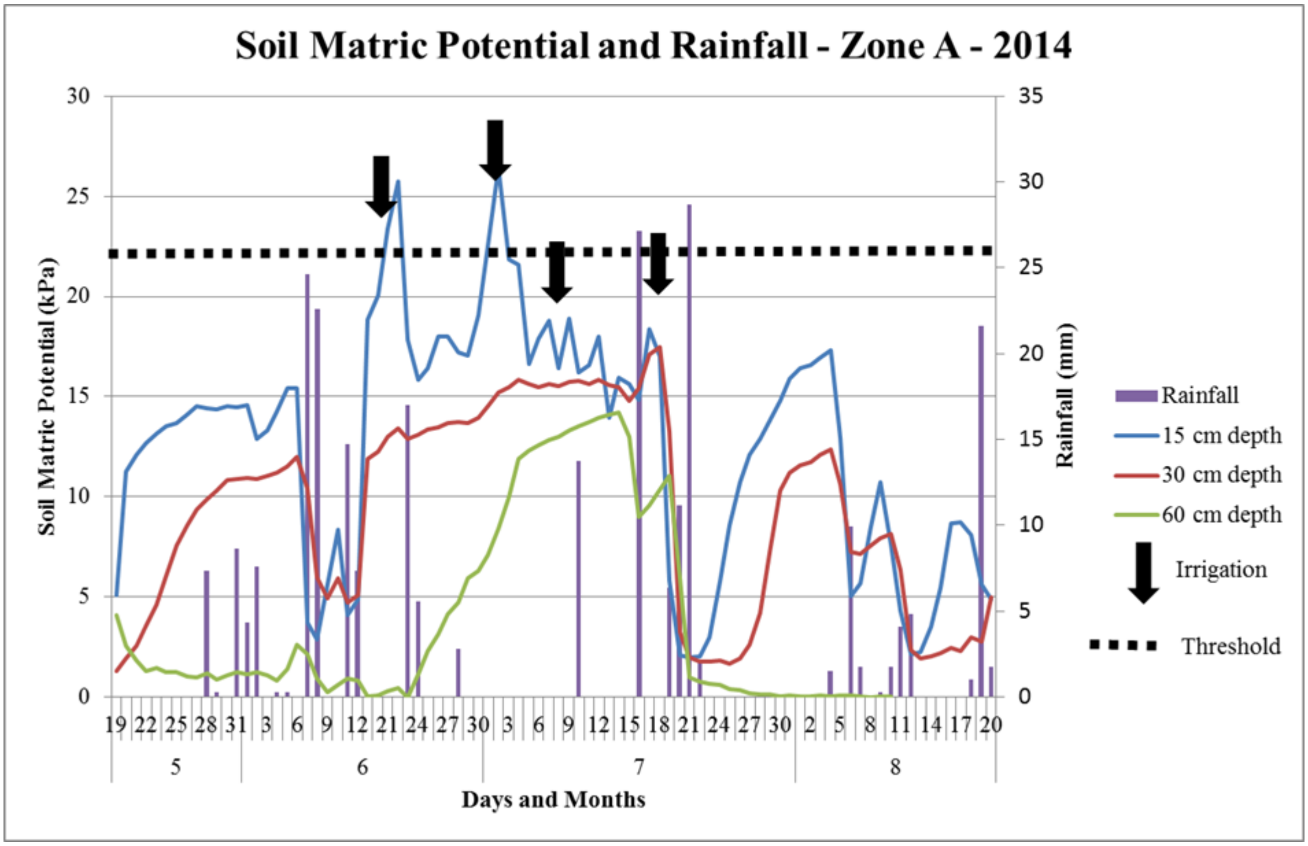


Figure 2.8 Changes in soil water Potential provided by sensor 6 installed in zone B during the growing season of 2014 at the EVSREC. The amounts of irrigation referred in the black arrows were values between 15 and 16 mm to avoid runoff.

