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USE OF LONG TERM WEATHER DATA AND SPATIALLY DELINEATED FIELD ATTRIBUTES TO PREDICT WATER AND ENERGY CONSERVATION FROM VARIABLE RATE IRRIGATION

Sahil Sharma
University of Nebraska - Lincoln, sahilsharma229@gmail.com

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by

Sahil Sharma

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Sahil Sharma, M.S.

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Adviser: William Kranz

The declining levels of the Ogallala aquifer calls for more judicious use of water. Studies have shown that VRI has the potential for water savings. But adoption of VRI is still very low. The major reason is lack of information on the returns from the VRI systems and its feasibility in different fields. Also, a quantification of the required reduction in prices of VRI is necessary. So, an economic return analysis of VRI strategies was done to compare it to uniform irrigation management (UIM) using a water balance model based on long term weather data and field properties for a field near Elgin, Nebraska, containing four soil textures, for a period of 1988-2016. Five strategies were established to work on the study, namely, Field Capacity-VRI, Driest Soil Trigger-VRI, Water Mining-VRI, CUIM and Total IUM. Thirteen field distributions were developed to study the variation in the field requirements of VRI and results were quantified based on three cost factors (100%, 75%, and 50%).

The water balance model predicted irrigation amounts and frequencies for the five strategies which were used to determine the total water applied, total cost of application as well as an input for the AquaCrop model to simulate the yields. Irrigation costs were

calculated based on three prices of VRI ($21,379, $16,034 and $10,690) and profits were calculated for each strategy and distribution and savings were established by comparing profits with those of CUIM.

Results indicate that VRI is not feasible for the field near Elgin, NE, at present costs because an average yearly application reduction of 2.4% was not able to justify the 4% yearly decline in monetary savings as compared to CUIM. TIUM is recommended for the field as it showed $2907 yearly savings on CUIM. It was also observed that VRI worked best in fields where water mining is justified, that is, the fields with higher variation in water holding capacities soils with the more wet soils covering at least 60% of area. Also, a reduction of at least 25% in the initial costs was considered essential for VRI to be beneficial.

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1.1 INTRODUCTION

Water, the most important element for the sustainability of life on this planet is also a crucial element for the sustainability of agriculture. There is an ever increasing demand for water in the agricultural sector which is highlighted by the fact that agriculture and livestock account for 39% of the total freshwater use in the United States. Out of this freshwater usage, 43% is derived from the groundwater sources (Maupin et. al, 2014). In Nebraska and in the high plains, most of the groundwater wells are fed by the Ogallala aquifer which supply water to approximately 174,000 wells which remove 81.9 billion cubic meters of water from the aquifer annually (Konikow, 2013). These conditions are forcing the government to apply pumping restrictions in several areas of central and southern High Plains and Platte River Valley in central Nebraska (Evans et al. 2013).

Given the scenario it is crucial to encourage producers to better manage their water use by employing technologies that would not only conserve water but also increase their profits. This is where Variable Rate Irrigation (VRI) comes into play. Site-specific VRI (SS-VRI) is the method of varying the application of water in a field to address the specific requirements of relatively small areas of a field be it soil texture changes, crop requirements or physical variation in the field such as ditches, roads or ponds etc. This variation in application can be achieved either by speeding up or slowing down the system (thus changing the application depth along the entire length of the center pivot) or to use pulse modulated nozzles that achieve greater precision by switching on or off at desired locations (thus influencing the application depth along the center pivot).

VRI technologies were first patented in 1991 by the University of Idaho as a complete theoretical method and physical equipment for varying the application of water in the field (McCann and Stark 1993). This technology has been intensely studied and improved over the last two decades with major focus on hardware development for management zone control. Fraisse et al. (1992) developed the laboratory set up of solenoid valves to control the flow from individual sprinklers and found that VRI based on solenoid valve control or pulse irrigation would be feasible with minimal effects on distribution patterns or efficiency of the system. King (1995) proposed the development of management zones for variable rate irrigation, based on soil physical attributes such as soil texture, depth and slope and areas of similar crop response to irrigation and fertilizers via remote sensing using satellite or aerial imagery. Evans et al. (1996) developed precision control systems for application of water as well as fertilizers and pesticides at site-specific level. They developed prescription maps using site specific soil data fed through GPS to the self-propelled irrigation system but found that the system was unable to rationally develop coherent maps. Camp and Sadler (1998) studied site specific crop management using modifications to commercially available center pivot systems and a GPS based program for irrigation depths. Their control system, which could be updated using real time soil data, was useful for site specific irrigation, pesticides and fertilizers applications. Perry et al. (2004) studied the effects of variable rate sprinkler cycling or repetitive on/off sprinkler cycle, on irrigation uniformity and application efficiencies and found that even though center pivots perform better with this method than lateral move systems, overall, there was little to no impact of VRI on the sprinkler systems uniformity or distribution efficiency.

These studies propelled the research of VRI into the modern age and to the addition of various new equipment and technologies for making improved decision. Kim et al. (2008) studied the use of wireless sensor networks to control the depth of water applied in various areas in the field by converting the linear move system to machine controlled by GPS inputs. With the aid of low-cost Bluetooth wireless radio transmissions, they developed a system of remotely controlling the irrigation machines; thus adding a new avenue to the VRI control support systems. O'Shaughnessy and Evett (2010) studied the use of infrared thermometer sensors (IRTs) to collect canopy temperatures to trigger irrigation in cotton. They found that the automatic water application plots had greater yields than the manually irrigated plots. Haghverdi et al. (2016) studied the use site specific water production functions to analyze uniform and VRI strategies in Cotton. They developed water production functions using k-nearest neighbor (k-NN), neural networks and multiple linear regression methods to develop management zones and compared them to conventional soil texture based management zones. They found that k-NN method produced the greatest yields; thus providing a new empirical tool for on-field irrigation management. These advancements have been replicated by the center pivot manufacturers (Kranz et al. 2012). They provide a variety of irrigation equipment and decision support software to the producers at ever more competitive rates.

But all this advancement and enthusiasm for VRI among the academia as well as the industry, somehow, is not shared by the producers. Currently, VRI is used mostly to address soil textural differences, localized over or under irrigation, ponding and other physical issues. There are several factors influencing the low adoption of VRI such as lack of evidence pointing to the profitability of VRI systems, low rate of return on investment, high maintenance costs, low government subsidies or cost shares, lack of broad scale decision support mechanisms or software for the VRI systems and high initial investments (Evans and King 2012). It all boils down to profit. Is it really worth investing in this technology?

There have been multiple studies evaluating the feasibility of VRI. Lambert and Lowenberg-De Boer (2000) reviewed 108 case studies on the profitability of site specific irrigation management and reported 63% net positive profit with the use of the technologies. Marek and Cox (2001) and Almas et al. (2003) studied the potential benefits of VRI in the Texas High Plains and concluded that feasibility of the systems depended largely on the spatial variation in the field as well as the crop value vs water cost (or availability) ratio. Sadler et al. (2002) studied spatial variation of responses of yields of corn in a three-year study and concluded that there are many potential benefits that can be achieved with VRI but initial information for the variability is a key factor for the VRI management to achieve the desired results. Nijbroek et al. (2003) used a crop model to compare VRI with uniform irrigation and found that VRI was more profitable with nearly $16 per ha increased profit over the uniform irrigation methods. Oliveiria et al. (2005) compared VRI to uniform irrigation using available water holding capacity method in tomatoes and found VRI required 20% less water than uniform irrigation but also had a lower yield average for the study period. There are several other studies reporting the potential benefits of VRI (Koch et al. 2004; King et al., 2006; DeJonge et.

al, 2007; Hedley and Yule, 2009; King et al., 2009; Hillyer and Higgins, 2014; Kranz et al., 2014; Lo et al., 2016). The potential of VRI water savings range from 0-26 % over the conventional uniform irrigation methods (Evans and King 2012). However, most of the studies done on the subjects are rather short term which leaves out the potential savings by the system across the lifetime of the equipment. This is the basic inspiration behind this study, that is, to analyze the potential benefits of VRI over the course of the average lifetime of the system.

In order to quantify and evaluate long-term potential of VRI technology, it is essential that a water balance tool be employed to simulate the dynamics of soil-plant-atmosphere continuum. Soil-water balance is based on the fact that the amount of water that enters the profile must be equal to the amount of water that leaves it. The principle components of a water-balance are: change in soil water content, precipitation, crop-water use (ET or ET_a), supplemental irrigation and water losses due to runoff and deep percolation. Understanding the relationship and interaction between the soil and atmosphere is one of the crucial elements in developing irrigation schedules and other soil water investigations (Saxton et al. 1986).

Extensive studies have been conducted to better understand and to develop the components of the water balance and to model these balances to either predict irrigation usages or to estimate the ET in the area. Milly (1994) developed a water balance model to test the theory that the long term water balance in any area is just dependent on the local fluctuations of water within the area and found that it held true if runoff losses are negated. Granier et al. (1999) also developed a water balance based model to predict duration and intensity of droughts in forests lands. The model helped quantify the drought events and the helped minimize the water stress index in the oak and spruce forests. Water balance has also been used to determine ground water recharge and to estimate long term ground water fluctuations. Eilers et al. (2007) used this approach in cropped lands in Nigeria for a continuous period of 36 years. The model inferred that for any particular area and in any particular year, the ground water recharge largely depends on temporal distribution of rainfall and the soil water from the previous season. Water balance is used in all of the major crop growth models such as SWATRE (Belmans et al. 1983); CERES-Maize (Jones et al. 1986); EPIC (Williams et al. 1991); CropSyst (Stöckle et al. 2003); DSSAT (Jones et al. 2003); Hybrid-Maize (Yang et al. 2004); BUDGET (Raes et al. 2006) and AquaCROP (Raes et al. 2009). It has also been used to calculate ET (Payero et al. 2005; Van Donk et al. 2009; Van Donk et al. 2010; Djaman and Irmak 2012; Rahgozar et al. 2012; Sharma and Irmak, 2012; Djaman and Irmak, 2013; Rudnick and Irmak, 2013; Rudnick and Irmak, 2014; Sharma and Irmak, 2017; Sharma et al, 2017).

However, most of the components of the soil water balance are based on the soil properties such as texture, structure and location of the soil. The measurement of the soil properties is a long and difficult process which is fairly expensive and is often not feasible for studies that are conducted over a short time and for the studies that require a remote investigation of attributes (Saxton et al. 1986). Especially, in a study like this, conducted using long term simulation, the field attributes and variation of these attributes do not get depicted in the physical method of determination. So, in order to perform a long-term simulation, we need to estimate some parameters, needed for the water-balance, as close to the original settings, as possible.

ET is one of the key components of the hydrological cycle and plays a vital role in computing water and energy balances (Chattopadhyay et al. 2009). It is the combination of evaporation from the soil surface and the transpiration from plant leaf stomata. ET is a crucial parameter and needs to be calculated precisely as over 90% of the total water that moves out of the soil is a direct result of ET (Irmak et al. 2002). Because of its importance, it is imperative that ET be measured or calculated precisely for any water balance model to achieve precision. Direct measurement of the ET components has its own challenges and is often non-reliable (Rahgozar et al. 2012). The direct method of measuring ET is either pan evaporation or lysimetric determination. The other method for ET estimation are the equation dependent on the temperature (Hargreaves-Samani Equation), humidity and solar radiation (Penmann-Montieth Equation).

Studies have measured the reliability of some of the methods to calculate and measure ET. Hargreaves and Samani (1985) evaluated the earlier methods of ET estimation which included direct methods such as evaporation pan method and the Blaney-Criddle method and estimation through the Hargreaves equation and the Jensen-Haise equation and found evaporation pan method to be the most precise among the direct methods and the Hargreaves method among the estimation models. Jackson et al. (1983) proposed the use of surface temperatures recorded via remote sensing to develop a coefficient for the estimation of ET from a single input during the day.

But the direct methods of estimation, however precise they may be, are not very feasible if they require expensive equipment. So, the widely used method for ET estimation is a dual procedure which is a combination of estimating ET from a reference surface and then calculating the ET from the desired crop using the crop-specific coefficients. The reference surfaces can be grass or alfalfa. The most widely used equation for the estimation of the reference ET is the Standardized Penman-Monteith Equation as recommended by the Food and Agricultural Organization and the American Society of Civil Engineers (ASCE-EWRI, 2005) which was used in this study.

The second input for the model would be high quality local precipitation. Precipitation is the opposite of ET in the soil water balance as it restores water back into the soil profile. It is the product of the condensation of water in the atmosphere which is delivered to the ground in the form of rain, hail, snow, mist or drizzle. In Nebraska, about 65% of annual precipitation occurs during the growing season of May-September (Kukal et al., 2016).

Using these parameters and with the knowledge of losses through runoff and deep percolation, it is possible to get irrigation requirements from any field, given the field specifics are known. Irrigation or supplemental irrigation is the amount of water that is artificially introduced into the soil profile to replace water that is lost by crop ET, often a portion of the total available water to the crop. Water balance has been used to predict irrigation requirements in various studies (Al-Kufaishi et al. 2006; DeJonge et al. 2007; Hassan-Esfahani et al. 2015; Hedley et al. 2009; Hedley and Yule 2009; King et al. 2006; Ma et al. 2013; Nijbroek et al. 2003; Oliveiria et al. 2005; Rahgozar et al. 2012; Ritchie and Amato 1990; Sadler et al. 2002; Sammis et al. 2012). Thus there is enough evidence that the water balance approach to simulate irrigation requirements is a feasible method.

VRI has shown some potential benefits but adoption has been low because of lack of long term benefit analysis. The goal of this study was to determine the long term feasibility of the VRI systems over its lifetime. To achieve this goal, we established the following objectives for this study:

1] To use a simple water balance based model to determine irrigation requirements for various irrigation management strategies;

2] To use the AquaCROP model to simulate long-term maize yields in the various water strategies following the established values of the model;

3] To evaluate the feasibility of the VRI strategies for long term water and energy conservation using 29 years of weather data and standard production practices.

1.2 MATERIALS AND METHODS

1.2.1 Site Description

The study was conducted on the basis of a private field (41°56’ 52.43” N, 98°11’ 42.91” W; elevation 619 m above mean sea level); about 6 miles southwest of the town of Elgin, in Antelope County, Nebraska as shown in Figure 1.1. The site has sub-humid climatic conditions with mean annual precipitation of 701 mm.

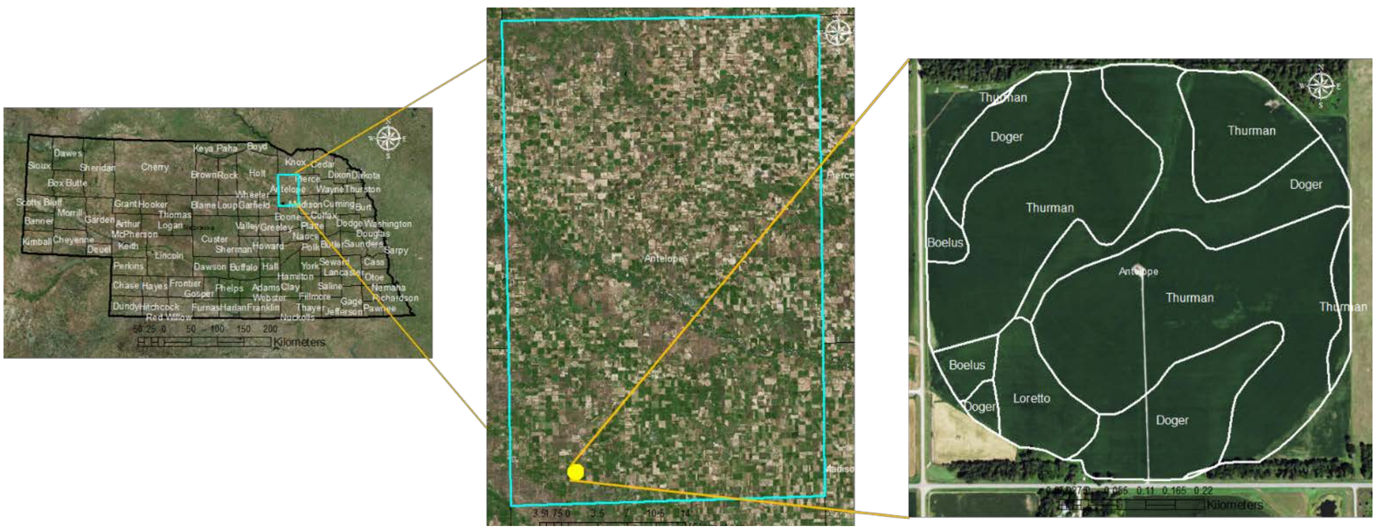

Figure 1.1: Location of the field in Antelope County, Nebraska.

The total field area is 62.5 ha comprising of four major soil textures. The total cropped/irrigated area of the field was 57.5 ha. The most predominant soil texture in the field was Thurman loamy fine sand covering 60% of the total or an area of 37.5 ha. The second major soil texture was the Doger loamy fine sand that is spread across an area of 19.6 ha. Combined with Thurman, these soil covered 91.4% of the total area. The other two soil textures were Boelus loamy fine sand and Loretto sandy loam covering 1.5 ha and 3.8 ha, respectively and contributed 8.6% of the total field area (Web Soil Survey, USDA-NRCS) represented by Figure 1.2(a). The field has minimum elevation of 616 m and the maximum elevation at 631 m with an elevation difference of 15 m between the northeast and southwest corners as shown in Figure 1.2(b).

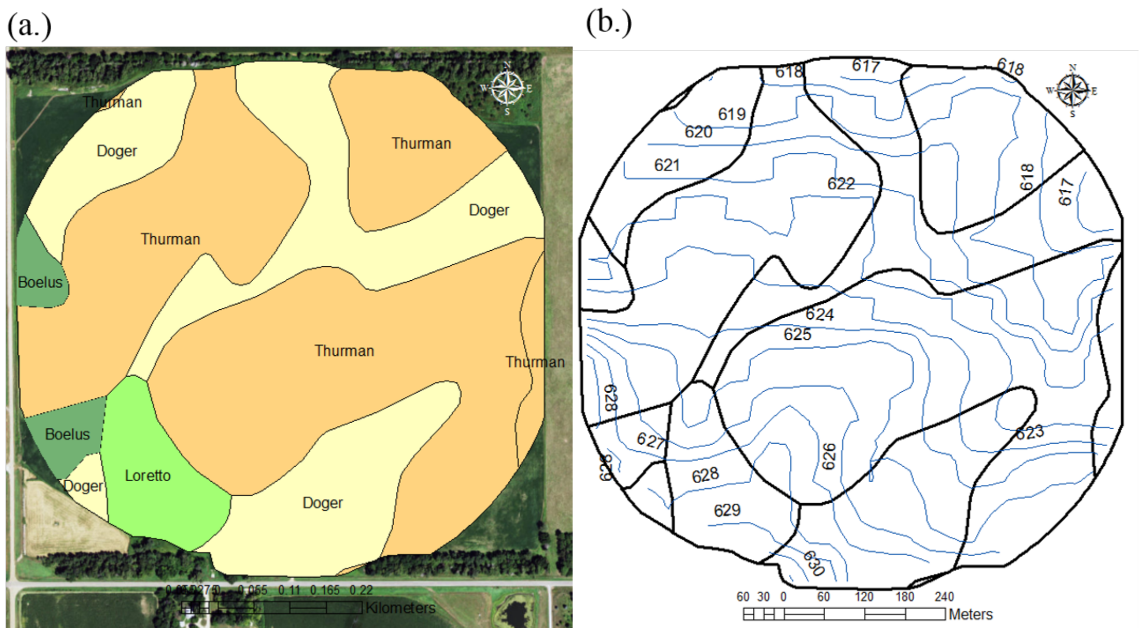

Figure 1.2: Map showing (a) land area under four soil textures (Thurman, Doger, Boelus and Loretto) and (b) elevation of the field near Elgin, Nebraska

Extensive soil sampling campaigns were conducted to collect samples from random locations in the field at 3 depths of 30.5 cm each; such that the sample would be representative of the soil texture mapping unit it was taken in and each soil texture was sampled to collect representative samples. A soil analysis was performed to calculate soil texture and composition, organic matter content (OM) and bulk density (BD). The soil textural classification was based on the USDA soil textural classifications.

1.2.2 Data Sources

To develop the water balance model, long term weather data were collected from the Elgin, NE weather station of High Plains Regional Climate Center (HPRCC-NRCS) located approximately 600 m from the center of the irrigated area. The weather station recorded precipitation, air temperature, incoming radiation, wind speed and humidity needed to estimate ET. The dataset included the period 1988 through 2016.

Soil electrical conductivity was recorded using the VERIS EC-3100 machine (Veris Technologies Inc., Salina, KS) which usesd a direct soil contact sensor and a GPS mapping system. The EC data were collected for both shallow (0-250 mm) and deep (0-800 mm) depths. Based on the data, soil electrical conductivity maps were developed using ArcGIS (Environmental Systems Research Institute, Redlands, CA) which are shown in Figure1.3a,b.

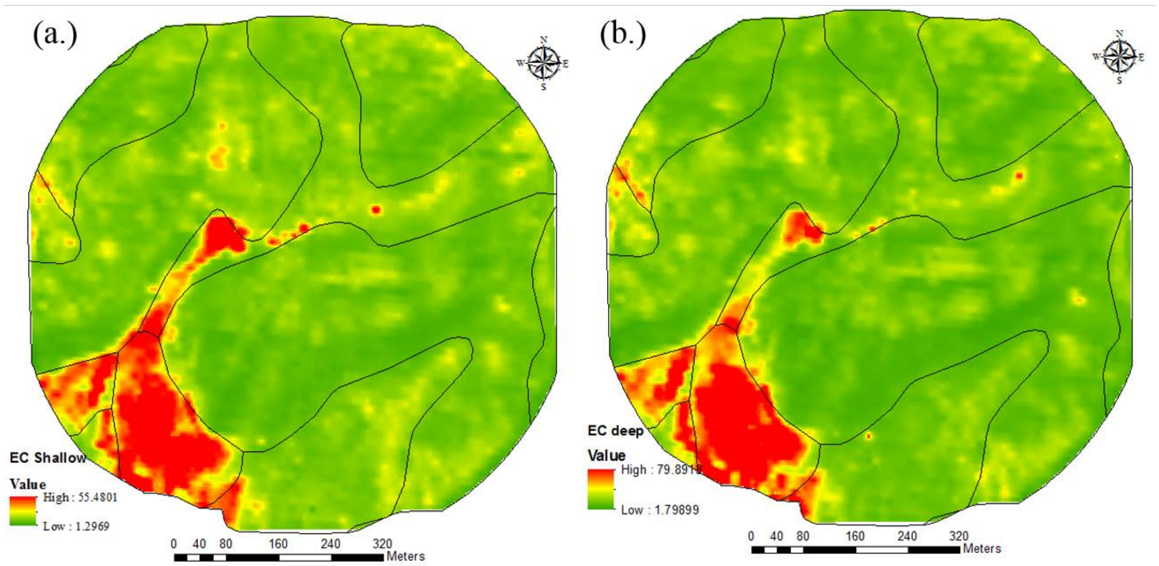

Figure 1.3: Map showing the variation of soil electrical conductivity at (a) Shallow depth (0-250 mm) and (b) deep depth (0-800 mm) at the field near Elgin, Nebraska

Soil texture acreage and physical parameters were recorded by the producer as well as derived from USGS Web Soil Survey. The soil survey provided the parameters of each soil texture in the field which were then compared to the field samples and the results were used to calculate the soil textural classifications and physical properties.

