DEVELOPMENT AND APPLICATION OF VARIABLE RATE IRRIGATION TECHNIQUES ON NON-UNIFORM SOILS USING CENTER-PIVOT IRRIGATION SYSTEMS

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ANDREW DAVID RACKERS

Dr. Allen Thompson, Thesis Supervisor

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

DEVELOPMENT AND APPLICATION OF VARIABLE RATE IRRIGATION TECHNIQUES ON NON-UNIFORM SOILS USING CENTER-PIVOT IRRIGATION SYSTEMS

presented by Andrew David Rackers

a candidate for the degree of Master of Science in Civil Engineering,

and hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Allen L. Thompson

Dr. Kenneth A. Sudduth

Dr. Kathleen M. Trauth

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DEVELOPMENT AND APPLIATION OF VARIABLE RATE IRRIGATION TECHNIQUES ON NON-UNIFORM SOILS USING CENTER-PIVOT IRRIGATION SYSTEMS

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ABSTRACT

Variable rate irrigation was studied for the production of corn and rice on a non-uniform soil texture using a three tower, conventional, center-pivot irrigation system on the East Marsh Pivot (Marsh Pivot) at the University of Missouri Delta Research Center in Portageville, MO. The soil of the Marsh Pivot is of the Hayti-Portageville-Cooter association which have a high variability ranging from poorly drained soils (low sand) to well drained soils (high sand). The use of a variable rate irrigation system allowed for the area under the pivot to be divided into sectors (areas divided at a specified degree from north) or zones (areas divided at a specified degree from north and along the length of the pivot arm). This division enabled the volume of applied water to be varied across the field to reduce water losses due to infiltration. Veris Technologies' Soil Electrical Conductivity (EC) System was used in 2002 to determine the sand content within the soil. The mean sand was calculated from two readings, one shallow and one deep. Only the deep reading was used to calculate the sand content of the soil across the pivot because the EC from the deep reading had the better correlation with the calibration soil samples from the Marsh Pivot.

Six irrigation treatments were used for corn irrigation in 2009 on the east half of the Marsh Pivot in nine sectors. Six irrigation treatments were also studied for corn production on the west half of the Marsh Pivot in six 30^{o} sectors. In 2009, 15

mm was used to produce the maximum yield for corn, but in 2010 46 mm was used to produce the maximum yield for corn on the non-uniform soils. However, for both years 8 mm produced yields equal to or greater than all other irrigation treatments at the 95% confidence interval. From the two years of available data, the best suited irrigation practice for corn production on the non-uniform soils at the Marsh Pivot is to irrigate a depth equal to the evapotranspiration rate of the corn for the given climate, 8 mm-d^{-1} for sub-humid regions. However, this practice may not be appropriate for all situations and therefore should be used with caution.

Variable rate irrigation was used to irrigate seven repetitions of six irrigation treatments on the east half of the Marsh Pivot to determine if center-pivot irrigation is suitable for cultivating rice while conserving water (compared to conventional flood irrigation) on non-uniform soils. Conventional flood irrigation was not utilized during this study. For comparison purposes, yield values for conventional flood irrigation from Vories et al. (2002) were used to determine if similar or greater yield values could be achieved for center-pivot irrigation in a sub-humid climate. Through this study it was shown that compared to conventional flood irrigation, center-pivot irrigation can produce average yields greater than conventional flood irrigation (8970 kg-ha^{-1} vs 7040 kg-ha^{-1}, Vories et al., 2002) while using less applied water for an application depth of at least 11 mm, applied every other day (790 mm vs 1200-1600 mm, Jehangir et al., 2004). This comparison does not provide a definitive conclusion for the use of center pivot irrigation over conventional flood irrigation, because study years and location were not the same. However, it does show the use of center-pivot irrigation for rice production is possible and should be further studied.