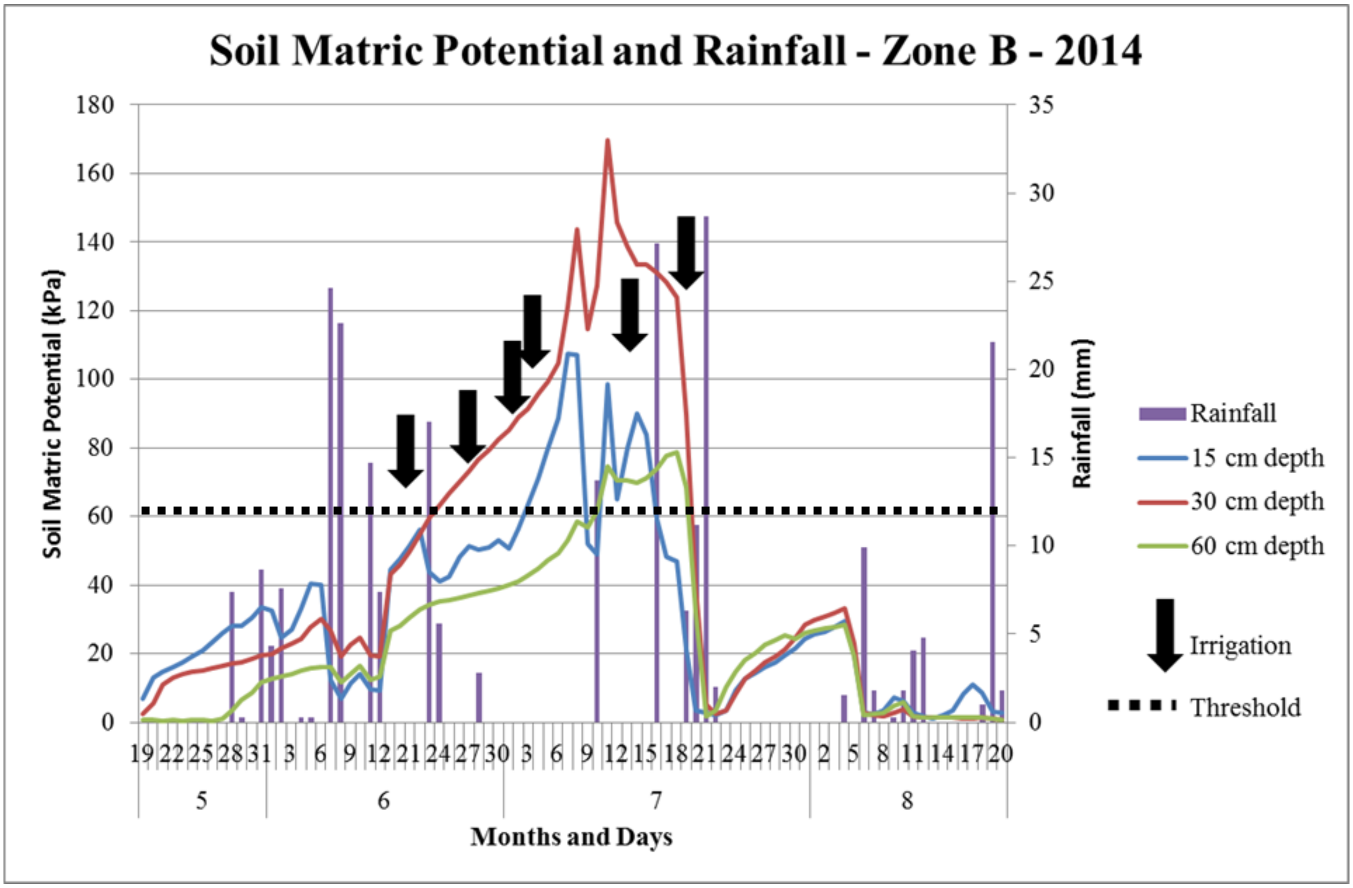


Figure 2.9 Changes in soil water Potential provided by sensor 8 installed in zone A during the growing season of 2015 at the EVSREC. The amounts of irrigation referred in the black arrows were values between 12 and 20 mm to avoid runoff.