Yield data were recorded by the producer using the combine yield monitor data for the years between 2010 and 2015. The yield data was projected using ArcGIS and spatial maps were produced to study the variation in yield within the field and across years. The yield of the years 2010 and 2011 are shown in Figure 1.4(a,b) as an example of the yield variation in the field.

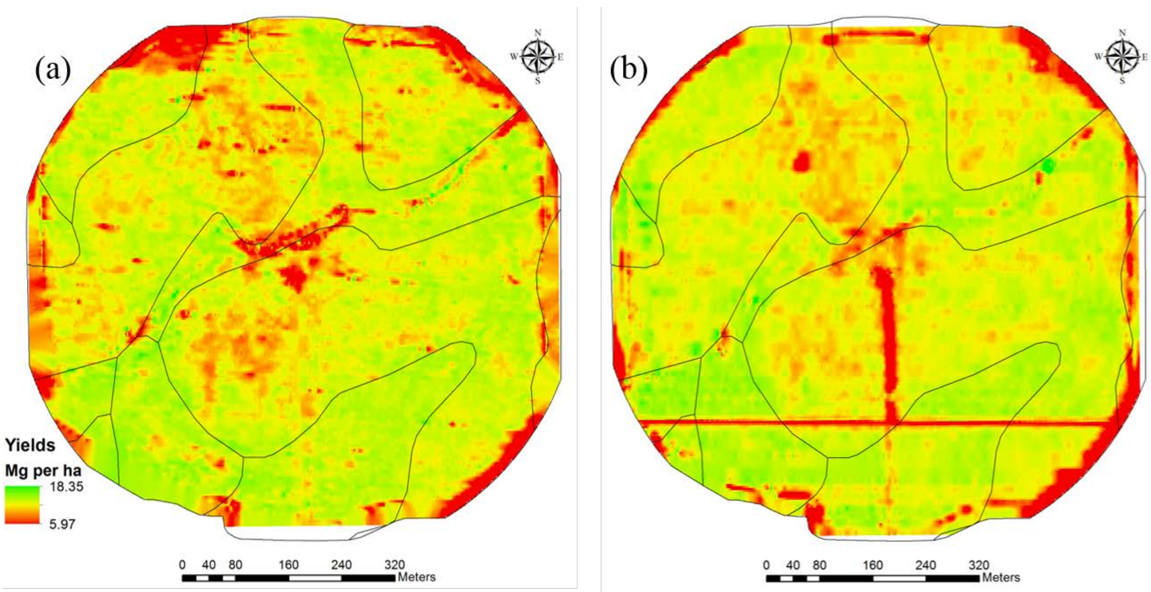

Figure 1.4: Map showing the yield (ton/ha) variation in the field near Elgin, Nebraska for the years (a) 2010 and (b) 2011

1.2.3 Zone Development

The most widely accepted basis of developing a management zone for the VRI management is soil available water holding capacity (AWHC) (Evans and King 2012). However, yield and electrical conductivity of the field are also considered in areas where other crop management practices have not been performed. These factors broadly cover most of the variation that occurs in the field and include the areas that need to be avoided or the areas that need further attention in any field. Since the spatial analysis of the variation in yield and electrical conductivity showed uniformity in the field, other than areas that had Loretto soils (Highlighted in Red in the EC maps in Figure 1.2), the zones were developed on the basis of AWHC to better address the minimal variation in the field as shown in Figure 1.5. These zones were developed to address the limitations of the present zone controls available in VRI equipped pivot systems which is about 0.01 ha/zone (Evans et al. 2013). If two soil textures were included in a single management zone, the soil with major area in that zone was defined as the trigger of that zone. The transition zones were considered to be the boundaries between any two zones.

Figure 1.5: Map showing the management zones developed according to the various soil textures in the field

1.2.4 Water Balance Model

Soil water balance is an essential tool for estimation of irrigation schedules and amounts and ET (Irmak et al. 2013; Ma et al. 2013). Water balance can provide an avenue to simulate daily soil water changes. The general equation for daily water balance for irrigation is described in Equation 1.1.

$$I = P + (SW_1 - SW_2) - ET_a - R - Dp \tag{1.1}$$

Where I = irrigation (mm); P = precipitation daily (mm); (SW_1 - SW_2) = change in soil water in the profile (mm); ET_a = actual ET (mm); R = Runoff (mm) and Dp = Deep percolation (mm).

1.2.4.1 Assumptions for Water Balance

To conduct a water balance that would remain unbiased for the duration of the study, we assumed some circumstances, to keep the seasonal boundaries as constant as possible across years, irrespective of the weather conditions. The assumptions were made for the field and irrigation parameters to achieve this objective.

First, the soil was assumed to be uniform within each soil texture boundary, that is, the spatial variation in soil texture within the same mapping unit was considered negligible. The elevation differences were not considered within the mapping unit but were taken into account for different soil textures during the calculation of surface runoff. Also, each soil was assumed to be at field capacity at the day before the start of the simulation. Therefore, each soil started at field capacity on first day of simulation (May 1, each year).

Second, crop growth was assumed to begin on May 1 of each year. Note that the growth initiation in the model is not equivalent to emergence. The season was considered to be from May 1 to September 27 each year. These inputs were also used as inputs for the AquaCROP model.

In the irrigation simulation, a few assumptions were made based on field data as well as management practices and ease of modelling. Each soil texture received irrigation that refilled it to field capacity and were not left under deficit irrigation beyond the maximum allowable depletion (MAD). Also, MAD was established to be 35% of the AWHC for each soil. The irrigation events were assumed to be completed the same day it was triggered to ease the transition of soil water for the next day to ensure a continuous water balance for each day. The application efficiency and uniformity was taken to be 85% (Irmak et al. 2011). For the first day of simulation, irrigation was considered to be zero.

1.2.4.2 Calculation of Soil Water Characteristics

To develop a water balance model for the timeline of the study, it was essential to simulate and calculate some soil and environmental parameters that would affect the water balance. Since the available field data was scarce, a general estimate based on the collected soil data was deemed sufficient (Saxton et al. 1986).

Soil physical parameters were calculated using the generalized pedo-transfer functions developed by Saxton et al. (1986) and Saxton and Rawls (2006). The equations are based on the soil texture and calculates the water content at field capacity, permanent wilting point and saturation. The general equation equates water potential at different pressures as function of water content at that pressure (Equation 1.2).

$$\psi = A\ \theta^{B} \tag{1.2}$$

Where, ψ = water potential, kPa; θ = water content, m^3/m^3 and A, B = constants based on soil texture;

Where,

$$A = \exp[-4.396 - 0.0715\ (\%Clay) - 4.880 * E - 4 * (\%Sand)^2 - 4.285 * E - 5(\%sand)^2 * (\%Clay)] * 100 \tag{1.3}$$

$$B = -3.140 - 0.00222(\%Clay)^2 - 3.484 * E - 5 * (\%sand)^2 * (\%Clay) \tag{1.4}$$

Using these equations, water content at field capacity (θ_{fc}) (ψ = 33 kPa) and permanent wilting point (θ_{pwp}) (ψ = 1500 kPa) were calculated for each soil texture. However, at saturation, this equation is undefined. The equation for water content at saturation (θ_s) (Equation 1.4) used was provided in Saxton et al., (1986). The values calculated are reported in Table 1.4.

$$\theta s = 0.332 - 7.251 * E - 4 * (\%sand) + 0.1276 * \log 10 * (\%Clay) \tag{1.4}$$

Obtaining the values of field capacity and permanent wilting point, available water holding capacity (AWHC) for each soil texture was calculated using equation 1.5 and is reported in Table 1.4 and surface runoff from the field was calculated using the SCS Runoff Curve Number Method (USDA-NRCS 1986).

$$AWHC = \theta_{fc} - \theta_{pwp} \tag{1.5}$$

1.2.4.3 Calculation of Environmental and Growth Parameters

A long term weather dataset was collected from the HPRCC weather station near the field which provided the temperature and precipitation data for the water balance.

The crucial environmental parameter was crop ET. Daily grass reference ET (ET_o) was calculated using the software Ref ET (Allen, 1999) which uses the Standardized Pennman Montieth Equation (Equation 1.6) following the procedures of FAO 56 (Allen et al. 1998; ASCE 2004). The software input was the daily weather data from the HPRCC weather station. The height of anemometer (3 m) and temperature and humidity sensors (1.5 m) along with the elevation and latitude were also the inputs. The software automatically makes adjustments of wind speeds from 3m to 2m. The actual daily ET was calculated as a product of ET_o and grass reference crop coefficient (Equation 1.7). The grass reference crop coefficients were calculated by the equation (Equation 1.8) based on days after effective emergence of the crop as developed by Djaman and Irmak (2012).

$$ET_o = \frac{0.408\,\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{[\Delta + \gamma(1 + 0.34u_2)]} \tag{1.6}$$

where ET_o = standardized grass-reference ET (mm d^{-1}), Δ = slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}), Rn = net radiation (MJ m^{-2} d^{-1}), G

= heat flux density at the soil surface, T = mean daily air temperature (°C), u_2 = mean daily wind speed at 2-m (m s^{-1}), e_s = saturation vapor pressure (kPa), e_a = actual vapor pressure (kPa), $e_s - e_a$ = vapor pressure deficit (VPD), γ = psychrometric constant (kPa °C^{-1}). The constant *900* represents the time step and aerodynamic resistance of the grass reference surface, *0.34* represents the time step, bulk surface resistance and aerodynamic resistance of the grass reference surface, and *0.408* is constant in m^2 mm MJ^{-1} ($1/\lambda$, where λ is latent heat of vaporization (2.45 MJ m^{-2} mm^{-1})).

$$ET_a = K_c * ET_o \tag{1.7}$$

Where, ET_a = Actual ET (mm d^{-1}), ET_o = standardized grass-reference ET (mm d^{-1}) and K_c = grass reference crop coefficient

$$Kc_i = 101.631\,E{-8}(DAE)^3 - 39.22\,E{-5}(DAE)^2 + 0.0375662(DAE) + 0.17629 \tag{1.8}$$

Where, K_{ci} = daily grass reference crop coefficient and *DAE* = days after effective emergence.

Root growth was also considered as a function of the daily time step using Equation 1.9 as reported in Steduto et al. (2009).

$$Z = Z_{ini} + (Z_x - Z_{ini}) \sqrt[n]{\frac{\left(t - \frac{to}{2}\right)}{\left(tx - \frac{to}{2}\right)}} \tag{1.9}$$

Where, Z = effective rooting depth at time ***t***; Z_{ini} = sowing depth (*0.08m*); Z_x = maximum effective rooting depth (*1.5m*), t_o = time from planting to effective (85-90%) emergence (*20 days*); t_x = time to reach maximum rooting depth (*110 days*); n = shape factor of the function (*1.2*).

1.2.5. Irrigation Scheduling and Management Strategies

Using all the aforementioned information, the water balance was conducted for each individual soil texture. Irrigation was triggered when the soil water content reached the Maximum Allowable Depletion (MAD) which was specified at 35% depletion from the field capacity of each soil texture. The depth of irrigation water applied at each irrigation event was dictated by the irrigation management strategy. The soil texture with lowest water holding capacity was referred to as the "driest" soil and the textures with greater water holding capacities were referred to as "wet" soils. For the study, five irrigation strategies were simulated to compare the VRI strategies with the conventional uniform irrigation (CUIM). The five irrigation strategies are reported in Table 1.1 and explained below.

Table 1.1: Irrigation management strategies employed in VRI and CUIM system configurations.

Management Strategy	VRI/ CUIM
Field Capacity Method (FC)	VRI

Driest Uniform (DU)	CUIM
Driest Soil Triggered Irrigation (DST)	VRI
Water Mining Method (WM)	VRI
Total Irrigation (TI)	CUIM

1.2.5.1 Field Capacity Method

Field capacity (FC-VRI) method is a VRI strategy that was dependent on the field capacity of each soil. According to this strategy, the irrigation was triggered individually for each soil when it reached the MAD. Once the irrigation was triggered, the depth of irrigation was equal to the product of difference between the FC and MAD of each soil mapping unit and the depth of root zone (Equation 1.10). The limitation to this method was that multiple triggers for multiple soils which will lead to more irrigation events than any strategy as highlighted in the example of the year 2008 in the Figure 1.6. The data for the figure is reported in Appendix 1(a). Notice that the soils with greater AWHC had less frequent irrigation events than the Doger (low AWHC) soil.

$$I_{FC} = (\theta_{fc} - \theta_{mad}) * d \qquad (1.10)$$

Where, I_{FC} = Irrigation depth based on Field Capacity refilling method; θ_{fc} = the water content at field capacity for each soil; θ_{mad} = the water content at maximum allowable depletion of each soil and d = depth of the root zone.

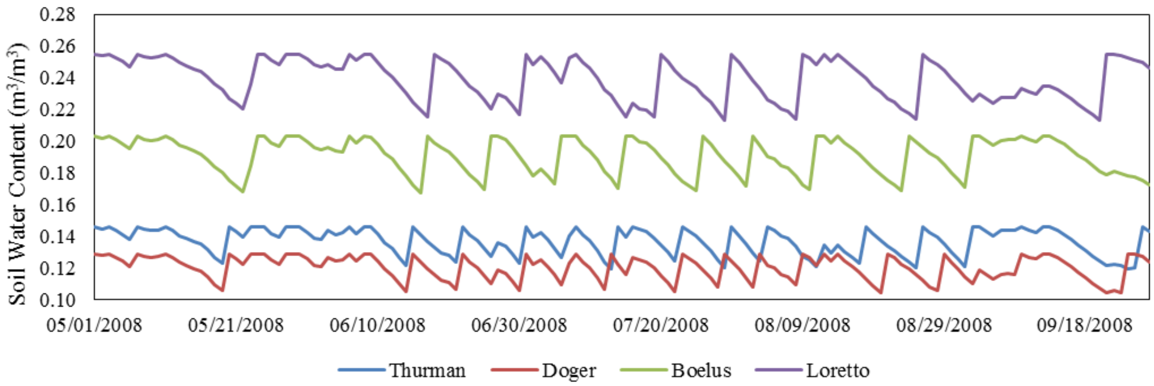

Figure 1.6: Simulated soil water contents using the field capacity VRI strategy in Year 2008 for four soil textures in the field near Elgin, Nebraska.

1.2.5.2 Driest Uniform Method

The Driest uniform method was a conventional uniform irrigation management strategy. The Doger soil was the driest soil in the field. Uniform irrigation was triggered by the driest soil and the depth of irrigation was either a fixed value of irrigation such as 15-35 mm or the depth needed to fill the driest soil back to field capacity. The Doger uniform method was filling the Doger soil back to field capacity and applying the same amount to the whole field, irrespective of the needs of other soils as depicted in the Figure 1.7. Notice the number of irrigation events increase from the FC method for the other three soils. Note that DU-CUIM, DU and CUIM are synonyms for the purposes of this study.

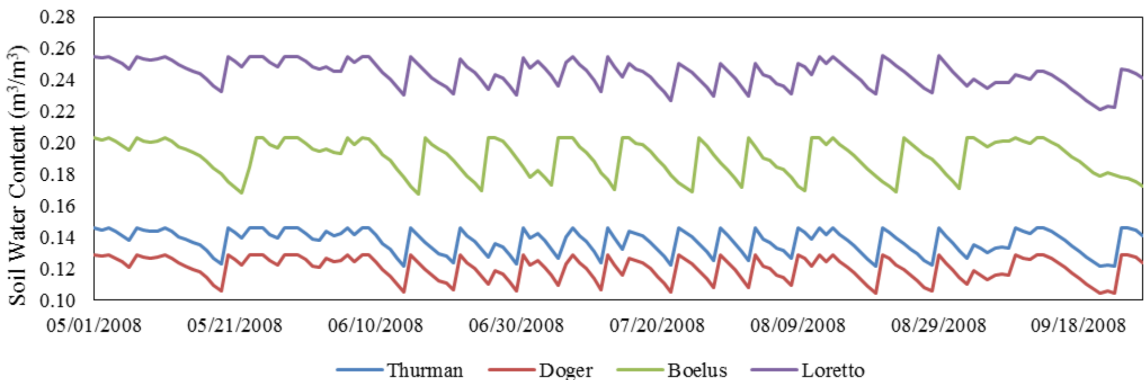

Figure 1.7: Simulated soil water content using the Driest Uniform CUIM strategy in Year 2008 for four soil textures in the field near Elgin, Nebraska

1.2.5.3 Driest Soil Trigger Method

Driest Soil Triggered (DST-VRI) method of irrigation management was a VRI strategy. According to this strategy, the irrigation was triggered by the driest soil in the field (Doger in this case) and the depth of irrigation is the deficit between field capacity and water level at that time and including all depths as depicted in the Equation 1.11. An example of the soil water content simulated using the driest soil trigger method is presented in Figure 1.8.

$$I_{DST} = (\theta_{fc} - \theta_i) * d \tag{1.11}$$

Where, I_{DST} = Irrigation depth required for the soil using Driest Soil Trigger Method θ_i = Water content of the soil at the time irrigation is triggered in the driest soil texture in the field and d = depth of root zone

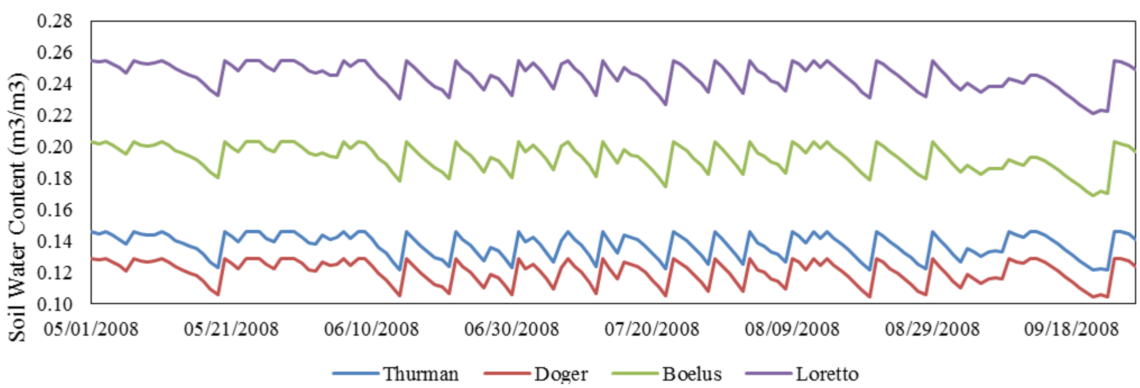

Figure 1.8: Simulated soil water contents using the Driest Soil Triggered (DST) VRI strategy in Year 2008 for four soil textures in the field near Elgin, Nebraska

1.2.5.4 Water Mining Method

Better utilization of rainfall and root zone water holding capacity (known as Water Mining) not only provides the potential to conserve water and energy but also could minimize leaching of nutrients and chemicals (Lo et al. 2016; Ritchie and Amato 1990). Conventionally, a water mining strategy would be to apply a fixed amount of irrigation in drier soil and skipping the "wetter" soil for that irrigation event. This method can be feasible until the "wet" soil reaches MAD.