Chapter 1:

INTRODUCTION

1.1 History of center-pivot irrigation

Center-pivot sprinkler irrigation has been utilized for more than fifty years as a form of agricultural irrigation in the United States and around the world. Center-pivot irrigation provides a method of irrigation that is not dependent on the surface topography or soil texture in a field to distribute water; unlike previous forms of gravitational irrigation which require a minimum slope and are dependent on the texture of the soil (Ganzel, 2006). Surface irrigation is infamous for its inefficiency due to high evaporation and infiltration losses. Seepage in soils where the texture is high in sand (well drained) can be overcome with an increase in slope to prevent the water from infiltrating below the root zone before reaching the end of the field, or by over irrigating to ensure water reaches the full length of the field (Ganzel, 2006).

The U.S. economic boom provided by World War II led to many new inventions that would greatly alter the lifestyles of both rural and urban dwellers. In 1947 one such invention revolutionized the agricultural industry around the world. Frank Zybach of Columbus, NE attended an irrigation exhibition in Strasburg, CO that demonstrated a means of irrigation using sprinklers which was not reliant on the topography or texture of the soil. Using pipes fitted with sprinkler heads, workers toiled to move the irrigation system from one location to another through the mud created by the irrigated water. Utilizing this basic design, Frank Zybach invented the first center-pivot irrigation system by creating a propulsion system that would pivot sprinklers around a central wellhead supplying the water (fig. 1.1).

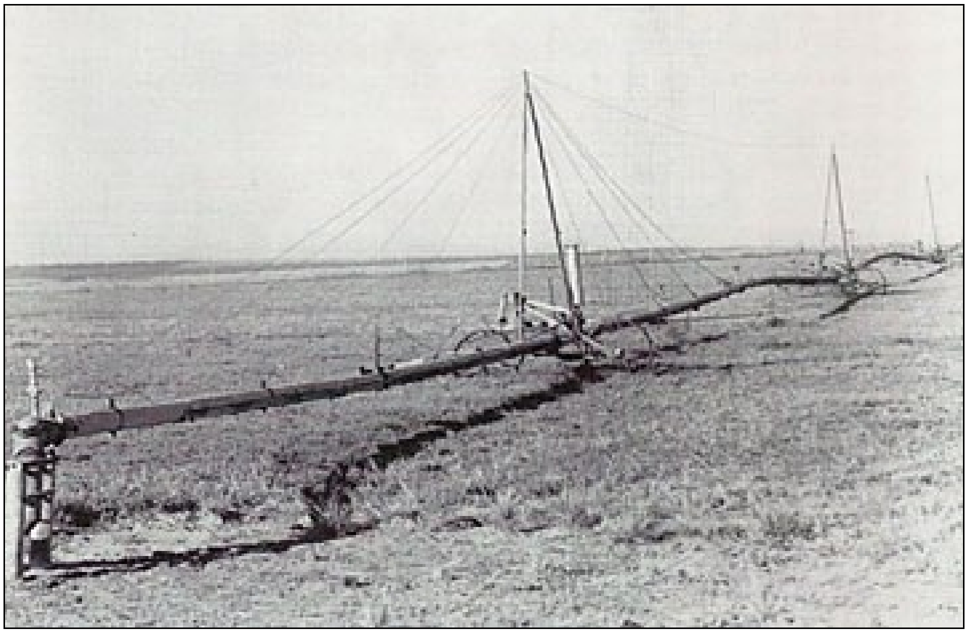

Figure 1.1: Frank Zybach's first center-pivot irrigation system (University of Nebraska, Lincoln).

The first system was supported by guide wires that resembled a suspension bridge with evenly spaced towers. The pipe contained evenly spaced sprinkler heads which irrigated the field. It traveled on skids (later replaced with steel wheels) located at the evenly spaced towers which were powered by water pressure from the wellhead. To keep the system in an even line, each tower was fitted with two-way water valves and control wires which acted as a switch. If one tower moved ahead of the rest of the system, the control wire would switch the two-way valve directing the water pressure away from the wheels, slowing the segment down (Ganzel, 2006).