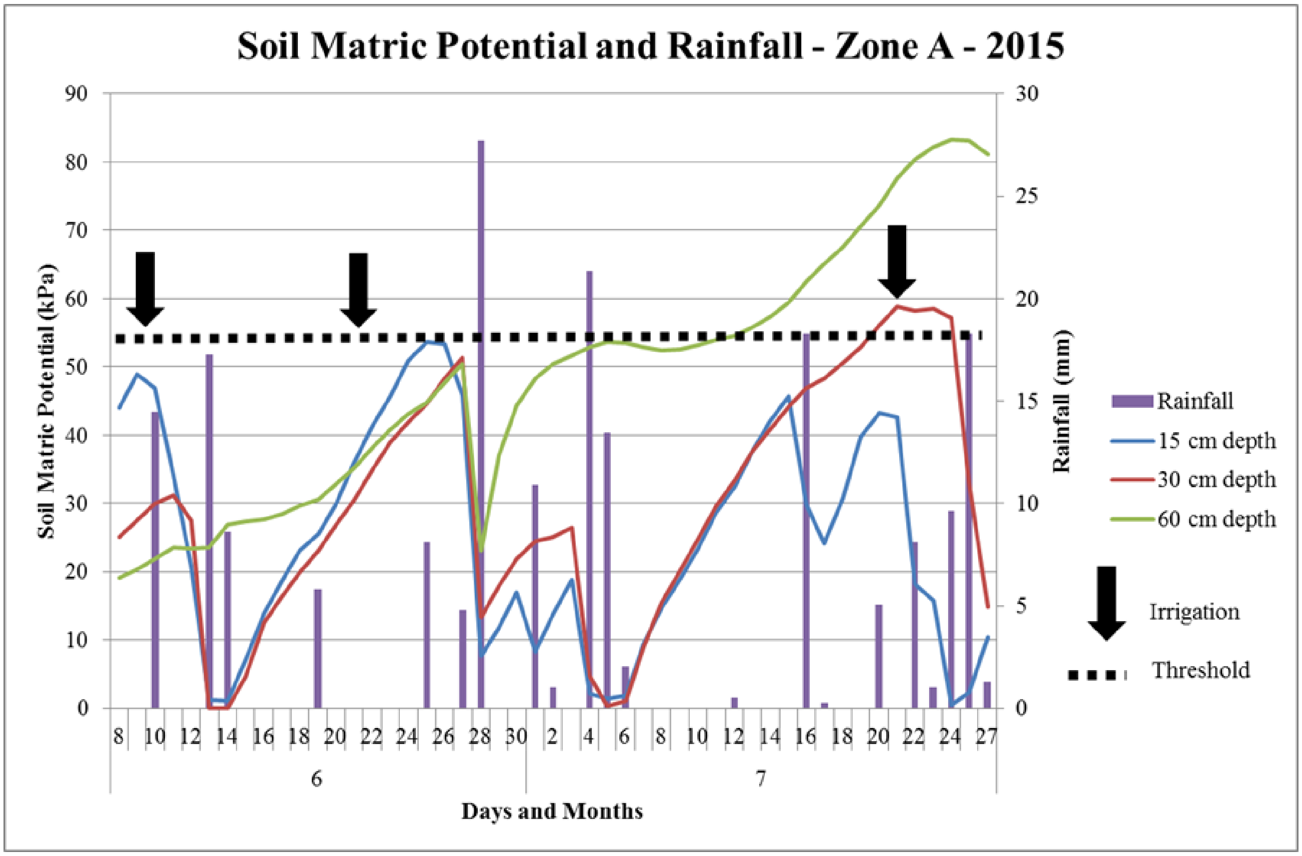
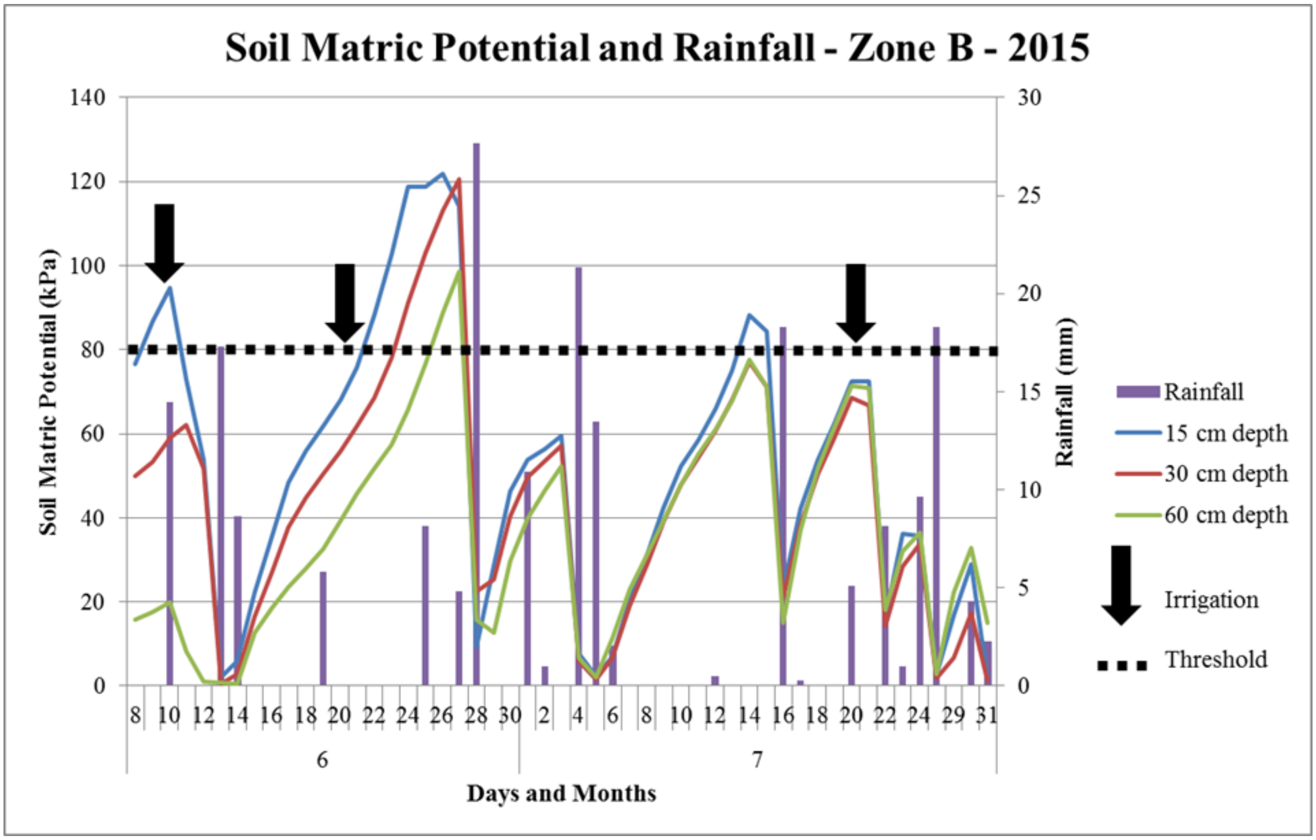


Figure 2.10 Changes in soil water Potential provided by sensor 4 installed in zone B during the growing season of 2015 at the EVSREC. The amounts of irrigation referred in the black arrows were values between 12 and 20 mm to avoid runoff.



REFERENCES

Abbasi M.K., Tahir M.M., Sadiq A., Iqbal M., Zafar M. (2012) Yield and nitrogen use efficiency of rainfed maize response to splitting and nitrogen rates in Kashmir, Pakistan. Agronomy Journal:448-457. DOI: 10.2134/agronj2011.0267.

Adams W.M. (1989) Definition and development in African indigenous irrigation. AZANIA: Journal of the British Institute in Eastern Africa:21-27.

Aina P.O., Periaswamy S.P. (1985) Estimating available water-holding capacity of western nigerian soils from soil texture and bulk-density, using core and sieved samples. Soil Science 140:55-58. DOI: 10.1097/00010694-198507000-00007.

Al-Kaisi M.M., Yin X. (2003) Effects of nitrogen rate, irrigation rate, and plant population on corn yield and water use efficiency. Agronomy Journal 95:1475-1482.

Ali M., Talukder M. (2008) Increasing water productivity in crop production—a synthesis. Agricultural Water Management 95:1201-1213.

Ali M.H., Hoque M.R., Hassan A.A., Khair A. (2007) Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. Agricultural Water Management 92:151-161. DOI: http://dx.doi.org/10.1016/j.agwat.2007.05.010.

Allen R.G., Pereira L.S., Raes D., Smith M. (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome 300:D05109.

Boomsma C.R., Vyn T.J. (2008) Maize drought tolerance: Potential improvements through arbuscular mycorrhizal symbiosis. Field Crops Research 108:14-31. DOI: 10.1016/j.fcr.2008.03.002.