In this study, we developed a different approach to water mining. Irrigation was triggered when the driest soil reached the MAD soil water content. Now, instead we altered the depth of water applied to the soils with greater AWHC. The alteration was based on the principles of deficit irrigation and on the amount of water the greater AWHC soils could have in storage compared to soils with less AWHC. This is called the reduction factor (RF) and is quantified in Equation 1.12. The irrigation depth was decreased by the reduction factor representing the ratio of AWHC for a soil divided by the AWHC of the greater AWHC soil (Equation 1.13a). This scenario works until a point when the greater AWHC soil reaches MAD. At MAD, the soil was refilled to field capacity again (Equation 1.13b). An example of soil water content simulation through the 2008 season using this water mining method is depicted in Figure 1.9.

$$RF = \left(1 - \left[\frac{Ad}{Aw} \right] \right) \tag{1.12}$$

Where, *RF* = Reduction Factor; A_w = Available water holding capacity of the "Wet" soil and A_d = Available water holding capacity of the driest soil.

$$I_{WM1} = ((\theta_{fc} - \theta_i)RF) * d \quad (1.13\{a\})$$

$$I_{WM2} = (\theta_{fc} - \theta_i) * d \quad (1.13\{b\})$$

Where, I_{WM1} = Irrigation amount required for each soil using water mining method till MAD and I_{WM2} = Irrigation amount for each soil if the soil reaches MAD and *d* = depth of root zone

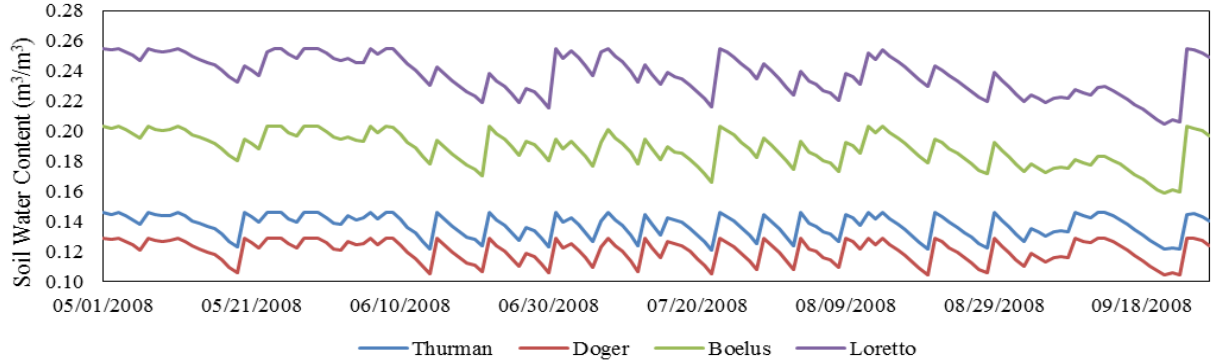

Figure 1.9: Simulated soil water contents using the Water Mining (WM) VRI strategy in Year 2008 for four soil textures in the field near Elgin, Nebraska

1.2.5.5 Total Irrigation Uniform Method

Total Irrigation Uniform method (TUIM) is a uniform irrigation management strategy. This method was based on the spatial variability of soils taking into account the areas under each soil texture. It was a marriage between VRI and Uniform Irrigation as water was monitored for all soils but irrigation was applied uniformly. The concept behind this management strategy is to develop an arbitrary or a unified field with one soil texture and thus requires uniform irrigation. The one soil texture has the properties of all the soils in the weighted field averages as explained in the Equation 1.14. The soil water balance model was then run for this averaged soil and irrigation amount was calculated based on the field capacity refilling method (refer to Equation 1.10) which was spread uniformly throughout the field; irrigation was applied irrespective of the soil requirements. In real time conditions, the water content would be monitored for all soil textures and the average soil water content would be the soil water content for the arbitrary (Total) soil. For this study the water content at field capacity, permanent wilting point and available water holding capacity of this arbitrary soil was 0.161, 0.065 and 0.096 m^3/m^3, respectively. An example of soil water content simulation throughout the season in 2008 using TIUM method is depicted in Figure 1.10 which also shows the simulation of water balance for the arbitrary soil named Total in the figure.

$$P = \frac{\sum_{i=1}^{n} Pi * Ai}{A} \tag{1.14}$$

Where, P = the desired soil property of the averaged soil; P_i = property of individual soil; A_i = Area under each soil; A= Total area of the field and n = number of soil textures in the field

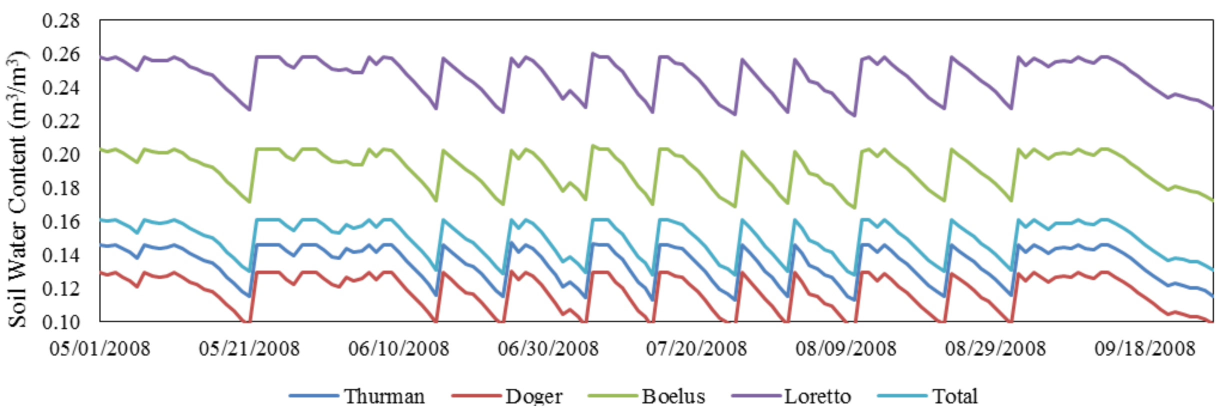

Figure 1.10: Simulated soil water contents using Total Irrigation (TI) UIM strategy in Year 2008 for the arbitrary and original four soil textures in the field near Elgin, Nebraska.

1.2.6. Yield Simulation using the AquaCrop Model

Maize accounts for almost 30% of the global grain production (Heng et al. 2009) and AquaCrop has been utilized extensively to simulate yields in maize (Abedinpour et al. 2014; Araya et al. 2017; Ahmadi et al. 2015; García-Vila and Fereres 2012; Heng et al. 2009; Mebane et al. 2013; Nyakudya and Stroosnijder 2015; Paredes et al. 2014). These studies document the ability of AquaCrop to precisely simulate growth conditions to produce accurate grain yield estimates based upon location specific inputs. The location specific inputs that were supplied to AquaCrop were climate (weather data for 29 years), soil characteristics (field capacity, permanent wilting point, saturation water content, horizon depths for each soil), crop characteristics, irrigation amounts and field management (residue cover and weed management) data. The methodology of providing these inputs were the instruction provided in (Raes et al. 2009). The calibration of the model is discussed further.

AquaCrop provides two methods of crop growth simulation; one based on growing degree days and the other based on the calendar day or days after planting (Raes et al. 2009). For the purpose of this study, days after planting method of growth simulation was used in the model to better reflect the producers’ inputs to the field. The conservative crop parameters that are universally followed were derived from the default parameters provided by Hsiao et al. (2009). Also, the parameters that are cultivar based and site specific in nature, were obtained from Araya et al. (2017) due to the close resemblance to the field in Elgin, both in soil textures and crop growth conditions. However, the duration of various stages of crop growth were adjusted according to the inputs provided by the producer. Also, no fertility stress was considered as the crop was simulated to be at optimum growing conditions.

The values for atmospheric carbon dioxide levels, canopy cover at emergence, canopy growth shape factor, stomatal stress coefficient curve shape factor, senescence stress coefficient shape factor and coefficient of inhibition of leaf growth and stomata on harvest index and harvest index were taken as reported by (Heng et al. 2009; Raes et al. 2009). The calibrated values of maximum canopy cover, canopy expansion functions, canopy decline, stomatal closure functions and canopy senescence were taken as reported by (Araya et al. 2017). The value for crop water productivity used was 33.7 g- m^{-2} (Araya et al. 2017; Hsiao et al. 2009).

The base and cut-off temperatures, of 10 ˚C and 30 ˚C, were used for climatic stress index as compared to 8˚C and 30˚C, respectively used a default for the AquaCrop (Hsiao et al. 2009). The maximum rooting depth was 1.5 m as compared to 2.4 m in (Araya et al. 2017). The crop was considered a 120-day relative maturity range hybrid with emergence after 20 days which takes into account 100-150 GDDs for emergence. The maximum value of the crop coefficient was taken to be 1.25 which was based on the crop coefficient values calculated using equations developed by Djaman and Irmak (2012). The salinity stress was not considered in the simulation because irrigation water in the region did not contain salts sufficient to impact growing conditions. The values used as inputs to the model are reported in Table 1.2.

Table 1.2: Inputs used in the AquaCrop model based on the field as adapted from Heng et al. (2009), Araya et al. (2017) and the crop practices in the field near Elgin, NE.

Parameter	Value
Canopy cover per seedling at 90% emergence (cm^2) (%/day)	6.5
Canopy expansion (CGC)	13.5
Maximum canopy cover (%)	80
Canopy decline (CDC) (%/day)	11.7
Emergence (days after planting)	20
Normalized crop water productivity (g/m2)	33.7
Maximum canopy cover (days after planting)	57
Start of senescence (days after planting)	120
Flowering (days after planting)	80
Root depth (m)	1.5
Maximum root depth (days after planting)	110
Maximum crop ET	1.25
Harvest index (HI) (%)	52
Canopy expansion function	
P-upper	0.1
P-lower	0.45
Shape	2.9
Stomatal closure function	
P-upper	0.65
Shape	6
Early canopy senescence function	
P-upper	0.45
Shape	2.7

Irrigation depths that were calculated using the simple water balance model; with the daily values fed into AquaCrop for each of the five water management strategies. Each soil was individually simulated for each strategy and each year. Thus, yield was a product of soil texture and water strategy while the crop, field and climatic conditions remained the same for each year. It was also assumed that the water used in irrigation was of optimum quality with EC_w = 0 dS/m. Also, it was assumed that no shallow water table suitable for irrigation existed in the area. The field management was based on the management practices followed by the producer. The field had medium mulches residue cover (25-40% cover) which were the result of no-till cropping system used in the field.

However, historically, this data was not recorded but was assumed for the sake of simplicity of the design of water balance model as well as for maintaining the precision of AquaCrop. Also, the mulches had small effect on the runoff (CN = 61) since each new crop was sown directly above the old one. Weed control was kept optimum but still a weed stress of 5% was assumed to account for the variation in timing of application. These management practices dictated a canopy stress of 15% which was accounted for in the yield.

Keeping the constant inputs (Crop characteristics, Initial conditions, Soil management and Irrigation efficiency and quality) for each year, Climate was varied. In each year, irrigation depths were entered into the model with the varying inputs of soil texture and irrigation strategy to simulate yield in each strategy.

1.2.7. Economics

One goal of the study was to understand the net returns from the VRI systems in the long term. Lo et al. (2016) reported that reductions in water application alone would not be sufficient for net positive returns from VRI. VRI systems are technically sophisticated systems that require more inputs than the conventional irrigation management. The costs of sampling, mapping of the field and the consultant fees for providing the best prescriptions for the VRI system are the overhead costs that need to be taken into account (Evans et al. 2013).

For this study, the cost of VRI zone control was set at $30,000 which included the cost of the system (average cost of system for 60 ha field is $21,379 (Milton and Perry (2006)), the initial installation and sampling costs and the consultants fee for the setup

(Verbal Communication from Rich Uhrenholdt, Producer for the field in Elgin, NE). A useful life of 29 years was assumed (present useful life of VRI systems is 15-20 years (Lee 2016)) to compare the returns on the length of the study. This would be the initial costs only. The system would require maintenance and repairs throughout its life. Hence, in order to get a true value of returns from the VRI, one has to account for all the costs (both operating and ownership costs) associated with the system. The costs were calculated using the worksheet provided by Dr. Derrell Martin (Professor, Biological Systems Engineering, University of Nebraska-Lincoln) which is based on the report by (Martin et al. 2010). These numbers were average for a typical field in Nebraska and were calculated according to the type of fuel (Diesel, electric motor or propane), location restrictions (Irrigation District) and various equipment added to the conventional pivot.

The pump was powered by a diesel engine with 42.7 m of lift and a system pressure requirement of 310 kPa; calculated by the guidelines of Kranz (2010). The total irrigated area, as mentioned earlier was 58 ha with a 10-span center pivot. The long term average cost of diesel fuel was $2.65 (EIA, U.S. Department of Energy). The initial costs that were established for the well, pump, engine, pivot and VRI system as well as the values of returns and repairs are reported in Table 1.3.

Table 1.3: Determination of initial costs and cost application of water in the field in Elgin, NE as per the guidelines of (Martin et al. 2010)**.**

Initial Costs (IC)	
Component	Cost
Irrigation Well	$16,500
Irrigation Pump	$11,163
Gear Head	$2,800

Pump Base, etc.	$1,100
Diesel Engine & Tank	$11,500
Center Pivot System	$75,000
VRI	$30,000
Additional Costs (% of Initial)	
Repair	2.4
Depreciation	3.4
Returns	
ROI	5%
Salvage	5% of IC
Total cost of water application	
Per cubic meter (VRI)	$0.157
Per cubic meter (CUIM)	$0.147

Using this data the cost of application of water through VRI systems was calculated to be \$0.157 m^{-3}. The cost of application of water using uniform irrigation strategies was \$0.147 m^{-3}. Savings was defined as the difference in profits of VRI systems and the profits from uniform irrigation as shown in Equation 1.15, 1.16 and 1.17. The historical trend in prices for the maize yield for Nebraska was derived from the National Agricultural Statistic Service (USDA) and the average value for the study period was \$124 Mg^{-1}. Since all the costs were incorporated in the irrigation costs, if the VRI shows a net positive savings in its life, it would be considered feasible.

$$Savings\ (\$) = Profits_{VRI} - Profits_{CUIM} \tag{1.15}$$

$$Profits\ (\$\ ha^{-1}) = Yield\ \ Revenue\ (\$\ ha^{-1}) - \ Cost\ of\ water\ (\$\ ha^{-1}) \qquad (1.16)$$

Where yield revenue is defined as,

$$Yield\ Revenue\ (\$\ ha^{-1}) = Yield\ (Mg\ ha^{-1}) * Price\ of\ Maize\ (\$\ Mg^{-1}) \qquad (1.17)$$

1.3 RESULTS AND DISCUSSION

1.3.1 Soil Sampling

Extensive soil sampling campaigns conducted throughout the field yielded results for texture, bulk density and organic matter content for the various soil textures present in the field. It was found that Loretto sandy loam had the least bulk density value while the Thurman loamy fine sand had the greatest bulk density. The soil textural classification was as expected in the trend of bulk density as Thurman, Doger and Boelus soils were rich in sand (> 50%) while Loretto was found to be rich in silt (> 47%). The greatest value of organic matter was found in the Boelus soil (1.33g cm^{-3}) with the least in Thurman fine sand (0.74 g cm^{-3}). The detailed values for each soil are reported in Table 1.4.

Table 1.4: Summary of the analysis of soil samples taken during 2016, for soil textures in the field near Elgin, Nebraska.

Soil Texture	**% Sand**	**% Silt**	**% Clay**	**OM %**	**BD g cm^{-3}**
Thurman	91	6	3	0.7	1.8

Doger	75	20	5	1.2	1.6
Boelus	61	29	10	1.3	1.8
Loretto	37	47	16	1.1	1.5

1.3.2 Soil Water Characteristics

Using the pedo-transfer functions reported by Saxton et al. 1986 and further perfected by Saxton and Rawls 2006, the soil water characteristics were calculated using the soil texture data from the soil samples. It was found that Loretto soils richer in silt and clay content, had the greatest values of Field Capacity (25.5%) and Saturation Water Content (45.7%). In contrast, the Doger soil was found to have the least field capacity (12.9%) as well as AWHC (7.2%) values. Thus, Doger was considered to be the driest soil in the field and the irrigation water management zones were defined on the basis of Doger soils. The detailed values for each soil's water content at field capacity, permanent wilting point, saturation and AWHC is reported in Table 1.5.

Table 1.5: Summary of the soil water characteristics for soils included in the field site near Elgin, NE, calculated in accordance to (Saxton et al. 1986). All values in (m^3/m^3) (θ_{FC} = water content at Field Capacity; θ_{PWP} = water content at permanent wilting point; *AWHC*= available water holding capacity; θ_{SAT} = saturation water content)

Soil texture	θ_{FC}	θ_{PWP}	*AWHC*	θ_{SAT}
Thurman	0.146	0.070	0.076	0.317
Doger	0.129	0.057	0.072	0.356
Boelus	0.203	0.101	0.102	0.407
Loretto	0.255	0.133	0.122	0.457

1.3.3 Weather Analysis

Weather data for the period of 1988-2016 was downloaded from the HPRCC for the weather station located near the site. The long term trends in the seasonal precipitation, mean seasonal temperatures, crop coefficient and actual ET were studied. The detailed data for each of the weather variables for the years are reported in Appendix A.

1.3.3.1 Precipitation

The long term average growing season precipitation was recorded at 384 mm. The long term trends in growing season precipitation for the site are depicted in Figure 1.11. The long term trends in daily precipitation are shown in Figure 1.12.

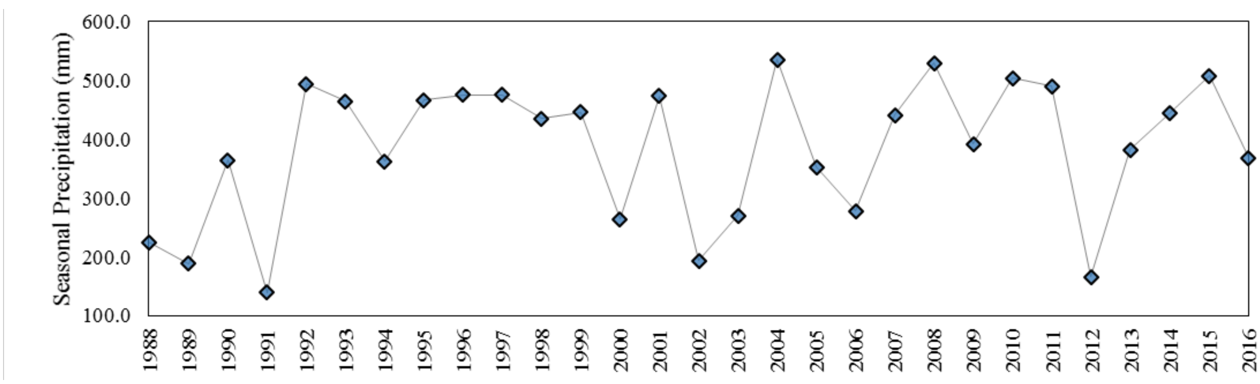

Figure 1.11: Seasonal precipitation levels over the period of 1988-2016 for the field site near Elgin, Nebraska.

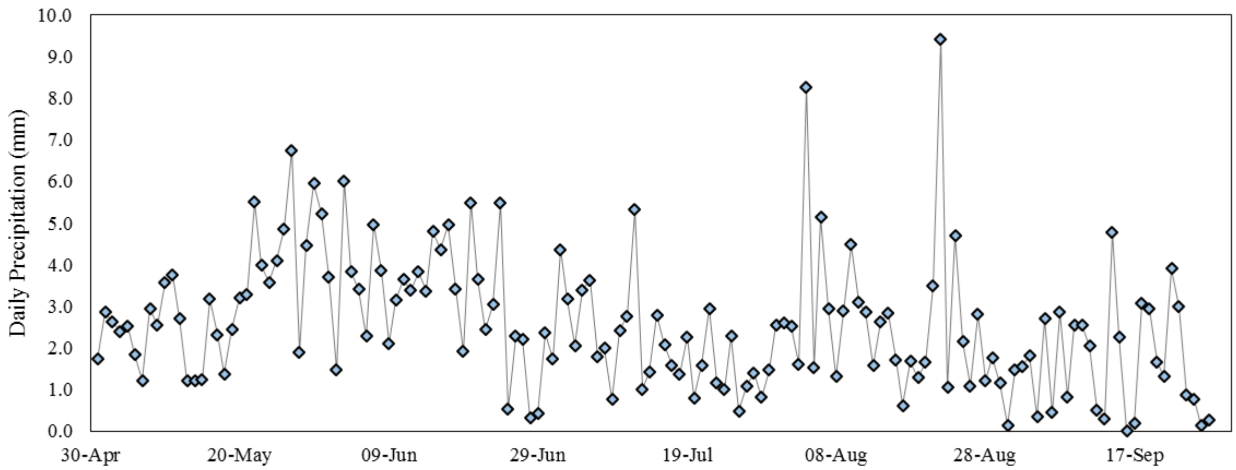

Figure 1.12: Long term average daily precipitation over the period of 1988-2016 for the field site near Elgin, Nebraska.

1.3.3.2 Mean Temperature

Using the long term weather data, the trends in seasonal mean temperatures were recorded. The mean temperature is the average between the greatest and the lowest temperature for the day. The average mean seasonal temperature for the period of 1988-2016 was 20.04^{o}C. The study of mean temperatures is crucial as the crop growth in the season is directly dependent on seasonal temperatures. The long term seasonal mean temperatures are presented in Figure 1.13. The long term annual average daily mean temperatures are presented in Figure 1.14.

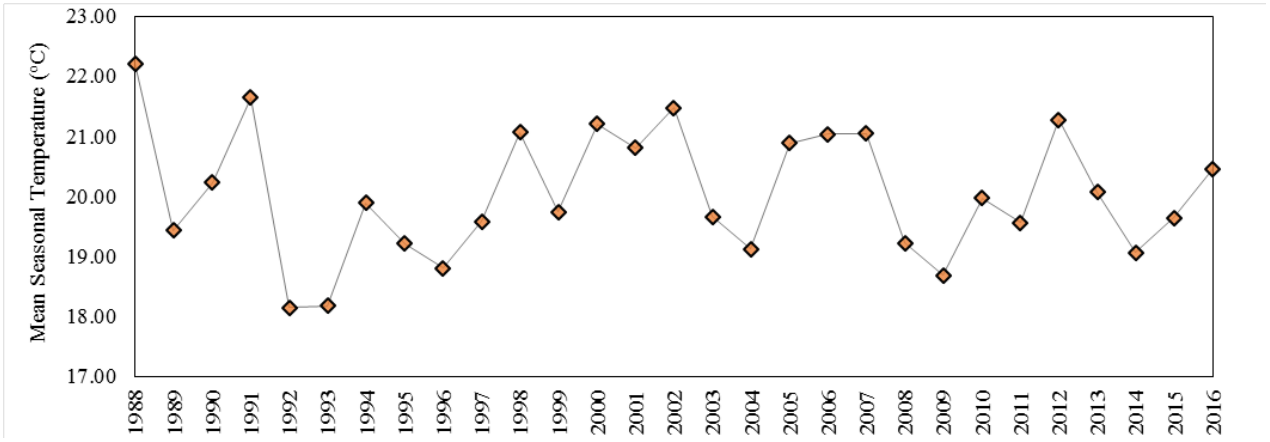

Figure 1.13: Annual average mean temperatures for the period of 1988-2016 for the field site near Elgin, NE.

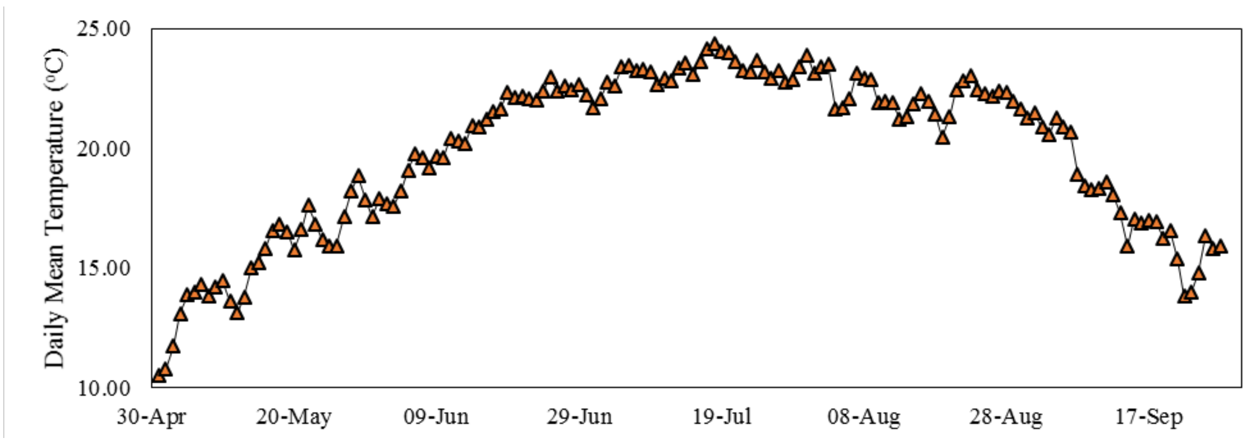

Figure 1.14: Seasonal long term average daily mean temperatures for the field site near Elgin, NE.