Many companies have contributed to center-pivot irrigation technology over the last half-century. Their concerns have all arisen from the needs and opinions stated by farmers utilizing center-pivots. Most innovations centered on making the system more reliable and cost-effective. The method of powering the movement around the center-pivot, keeping the towers in line with each other, distributing water evenly across the span of the center-pivot and supporting the system above the ground are just a few of the many innovations created by farmers to better irrigate their crops using center-pivots.

A small farm equipment manufacturing company in Valley, NE, named Valley Manufacturing, would later buy the patent rights from Frank Zybach for his center-pivot irrigation system and would alter the system to make it more reliable and efficient. According to Ganzel (2006), Valley Manufacturing re-engineered Frank Zybach's design to include a variable speed drive to allow different depths of water to be applied, end guns (high pressure sprinklers) to increase the area being irrigated, and an automatic shutoff system to prevent equipment destruction in the cases of low water pressure or if the system towers became too far out of alignment.

Several competing companies would re-engineer Valley Manufacturing's center-pivot design by making slight mechanical changes to avoid patent infringement. In 1959 the Grasslands center-pivot was introduced by an Australian manufacturing company. The Grasslands replaced the water driven wheels with electric motors. The Grasslands was brought to the United States and re-named the Raincat, with rubber tires replacing the steel wheels. Nebraska was the leading innovative state for center-pivot irrigation, which continued with Richard Rienke. According to Ganzel (2006), Richard Rienke "patented over 30 innovations for center-pivot designs." A few examples would be reversible electric gear systems and bow-string truss system, both of which are utilized on today's center-pivots. Lindsay Manufacturing introduced the uni-knuckle joint for connecting pivot sections versus the ball joint used by other manufacturers. The uni-knuckle enabled a greater degree of deviation from center at the joints, enabling the system to move over much hillier terrain. T-L Irrigation would introduce the hydraulic motor for tower movement versus the electric motor used by all other center-pivot manufacturers. According to Ganzel (2006), T-L Irrigation claimed “their systems are more reliable, can be fixed by farmers who are used to hydraulic systems, and apply water more evenly.”

By the mid-1970’s center-pivots had become the dominant method for irrigating on the high plains of the United States. Valley Manufacturing steamed ahead the innovation for the center-pivot into one of the most efficient methods of crop irrigation in the world. Most systems are now computer controlled and easily reach spans of one quarter mile in length (fig. 1.2). The innovation continues to this day, with engineering focused on variable rate irrigation using the sprinkler system on center-pivots.

Figure 1.2: 8000 series center-pivot by Valley Manufacturing (www.valleyirrigation.com)

Valley Manufacturing’s *Valley Zone Control* allows for over 5,000 management zones and can control individual sprinklers or spans of sprinklers to provide the precise irrigation required for different topographies, soil textures, or other soil properties.

1.2 Growth and development of corn

Corn is an annual plant that is grown around the world. In Missouri, it is often planted in the beginning of May and harvested in September, providing the corn its 120 to 150 day life cycle. Depending on the plant variety, corn can grow from two to three meters tall and produce one or two ears of corn (KCGA, 2010). Each ear can produce greater than 12 rows of kernels (seeds) that are harvested and used as a resource for a number of different foods and products (KCGA, 2010). For successful growth through each growth stage, a corn plant requires a minimum of 586 mm of water during its growing season (Lamm et al, 1994).

The life cycle of corn is very similar to the basic life cycle of all plants. The kernels begin as the bared fruit from a previous generation of corn and when planted, will produce the corn plant again. After planting, the kernel will absorb water from the soil and using the endosperm in the kernel as a food source, it will form a germinated seed (KCGA, 2010). During germination the corn plant will grow in two directions, one producing roots to anchor the corn plant and provide nutrients and water during growth, and the second producing the plant material used during photosynthesis, reproduction and fruit baring.