Bruton J.M., McClendon R.W., Hoogenboom G. (2000) Estimating daily pan evaporation with artificial neural networks. Transactions of the Asae 43:491-496.

Chanzy A., Chadoeuf J., Gaudu J., Mohrath D., Richard G., Bruckler L. (1998a) Soil moisture monitoring at the field scale using automatic capacitance probes. European Journal of Soil Science 49:637-648.

Chanzy A., Chadoeuf J., Gaudu J.C., Mohrath D., Richard G., Bruckler L. (1998b) Soil moisture monitoring at the field scale using automatic capacitance probes. European Journal of Soil Science 49:637-648. DOI: 10.1046/j.1365-2389.1998.4940637.x.

Chapman D.V. (1996) Water quality assessments: a guide to the use of biota, sediments, and water in environmental monitoring.

Chauhan B.S., Mahajan G., Sardana V., Timsina J., Jat M.L. (2012) Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: problems, opportunities, and strategies. Advances in Agronomy 117:315-369.

Chen X.P., Cui Z.L., Vitousek P.M., Cassman K.G., Matson P.A., Bai J.S., Meng Q.F., Hou P., Yue S.C., Romheld V., Zhang F.S. (2011) Integrated soil-crop system management for food security. Proceedings of the National Academy of Sciences of the United States of America 108:6399-6404. DOI: 10.1073/pnas.1101419108.

Chuan L.M., He P., Jin J.Y., Li S.T., Grant C., Xu X.P., Qiu S.J., Zhao S.C., Zhou W. (2013) Estimating nutrient uptake requirements for wheat in China. Field Crops Research 146:96-104. DOI: 10.1016/j.fcr.2013.02.015.

Ciampitti I.A., Vyn T.J. (2011) A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crops Research 121:2-18. DOI: 10.1016/j.fcr.2010.10.009.

Ciampitti I.A., Vyn T.J. (2012) Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review (vol 133, pg 48, 2012). Field Crops Research 137:202-202. DOI: 10.1016/j.fcr.2012.05.009.
Ciampitti I.A., Vyn T.J. (2013) Grain Nitrogen Source Changes over Time in Maize: A Review. Crop Science 53:366-377. DOI: 10.2135/cropsci2012.07.0439.
Cook R., Papendick R. (1972) Influence of water potential of soils and plants on root disease. Annual Review of Phytopathology 10:349-374.
Corwin D.L., Lesch S.M. (2003) Application of Soil Electrical Conductivity to Precision Agriculture. Agronomy Journal 95:455-471. DOI: 10.2134/agronj2003.4550.
Cox W.J., Kalonge S., Cherney D.J.R., Reid W.S. (1993) Growth, yield, and quality of forage maize under different nitrogen management-practices. Agronomy Journal 85:341-347.
Djaman K., Irmak S., Martin D.L., Ferguson R.B., Bernards M.L. (2013) Plant Nutrient Uptake and Soil Nutrient Dynamics under Full and Limited Irrigation and Rainfed Maize Production. Agronomy Journal 105:527-538. DOI: 10.2134/agronj2012.0269.
Dukes M.D., Perry C. (2006) Uniformity testing of variable-rate center pivot irrigation control systems. Precision Agriculture 7:205-218. DOI: 10.1007/s11119-006-9020-y.
Eck H.V. (1984) Irrigated corn yield response to nitrogen and water. Agronomy Journal 76:421-428.
Edminster T., Reave R.C. (1957) Drainage problems and methods. Soil, The Yearbook of Agriculture 195.
Eghball B., Maranville J.W. (1993) Root development and nitrogen influx of corn genotypes grown under combined drought and nitrogen stresses. Agronomy Journal 85:147-152.
Eldridge E.F. (1963) Irrigation as a source of water pollution. Journal (Water Pollution Control Federation):614-625.
Evans R.G., Han S., Kroeger M., Schneider S.M. (1996a) Precision center pivot irrigation for efficient use of water and nitrogen. Precision Agriculture:75-84.
Evans R.G., Han S., Schneider, S.M., , Kroeger M.W. (1996b) Precision center pivot irrigation for efficient use of water and nitrogen. Proceedings of the 3rd International Conference on Precision Agriculture:75–84.
Evans R.G., LaRue J., Stone K.C., King B.A. (2013) Adoption of site-specific variable rate sprinkler irrigation systems. Irrigation Science 31:871-887. DOI: 10.1007/s00271-012-0365-x.
Evett S.R., Parkin G.W. (2005) Advances in soil water content sensing: The continuing maturation of technology and theory. Vadose Zone Journal 4:986-991. DOI: 10.2136/vzj2005.0099.
Fabrizzi K.P., Garcia F.O., Costa J.L., Picone L.I. (2005) Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of Argentina. Soil & Tillage Research 81:57-69. DOI: 10.1016/j.still.2004.05.001.
Fares A., Alva A.K. (2000) Evaluation of capacitance probes for optimal irrigation of citrus through soil moisture monitoring in an entisol profile. Irrigation Science 19:57-64. DOI: 10.1007/s002710050001.
Fereres E., Goldhamer D. (1990) Deciduous fruit and nut trees. Agronomy (USA).
Ferguson R., Shapiro C., Hergert G., Kranz W., Klocke N., Krull D. (1991) Nitrogen and irrigation management practices to minimize nitrate leaching from irrigated corn. Journal of Production Agriculture 4:186-192.