1.3.3.3 Actual ET (ET_a)

The long term average daily crop coefficients calculated using the equation from Djaman and Irmak (2012) were recorded and graphed. The results of the seasonal trend in crop coefficient (Kc) is shown in Figure 1.15.

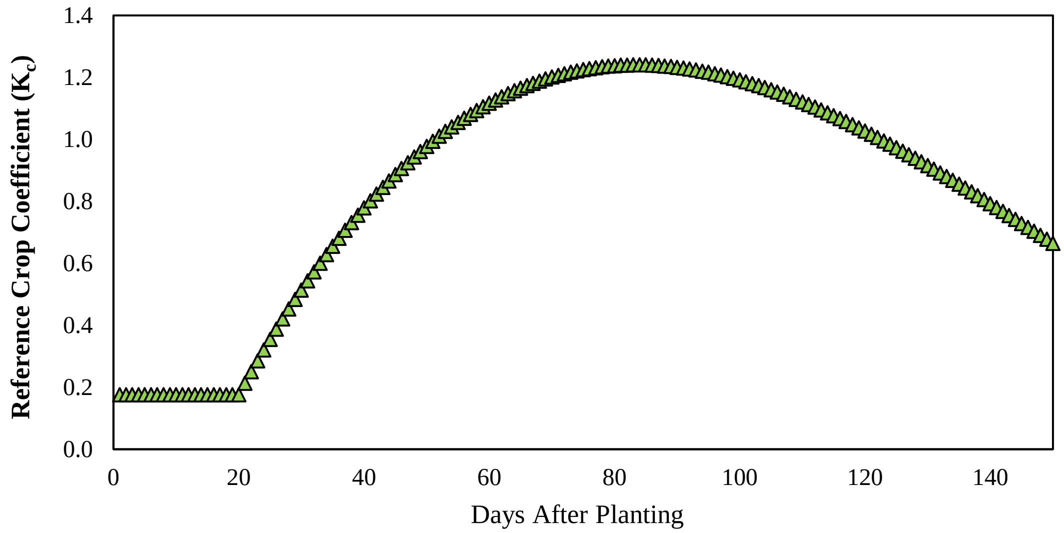

Figure 1.15: Long term average daily crop coefficient (Kc) modeled using equation from Djaman and Irmak (2012).

Using the Kc values, actual ET was calculated and the long term trend is presented in Figure 1.16. The greatest value of ET_a was observed in the year 2012 with a seasonal ET_a of 744 mm followed by the years 1988 and 2003 with seasonal ET_a values of 732 and 672 mm respectively. The lowest seasonal ET was observed in 1992 at 484 mm. The long term average seasonal ET for the field was 589 mm.

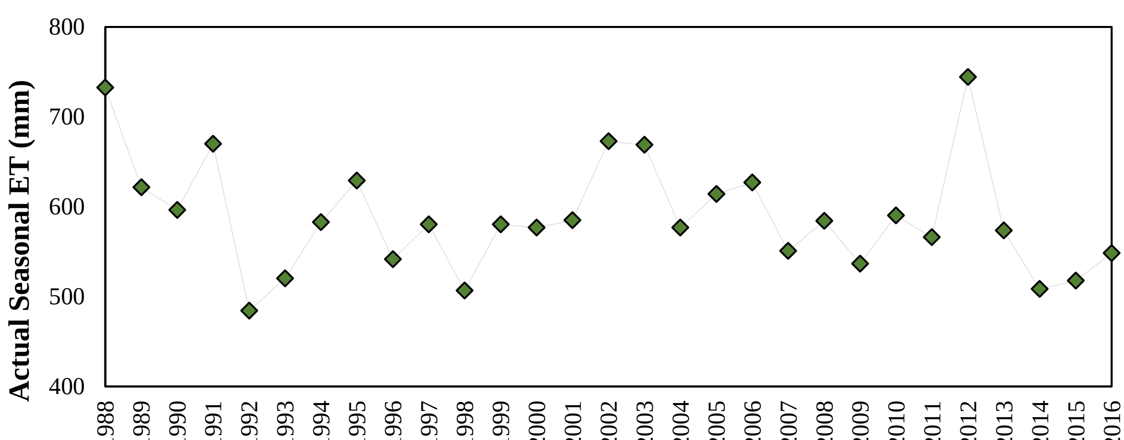

Figure 1.16: Long term actual ET_a calculated for the period of 1988-2016 for the field site near Elgin, NE.

The trends in daily actual ET averaged for the period of 1988-2016 showed that the maximum ET_a was observed in the month of July with an average value of 195 mm followed by the month of June with an average of 162 mm of ET. The long term average daily ET is shown in Figure 1.17.

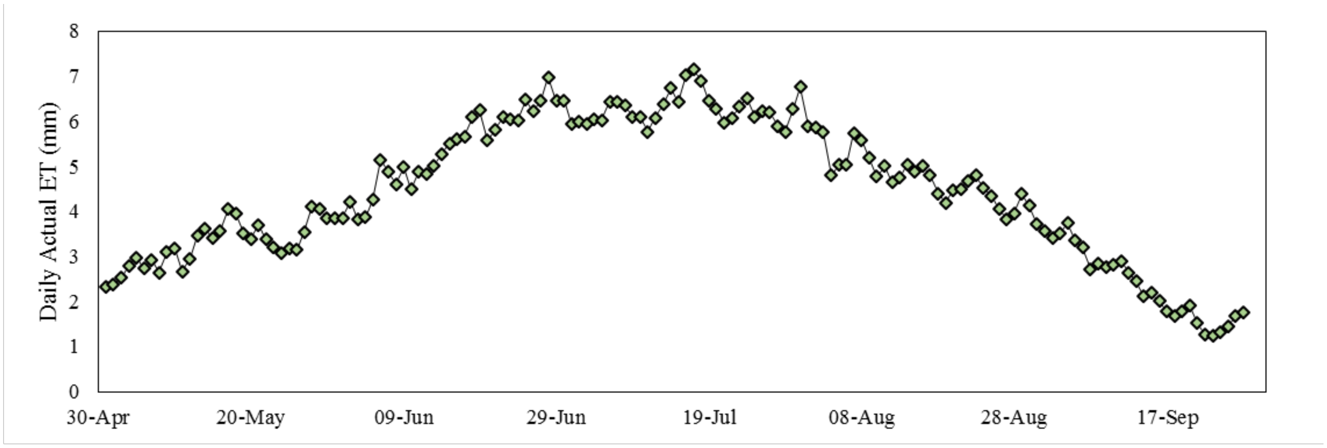

Figure 1.17: Seasonal trend in long term average daily actual ET_a calculated for the period 1988-2016.

1.3.4 Irrigation Management Strategies

1.3.4.1 Irrigation Amounts

Irrigation depths for each season were defined as the depth of water applied to the field for the whole season based on the amounts decided under each irrigation management strategy. It was observed that strategies performed similarly in terms of depth of water applied according to the precipitation in each year. The greatest depth of water applied was in the Driest Uniform CUIM strategy with a long term average of 446 mm. The difference in long term averages of the VRI strategies when compared to CUIM were not significant ($p > 0.05$). The VRI methods (Field Capacity, Driest Soil Trigger and Water Mining) showed minimal differences from Driest Uniform with long term average seasonal depths of 442, 446 and 441 mm. The Total Irrigation uniform irrigation strategy showed significant difference in water application with a seasonal long term average depth of 426 mm, a difference of 20.5 mm ($p = 0.01$) from the CUIM strategy. It was also observed that in the years of low precipitation (< 300 mm), the differences in the application depths were very low especially during the peak dry years of 1991, 2002 and 2012 which can be attributed to the increased irrigation in those years. The long term trend in application depths is depicted in Figure 1.18.

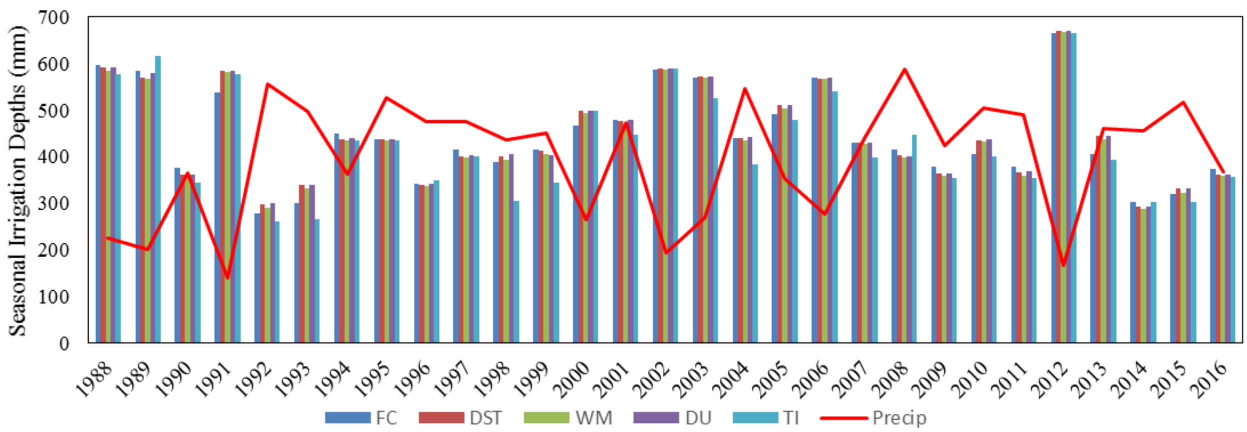

Figure 1.18: Long term trends in seasonal application depths for the five irrigation management strategies for the period of 1988-2016

Also, the difference in application depths was calculated on a yearly basis. It was observed that the FC-VRI was the most beneficial in terms of water reductions when compared to the other two VRI management strategies with a net application depth reduction of 150 mm ($p>0.05$). However, FC-VRI also showed the greatest fluctuations throughout the years with a range of application depth reductions of 15.3 mm (increased) in 1990 to 44.9 mm in 1991. It was also observed that Water Mining (WM-VRI) strategy had consistent net positive non-significant reductions when compared to CUIM with a net application depth reduction of 145.7 mm (p >0.05). The reason for the insignificant difference can be attributed to the area distribution of soil textures with similar soils (Thurman and Doger) contributing to 91% of the area of the field which gives little opportunity for water mining from the higher AWHC soils (Loretto and Boelus: 8% of total area). The yearly trends in depth reductions from VRI as compared to CUIM is depicted in Figure 1.19.

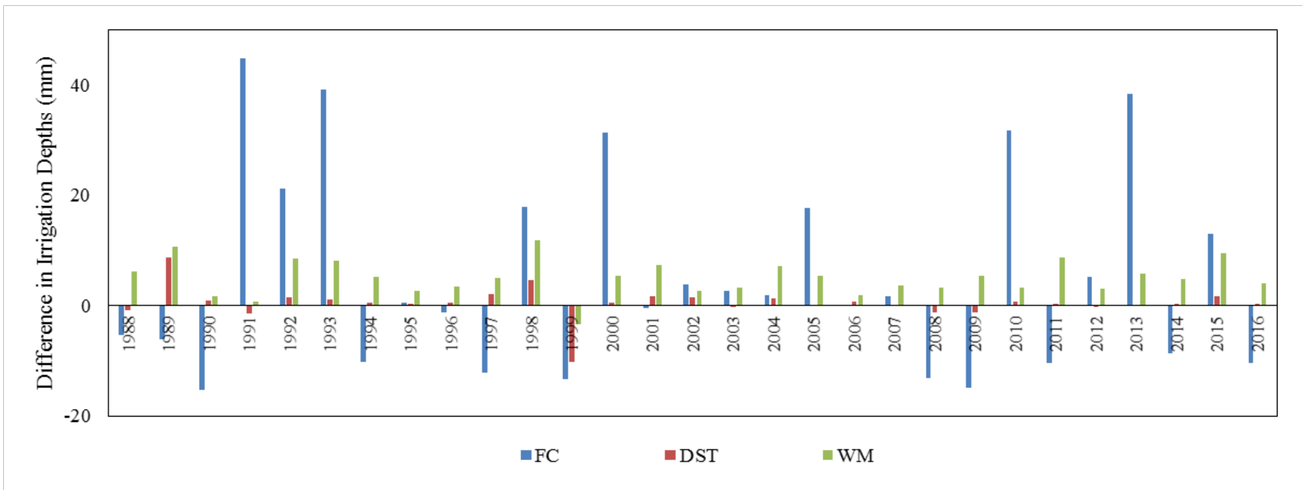

Figure 1.19: Seasonal application depth reductions using VRI strategies when compared to CUIM (DU) strategy for the period of 1988-2016.

The reduction in seasonal application depth from the CUIM strategy was also calculated for the TIUM strategy. For this field, the TIUM was the most beneficial management strategy in terms of application depth reductions with a net positive reduction of 594 mm (p = 0.01) for the period of 1988-2016. Since TIUM accounts for the average values for each of the texture, the resulting arbitrary soil becomes perfect under optimum management conditions. However, in the years of 1989, 2008 and 2014, the depth of water applied was much greater than the CUIM with 39, 45 and 8 mm of excess water applied in the season. The trend in the depth reductions using TIUM is depicted in Figure 1.20.

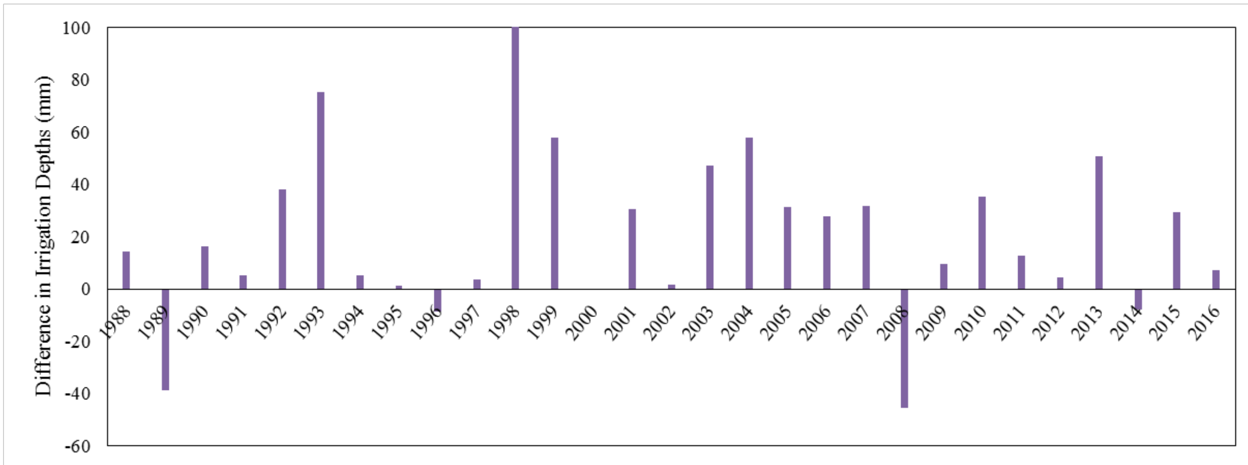

Figure 1.20: Seasonal application depth reductions using the TIUM strategy when compared to the CUIM (DU) strategy for the period of 1988-2016.

1.3.4.2 Irrigation Frequency

Irrigation frequency of any management strategy is the number of individual irrigation events that occur in a season using that strategy. The irrigation frequency is the direct factor affecting the energy consumption and costs. The irrigation frequencies for the five strategies were calculated and it was observed that DST-VRI and WM-VRI had the same irrigation frequencies as the DU-CUIM, which is predictable as both these VRI systems are triggered the same way as the DU-CUIM. The long term seasonal irrigation frequency average for these methods was 13 irrigation events per season. It was also observed that the TIUM strategy had the least frequent irrigation events for the period 1988-2016 with a long term seasonal frequency average of 10 events.

In contrast, the FC-VRI had the greatest value for irrigation frequency in any year with a long term seasonal frequency average of 33 events in a season. The numbers are justified as the FC-VRI method is an on/off system of VRI. Since water application is dependent on the trigger of the soil and the different soil triggers have different timing, irrigation events in that scenario should be greater. However, the total water applied to the field would not vary that much. The variation of frequency of FC-VRI from the DU-CUIM and TIUM was calculated and it was found that FC-VRI on average had 20 and 23 events more than CUIM and TIUM, respectively, which is an increase of 150% when compared to the CUIM strategy and 174% greater than the TIUM strategy. The long term trend in irrigation frequency for the period of 1988-2016 for the three strategies is depicted in Figure 1.21. Note that the DST-VRI and WM-VRI have frequencies equal to the DU-CUIM strategy, therefore, their individual events are depicted under DU-CUIM only.

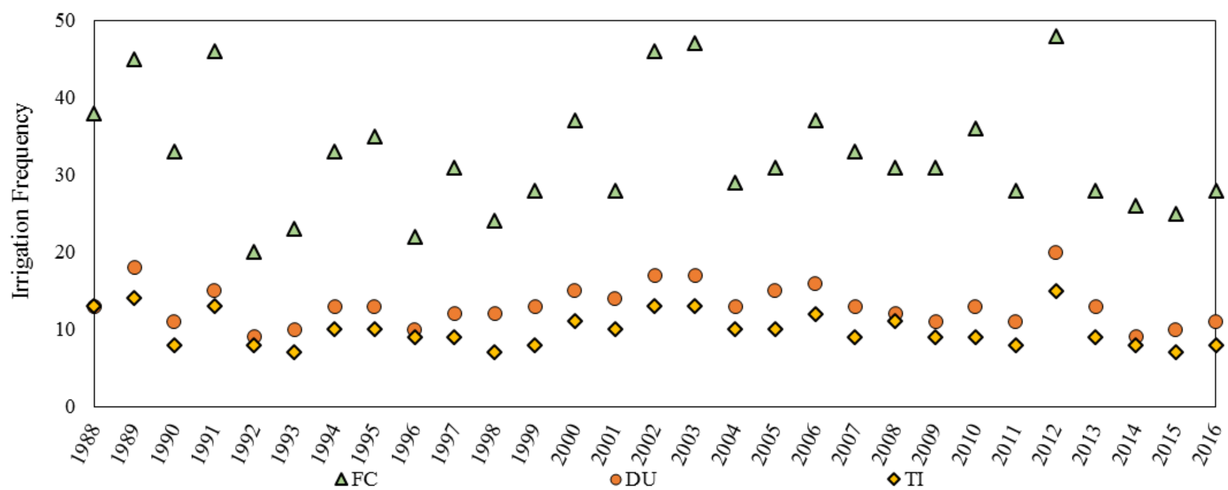

Figure 1.21: Summary of seasonal irrigation frequency for FC-VRI, DU-CUIM and TIUM irrigation strategies for the period of 1988-2016

1.3.5 Yields

Yields were simulated for 29 years using the five strategies as a variable input. The data was compared with the combine yield monitor data available for the years 2010-2015. The average yields for the field was 12.1 Mg ha^{-1} while the simulated average yields came out to be 13.3 Mg ha^{-1} for the same period. It was also observed that the yields simulated were overestimated more than 20% in 3 years; marginally overestimated in 2 years and underestimated in one year of the comparison. Overall, the simulation overestimated yields by 9.98% on average when compared to the field data available. The yields were not statistically different (P-value = 0.08). One of the major potential reasons for this overestimation might be non-inclusion of actual field level irrigation schedule as a calibrating parameter in AquaCrop. Instead, the simulation was based on the irrigation schedule for uniform irrigation used in the study; which may vary from the actual irrigation applied in the field. Also, yield loss has often been observed due to irregular irrigation by end-guns, loss due sprayer tracks and during harvesting procedures like dropped ears.

For the simulated yields, the long term average yields of the five strategies namely, FC-VRI, DST-VRI, WM-VRI, DU-CUIM and TIUM were 13.09, 13.10, 13.10, 13.10, 13.14 Mg ha^{-1}, respectively. The yields were not significantly different from each other ($p>0.05$ for each comparison). This can be justified by the fact that in all strategies, full irrigation was applied. Further, since these numbers were averaged for the whole field, the variation among soils was diminished by the greater areas with similar soil properties (Thurman and Doger Soils covering 91% of the total field area). The long term trends in yield is shown in Figure 1.22.

FC-VRI showed the most variable yield (statistically insignificant). However, WM-VRI and DST-VRI followed similar trends as CUIM. The yield variations of VRI from the CUIM strategy are depicted in Figure 1.23.

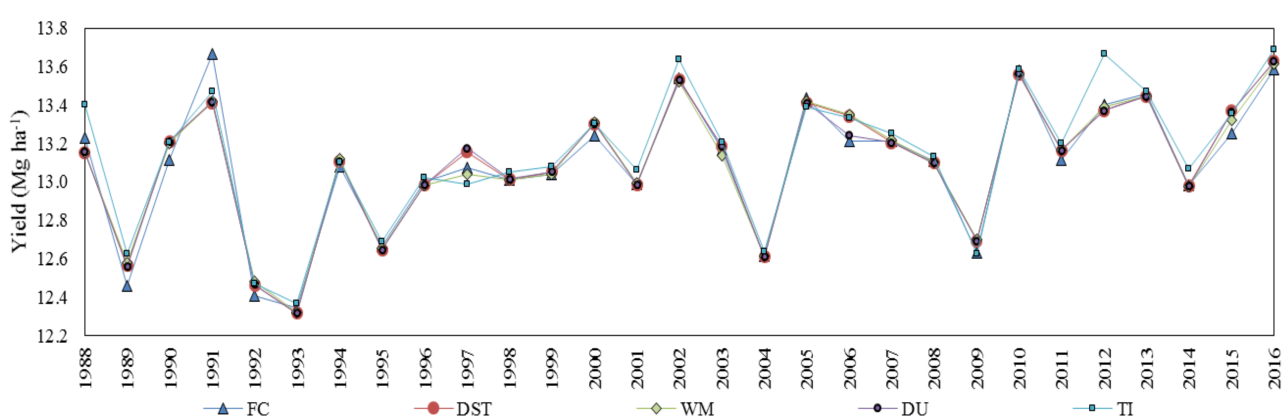

Figure 1.22: Field averaged yields for the five irrigation strategies for the period of 1988-2016.