The corn plant will undergo two distinct growth stages as indicated by Lee (2010): vegetative growth and reproduction. During the vegetative growth phase, all plant resources are used to produce the roots, stalk and leaves of the plant. The vegetative growth stage comes to completion at tasseling. It is during tasseling, and subsequent reproductive growth stages, the corn plant is most sensitive to changes in water availability. A study conducted by Robins and Doming (1953) compared the yield produced by six different irrigation timings near the tasseling growth stage for corn. From the two extremes of the study (corn wilted 6 to 8 days at tasseling with one subsequent irrigation and irrigation at tasseling with three subsequent irrigations), significant yield gains were produced for irrigation at tasseling (8670 kg-ha^{-1}) and significant yield losses were produced for wilting at tasseling (4180 kg-ha^{-1}).

During the reproductive phase, tassels form at the top of the corn plant to produce pollen. The ears of a corn plant are produced at the junction of the plant leaves with the stalk. The ears produce a silk, which must be pollinated to produce kernels (KCGA, 2010). Pollination is facilitated by many natural factors such as wind, birds and insects. After pollination, there are five steps to the corn plant life cycle before physiological maturity (tab. 1.1).

The time required for the complete life cycle of a corn plant is controlled by the temperature of the soil and the atmosphere, and dictated by the genetics of the plant. The warmer the climate in which the plant is introduced, the quicker the plant will mature and bear fruit. Cooler climates result in longer time periods for the plant to reach maturity. This difference can be seen across the state of Missouri, where corn planted in the southeastern portion of the state is often harvested several weeks prior to corn in the northwestern corner of the state.

Table 1.1: Corn growth stages from silking to maturity (after Lee, 2010).

Growth Stage	Plant Characteristics	Characteristics description
R1	Silking	Rapid N and P uptake. P uptake is nearly complete but water is needed for pollination to occur.
R2	Blister	Ear growth is nearly complete and silks are beginning to dry out.
R3	Dough	Kernels have accumulated 1/2 of their total dry weight and five leaves have formed in the kernel.
R4	Dent	Most kernels on each cob have dented and are near 55% moisture. Starch layer has formed and is progressing down the kernel.
R5	Physiological Maturity	The black layer has formed at the bottom of the kernel with the kernel at 30 to 35% moisture. Harvesting is imminent and solely dependant on the future use of the corn.

1.3 Growth and development of rice

The growth stages of rice are divided into two categories, vegetative growth and reproduction. The first six to eight weeks after planting are associated solely with vegetative growth and plant development. Following week eight and continuing to harvest, reproduction and fruit bearing are the primary uses of energy supplied by the rice plant (Leonards, 2010).

Vegetative growth begins with germination and emergence, which are directly linked to the depth at which the seed was planted. Vegetative growth occurs in two directions prior to emergence. One is for the root system away from the soil surface to provide nutrients for the growth of the plant once germination has taken place. The root system for rice extends 7 to 10 cm into the soil. The second is for the plant structure, which will grow to approximately 1 m in height. For drill planting, which occurs in most industrialized nations, germination and emergence are separated by the time it takes for the germinated shoot to break the soil surface. According to Leonards (2010), the seedling stages occur during weeks two through five after germination, and are characterized by the number of leaf blades developing on the plant, which are designated as leaf-1, leaf-2, etc. As the rice plant enters the leaf-3 and leaf-4 stages, it begins its final vegetative growth stage, tillering. Tillers are the structures that produce the flowers to enable reproduction and seed formation by the rice plant (Leonards, 2010).

The reproductive growth phase begins with the panicle initiation which develops inside the stem of the rice plant. The panicle determines the location for the internodes (green rings) in the rice stem. At the conclusion of the internode formation (a maximum of five internodes can be produced in each plant) the panicle differentiation stage occurs (Leonards, 2010). During panicle differentiation, the panicle develops a boot, which will support the panicle outside the stem. The heading stage of reproduction is observed when the panicle can be visually seen outside the stem of the rice plant. During heading, the rice plant will undergo flowering and pollination in preparation for grain filling, which occurs during the post reproductive stages (Leonards, 2010).