Fridgen J.J., Kitchen N.R., Sudduth K.A., Drummond S.T., Wiebold W.J., Fraisse C.W. (2004) Management zone analyst (MZA). Agronomy Journal 96:100-108.
Gardner W.H., Klute A. (1986) Water content. Methods of soil analysis. Part 1. Physical and mineralogical methods:493-544.
Geerts S., Raes D. (2009) Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agricultural Water Management 96:1275-1284. DOI: 10.1016/j.agwat.2009.04.009.
Glass M. K., Monks, C. D., Delaney D. P., Ortiz B. (2015) Performance of field corn hybrids in Alabama, 2015. Department of Crop Soils and Environmental Sciences, Auburn University, AL.
Goldhamer D.A., Fereres E., Mata M., Girona J., Cohen M. (1999) Sensitivity of continuous and discrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. Journal of the American Society for Horticultural Science 124:437-444.
Greenwood E.A.N. (1976) Nitrogen Stress in Plants, in: N. C. Brady (Ed.), Advances in Agronomy, Academic Press. pp. 1-35.
Guo J.H., Liu X.J., Zhang Y., Shen J.L., Han W.X., Zhang W.F., Christie P., Goulding K.W.T., Vitousek P.M., Zhang F.S. (2010) Significant Acidification in Major Chinese Croplands. Science 327:1008-1010. DOI: 10.1126/science.1182570.
Hagedorn F., Steiner K.G., Sekayange L., Zech W. (1997) Effect of rainfall pattern on nitrogen mineralization and leaching in a green manure experiment in South Rwanda. Plant and Soil 195:365-375. DOI: 10.1023/a:1004266205502.
Hanks R. (1974) Model for predicting plant yield as influenced by water use. Agronomy Journal 66:660-665.
Hanson B., Orloff S., Peters D. (2000) Monitoring soil moisture helps refine irrigation management. California Agriculture 54:38-42.
Harrison K., Lee D. (2007) Scheduling and managing corn irrigation. A Guide to Corn Production in Georgia. The University of Georgia, College of Agricultural and Environmental Sciences, Cooperative Extension Service, Crop and Soil Sciences Department:36-39.
Hedley C.B., Yule I.J. (2009) Soil water status mapping and two variable-rate irrigation scenarios. Precision Agriculture 10:342-355. DOI: 10.1007/s11119-009-9119-z.
Herrmann A., Taube F. (2004) The Range of the Critical Nitrogen Dilution Curve for Maize (Zea mays L.) Can Be Extended Until Silage Maturity. Agronomy Journal 96:1131-1138. DOI: 10.2134/agronj2004.1131.
Hlavek R. (1995) Selection criteria for irrigation systems ICID.
Hoffman G.J., Howell T.A., Solomon K.H. (1990) Management of farm irrigation systems The American Society of Agricultural Engineers (ASAE).
Hou P., Gao Q., Xie R.Z., Li S.K., Meng Q.F., Kirkby E.A., Romheld V., Muller T., Zhang F.S., Cui Z.L., Chen X.P. (2012) Grain yields in relation to N requirement: Optimizing nitrogen management for spring maize grown in China. Field Crops Research 129:1-6. DOI: 10.1016/j.fcr.2012.01.006.
Howell T. (1996) Irrigation scheduling research and its impact on water use, Proc. Intl. Conf. on Evapotranspiration and Irrigation Scheduling, Citeseer. pp. 21-33.
Howell T.A., Schneider A.D., Evett S.R. (1997) Subsurface and surface microirrigation corn - Southern High Plains. Transactions of the Asae 40:635-641.

Irmak S., Burgert M.J., Yang H.S., Cassman K.G., Walters D.T., Rathje W.R., Payero J.O., Grassini P., Kuzila M.S., Brunkhorst K.J., Eisenhauer D.E., Kranz W.L., VanDeWalle B., Rees J.M., Zoubek G.L., Shapiro C.A., Teichmeier G.J. (2012) Large-scale on-farm implementation of soil moisture-based irrigation management strategies for increasing maize water productivity. Transactions of the Asabe 55:881-894.

Irmak S., Payero J.O., VanDeWalle B., Rees J., Zoubek G. (2014) Principles and operational characteristics of Watermark granular matrix sensor to measure soil water status and its practical applications for irrigation management in various soil textures.

Irmak S., Rees J.M., Zoubek G.L., van DeWalle B.S., Rathje W.R., DeBuhr R., Leininger D., Siekman D.D., Schneider J.W., Christiansen A.P. (2010) Nebraska agricultural water management demonstration network: integrating research and extension/outreach. Applied Engineering in Agriculture 26:599-613.

Jensen M., Rangeley W., Dieleman P. (1990) Irrigation trends in world agriculture. Agronomy:31-67.

Jokela W.E., Randall G.W. (1989) Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agronomy Journal 81:720-726.

Jones H.G. (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. Journal of Experimental Botany 55:2427-2436. DOI: 10.1093/jxb/erh213.

Ju X.T., Xing G.X., Chen X.P., Zhang S.L., Zhang L.J., Liu X.J., Cui Z.L., Yin B., Christie P., Zhu Z.L., Zhang F.S. (2009a) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. Proceedings of the National Academy of Sciences of the United States of America 106:3041-3046. DOI: 10.1073/pnas.0813417106.

Ju X.T., Xing G.X., Chen X.P., Zhang S.L., Zhang L.J., Liu X.J., Cui Z.L., Yin B., Christie P., Zhu Z.L., Zhang F.S. (2009b) Reducing environmental risk by improving N management in intensive Chinese agricultural systems (vol 106, pg 3041, 2009). Proceedings of the National Academy of Sciences of the United States of America 106. DOI: 10.1073/pnas.0902655106.