The comparison of the TIUM strategy with CUIM was also made and it was observed that TIUM showed consistently greater yields than DU-CUIM with the exception of five years where it showed marginally less yield. Overall, the yields increased 9.1% using TIUM ($p>0.05$) when compared to using CUIM. The variation in the yields of TIUM from CUIM is shown in Figure 1.24.

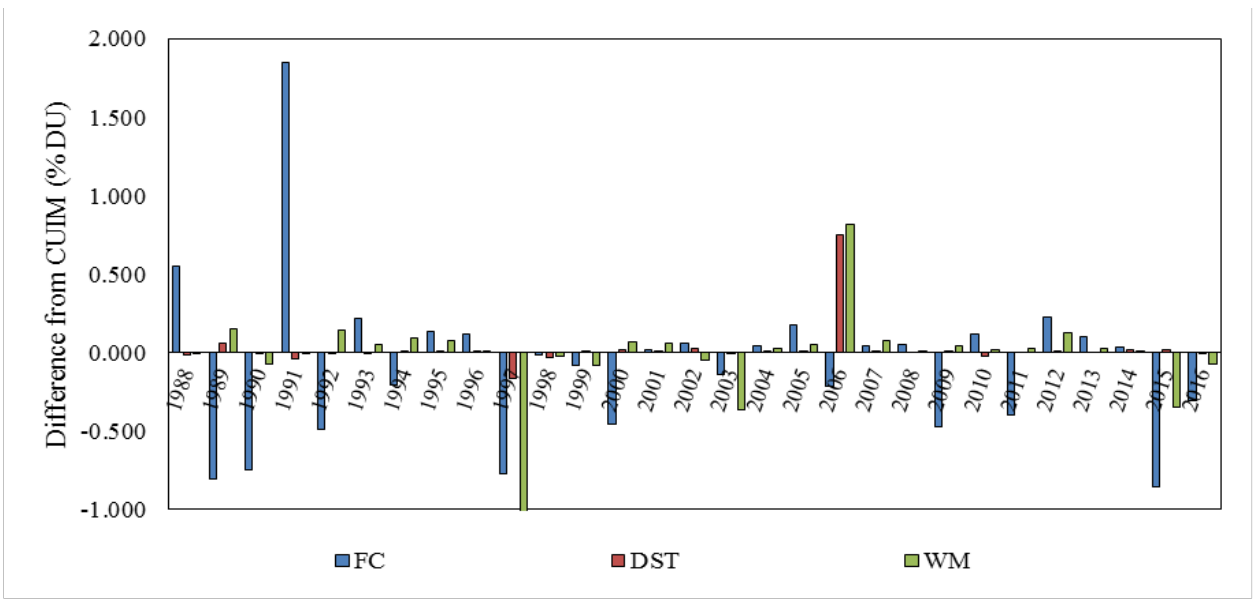

Figure 1.23: Yield differences of VRI management strategies when compared to the CUIM strategy for the period of 1988-2016.

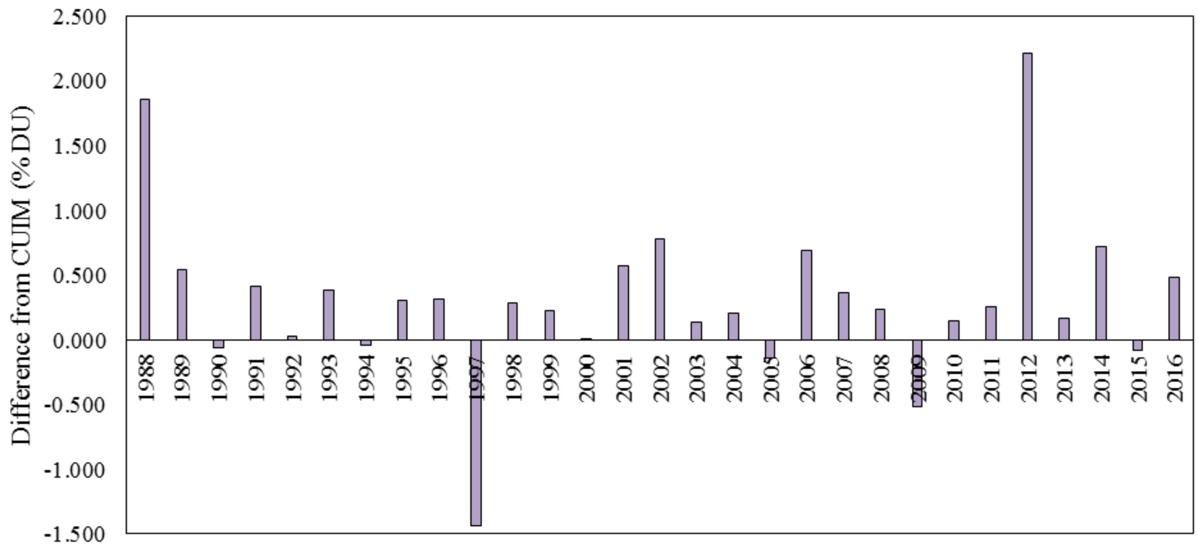

Figure 1.24: Yield differences of the TIUM strategy when compared to the CUIM strategy for the period of 1988-2016.

1.3.6 Economics

The economic return of all the strategies were computed as a difference of the yield revenue generated and the cost of application of water using the defined strategy. The variation in revenues generated and the cost encumbered are discussed below.

1.3.6.1 Yield Revenue

The yield revenue was defined as the product of yield and the price of corn. Using the long term average price of corn at \$124 Mg^{-1} and 58 ha of land area irrigated, the total revenue from yields were calculated for each strategy. It was observed that FC-VRI, DST-VRI and WM-VRI generated fairly equal revenue with long term averages of \$1623, \$1625, \$1624 ha^{-1}, respectively. The uniform irrigation methods also generated revenues in the same quadrant with long term averages of CUIM and TIUM generating \$1624, \$1629 ha^{-1}, respectively. However, when comparing the sum of revenue generated by each strategy over the span of 29 years with the uniform irrigation strategy, it was observed that FC-VRI performed the worst of all strategies with an overall negative revenue of \$35 ha^{-1}, followed by the WM-VRI with overall marginal negative revenue of \$4 ha^{-1}. The DST-VRI strategy and TIUM strategy performed better in terms of overall revenue with DST-VRI summing up to a net positive revenue of \$10 ha^{-1} when compared to CUIM. TIUM performed best in revenue generation from yields with an overall net positive revenue of \$149 ha^{-1}.

Studying the trend in the yield revenue over the years, it was observed that TIUM performed better than the rest of the strategies in 20 of the 29 years simulated, followed by the WM-VRI, which performed best in 4 of the remaining 8 years. FC-VRI and CUIM, both performed best in two years each. Studying the yield increase trends for individual strategies and comparing it to CUIM, it was observed that FC-VRI performed better than CUIM in 15 years with an average revenue increase of \$4 ha^{-1} in those years. The best year for FC-VRI was 1991 with an increased revenue of \$31 ha^{-1}. In the rest of the 13 years, FC-VRI had yielded lesser revenue with an average decrease in yield revenue of \$7 ha^{-1} as compared to CUIM with the worst performance of \$14 ha^{-1} decrease in 2015. DST-VRI performed marginally better than CUIM in 16 years with an average increased yield from CUIM at \$1 ha^{-1}. The best year for DST-VRI was 2006 with a total increase in yield revenue of \$ 12 ha^{-1}. DST-VRI performed marginally less than CUIM in 9 years with an average decline in yield revenue of \$0.5 ha^{-1} and the worst year decline of \$2.7 ha^{-1} in 1997. Using the WM-VRI strategies, increased yields were observed in 19 years with an average of \$1.6 ha^{-1} increase in yield revenue for these years. The best performance year for this strategy was 2006 with an increased revenue of \$13.5 ha^{-1}. The yield revenue dropped in the rest of the years by an average of \$3 ha^{-1} with the worst decline of \$17 ha^{-1} in the year 1997. Using the TIUM strategy resulted in greater yield revenues than CUIM in 23 years with an average increase in yield revenue of \$8 ha^{-1} in those years. The best year for TIUM strategy was observed to be 2012 with an increased revenue of \$36.8 ha^{-1}. The yield revenue dropped an average \$ 6.1 ha^{-1} in the remaining years with the worst performance of \$23.4 ha^{-1} decline in revenue in the year 1997.

Overall, for the duration of the study, TIUM and DST-VRI produced net positive revenues as compared to CUIM strategy, while FC-VRI and WM-VRI produced net negative revenues. The trends in the variation of revenues from the five strategies in depicted in the Figure 1.25.

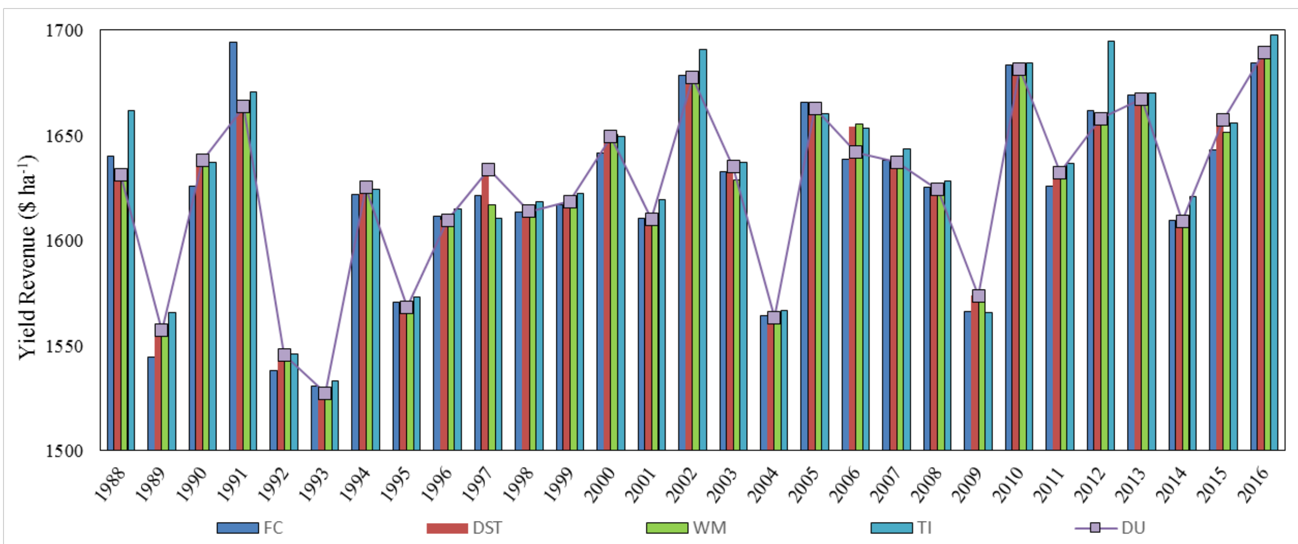

Figure 1.25: Summary of yield revenues for five irrigation strategies for the period of 1988-2016.

1.3.6.2 Irrigation Costs

Irrigation costs were defined as the total cost of application of water on the field based on the area restrictions, pricing, equipment maintenance charges and overall ownership costs. Using the calculated costs of water application of $ 0.147 m^{-3} for CUIM and $0.157 m^{-3} for VRI strategies, the water application costs were summarized for the period of 1988-2016. The average costs of application using VRI strategies were $693 ha^{-1}, $700 ha^{-1} and $693 ha^{-1} for the FC-VRI, DST-VRI and WM-VRI, respectively. The average cost of application for CUIM and TIUM were recorded at $656 ha^{-1} and $626 ha^{-1}, respectively. The yearly cost of each strategy was compared with the uniform irrigation and it was observed that even though, VRI systems showed some application reductions, the cost of application in VRI was always greater than that of CUIM with an average $35 ha^{-1}, $43 ha^{-1} and $36 ha^{-1} additional costs using FC-VRI, DST-VRI and WM-VRI, respectively. TIUM performed much better in comparison to CUIM with an average reduction of cost at $30 ha^{-1}. The annual cost for each strategy showed that DST-VRI and WM-VRI, both had additional costs attached to it for all the years as compared to CUIM. The years of best performance for DST-VRI were 1992 with $27 ha^{-1} of additional costs and the worst was in 2012 with $65 ha^{-1} of additional cost compared to CUIM. For WM-VRI, the least additional cost was observed in 1992 with $16 ha^{-1} additional costs and the most added cost was in 2012 with $60 ha^{-1} of added costs. FC-VRI, on the other hand, showed positive reduction in cost in 6 years with an average reduction of $12 ha^{-1} in those years. The best performance for FC-VRI was in 1993 with a net reduction of $29 ha^{-1}. The worst performance for FC-VRI occurred in 1988 with an added cost of $66 ha^{-1} as compared to CUIM. Comparing the TIUM strategy with CUIM, it was observed that it showed positive reduction in costs in 24 years with an average reduction of $43 ha^{-1} in those years. The best performance for TIUM was observed in 1998 with a net reduction of $152 ha^{-1}. TIUM also showed additional costs as compared to CUIM in 4 years with an average added cost of \$30 ha^{-1} in those years. The worst performance was observed as an added cost of \$67 ha^{-1} in 2008. Even though VRI showed positive reductions in depth but in terms of irrigation costs, VRI was found to be a costlier venture than CUIM. However, for this field site, TIUM proved to show valuable reductions in irrigation costs when compared to CUIM.

1.3.6.3 Profits and Savings

Profit was defined as the result of the subtraction of all irrigation costs from the yield revenue. The long term average profits from the five irrigation strategies were \$930 ha^{-1} for FC-VRI, \$924 ha^{-1} for DST-VRI, \$931 ha^{-1} for WM-VRI, \$966 ha^{-1} for CUIM and \$1002 ha^{-1} for TIUM. The yearly trends showed that the profits were the least in the years 1989 and 2012 with profits dropping 34% from the average in these years. Also, it was observed that among VRI strategies, WM-VRI was the most profitable and DST-VRI was the least profitable. Overall, TIUM was the most profitable water application strategy.

Savings were defined as the increase in profit using VRI over CUIM while losses were the decrease in profits. It was observed that VRI methods did not show savings when compared to CUIM. It was observed that DST-VRI was the worst VRI strategy with an average loss of \$42 ha^{-1} or \$2435 per year. FC-VRI and WM-VRI also showed an average loss of \$2102 and \$2052. It is to be noted that FC-VRI did show savings in 4 years with an average saving of \$1504 per year. The best year for FC-VRI was 1991 with a saving of \$2562 in that year. DST-VRI and WM-VRI did not show any savings in the years of study. Overall, using VRI did not produce enough savings to justify its initial costs in the field in Elgin. On the contrary, using VRI showed a loss 4% in the timeline of the study. Individually, FC-VRI showed a loss of 3.8%, DST-VRI of 4.4% and WM-VRI of 3.7%.

However, using TIUM showed savings in 23 years with an average of $2907 per year. It also showed losses in 6 years with an average of $1322 per year. Overall TIUM saved an average of $2033 per year. The detailed summary of all the parameters discussed above are reported strategy vise in Appendix B.

1.4 CONCLUSION

An economic return analysis of VRI strategies was done comparing it to the Conventional Uniform Irrigation Management strategy using a developed water balance model based on long term weather data and field properties for a field near Elgin, Nebraska for a period of 1988-2016. Five strategies were established to work on the study, namely, FC-VRI, DST-VRI, WM-VRI, CUIM and TIUM. The water balance model predicted irrigation amounts and frequencies for the five strategies which were used to determine the total water applied, total cost of application as well as an input for the AquaCrop model.

The yields were simulated using the AquaCrop model and produced reliable results with justified variation due to variation in the simulated and field conditions in terms of water application amounts and frequencies. The yield results from AquaCrop were turned into yield revenue and were subtracted from the irrigation costs to produce profits for each strategy.

The main goal of the study was to determine whether VRI would produce enough savings as compared to CUIM to justify its added costs. It was observed that using VRI did produce some positive results in water reduction and yield increase. However, the reductions in water applications were not enough to produce the required savings to offset the costs associated with the technology in the field site near Elgin. Overall, using VRI, did not show much increase in yields but showed a 2.4% reduction in water application. However, it showed a 4% decline in profits which hinders its use in this field. It is recommended that given the lack of extent of areas of variation in the field, VRI would not be a profitable venture at this time. Although, the water savings that can be done using VRI may be of use in the times of restricted water access as VRI has shown the capability to reduce water usage without affecting yields in this field.

Also, using TIUM strategy in this field showed a 3% increase in yields, 4.6% decline in water application depths and 3.6% increase in yearly profits. So, in order to increase yields while reducing water usage and thus increasing profit, Total Irrigation management strategy be used in the field. TIUM has shown potential of both water savings and yield increases in this field. More field based research would be required for evaluating the returns from the strategy in real conditions.

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CHAPTER 2: OPTIMIZING SOIL AREA DISTRIBUTION AND COST REDUCTIONS TO MAXIMIZE RETURNS WITH VARIABLE RATE IRRIGATION SYSTEMS

2.1 INTRODUCTION

Variable rate irrigation has developed a lot since its humble beginnings in 1991. More than two and a half decades of research has made VRI an integral part of the irrigation industry. However, the adoption has not been as encouraging. According to estimates, out of the 175,000 center pivot and linear move sprinkler systems; which contribute to 84% of all irrigation systems in the United States, less than 200 systems had variable rate irrigation capabilities to some extent (USDA-NASS 2009). These numbers have seen some growth since 2009 as more and more industry efforts have been concentrated on VRI. The technology is now readily available as companies like Lindsay Corporation, Valley Irrigation and Reinke Irrigation have developed their lines of variable rate irrigation application, control and decision support systems. But there is still a gap in knowledge between the potential benefits of VRI and the realization of those benefits.

There have been several studies in the field that analyzed the potential benefits from VRI technologies. Sadler et al. (2005) produced scenarios for the better utilization of VRI technologies by presenting three case studies during the years of 1999, 2000 and 2001 near Florence, South Carolina. They concluded that using VRI, water application reductions up to 50% were possible. Hedley et al. (2009) studied the performance of VRI as compared to uniform irrigation in four types of fields including planted corn and potatoes over a four year period. The studied compared the two strategies based on irrigation water use, drainage water loss, nitrogen leaching and irrigation water use efficiency. They concluded that VRI can potentially save 9-19% of irrigation water and achieve 25-45% reductions in drainage losses and thus nitrogen leaching. Hedley et al. (2011) studied the performance of VRI compared to uniform irrigation in three highly variable fields in New Zealand. The variation in available water holding capacity of the soils was from 65mm/m and as high as 163 mm/m of root zone. They concluded that given the variation in soils, VRI can potentially provide 15-34% in water savings as compared to uniform irrigation in the same field. Hillyer and Higgins (2014) studied the benefits of VRI in a three year study in Oregon, Washington and Idaho and found the potential water application depth reductions to be between 4-8.7% when compared to the uniformly irrigated areas. More studies have been reported in Chapter 1, section 1.1.

However, the above mentioned studies did not look into the economics of the added technology over the existing irrigation system. Lu et al. (2005) analyzed the returns from VRI in south eastern coastal plains near Florence, South Carolina between the years of 1999-2001. The study was conducted using 396 plots for comparison of VRI to uniform application and found that the returns from yield increase and water reduction using VRI were greater than that of uniform application. However, the added cost of the equipment for the VRI hindered the advantage provided by VRI. They concluded that if the cost of equipment does not decline in the future, the technology would not be a feasible. King et al. (2006) compared VRI with uniform application to study the yield variation as well as quality in potatoes for two years in Idaho. The study found that there was a 4 % increase in the yield using VRI with a minimal difference in water application depth. The study concluded that the even though VRI produced \$159 ha^{-1} more profit than uniform irrigation, the total cost of the system minimized the economic returns from VRI. DeJonge et al. (2007) studied the returns from VRI by simulating field conditions using 28 years of weather data in Iowa. The study compared rainfed corn with uniformly irrigated corn and precision irrigated corn using simulated growth using CERES-Maize and found that precision irrigation produced less yield than uniform application. Also VRI was not feasible in 27 out of 28 years simulated and high initial capital investment was the reason. Lo et al. (2016) studied potential water pumpage reductions and consequently, energy and water savings using unutilized root zone water with the help of VRI. They studied the reductions scenarios for 49,220 center pivots in Nebraska and found that the reductions of more than 51 mm per year from VRI, were in just 2% of the fields and reductions of more than 25 mm per year were reported in only 13% of the field. They concluded that reductions were not enough to justify the costs of the system.

So, the lack of adoption of VRI is not only contributed to initial investments and lack of knowledge of the returns but also to the lack of knowledge of the application areas of VRI as using VRI does not guarantee an increase in yield or water savings (Feinerman and Voet 2000). One has to realize that VRI is not a magical tool. It is a technology; one which has implications as well as limitations. VRI is not suitable to use in every field (Sharma, 2017). Nonetheless, there is still a need to understand the applicability of variable rate irrigation systems in the various field scenarios. Also, there is a need to analyze the cost reduction that has to be achieved for VRI to be beneficial.

The underlying concept behind analyzing the benefits of VRI under field conditions is understanding the soil distribution of the field or the land area covered by each soil texture that is present in the field. Understanding the distribution, enables a producer to make a well informed decision about which VRI system has to be installed in the field. If the soil textures are varying along the length of the field, a speed control system would be more preferable as it would have low initial setup cost ($2000-$3000). This, in turn, would produce higher profits from the same field as compared to uniform irrigation. Speed control is also very viable option if the areas of non-irrigation lies along the length of the pivot. Thus, speed control would be beneficial in areas with soil textures varying along the length of the pivot as shown in Figure 2.1(a).

However, if the soil distribution is across the length of the pivot, the variation in the soils will not be addressed using the speed control VRI. In this case, to fully address the variation in soil textures as well as the non-irrigated areas, one has to employ Zone Control VRI as shown in Figure 2.1(b).