As stated by Leonards (2010) "…grain filling stages begin within one to five days after heading, and grain filling is complete within three weeks." The grain filling stage is separated into three physiological maturity stages: milking, dough, and maturity. Milking normally occurs within seven to ten days after heading and can be visually identified as a white milky substance within the grain. The dough stage occurs as the grain begins to lose moisture and take on a dough texture (typically a week after the milk stage). When the moisture content of the grain is near 30% the grain is at physiological maturity. The moisture content of the grain will continue to decrease until it is near 20% (after an additional two weeks), after which the grain is ready to harvest (Leonards, 2010).

Historical cultivation of rice was done through flood irrigation. During flood irrigation, water is pooled within the crop field to a depth of 50 to 75 mm during most of the growing season (Jehangir et al., 2004). This method was utilized because the root zone of a rice plant has the ability to survive in anaerobic conditions, which are formed beneath the surface of the flooding water. This anaerobic zone prevents the establishment of weeds while providing the estimated average annual water requirement of 640 mm to sustain the rice crop. To maintain the required flooding depth to create the anaerobic root zone, a seasonal water requirement of 1200 mm – 1600 mm is needed to produce a rice crop through flood irrigation (Jehangir et al., 2004).

1.4 Statement of problem

Weather patterns across the world can vary significantly from year to year, affecting the naturally available water for crop production. Today’s global markets mean crops grown in the United States can be sold to other countries and a disruption in the supply due to water shortages can create food shortages in other countries. For this reason today’s farmers rely heavily on irrigation practices, which include center-pivot irrigation systems.

The length of a center-pivot directly correlates to the time it takes to perform one complete circumference of irrigation. The longer the system the more time required, which will often reach the length of one full day. In addition, with variable rate irrigation the further the distance from the irrigation pivot, the greater the annulus area to be irrigated (further increasing irrigation time). With an operating time approaching one day, farmers cannot rely on weather forecasts to predict whether they should irrigate on a given day because if irrigation does not occur with the expectation of rainfall and the rain does not come, the field will have a deficit in its water balance which can lead to plant stress and decreased yields.

The United States is a major producer of cereal crops for the world with 66.3 million hectares used for cereal crops. Of these 66.3 million hectares, 52.7% (35 million hectares) were used for corn production (all values from 2009) (USDA NASS, 2011). For this large production, center-pivot irrigation is one irrigation method used, but its use is beginning to spread to the other major cereal crops consumed throughout the world including rice. In the United States only 1.9% of the acreage utilized for cereal crops was used for rice (1.3 million hectares in 2009), but this value has grown over the last three years. For 2006, 2007 and 2008 the number of hectares used for rice production in the United States was 1.13, 1.09 and 1.2 million, respectively (USDA NASS, 2011). Center-pivot irrigation provides a method of irrigation with the possibility of conserving water while maintaining consistent yields.

The conservation of water is desired to ensure adequate supplies of water are available for future users. Groundwater supplies are being strained and according to the Arkansas Watershed Advisor Group's (AWAG) publication *Arkansas Water: Why*

Wait for the Crisis (1982), over irrigation has severely depleted the groundwater resources in eastern Arkansas as indicated by the increase in well depth required to supply a consistent flow of water. The University of Missouri Delta Center is located in the same region this study was conducted. For example in 1945 near Stuggart, AR, groundwater wells were drilled to 12.2 m below ground surface (bgs), but in 1980 groundwater wells needed to be drilled to 42.5 m bgs. "Over irrigation leads to large amounts of unused water in the soil profile and high volumes of runoff containing constituents such as pesticides, herbicides and nutrients which pollute surface water sources," as stated by the AWAG (1982). However, if the needs of the crop are not met the farmer will suffer decreased yields and correspondingly decreased profits. To ensure farmers see proper yields while simultaneously conserving water, three questions must be answered:

1. How much water does corn or rice use on a daily basis?
2. What water application depth will produce the greatest yield without over-irrigating?
3. What irrigation frequency will a given application depth of water produce the greatest yield?