Jury W.A., Vaux H.J. (2007) The emerging global water crisis: Managing scarcity and conflict between water users, in: D. L. Sparks (Ed.), Advances in Agronomy, Vol 95. pp. 1-76.

Kapinos J. (2006) Irrigation Sensors Benefit Afghanistan Farmers. United States Air Force, 455th Air Expeditionary Wing Public Affairs, Camp Cunningham, Bagram Airfield, Afghanistan.

King B.A., Kincaid D.C. (2004) A variable flow rate sprinkler for site-specific irrigation management. Applied Engineering in Agriculture 20:765-770.

Kizito F., Campbell C.S., Campbell G.S., Cobos D.R., Teare B.L., Carter B., Hopmans J.W. (2008) Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor. Journal of Hydrology 352:367-378. DOI: 10.1016/j.jhydrol.2008.01.021.

Ko J., Piccinni G. (2009) Corn yield responses under crop evapotranspiration-based irrigation management. Agricultural Water Management 96:799-808. DOI: 10.1016/j.agwat.2008.10.010.

Leib B.G., Hattendorf M., Elliott T., Matthews G. (2002) Adoption and adaptation of scientific irrigation scheduling: trends from Washington, USA as of 1998. Agricultural Water Management 55:105-120.

Leib B.G., Jabro J.D., Matthews G.R. (2003) Field evaluation and performance comparison of soil moisture sensors. Soil Science 168:396-408.

Liu Y., Li J., Li Y. (2015) Effects of split fertigation rates on the dynamics of nitrate in soil and the yield of mulched drip-irrigated maize in the sub-humid region. Applied Engineering in Agriculture 31:103-117. DOI: 10.13031/aea.31.10773.

Martin D., Stegman E., Fereres E. (1990) Irrigation scheduling principles. IN: Management of Farm Irrigation Systems. American Society of Agricultural Engineers, St. Joseph, MI. 1990. p 155-203, 19 fig, 9 tab, 81 ref.

Matson P.A., Parton W.J., Power A.G., Swift M.J. (1997) Agricultural intensification and ecosystem properties. Science 277:504-509. DOI: 10.1126/science.277.5325.504.

McCullough D.E., Mihajlovic M., Aguilera A., Tollenaar M., Girardin P. (1994) Influence of N supply on development and dry matter accumulation of an old and a new maize hybrid. Canadian Journal of Plant Science 74:471-477. DOI: 10.4141/cjps94-087.

Mitchell C.C., Huluka G. (2012) Nutrient recommendation tables for alabama crops.

Molden D. (1997) Accounting for water use and productivity Iwmi.

Montazar A., Azadegan B. (2012) Effects of seasonal water use and applied n fertilizer on wheat water productivity indices. Irrigation and Drainage 61:52-59. DOI: 10.1002/ird.620.

Moser S. (2006) Effects of pre-anthesis drought, nitrogen fertilizer rate, and variety on grain yield, yield components, and harvest index of tropical maize. Agricultural Water Management 81:41-58. DOI: 10.1016/j.agwat.2005.04.005.

Novoa R., Loomis R.S. (1981) Nitrogen and plant production. Plant and Soil 58:177-204. DOI: 10.1007/bf02180053.

Oki T., Agata Y., Kanae S., Saruhashi T., Musiake K. (2003) Global water resources assessment under climatic change in 2050 using TRIP. International Association of Hydrological Sciences, Publication:124-133.

Pan L., Adamchuk V.I., Martin D.L., Schroeder M.A., Ferguson R.B. (2013) Analysis of soil water availability by integrating spatial and temporal sensor-based data. Precision Agriculture 14:414-433. DOI: 10.1007/s11119-013-9305-x.

Pandey R.K., Herrera W.A.T., Pendleton J.W. (1984) Drought response of grain legumes under irrigation gradient, yield and yield components. Agronomy Journal 76:549-553.

Pandey R.K., Maranville J.W., Chetima M.M. (2000) Deficit irrigation and nitrogen effects on maize in a Sahelian environment II. Shoot growth, nitrogen uptake and water extraction. Agricultural Water Management 46:15-27. DOI: 10.1016/s0378-3774(00)00074-3.

Pereira L. (1996) Inter-relationships between irrigation scheduling methods and on-farm irrigation systems. Water Reports (FAO).

Pereira L., Feddes R., Gilley J., Lesaffre B. (2013) Sustainability of irrigated agriculture Springer Science & Business Media.

Pereira L.S. (1999) Higher performance through combined improvements in irrigation methods and scheduling: a discussion. Agricultural Water Management 40:153-169.

Pereira L.S., Oweis T., Zairi A. (2002) Irrigation management under water scarcity. Agricultural Water Management 57:175-206.

Perry C., Pocknee S. (2003) Development of a Variable-Rate Pivot Irrigation Control System.

Phene C.J., Howell T.A. (1984) Soil sensor control of high-frequency irrigation systems. Transactions of the Asae 27:392-396.

Ponnamperuma F. (1984) Effects of flooding on soils. Flooding and plant growth:9-45.

Qadir M., Boers T.M., Schubert S., Ghafoor A., Murtaza G. (2003) Agricultural water management in water-starved countries: challenges and opportunities. Agricultural Water Management 62:165-185.

Qiu S.J., He P., Zhao S.C., Li W.J., Xie J.G., Hou Y.P., Grant C.A., Zhou W., Jin J.Y. (2015) Impact of Nitrogen Rate on Maize Yield and Nitrogen Use Efficiencies in Northeast China. Agronomy Journal 107:305-313. DOI: 10.2134/agronj13.0567.