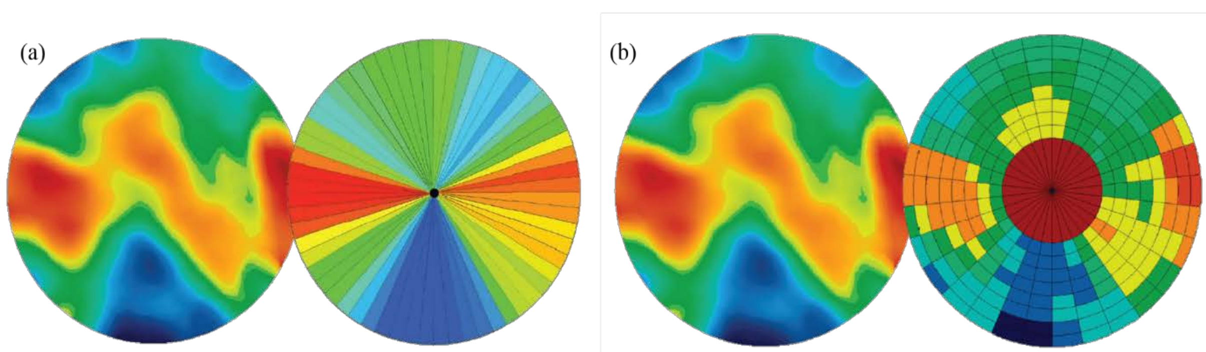

Figure 2.1: Soil variability addressed using (a) Sector or Speed control VRI (b) Zone control VRI. Image Courtesy: https://www.reinke.com/variable-rate.html

Zone Control enables the producer to vary the amount of water application to as low as 0.1 ha (Evans et al. 2013). However, Zone Control VRI has greater initial setup cost. The maintenance cost of the zone control would also increase from 3-5 times of that a speed control VRI (Kranz et al. 2014). This would in turn have a negative effect on the total profit to the producer since water savings from VRI might not be able to justify its cost (Lo et al. 2016; Sharma 2017).

Field variation is the driving factor in the decision of whether VRI is suited for the field. Even if the perfect VRI is chosen for the field, an intensive soil sampling survey must be conducted to understand the soils within the field. VRI would not be beneficial if the soils in the field do not have variable root zone water holding capacities (Lo et al. 2016). Also, the benefits from VRI will be overshadowed if the area under these variable soils is insufficient to produce an overall reduction in water application or increase in overall yields (Chapter 1, Section 1.4). These factors have to be analyzed for a producer to make an informed decision on a specific field.

The most influential reason for a lack of returns from VRI systems is the high initial cost of custom fitting a VRI system on the center pivot. Numerous studies have indicated that at the given price of the VRI system, returns from VRI become negligible as compared to the uniform application (DeJonge et al. 2007; Evans and King 2012; King et al. 2006, 2009; Lo et al. 2016; Lu et al. 2005; Sadler et al. 2005). So a reduction of prices is required if the utilization of this technology is to be encouraged. Quantification of these reductions is required to provide the industry with a goal.

The objectives of this study were to 1] analyze the different field area distribution scenarios in which variable rate irrigation would be feasible 2] analyze the different prices for which custom fitted VRI systems would produce better results.

2.2 MATERIALS AND METHODS

2.2.1 Site Description

The base field site had a total cropped/irrigated area of the field is 58 ha and comprised of four soil textures Thurman loamy fine sand, Doger loamy fine sand, Boelus loamy sand and Loretto sandy loam covering an area of 37.5 ha, 19.6 ha, 1.5 ha and 3.8 ha, respectively. The field is described in detail in Chapter 1 (refer to Section 1.2.1).

2.2.2 Data Sources

The precipitation, air temperature, incoming radiation, wind speed and humidity (needed to estimate ET) data for the period 1988 through 2016 were collected from the Elgin weather station of High Plains Regional Climate Center (HPRCC-NRCS) located approximately 600 m from the center of the irrigated area.

Soil electrical conductivity was recorded for both shallow (0-250 mm) and deep (0-800 mm) depths, using the VERIS EC-3100 machine (Veris Technologies Inc., Salina, KS) and EC maps were developed.

Soil texture acreage and physical parameters to calculate the soil textural classifications and physical properties were recorded by the producer as well as derived from USGS Web Soil Survey.

The detailed description of the data sources for weather and field specific data is reported in Chapter 1 (refer to Section 1.2.2).

2.2.3 Soil Water Content

Soil physical parameters were calculated using the generalized equations developed by Saxton et al. (1986) and Saxton and Rawls (2006) (Equation 1.2). Daily grass reference ET (ETo) was calculated using Ref ET (Allen, 1999) which uses the Standardized Pennman Montieth Equation (Equation 1.8) following the procedures of FAO 56 (Allen et al. 1998; ASCE 2004). The actual daily ET was calculated as a product of ET_o and grass reference crop coefficient (Equation 1.9). The grass reference crop coefficients were calculated by the equation (Equation 1.10) based on the GDDs of the crop as developed by Djaman and Irmak (2012). Using these inputs, the soil water content for the four different soil textures for the period of 1988-2016 was simulated using the water balance developed in Chapter 1 (Refer to 1.2.4). The assumptions and the associated equation used for the model are also described.

2.2.4 Irrigation Scheduling

Using the water balance model, irrigation depths and schedules were simulated for the four textures, according to four irrigation strategies namely, Field Capacity Method (FC-VRI) (refer to 1.2.5.1), Driest Uniform Method (DU-CUIM) (refer to 1.2.5.2), Driest Soil Trigger Method (DST-VRI) (refer to 1.2.5.3) and Water Mining Method (WM-VRI) (refer to 1.2.5.4). Irrigation was triggered when the soil water content reached the Maximum Allowable Depletion (MAD) which was specified at 35% depletion from the field capacity of each soil texture. The depth of irrigation water applied at each irrigation event was dictated by the irrigation management strategy. The irrigation scheduling for each strategy is discussed in detail in Chapter 1 (Refer to 1.2.5).

2.2.5 Soil Distribution

For the analysis of soil distribution, the various soil textures were redistributed to create a gradient of soil texture distribution within the field. The distribution of soils within the field were changed to evaluate the impact of a different number of hectares in each soil texture. The distributions that would be analyzed are discussed further. The total field area was 58 ha. The field capacity, permanent wilting point, water holding capacities and saturation point water content for each soil texture are described in detail in Table 2.1.

Table 2.1: Summary of the soil water characteristics for soils included in the field site near Elgin, NE. All values in (m^3/m^3) (θ_{FC} = water content at Field Capacity; θ_{PWP} = water content at permanent wilting point; AWHC= available water holding capacity; θ_{SAT} = saturation water content)

Soil texture	θ_{FC}	θ_{PWP}	*AWHC*	θ_{SAT}
Thurman	0.146	0.070	0.076	0.317
Doger	0.129	0.057	0.072	0.356
Boelus	0.203	0.101	0.102	0.407
Loretto	0.255	0.133	0.122	0.457

2.2.5.1 Initial Field

The first scenario was the Initial Field (IF) distribution of soil textures. The distribution was 60% (32.5 ha) Thurman; 31% (19.6 ha) Doger; 3% (1.5 ha) Boelus and 7% (3.8 ha) Loretto soils. The distribution is shown in Figure 2.2(a) and is described in

Table 2.2. The water balance was conducted for each soil texture for the period of 1988-2016. The soil textures were then compared with different costs of VRI.

2.2.5.2 L-T Interchange

According to L-T interchange (LT) distribution, the area under Thurman soil and Loretto soils were interchanged. The area under Doger and Boelus remained the same. So the field distribution becomes: 7% (3.8 ha) Thurman; 31% (19.6 ha) Doger; 3% (1.5 ha) Boelus and 60% (32.5 ha) Loretto soils. The distribution is shown in Figure 2.2(b) and is described in the Table 2.2. The goal for this distribution was to provide an idea of savings from VRI by putting low water holding capacity soils in similar area to the high water holding capacity soils. Since the variation in the water holding capacity of these soils may show some water savings using VRI, those savings would increase with area in greater water holding capacity soils.

2.2.5.3 L-T/B-D Interchange

According to L-T/B-D Interchange (LTBD) distribution, the area under Thurman and Loretto soils were interchanged. Also, the area under Doger and Boelus soils is interchanged. So the field distribution becomes: 7% (3.8 ha) Thurman; 3% (1.5 ha) Doger; 31% (19.6 ha) Boelus and 60% (32.5 ha) Loretto soils. The distribution is shown in Figure 2.2(c) and is described in the Table 2.2. This distribution provides the other end of the spectrum with greater water holding capacity soils covering most of the field. This scenario was the mirror image of the initial field with the Loretto and Boelus covering the area under Thurman and Doger soils respectively.

2.2.5.4 Equal Area

In Equal Area (EA) distribution, the field was divided equally among the four soil textures such that each soil texture covered 25% of the total area. Thus, each soil texture would cover 14.4 ha. The goal for this distribution is provide a middle ground for the spectrum of area distribution. This field would be a very rare possibility in reality. But for this study, it would provide an outlook on the field distributions for the sector control VRI. The distribution is shown in Figure 2.2(d) and is described in the Table 2.2.

2.2.5.5 Gradual Increase

Apart from the four major distributions, 9 more distributions were created by gradual increasing the areas under the Loretto and Boelus textures while simultaneously decreasing the area under Thurman and Doger textures. The aim for this variation was to broaden the gradient for analyzing the feasibility of VRI systems. Since Thurman soil covered 32 ha, it was decreased by 10 ha and Doger was decreased by 5ha. So, each 10 ha increment in Loretto or Boelus would result in 10 ha decrease in Thurman. Similarly, each 5 ha increment would result in 5 ha decrease in Doger. The nine distributions were: L10, L20, L30 (Increasing Loretto by 10, 20 and 30ha, respectively); B5, B10, B15 (Increasing Boelus by 5, 10, and 15 ha, respectively); L5B10, L10B20, L15B30 (Increasing Loretto in 5 ha and Boelus in 10 ha increments). The distribution is described in the Table 2.2.

Table 2.2: Area covered by each soil texture in four different distributions (IF, LT, LTBD and EA)

Soil Texture	Area Covered (ha)			
	IF	LT	LT/BD	EA
Thurman	32.50	3.80	3.80	14.40
Doger	19.60	19.60	1.50	14.40
Boelus	1.54	1.50	19.60	14.40
Loretto	3.80	32.50	32.50	14.40

Table 2.3: Area covered by each soil texture in nine subdivided distributions

Soil Texture	Area Covered (ha)								
	L10	L20	L30	B5	B10	B15	L5B10	L10B20	L15B30
Thurman	22.50	12.50	2.50	32.50	32.50	32.50	22.50	12.50	2.50
Doger	19.60	19.60	19.60	14.60	9.60	4.60	14.60	9.60	4.60
Boelus	1.50	1.50	1.50	6.50	11.50	16.50	11.50	21.50	31.50
Loretto	13.80	23.80	33.80	3.80	3.80	3.80	8.80	13.80	18.80

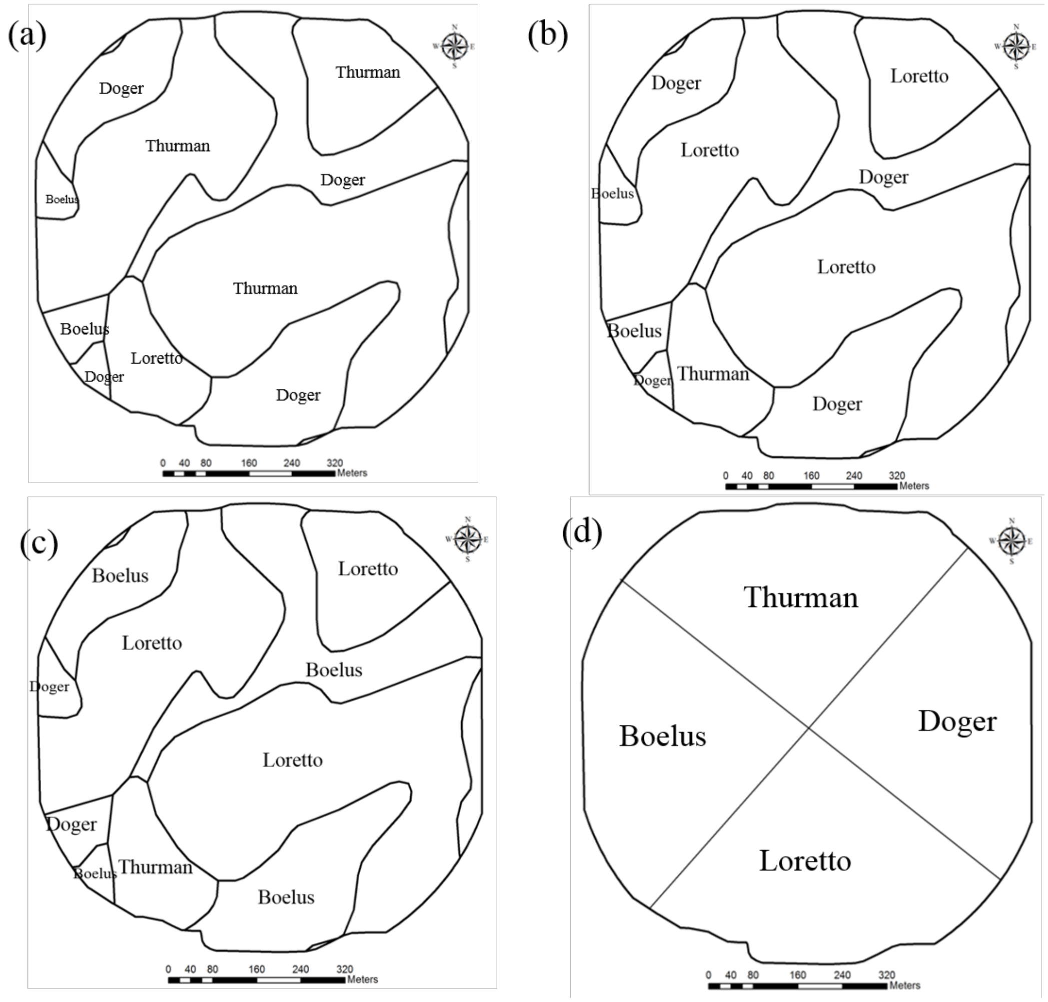

Figure 2.2: The area distribution of soil textures in the field according to (a) Initial Field (b) L-T Interchange (c) L-T/B-D Interchange and (d) Equal Area distributions

2.2.6 Yields

For each of the soil texture, yields were simulated using AquaCrop model. The specifications for the input parameters and model calibration units are described in Chapter 1 (refer to 1.2.6) which were a combination of standard inputs (Heng et al., 2009), cultivar specific inputs (Araya et. al., 2017) and site specific inputs. These yields were based on the irrigation amounts derived from the water balance model using the four irrigation strategy as described in section 2.2.4. The yields obtained for each soil texture for each of the VRI strategies (FC, DST and WM) were compared to the uniform irrigation strategy (DU). The average field yields for the 13 soil distributions were computed using weighted averages for the yields of individual soil textures and each irrigation strategy.

2.2.7 Economics

The yield revenue and water application savings were computed as discussed in Chapter 1 (Refer to Section 1.2.7). The cost for water application for each strategy, under each soil texture distribution was calculated and compared with the uniform strategy for each soil texture distribution.

The cost for custom fitting a VRI Zone control on an existing center pivot of 10 spans for a 60 ha field is approximately $21, 379 (Milton and Perry, 2006) or $372 ha^{-1}. Two reductions in the cost were analyzed in this study. The two reductions were a 25% drop in price and 50% drop in price. The 25% drop in price would produce a price for the VRI of $16,034 or $279 ha^{-1}; which is a drop $5345 from existing prices. Similarly, The 50% drop in price would produce a price for the VRI of $10,690 or $186 ha^{-1}; which is a drop $10,689 from existing prices.

These three prices were put in the irrigation cost calculations as discussed in Chapter 1 (refer to section 1.2.7) to produce the final revenues from each of the water application strategy in each soil texture distribution. The irrigation costs for each VRI system price were: $0.157 per cubic meter for 100% initial cost; $0.154 per cubic meter for 75% initial cost; \$0.151 per cubic meter for 50% initial costs and \$0.147 per cubic meter for uniform irrigation scenarios.

Based on these costs, feasibility was defined as whether or not the system produces enough savings to pay for it over the course of its life. The feasibility was considered after the end of the simulation period, instead of yearly to address the variability in the years where VRI might not be economical. Two categories were classified namely: Feasible and Not Feasible. Since initial and added costs were already incorporated in the cost of irrigation, any scenario with a net positive monetary savings at the end of simulation period would be considered feasible.

2.3 RESULTS AND DISCUSSION

2.3.1 Yields

The variation in yields for the four application strategies for the initial field distribution has been discussed in details in Chapter 1 (refer to section 1.3.5).

DST-VRI produced the maximum yields with long term average field yield of 13 Mg ha^{-1}. When compared with the uniform irrigation, the FC-VRI performed the worst with an average yield decline of 0.3 Mg ha^{-1}. WM-VRI showed a marginal decline in yield in this distribution as compared to uniform. DST-VRI showed a marginal increase in yields as compared to CUIM. However, the differences in yields were not significant ($p > 0.05$) for all the comparisons.

The lowest average yields were observed in L30 distribution followed by LT and L20 distributions. The simulated yields for Loretto were the lowest when compared to

Thurman, Doger and Boelus and were significantly different (p=0.01). This variation largely affected the yields as the area under Loretto soil increased. Also, the yields were also the lowest for Loretto in FC-VRI when compared to other irrigation strategies but were not significantly different (p >0.05). So, Loretto affected the overall yields in the distributions where Loretto soils covered higher areas. The variation of yields among the different area distributions and irrigation strategies are depicted in Figure 2.3.

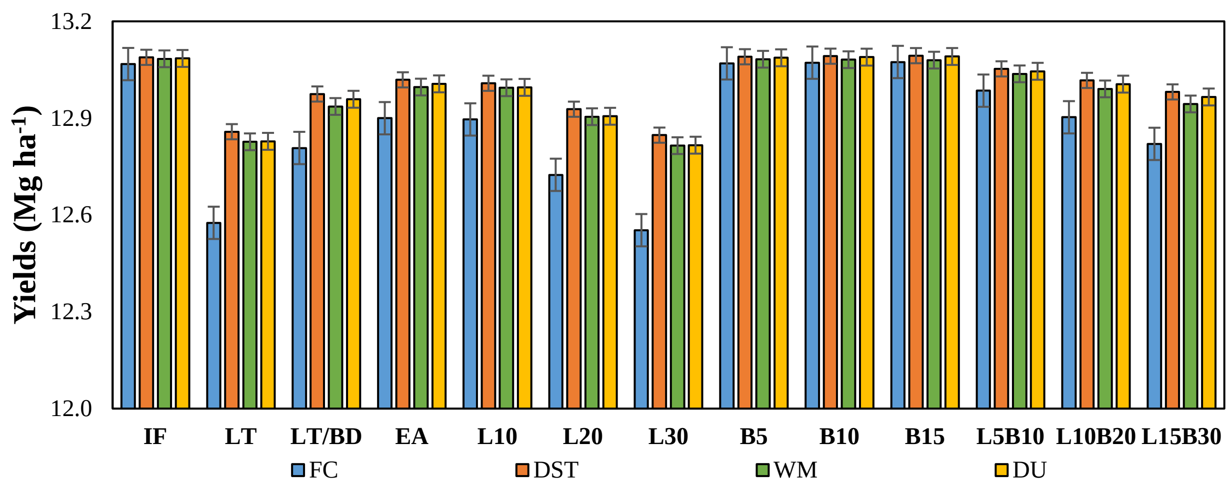

Figure 2.3: Field averaged yields for the 13 area distributions and four irrigation strategies

2.3.2 Irrigation Costs and Water Savings

Irrigation costs were calculated for the four strategies; under four field soil texture distributions based on three initial costs of the VRI system. The cost of water application under the strategies are recorded in Table 2.4. The variation in water applications for the four application strategies for the initial field distribution at 100% initial VRI costs was discussed in details in Chapter 1 (refer to section 1.3.4.1 and 1.3.6.2).

2.3.2.1 100% VRI Costs

At 100% of the VRI costs ($21,379 for the system or $379 ha^{-1}), the maximum cost of water application was found to be in the DST-VRI strategy in the Initial field (IF) distribution; with an average cost of water application of $700 ha^{-1}. The overall trend shows that application costs were the greatest in the IF soil texture distribution; which can be justified with the fact that water savings in this soil texture distribution are not enough to produce lower costs. Also, the lowest cost of application was observed in the WM-VRI strategy in the LT/BD soil texture distribution; with the cost of $641 ha^{-1}.

For the LT interchange soil texture distribution, the lowest cost of water application was observed in WM-VRI with a cost of $653 ha^{-1} and the highest costs were observed in DST-VRI with a cost of 694 ha^{-1}. Also, in the drier years (low precipitation years) the lowest costs were observed in the FC-VRI strategy as compared to other strategies. Overall, the average cost of water application through VRI in this soil texture distribution was $671 ha^{-1} as compared to $657 ha^{-1} of uniform application costs.

For the LT/BD interchange soil texture distribution, the lowest cost of water application was observed in WM-VRI with a cost of $641 ha^{-1} and the highest costs were observed in DST-VRI with a cost of 692 ha^{-1}. Also, FC-VRI strategy showed a similar trend of low costs in the drier years as compared to other strategies. Overall, the average cost of water application through VRI in this soil texture distribution was $665 ha^{-1} as compared to $658 ha^{-1} of uniform application costs.

For the Equal Area soil texture distribution, the general trend remained the same with the lowest cost of water application being observed in WM-VRI with a cost of \$666 ha^{-1} and the highest costs being observed in DST-VRI with a cost of 696 ha^{-1}. Overall, the average cost of water application through VRI in this soil texture distribution was \$680 ha^{-1} as compared to \$658 ha^{-1} of uniform application costs.

For the Gradual Increase distributions, the highest costs were reported in B5 distribution and the lowest costs were observed in L15B30 distribution with an average cost of \$692 ha^{-1} and \$667 ha^{-1} respectively. The trend for irrigation costs was: L15B30 < L30< L10B20< L20< L5B10< (L10, B15) < B10< B5. The costs are reported in Table 2.5.

In terms of water strategies, a general trend of lowest costs in the LT/BD soil texture distribution was observed for each strategy. Generally, DST-VRI strategy showed the maximum costs in all the distributions and WM-VRI showed the lowest. Comparing the costs of application with uniform application, it was observed that in IF soil texture distribution , the costs were always higher in VRI than uniform with the highest in DST-VRI (\$42 ha^{-1} more than uniform) and lowest in WM-VRI (34 ha^{-1} more). This trend was also followed in the EA soil texture distribution with DST-VRI showing \$38 ha^{-1} more costs and WM-VRI showing \$8 ha^{-1} more than uniform. However, in the LT and LT/BD strategies, even though, the trend remained the same, WM-VRI actually showed a decline in costs from uniform application with a decline of \$5 ha^{-1} in LT interchange soil texture distribution and a decline of \$17 ha^{-1} in the LT/BD interchange soil texture distribution.

The water savings of these strategies as compared to uniform irrigation are recorded in Table 2.6 and the variation in 9 subdivisions are reported in Table 2.7.

2.3.2.2 75% VRI Costs

At 75% VRI cost ($16,034 for the system or $278 ha^{-1}), the trend in costs remained similar with the highest cost being in DST-VRI of $684 ha^{-1} in the IF soil texture distribution and the lowest cost being in WM-VRI of $626 ha^{-1} in the LT/BD soil texture distribution. The overall trends in each interchange remained the same and are quantified in the Table 2.5. Overall, it was observed that a 25% drop in pricing of VRI, produced an average of 43% increase in potential costs savings. The comparison is quantified in the Table 2.6.

2.3.2.3 50% VRI Costs

At 50% VRI cost ($10,690 for the system or $186 ha^{-1}), the highest cost was in DST-VRI of $670 ha^{-1} in the IF soil texture distribution and the lowest cost was in WM-VRI of $614 ha^{-1} in the LT/BD soil texture distribution. The overall trends in each interchange remained the same and are quantified in the Table 2.5. Overall, by dropping the price of VRI to 50% of the initial cost, an average increase of 77.67% in potential cost savings was observed.

Table 2.4: The cost of water application using VRI (FC, DST and WM) and uniform (DU) in the four field soil texture soil texture distributions (IF, LT interchange, LT/BD interchange and EA) for the three initial pricing of VRI systems

Initial Cost VRI	Strategy	Irrigation Costs ($ per ha)			
		IF	LT	LT/BD	EA

100%	***FC***	694	668	663	678
	DST	700	694	692	696
	WM	692	653	641	666
	DU	657	657	658	658
75%	***FC***	678	653	648	663
	DST	684	678	676	680
	WM	676	638	626	651
50%	***FC***	665	640	635	650
	DST	670	664	663	667
	WM	663	625	614	638

Table 2.5: The cost of water application using VRI (FC, DST and WM) and uniform (DU) in the 9 field soil texture soil texture distributions for the three initial pricing of VRI systems

Initial Cost VRI	Strategy	Irrigation Costs ($ per ha)								
		L10	**L20**	**L30**	**B5**	**B10**	**B15**	**L5B10**	**L10B20**	**L15B30**
100%	***FC***	685	676	667	691	688	685	684	674	664
	DST	698	696	693	699	698	698	697	695	692
	WM	678	665	651	687	682	677	676	660	643
	DU	657	657	657	658	658	658	658	658	658
75%	***FC***	669	660	651	675	673	670	669	659	649
	DST	682	680	677	683	682	682	681	679	676
	WM	663	649	636	671	666	662	660	644	629
50%	***FC***	656	647	639	662	659	657	655	646	636
	DST	668	666	664	670	669	668	668	665	663
	WM	650	637	624	658	653	649	647	632	616

Table 2.6: Difference in cost of VRI (FC, DST and WM) strategies when compared to uniform irrigation for the four field soil texture distributions and three initial costs of the VRI system.

	Strategy	Variation from Uniform ($ ha^{-1})

Initial Cost VRI		IF	LT	LT/BD	EA
100%	***FC***	37	10	5	20
	DST	42	36	34	38
	WM	34	-5	-17	8
75%	***FC***	21	-5	-10	5
	DST	26	20	18	22
	WM	18	-20	-31	-7
50%	***FC***	7	-18	-23	-8
	DST	13	7	5	9
	WM	5	-32	-44	-20

A (-) indicates less cost when compared to uniform irrigation.

Table 2.7: Difference in cost of VRI (FC, DST and WM) strategies when compared to uniform irrigation for the 9 field soil texture sub-distributions and three initial costs of the VRI system.

Initial Cost VRI	Treatment	Irrigation Costs ($ per ha)								
		L10	**L20**	**L30**	**B5**	**B10**	**B15**	**L5B10**	**L10B20**	**L15B30**
100%	***FC***	28	18	9	34	31	28	27	17	7
	DST	40	38	36	42	41	40	40	37	34
	WM	21	7	-7	29	24	19	18	2	-14
75%	***FC***	12	3	-6	18	15	12	11	1	-9
	DST	24	22	20	26	25	24	24	21	19
	WM	5	-8	-21	14	9	4	3	-13	-29
50%	***FC***	-1	-10	-19	5	2	-1	-2	-12	-21
	DST	11	9	7	12	11	10	10	8	5
	WM	-8	-21	-34	0	-4	-9	-10	-26	-41

A (-) indicates less cost when compared to uniform irrigation.

2.3.3 Profits

Profits were defined as the difference between yield revenue and irrigation costs. Profits would indicate the interaction of yields (increase or decrease) and application reduction. The profits for all strategies, for all soil texture soil texture distributions and for the three initial costs are presented in Table 2.8 and Table 2.9.

For 100% cost of VRI systems, the greatest profits were observed in the LT/BD interchange soil texture distribution with an average profit from VRI at \$963 ha^{-1}. The difference in profit for the IF soil texture distribution has been discussed in detail in Chapter 1 (refer to section 1.3.6). The least profits were observed in the LT soil texture distribution. The WM-VRI strategy resulted in the maximum profits for all soil texture distributions. DST-VRI showed the lowest net profits in all the soil texture distributions. The profits are reported in Table 2.8.

For 75% cost of VRI systems, the greatest profits observed in LT/BD interchange soil texture distribution with an average profit from VRI at \$954 ha^{-1}. The lowest profits were observed in the LT soil texture distribution with average net profit of \$929 ha^{-1}. The profits are reported in Table 2.8. Using the 25% reduction in VRI system prices, the net profit increased by \$841 per year.

For 50% cost of VRI systems, the net profits showed the same trend with the highest average profit from LT/BD interchange soil texture distribution of \$963 ha^{-1}. The lowest profits were observed in the LT soil texture distribution with average net profit of

\$938 ha^{-1}. The profits are reported in Table 2.8. Using the 50% reduction in VRI system prices, the net profit increased by \$1643 per year.

Table 2.8: Average yearly profits for the VRI strategies (FC, DST, WM) for the four major field soil texture distributions for three cost (100%, 75%, 50%)

Initial Cost VRI	Strategy	Profits ($ per ha)			
		IF	**LT**	**LT/BD**	**EA**
100%	***FC***	926	891	925	921
	DST	923	901	917	918
	WM	931	938	963	946
75%	***FC***	942	907	940	937
	DST	939	917	933	934
	WM	946	952	968	960
50%	***FC***	955	920	953	950
	DST	952	930	946	947
	WM	960	965	990	974

Table 2.9: Average yearly profits for the VRI strategies (FC, DST, WM) for the 9 field soil texture Sub-distributions for three cost (100%, 75%, 50%)

Initial Cost VRI	Treatment	Profits ($ per ha)								
		L10	**L20**	**L30**	**B5**	**B10**	**B15**	**L5B10**	**L10B20**	**L15B30**
100%	***FC***	914	902	890	929	933	936	926	926	925
	DST	915	907	900	924	925	926	921	919	918
	WM	933	936	938	935	940	945	941	951	962
75%	***FC***	930	917	905	945	948	951	942	941	941
	DST	931	923	916	940	941	942	937	935	933
	WM	948	950	952	951	956	960	956	966	976

	FC	943	930	918	959	962	965	955	954	953
50%	***DST***	945	937	929	953	954	955	951	949	947
	WM	962	964	966	964	969	973	969	979	989

2.3.4 Savings and Feasibility

Savings were defined as the difference of the profits from VRI and uniform irrigation strategies. The savings were calculated for each year between 1988 and 2016.

For 100% VRI costs, the VRI strategies did not produce any savings in IF and EA distributions. Contrastingly, using VRI actually costed more than using uniform irrigation by a factor $1468 per year. The variation in savings for IF soil texture distribution has been discussed in detail in Chapter 1 (refer to section 1.3.6). For this soil texture distribution, VRI costed on an average $2212 more per year as compared to uniform irrigation. However, if we compare strategies, then WM-VRI showed positive returns, in this cost, in LT, LT/BD, L30 and L15B30 interchange soil texture distributions with an average annual savings of $263, $797, $367 and $671 for LT, LT/BD, L30 and L15B30 soil texture distributions respectively. It showed a loss in the rest. The higher opportunity of mining the unutilized root zone water produced enough savings to justify VRI in these scenarios. DST-VRI did not produce any savings with average annual loss for all soil texture distributions of $2113 as compared to uniform irrigation. FC-VRI also showed losses for all soil texture distributions with average annual decline of $1978 as compared to CUIM. The variation in savings when compared to CUIM are shown in Figure 2.4.

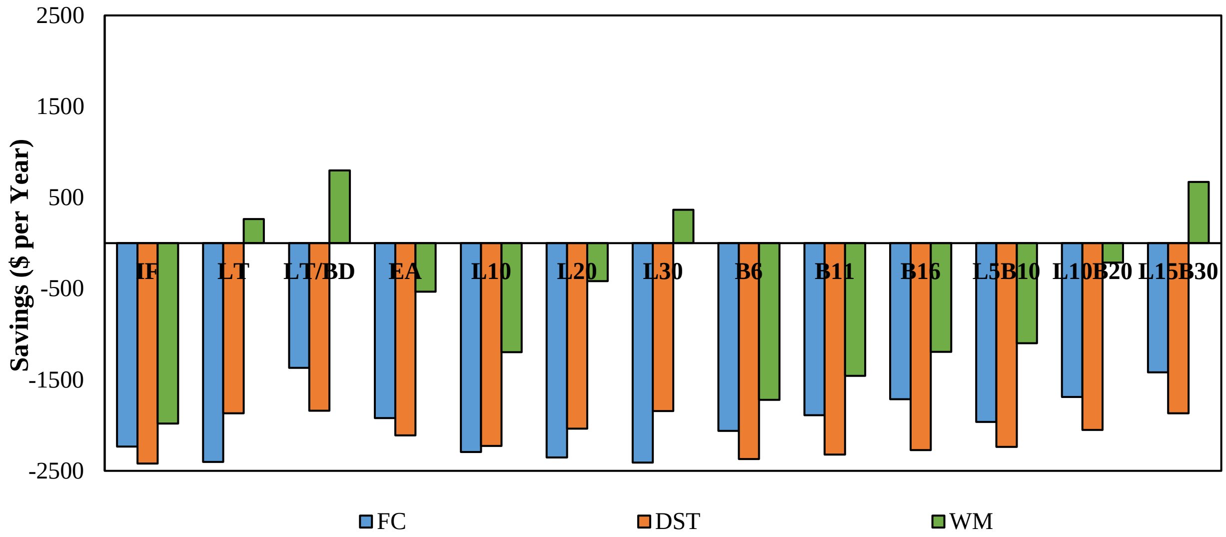

Figure 2.4: Savings/Loss from using VRI strategies when compared to CUIM for 13 soil distributions at 100% of present costs of VRI

For 75% VRI costs, IF soil texture distribution was not feasible producing an average annual decline in profits of $1298 by using VRI over CUIM, even though the performance was improved. Studying the variation in individual strategies, WM-VRI performed the best with average annual savings of $219 in the 13 soil texture distributions. It performed best in the L15B30 soil texture distribution, producing an annual savings of $1484. It also showed positive net savings of $1161, $1108, $1061, $630, $415 and $319 per year in L30, LT/BD, LT, L10B20, L20 and EA soil texture distributions respectively. In the IF soil texture distribution, WM-VRI costed more than CUIM at $1077 per year. FC-VRI and DST-VRI costed more than CUIM with average annual loss of $1084 and $1195 for the 13 soil texture distributions. FC-VRI performed best in LT/BD soil texture distribution while DST-VRI performed best in LT interchange soil texture distribution.

Using the 25% reduction, the overall net annual savings increased by $889 per year. In terms of strategies, the 25% reduction in prices produced $894 per year increase in net savings in FC-VRI; $918 increase in DST-VRI savings and $813 per year increase in WM-VRI. The maximum increase in savings with this reduction in price was observed in DST-VRI in the IF soil texture distribution with an average annual increase in savings of $923. The variation in savings when compared to CUIM are shown in Figure 2.5.

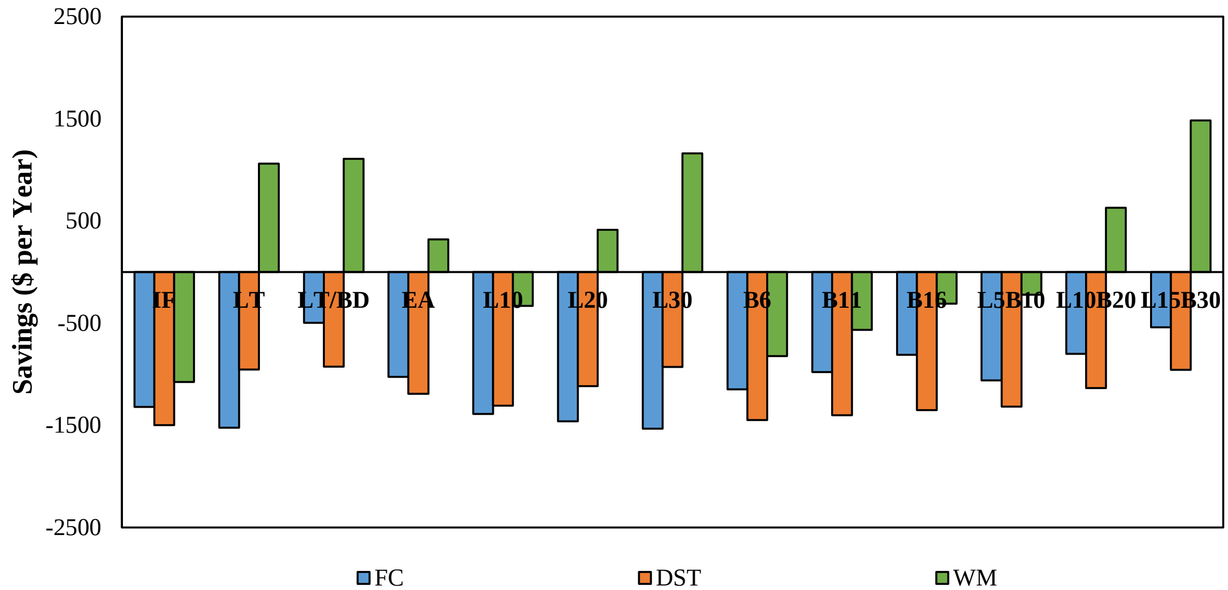

Figure 2.5: Savings/Loss from using VRI strategies when compared to CUIM for 13 soil distributions at 75% of present costs of VRI

For 50% VRI costs, IF soil texture distribution still did not produce net positive savings with an average annual loss of $527 by using VRI over CUIM. For individual strategies, WM-VRI performed best again, with average annual savings of $1023 in the 13 soil texture distributions. It performed best in the LT/BD soil texture distribution, producing an annual savings of $2351. It also showed positive net savings in 10 other distributions. In the IF soil texture distribution, WM-VRI costed more than CUIM at $305 per year. FC-VRI showed positive net savings of $236 and $191 per year in LT/BD and L15B30 soil texture distributions. DST-VRI showed no net positive savings in any soil texture distribution with an average annual loss of $426 for the 13 soil texture distributions.

Using the 50% reduction, the overall net annual savings increased by $1650 per year. In terms of strategies, the 50% reduction in prices produced $1644 per year increase in net savings in FC-VRI; $1686 increase in DST-VRI savings and $1616 per year increase in WM-VRI. The maximum increase in savings with this reduction in price was observed in DST-VRI in the IF soil texture distribution with an average annual increase in savings of $1696. The variation in savings when compared to CUIM are shown in Figure 2.6. The detailed summary of the savings from VRI in different soil texture distributions and in different costs is reported in Appendix 3.

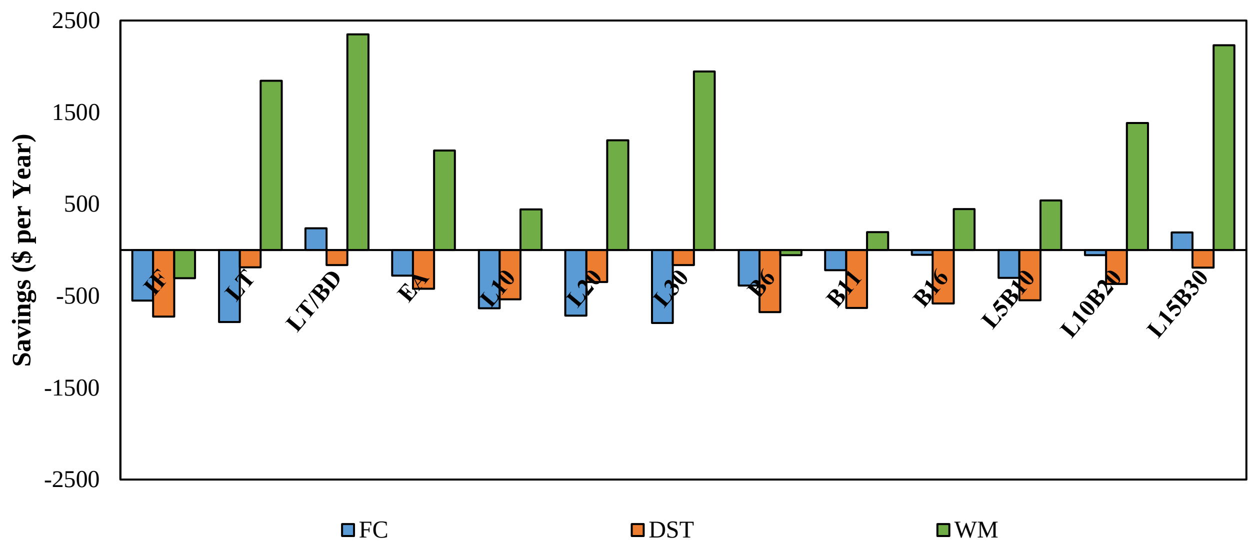

Figure 2.6: Savings/Loss from using VRI strategies when compared to CUIM for 13 soil distributions at 75% of present costs of VRI

In terms of feasibility, it was observed that DST-VRI was not feasible in any of the soil texture distributions or any price ranges. Also, the IF soil texture distribution showed no feasibility for VRI system in any strategy or cost reductions. Further, it was observed that FC-VRI would only be feasible in the LT/BD and L15B30 soil texture distribution and a price reduction of 50%. WM-VRI was observed to be the most feasible in all price ranges in the L30, L15B30, LT and LT/BD interchange soil texture distributions. LT/BD interchange soil texture distribution was observed to be most feasible soil texture distribution for VRI systems. A detail description of all soil texture soil distributions and VRI strategies for the three prices is reported in Table 2.10 and Table 2.11.

Table 2.10: Feasibility of the VRI systems through its lifetime in the four field soil texture distributions and the three price ranges of the system; Y= Feasible; x= Not Feasible

Initial Cost VRI	**Strategy**	**Feasibility**			
		IF	**LT**	**LT/BD**	**EA**
100%	***FC***	x	x	x	x
	DST	x	x	x	x
	WM	x	**Y**	**Y**	x
75%	***FC***	x	x	x	x
	DST	x	x	x	x
	WM	x	**Y**	**Y**	*
50%	***FC***	x	x	**Y**	x
	DST	x	x	x	x
	WM	x	**Y**	**Y**	**Y**

Table 2.11: Feasibility of the VRI systems through its lifetime in the 9 field soil texture sub-distributions and the three price ranges of the system; Y= Feasible; x= Not Feasible

Initial Cost VRI	Strategy	Feasibility								
		L10	**L20**	**L30**	**B5**	**B10**	**B15**	**L5B10**	**L10B20**	**L15B30**
100%	***FC***	x	x	x	x	x	x	x	x	x
	DST	x	x	x	x	x	x	x	x	x
	WM	x	x	**Y**	x	x	x	x	x	**Y**
75%	***FC***	x	x	x	x	x	x	x	x	x
	DST	x	x	x	x	x	x	x	x	x
	WM	x	**Y**	**Y**	x	x	x	x	**Y**	**Y**
50%	***FC***	x	x	x	x	x	x	x	x	**Y**
	DST	x	x	x	x	x	x	x	x	x
	WM	x	**Y**	**Y**	x	**Y**	**Y**	**Y**	**Y**	**Y**

2.4 CONCLUSIONS

An analysis of returns from VRI strategies through its lifetime was performed for the four major and 9 sub divided field soil texture distributions, Initial Field (based on the study site), L-T interchange (providing higher areas for high water holding capacity soils), L-T/B-D interchange (maximizing area under high water holding capacity soils) and Equal Area and Gradual Increase (L10, L20, L30, B5, B10, B15, L5B10, L10B20 and L15B30) soil texture distributions. It was observed that L-T/B-D interchange soil texture distributions provide maximum opportunity for the VRI to be feasible. However, only through WM-VRI strategies the net returns from VRI systems became positive.

An analysis of quantification of price reductions in VRI systems was also performed on the same field soil texture distributions and strategies. It was found that VRI systems would be feasible for WM-VRI strategies in L20, L30, L10B20, L15B30, LT interchange and L-T/B-D interchange soil texture distributions at 25% reduction in the initial pricing of the VRI systems. Further, at a 50% reduction in pricing, VRI would become feasible under WM-VRI strategies in all the scenarios except in IF, L10 and B5.

It has be noted that returns from VRI were a combination of yield increase, water application reductions, soil texture distribution of the soil texture in the field as well as the cost of the system. At present costs, VRI is not feasible if the soils of greater water holding capacities do not cover the majority area in the field. Also, there has to be enough variability in the water holding capacities of the soils in the field to enable water mining efforts.

VRI has shown potential of water savings and profitability but the present costs are inhibiting its full potential. At least a 25% reduction in the prices is required for the system to become feasible. Subsidies of up to 50% should be offered by the government agencies if the use of this technology is to be encouraged. Also, the producer should do a detailed soil sampling survey of the field to determine whether or not any of the VRI strategies suggested in this study would be feasible in their field because VRI is not feasible in every field soil texture distributions. Producers should also think about whether the variability in their fields can be addressed using the Sector Control VRI rather than Zone Control VRI to reduce the initial costs and thus increasing the chances for the VRI system to be feasible.