Ray D.K., Mueller N.D., West P.C., Foley J.A. (2013) Yield Trends Are Insufficient to Double Global Crop Production by 2050. Plos One 8. DOI: 10.1371/journal.pone.0066428.

Rhades J., Bernstein L., Ciaccio L. (1971) Chemical, physical and biological characteristics of irrigation and soil water. Water and water pollution handbook 1:141-222.

Rhoads F., Yonts C. (2000) Irrigation Scheduling for Corn–Why and How. National Corn Handbook. Water Management (Irrigation). US Department of Agriculture (USDA). En línea: http://corn. agronomy. wisc. edu/Management/pdfs/N CH20. pdf.

Richards L.A., Weaver L.R. (1944) Moisture retention by some irrigated soils as related to soil-moisture tension. Journal of Agricultural Research 69:0215-0235.

Ringler C., Biswas A.K., Cline S.A. (2010) Global change: impacts on water and food security Springer.

Rosegrant M.W., Ringler C. (1999) Impact on food security and rural development of reallocating water from agriculture, International Food Policy Research Institute (IFPRI).

Rosegrant M.W., Ringler C., Zhu T.J. (2009) Water for Agriculture: Maintaining Food Security under Growing Scarcity, Annual Review of Environment and Resources. pp. 205-222.

Rudnick D.R., Irmak S. (2013) Impact of water and nitrogen management strategies on maize yield and water productivity indices under linear-move sprinkler irrigation. Transactions of the Asabe 56:1769-1783.

Runge E. (1968) Effects of rainfall and temperature interactions during the growing season on corn yield. Agronomy Journal 60:503-507.

Sadler E.J., Camp C.R., Evans D.E., Millen J. (2002) Spatial variation of corn response to irrigation. Transactions of the Asae 45:1869.

Sadler E.J., Evans R.G., Stone K.C., Camp C.R. (2005) Opportunities for conservation with precision irrigation. Journal of Soil and Water Conservation 60:371-379.

Sarwar A., Perry C. (2002) Increasing water productivity through deficit irrigation: Evidence from the Indus plains of Pakistan. Irrigation and Drainage 51:87-92.

Schaible G., Aillery M. (2012) Water conservation in irrigated agriculture: Trends and challenges in the face of emerging demands. USDA-ERS Economic Information Bulletin.

Schneider A.D., Howell T.A. (1997) Methods, amounts, and timing of sprinkler irrigation for winter wheat. Transactions of the Asae 40:137-142.

Sedlak D. (2014) Water 4.0: the past, present, and future of the world's most vital resource Yale University Press.

Setiyono T.D., Walters D.T., Cassman K.G., Witt C., Dobermann A. (2010) Estimating maize nutrient uptake requirements. Field Crops Research 118:158-168. DOI: 10.1016/j.fcr.2010.05.006.

Seyfried M. (1993) Field calibration and monitoring of soil-water content with fiberglass electrical resistance sensors. Soil Science Society of America Journal 57:1432-1436.

Seyfried M.S., Murdock M.D. (2004) Measurement of soil water content with a 50-MHz soil dielectric sensor. Soil Science Society of America Journal 68:394-403.

Shaahan M.M., El-Sayed A.A., Abou El-Nour E.A.A. (1999) Predicting nitrogen, magnesium and iron nutritional status in some perennial crops using a portable chlorophyll meter. Scientia Horticulturae 82:339-348. DOI: 10.1016/s0304-4238(99)00060-6.

Shangguan Z.P., Shao M.A., Dyckmans J. (2000) Nitrogen nutrition and water stress effects on leaf photosynthetic gas exchange and water use efficiency in winter wheat. Environmental and Experimental Botany 44:141-149. DOI: 10.1016/s0098-8472(00)00064-2.

Shepherd M. (1992) Effect of irrigation on nitrate leaching from sandy soils. Water and Irrigation Review 12:19-22.

Shi Z.L., Li D.D., Jing Q., Cai J., Jiang D., Cao W.X., Dai T.B. (2012) Effects of nitrogen applications on soil nitrogen balance and nitrogen utilization of winter wheat in a rice-wheat rotation. Field Crops Research 127:241-247. DOI: 10.1016/j.fcr.2011.11.025.

Smith M., Pereira L., Berengena J., Itier B., Goussard J., Tollefson L., Van Hofwegen P. (1997) Irrigation scheduling: From theory to Practice.

Stanhill G. (2002) Is the Class A evaporation pan still the most practical and accurate meteorological method for determining irrigation water requirements? Agricultural and Forest Meteorology 112:233-236. DOI: http://dx.doi.org/10.1016/S0168-1923(02)00132-6.

Sui R., Fisher D.K., Barnes E.M. (2012) Soil moisture and plant canopy temperature sensing for irrigation application in cotton. Journal of Agricultural Science 4:93.

Sylvester R.O., Seabloom R.W. (1962) A study on the character and significance of irrigation return flows in the Yakima River basin University of Washington, Department of Civil Engineering.

Szeles A.V., Megyes A., Nagy J. (2012) Irrigation and nitrogen effects on the leaf chlorophyll content and grain yield of maize in different crop years. Agricultural Water Management 107:133-144. DOI: 10.1016/j.agwat.2012.02.001.

Tarchitzky J., Chen Y. (2002) Rheology of Sodium-montmorillonite suspensions. Soil Science Society of America Journal 66:406-412.

Thom A.S., Thony J.L., Vauclin M. (1981) On the proper employment of evaporation pans and atmometers in estimating potential transpiration. Quarterly Journal of the Royal Meteorological Society 107:711-736. DOI: 10.1256/smsqj.45315.