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APPENDIX-A: Summary of the analysis performed on weather parameters (Total seasonal precipitation, seasonal mean temperature, total seasonal reference ET and total seasonal actual ET)

Years	**Precipitation** (mm)	**Mean Temperature** (°C)	**Reference ET** (mm)	**Actual ET** (mm)
1988	225	22.2	717	732
1989	189	19.4	721	622
1990	364	20.2	649	596
1991	140	21.6	644	670
1992	494	18.1	593	484
1993	465	18.2	588	520
1994	362	19.9	697	583
1995	467	19.2	656	629
1996	475	18.8	580	541
1997	475	19.6	670	580
1998	435	21.1	583	506
1999	446	19.7	670	580
2000	264	21.2	657	577
2001	473	20.8	654	585
2002	193	21.5	739	673
2003	270	19.7	724	669
2004	535	19.1	668	577
2005	352	20.9	682	614
2006	278	21.0	722	627
2007	440	21.0	624	551
2008	529	19.2	656	584
2009	392	18.7	619	537
2010	504	20.0	665	590
2011	490	19.6	649	566
2012	166	21.3	849	744
2013	382	20.1	647	573
2014	444	19.1	595	509
2015	507	19.6	579	518
2016	369	20.5	633	548

APPENDIX-B: Summary statistics of the variables addressed in Chapter-1 for various irrigation management strategies

Table B1: Summary statistics of variables addressed in chapter-1 for FC-VRI strategy for the period of 1988-2016

Years	***Yields*** (Mg ha^{-1})	***Irrigation Depth*** (mm)	***Yield Revenue*** ($)	***Irrigation Costs*** ($)	***Profits*** ($)	***Savings*** ($)
1988	14.4	597	102553	58573	45755	-1744
1989	13.5	584	96358	57378	40730	-3316
1990	14.2	377	101536	36955	65698	-3409
1991	14.8	538	105932	56458	51204	911
1992	13.5	278	96077	27219	69696	603
1993	13.4	301	95707	29580	67052	2927
1994	14.2	449	101264	44118	58490	-2570
1995	13.8	436	98195	42874	56634	-1157
1996	14.1	342	100768	33568	68222	-1034
1997	14.2	416	101014	40862	61396	-3347
1998	14.1	388	100864	38018	64004	526
1999	14.2	416	101109	40855	61511	-2582
2000	14.4	466	102466	45868	58024	852
2001	14.1	479	100699	46988	55140	-1453
2002	14.7	587	104875	57589	49044	-1353
2003	14.3	569	102083	55841	47942	-1596
2004	13.7	440	97802	43142	55971	-1087
2005	14.6	492	104103	48272	57309	392
2006	14.3	569	102176	55866	48019	-1957
2007	14.4	429	102409	42103	61589	-1087
2008	14.2	414	101604	40694	62144	-2441
2009	13.7	378	97715	37156	61687	-3097
2010	14.7	405	105208	39768	66673	1817
2011	14.2	378	101545	37020	65639	-2523
2012	14.6	665	103900	65296	40599	-1288
2013	14.6	406	104370	39863	65745	2443
2014	14.1	302	100535	29652	71780	-1677
2015	14.4	319	102533	31325	72169	-770
2016	14.7	373	105249	36614	69748	-2520

Table B2: Summary statistics of variables addressed in chapter-1 for DST-VRI strategy for the period of 1988-2016

Years	***Yields*** (Mg ha^{-1})	***Irrigation Depth*** (mm)	***Yield Revenue*** ($)	***Irrigation Cost*** ($)	***Profits*** ($)	***Savings*** ($)
1988	14.3	592	101971	58186	45559	-1940
1989	13.6	570	97398	55953	43160	-887
1990	14.3	360	102398	35400	68080	-1027
1991	14.6	585	103980	57442	48297	-1996
1992	13.5	297	96625	29199	68317	-777
1993	13.4	339	95475	33306	63186	-939
1994	14.2	438	101513	43059	59770	-1289
1995	13.7	437	98057	42889	56480	-1311
1996	14.1	340	100644	33400	68265	-991
1997	14.3	402	101741	39417	63527	-1216
1998	14.1	401	100847	39349	62696	-783
1999	14.2	413	101210	40569	61894	-2199
2000	14.4	497	103068	48860	55702	-1469
2001	14.1	477	100683	46816	55297	-1295
2002	14.7	589	104834	57833	48768	-1629
2003	14.3	572	102229	56179	47768	-1770
2004	13.7	440	97759	43243	55837	-1221
2005	14.6	510	103908	50078	55362	-1555
2006	14.5	568	103301	55791	49215	-760
2007	14.3	430	102361	42283	61371	-1305
2008	14.2	402	101547	39543	63215	-1371
2009	13.8	365	98271	35820	63548	-1236
2010	14.7	436	105060	42805	63563	-1292
2011	14.3	367	102029	36075	67057	-1105
2012	14.5	671	103662	65869	39808	-2080
2013	14.6	444	104244	43644	61934	-1367
2014	14.1	293	100524	28788	72616	-841
2015	14.5	331	103587	32468	72110	-830
2016	14.8	362	105652	35563	71176	-1091

Table B3: Summary statistics of variables addressed in chapter-1 for WM-VRI strategy for the period of 1988-2016

Years	***Yields*** (Mg ha^{-1})	***Irrigation Depth*** (mm)	***Yield Revenue*** ($)	***Irrigation Cost*** ($)	***Profits*** ($)	***Savings*** ($)
1988	14.3	585	101991	57470	46272	-1226
1989	13.7	568	97503	55762	43451	-596
1990	14.3	360	102323	35311	68091	-1017
1991	14.6	582	104022	57214	48560	-1733
1992	13.6	290	96790	28425	69226	132
1993	13.4	332	95540	32560	63969	-156
1994	14.2	434	101606	42553	60350	-710
1995	13.8	434	98137	42643	56797	-994
1996	14.1	337	100654	33087	68576	-680
1997	14.1	399	100755	39097	62848	-1895
1998	14.1	394	100854	38594	63431	-48
1999	14.2	406	101092	39826	62492	-1601
2000	14.5	492	103128	48343	56262	-910
2001	14.1	471	100744	46202	55950	-642
2002	14.7	588	104748	57692	48817	-1580
2003	14.3	569	101788	55825	47669	-1869
2004	13.7	434	97781	42615	56464	-594
2005	14.6	505	103971	49515	55965	-952
2006	14.5	567	103378	55664	49414	-561
2007	14.4	427	102454	41921	61812	-864
2008	14.2	398	101561	38733	64009	-577
2009	13.8	358	98313	35134	64253	-531
2010	14.7	433	105110	42522	63884	-971
2011	14.3	359	102061	35182	67950	-212
2012	14.5	667	103817	65516	40303	-1585
2013	14.6	438	104273	43032	62554	-747
2014	14.1	289	100524	28315	73071	-386
2015	14.5	323	103158	31661	72459	-480
2016	14.8	358	105564	35160	71478	-789

Table B4: Summary statistics of variables addressed in chapter-1 for DU-CUIM strategy for the period of 1988-2016

Years	***Yields*** (Mg ha^{-1})	***Irrigation Depth*** (mm)	***Yield Revenue*** ($)	***Irrigation Cost*** ($)	***Profits*** ($)
1988	14.3	591	101993	54494	47498
1989	13.6	578	97338	53292	44047
1990	14.4	361	102407	33300	69108
1991	14.6	583	104031	53738	50293
1992	13.5	299	96633	27540	69094
1993	13.4	340	95485	31360	64125
1994	14.2	439	101512	40453	61060
1995	13.7	437	98055	40264	57791
1996	14.1	341	100641	31384	69257
1997	14.3	404	101937	37194	64743
1998	14.1	406	100886	37407	63479
1999	14.2	403	101203	37110	64093
2000	14.4	498	103051	45879	57172
2001	14.1	478	100677	44084	56593
2002	14.7	590	104801	54404	50397
2003	14.3	572	102234	52696	49538
2004	13.7	442	97753	40695	57058
2005	14.6	510	103906	46989	56917
2006	14.3	569	102394	52418	49976
2007	14.3	431	102361	39685	62676
2008	14.2	401	101547	36961	64586
2009	13.8	363	98270	33486	64784
2010	14.7	437	105088	40232	64856
2011	14.3	368	102029	33867	68162
2012	14.5	670	103660	61773	41888
2013	14.6	444	104244	40942	63301
2014	14.1	294	100504	27048	73457
2015	14.5	332	103570	30630	72940
2016	14.8	362	105653	33385	72267

Table B5: Summary statistics of variables addressed in chapter-1 for TIUM strategy for the period of 1988-2016

Years	***Yields*** (Mg ha^{-1})	***Irrigation Depth*** (mm)	***Yield Revenue*** ($)	***Irrigation Cost*** ($)	***Profits*** ($)	***Savings*** ($)
1988	14.6	577	103877	53168	50709	3210
1989	13.7	617	97728	56861	40868	-3179
1990	14.3	345	102328	31820	70508	1400
1991	14.6	578	104461	53266	51194	901
1992	13.5	261	96647	24039	72607	3514
1993	13.4	265	95866	24414	71453	7328
1994	14.2	434	101426	39983	61443	383
1995	13.8	436	98367	40162	58205	414
1996	14.1	349	100959	32172	68787	-470
1997	14.1	400	100409	36849	63559	-1184
1998	14.2	304	101156	27997	73158	9679
1999	14.2	345	101434	31781	69653	5560
2000	14.4	498	102983	45912	57071	-101
2001	14.2	448	101252	41271	59981	3388
2002	14.8	589	105619	54271	51348	951
2003	14.3	525	102363	48357	54007	4469
2004	13.7	384	97948	35371	62577	5519
2005	14.5	479	103606	44096	59510	2592
2006	14.5	541	103166	49864	53301	3326
2007	14.4	399	102735	36759	65976	3300
2008	14.3	447	101788	41145	60643	-3943
2009	13.7	354	97700	32605	65095	311
2010	14.7	401	105246	36985	68260	3405
2011	14.3	355	102250	32697	69553	1390
2012	14.8	666	105885	61367	44518	2630
2013	14.6	394	104423	36289	68134	4833
2014	14.2	302	101222	27791	73431	-26
2015	14.5	303	103426	27942	75485	2545
2016	14.9	355	106135	32732	73403	1136

APPENDIX-C: Summary of savings from VRI as comapred to CUIM in different field soil texture soil texture distribution s and initial VRI system costs

Table C1: Summary of yearly savings from VRI strategies (FC, DST, WM) as compared to CUIM for the four field soil texture soil texture distribution s (Initial Field, LT interchange, LT/BD interchange, Equal Area) for 100% of the present cost of VRI; (-) sign indicate using VRI costed more than CUIM; (bold) indicate positive savings

Savings ($)	**IF**			**LT**			**LTBD**			**EA**		
Year	*FC*	*DST*	*WM*	*FC*	*DST*	*WM*	*FC*	*DST*	*WM*	*FC*	*DST*	*WM*
1988	-3519	-3713	-2978	-997	-4495	-1990	**108**	-4751	-2126	-1648	-4241	-2507
1989	-5067	-2602	-2306	-14920	-1866	-1127	-10475	-906	**939**	-8791	-1871	-909
1990	-4526	-2109	-2095	-7871	-1416	-1353	-10545	-1555	-1314	-7307	-1776	-1664
1991	-819	-3755	-3484	-1337	-5501	-4014	-1235	-4784	-3476	-1272	-4446	-3575
1992	-235	-1668	-729	-2034	-754	**6120**	-338	-183	**7038**	-703	-934	**3443**
1993	**2002**	-1956	-1145	**3086**	-1267	**3690**	**5155**	-803	**4614**	**3134**	-1389	**1898**
1994	-3914	-2606	-2007	-5703	-2201	**1650**	-5047	-1987	**2935**	-4577	-2295	**529**
1995	-2469	-2623	-2297	-2407	-2397	-832	-1705	-2298	**284**	-2169	-2456	-1049
1996	-2057	-2012	-1690	-409	-1633	**13**	**163**	-1460	**833**	-895	-1732	-426
1997	-4590	-2419	-3084	-13219	-2371	-7287	-6755	-1682	-8558	-6780	-2121	-5924
1998	-633	-1981	-1219	**5208**	**2147**	**5412**	**6621**	**365**	**5700**	**3107**	-375	**2569**
1999	-3838	-3452	-2826	-3110	-3403	-368	-3146	-3836	**944**	-3557	-3742	-1105

2000	-573	-2963	-2387	-9689	-2515	**119**	-4831	-2433	**1001**	-4012	-2679	-661
2001	-2882	-2725	-2050	**153**	-1553	**2413**	**2148**	-988	**3041**	-372	-1848	**670**
2002	-3111	-3396	-3341	-466	-2152	-1279	410	-1574	-1924	-1297	-2474	-2441
2003	-3296	-3488	-3575	**284**	-3563	-5886	**1485**	-3558	-3475	-800	-3526	-3926
2004	-2399	-2542	-1892	**1446**	-1626	**2151**	**3558**	-1187	**2590**	**598**	-1858	**520**
2005	-1086	-3087	-2462	**4625**	-2988	**1216**	**2033**	-2958	**1775**	**987**	-3018	-198
2006	-3666	-2466	-2261	-3465	**6030**	**7376**	-2482	**2102**	**4580**	-3146	**737**	**2021**
2007	-2371	-2598	-2144	**314**	-2461	**511**	-131	-2392	**592**	-1038	-2493	-638
2008	-3676	-2583	-1758	-1707	-3477	**2029**	-2916	-3958	**701**	-2942	-3268	-180
2009	-4225	-2333	-1605	-8827	-3090	**458**	-6492	-3549	**182**	-5766	-2934	-586
2010	**584**	-2601	-2268	**1148**	-2060	**695**	**766**	-2505	**284**	**516**	-2472	-775
2011	-3637	-2208	-1283	-1823	-2040	**3149**	-1590	-1949	**3468**	-2410	-2077	**1291**
2012	-3284	-4095	-3587	-644	-4200	-713	-963	-4272	-994	-1967	-4179	-2099
2013	**1205**	-2702	-2060	**2747**	-2700	**628**	**4451**	-2699	**1813**	**2466**	-2699	-112
2014	-2574	-1721	-1248	-370	-1442	**2052**	**852**	-823	**1395**	-781	-1322	**328**
2015	-1732	-1821	-1443	-8026	-571	-294	-7160	**127**	**1836**	-4984	-849	**9**
2016	-3632	-2178	-1864	-7751	-2024	-1195	-3194	-1929	-492	-4066	-2054	-1230

Table C2: Summary of yearly savings from VRI strategies (FC, DST, WM) as compared to CUIM for the four field soil texture soil texture distribution s (Initial Field, LT interchange, LT/BD interchange, Equal Area) for 75% of the present cost of VRI; (-) sign indicate using VRI costed more than CUIM; (bold) indicate positive savings

Savings ($)	IF			LT			LTBD			EA		
Year	*FC*	*DST*	*WM*	*FC*	*DST*	*WM*	*FC*	*DST*	*WM*	*FC*	*DST*	*WM*
1988	-2177	-3713	-1226	**286**	-4495	**319**	**1388**	-4751	**214**	-345	-4241	-382
1989	-3752	-2602	-596	-13632	-1866	**1143**	-9149	-906	**3163**	-7478	-1871	**1150**
1990	-3680	-2109	-1017	-7087	-1416	**41**	-9727	-1555	**59**	-6486	-1776	-385
1991	**475**	-3755	-1733	-59	-5501	-1654	**38**	-4784	-1135	**11**	-4446	-1438
1992	**388**	-1668	**132**	-1480	-754	**7044**	**234**	-183	**7918**	-109	-934	**4349**
1993	**2680**	-1956	-156	**3763**	-1267	**4838**	**5790**	-803	**5715**	**3801**	-1389	**2989**
1994	-2903	-2606	-710	-4703	-2201	**3251**	-4030	-1987	**4531**	-3568	-2295	**2034**
1995	-1487	-2623	-994	-1413	-2397	**880**	-732	-2298	**1935**	-1189	-2456	**498**
1996	-1288	-2012	-680	**334**	-1633	**1299**	**889**	-1460	**2083**	-149	-1732	**755**
1997	-3654	-2419	-1895	-12264	-2371	-5842	-5848	-1682	-7161	-5855	-2121	-4574
1998	**238**	-1981	-48	**5938**	**2147**	**6698**	**7325**	**365**	**6984**	**3891**	-375	**3841**
1999	-2902	-3452	-1601	-2206	-3403	**1104**	-2242	-3836	**2428**	-2637	-3742	**305**
2000	**478**	-2963	-910	-8579	-2515	**2011**	-3751	-2433	**2871**	-2935	-2679	**1084**
2001	-1806	-2725	-642	**1165**	-1553	**4140**	**3114**	-988	**4728**	**649**	-1848	**2285**
2002	-1792	-3396	-1580	**810**	-2152	**998**	**1664**	-1574	**324**	-11	-2474	-350
2003	-2017	-3488	-1869	**1469**	-3563	-3674	**2659**	-3558	-1266	**421**	-3526	-1887
2004	-1410	-2542	-594	**2353**	-1626	**3735**	**4419**	-1187	**4150**	**1522**	-1858	**2009**

2005	**20**	-3087	-952	**5618**	-2988	**3111**	**3110**	-2958	**3634**	**2064**	-3018	**1559**
2006	-2386	-2466	-561	-2184	**6030**	**9597**	-1210	**2102**	**6771**	-1870	**737**	**4052**
2007	-1406	-2598	-864	**1227**	-2461	**2148**	**788**	-2392	**2209**	-101	-2493	**873**
2008	-2744	-2583	-577	-813	-3477	**3460**	-1996	-3958	**2186**	-2024	-3268	**1198**
2009	-3374	-2333	-531	-7984	-3090	**1818**	-5637	-3549	**1568**	-4918	-2934	**692**
2010	**1496**	-2601	-971	**2045**	-2060	**2327**	**1675**	-2505	**1901**	**1429**	-2472	**743**
2011	-2789	-2208	-212	-1120	-2040	**4413**	-834	-1949	**4715**	-1625	-2077	**2497**
2012	-1788	-4095	-1585	**800**	-4200	**1905**	**486**	-4272	**1606**	-498	-4179	**300**
2013	**2119**	-2702	-747	**3648**	-2700	**2286**	**5304**	-2699	**3417**	**3359**	-2699	**1413**
2014	-1895	-1721	-386	**259**	-1442	**3094**	**1472**	-823	**2413**	-136	-1322	**1308**
2015	-1014	-1821	-480	-7359	-571	**829**	-6462	**127**	**2860**	-4281	-849	**1053**
2016	-2793	-2178	-789	-6917	-2024	**182**	-2425	-1929	**876**	-3257	-2054	**43**

Table C3: Summary of yearly savings from VRI strategies (FC, DST, WM) as compared to CUIM for the four field soil texture soil texture distribution s (Initial Field, LT interchange, LT/BD interchange, Equal Area) for 50% of the present cost of VRI; (-) sign indicate using VRI costed more than CUIM; (bold) indicate positive savings

Savings ($)	**IF**			**LT**			**LTBD**			**EA**		
Year	FC	DST	WM	FC	DST	WM	FC	DST	WM	FC	DST	WM
1988	-1052	-1263	-558	**1361**	-2020	**387**	**2460**	-2237	**283**	**747**	-1768	-103
1989	-2651	-246	**42**	-12554	**472**	**1209**	-8038	**1408**	**3228**	-6379	**467**	**1416**
1990	-2970	-619	-608	-6431	**49**	**83**	-9041	-104	**101**	-5797	-306	-215
1991	**1559**	-1337	-1075	**1012**	-3028	-1587	**1104**	-2331	-1068	**1086**	-2006	-1165
1992	**911**	-439	**468**	-1016	**434**	**7078**	**714**	**982**	**7952**	**389**	**263**	**4489**
1993	**3248**	-554	**226**	**4330**	**102**	**4877**	**6323**	**550**	**5754**	**4360**	-12	**3148**
1994	-2056	-793	-215	-3865	-405	**3302**	-3178	-200	**4581**	-2723	-496	**2240**
1995	-664	-817	-501	-580	-600	**931**	**83**	-506	**1986**	-368	-658	**703**
1996	-644	-606	-297	**957**	-242	**1339**	**1496**	-77	**2122**	**477**	-338	**915**
1997	-2870	-759	-1438	-11463	-773	-5795	-5088	-117	-7115	-5079	-509	-4384
1998	**968**	-324	**406**	**6551**	**3616**	**6745**	**7915**	**1916**	**7031**	**4547**	**1208**	**4030**
1999	-2118	-1744	-1149	-1449	-1699	**1150**	-1484	-2101	**2474**	-1866	-2018	**494**
2000	**1358**	-906	-351	-7649	-470	**2068**	-2845	-395	**2928**	-2032	-633	**1317**
2001	-904	-754	-105	**2013**	**371**	**4195**	**3924**	**911**	**4783**	**1505**	**86**	**2509**
2002	-687	-961	-912	**1878**	**241**	**1066**	**2714**	**795**	**392**	**1066**	-73	-71
2003	-945	-1123	-1224	**2462**	-1196	-3608	**3643**	-1190	-1200	**1444**	-1161	-1619
2004	-582	-721	-98	**3114**	**158**	**3786**	**5141**	**578**	**4201**	**2297**	-66	**2215**

2005	**946**	-978	-377	**6450**	-883	**3170**	**4012**	-854	**3693**	**2967**	-913	**1799**
2006	-1313	-117	**82**	-1112	**8356**	**9663**	-144	**4416**	**6837**	-801	**3067**	**4320**
2007	-598	-817	-379	**1991**	-687	**2198**	**1558**	-620	**2259**	**684**	-718	**1075**
2008	-1962	-918	-127	-65	-1775	**3506**	-1225	-2235	**2232**	-1255	-1576	**1386**
2009	-2660	-825	-125	-7277	-1549	**1859**	-4921	-1991	**1610**	-4207	-1401	**861**
2010	**2259**	-798	-477	**2796**	-280	**2378**	**2437**	-737	**1952**	**2193**	-687	**949**
2011	-2078	-689	**198**	-532	-528	**4455**	-200	-441	**4757**	-968	-565	**2668**
2012	-534	-1321	-828	**2010**	-1422	**1982**	**1701**	-1491	**1684**	**732**	-1403	**615**
2013	**2884**	-864	-249	**4403**	-862	**2337**	**6019**	-861	**3468**	**4108**	-862	**1621**
2014	-1326	-509	-56	**786**	-242	**3128**	**1990**	**371**	**2447**	**405**	-119	**1445**
2015	-413	-454	-110	-6801	**747**	**867**	-5877	**1419**	**2898**	-3693	**480**	**1207**
2016	-2090	-681	-383	-6219	-533	**223**	-1780	-442	**918**	-2580	-563	**212**