Toth V.R., Meszaros I., Veres S., Nagy J. (2002) Effects of the available nitrogen on the photosynthetic activity and xanthophyll cycle pool of maize in field. Journal of Plant Physiology 159:627-634. DOI: 10.1078/0176-1617-0640.

Uribelarrea M., Crafts-Brandner S.J., Below F.E. (2009) Physiological N response of field-grown maize hybrids (Zea mays L.) with divergent yield potential and grain protein concentration. Plant and Soil 316:151-160. DOI: 10.1007/s11104-008-9767-1.

Van Genuchten M.T. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44:892-898.

Vaux H., Pruitt W.O. (1983) Crop-water production functions. Advances in irrigation 2:61-95.

Vellidis G., Tucker M., Perry C., Wen C., Bednarz C. (2008) A real-time wireless smart sensor array for scheduling irrigation. Computers and Electronics in Agriculture 61:44-50. DOI: 10.1016/j.compag.2007.05.009.

Vermillion D.L. (1997) Impacts of irrigation management transfer: A review of the evidence IWMI.

Wienhold B.J., Trooien T.P., Reichman G.A. (1995) Yield and nitrogen use efficiency of irrigated corn in the northern Great Plains. Agronomy Journal 87:842-846.

Wilcox L.V. (1962) Salinity caused by irrigation. Journal (American Water Works Association) 54:217-222.

Williams B.G., Hoey D. (1987) The use of electromagnetic induction to detect the spatial variability of the salt and clay contents of soils. Australian Journal of Soil Research 25:21-27. DOI: 10.1071/sr9870021.

Williamson R. (1964) The effect of root aeration on plant growth. Soil Science Society of America Journal 28:86-90.

Winter T.C. (1998) Ground water and surface water: a single resource DIANE Publishing Inc.

Woli K.P., Boyer M.J., Elmore R.W., Sawyer J.E., Abendroth L.J., Barker D.W. (2016) Corn Era Hybrid Response to Nitrogen Fertilization. Agronomy Journal 108:473-486. DOI: 10.2134/agronj2015.0314.

Wright J., Bergsrud F. (1991) Irrigation scheduling: Checkbook method. Bulletin AG-FO-13322-C. St. Paul, Minn.: Minn. Ext. Serv.

Yao T., Wierenga P.J., Graham A.R., Neuman S.P. (2004) Neutron probe calibration in a vertically stratified vadose zone. Vadose Zone Journal 3:1400-1406.

Zwart S.J., Bastiaanssen W.G.M. (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69:115-133. DOI: 10.1016/j.agwat.2004.04.007.

Appendix

Appendix 1 Irrigation amounts and dates referred to the Pan evaporation and Sensor-based irrigation irrigation scheduling methods during the growing season of 2014 at TVREC.

Date	Pan evaporation	Sensor-based	
	Irrigation Applied (mm)	Plots by N rate (kg ha^{1})	Irrigation Applied (mm)
5/26/2014	6	202,269,336	5
6/4/2014	15	202,269,336	15
6/17/2014	15	.	0
6/22/2014	15	202,269	15
6/26/2014	15	202,336	15
7/3/2014	8	202,269	8
7/7/2014	8	202,336	8
7/17/2014	15	202,269,336	15
8/7/2014	25	202,269,336	25
8/16/2014	15	202,269,336	15
Total	138	.	Depending on N rate plot

Plot (kg N ha^{1})	Total Irrigation by N rate (mm)
202	122
269	99
336	99

Appendix 2 Irrigation amounts and dates referred to the Pan evaporation and Sensor-based irrigation scheduling methods during the growing season of 2015 at TVREC.

Date	Pan Evaporation	Sensor-based	
	Irrigation Applied (mm)	Plots by N rate (kg N ha^{1})	Irrigation Applied (mm)
6/9/2015	25	.	0
6/14/2015	25	.	0
6/16/2015	0	202, 336	25
6/17/2015	0	269	25
6/18/2015	25	.	0
6/19/2015	0	202,269,336	25
6/22/2015	0	202	25
6/23/2015	25	269,336	25
6/30/2015	18	202,336	25
7/1/2015	19	.	0
7/10/2015	19	.	0
7/13/2015	19	.	0
7/27/2015	19	202,269,336	25
8/3/2015	0	202,269,336	25
8/5/2015	19	.	0
Total	215		Depending on N rate plot

Plot (kg N ha^{1})	Total Irrigation by N rate (mm)
202	152
269	127
336	152

Appendix 3 Irrigation amounts and dates referred to the Checkbook and Sensor-based irrigation scheduling methods during the growing season of 2014 at EVSREC.

Date	Checkbook	Sensor-based	
	Irrigation (mm)	Irrigation - Zone A (mm)	Irrigation - Zone B (mm)
6/20/2014	15	0	0
6/21/2014	0	15	15
6/27/2014	15	0	0
6/30/2014	0	0	16
7/2/2014	0	15	0
7/4/2014	21	0	15
7/7/2014	21	15	15
7/9/2014	21	0	0
7/11/2014	20	0	0
7/14/2014	20	0	15
7/17/2014	20	15	15
7/28/2014	20	0	0
7/31/2014	20	0	0
Total	193	60	91

Appendix 4 Irrigation amounts and dates referred to the Checkbook and Sensor-based irrigation scheduling methods during the growing season of 2015 at EVSREC.

Date	Checkbook	Sensor-based	
	Irrigation (mm)	Irrigation - Zone A (mm)	Irrigation - Zone B (mm)
5/9/2015	12	12	12
6/13/2015	19	19	19
6/20/2015	19	19	19
6/25/2015	20	0	0
7/8/2015	12	0	0
7/17/2015	19	0	0
7/21/201	20	20	20
Total	121	70	70