1.5 Objectives of study

The major goal of this research was to determine a suitable irrigation depth for irrigating corn and rice under a computer-controlled center-pivot irrigation system for a non-uniform soil texture. The suitable irrigation application depth for a given soil texture can be used by crop producers to reduce their water consumption and enhance the water quality leaving irrigated lands and entering waterways. The irrigation methodology can be utilized not only in southeast Missouri's sub-humid climate, but also in many other states with sub-humid climates that utilize center-pivot irrigation technology. Additionally the major goal has been reduced to two principal objectives.

1. Irrigating corn using a conventional center-pivot irrigation system, an irrigation scheduler, and a variable rate irrigation program on a non-uniform soil texture based on an estimated corn evapotranspiration rate of 8 $mm\text{-}d^{-1}$ to determine an applicable irrigation depth and interval for production on non-uniform soils.
2. Irrigating rice using a conventional center-pivot irrigation system on a non-uniform soil texture based on an estimated rice evapotranspiration rate of 6.5 $mm\text{-}d^{-1}$ using a variable rate irrigation program to determine the effectiveness of center-pivot irrigation at water conservation.

1.6 Chapter summary

Chapter 1 began with an overview of the historical background of center-pivot irrigation and the innovations it experienced from 1947 to today. A brief background of the growth mechanisms of two major cereal crops in the United States (rice and corn) was discussed, followed by the impact such a growth in the irrigation field has had on ground water supplies. Key questions fundamental to this research were stated, followed by the major goals of this research in which answers for these key questions can be found.

Chapter 2:

LITERATURE REVIEW

2.1 Crop coefficients

Evapotranspiration (ET) rate is defined as the rate at which the plant uses water on a daily basis. The ET value is based on climatic data for given region. Climatic factors that are used to calculate ET for a given plant are precipitation, temperature, relative humidity, wind speed and solar radiation. The Food and Agricultural Organization of the United Nations Irrigation and Drainage Paper Number 24 (FAO-24) was written to compute the crop water requirements (potential ET, ET_o) on a 24-hour time stamp for the previously given parameters using the Penman-Montieth (PM) equation (Doorenbos and Pruitt, 1977). The PM equation was further modified in FAO-56 to improve estimated daily ET values by instituting a crop coefficient (K_c) to be utilized with ET_o. As stated by Allen et al. (2005), ET_o utilizes the “FAO-56 Penman-Monteith equation…to calculate…$ET_{o,}$ from a hypothetical grass reference that is 0.12 meters in height, having a surface resistance of 70 seconds per meter for 24-hour time steps and albedo of 0.23”. The PM equation published by Allen et al. (1998) can be seen in equation 2.1.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{2.1}$$

Where:

Rn = net radiation at the crop surface ($MJ\text{-}m^{-2}d^{-1}$)
G = soil heat flux density ($MJ\text{-}m^{-2}d^{-1}$)
T = mean daily air temperature at 2 m height (^oC)
e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)
u = wind speed at 2 m height ($m\text{-}s^{-1}$)
γ = psychometric constant ($kPa\text{-}^{o}C^{-1}$)
Δ = slope vapor pressure curve ($kPa\text{-}^{o}C^{-1}$)

According to Allen et al. (2005), the crop coefficient is defined as the ratio of ET for a specific crop (ET_c) to ET_o (eq. 2.2).

$$K_c = ET_c / ET_o \tag{2.2}$$

where: K_c = crop coefficient
ET_c = crop evapotranspiration
ET_o = potential evapotranspiration

Potential evapotranspiration is often substituted with a reference crop evapotranspiration (ET_r) such as grass. Substituting ET_o with ET_r, eq. 2.2 becomes:

$$K_c = ET_c / ET_r \tag{2.3}$$

where: ET_r = reference crop evapotranspiration

Equation 2.3 can be manipulated to calculate ET_c, where ET_c is the product of K_c and ET_r.

$$ET_c = K_c ET_r \tag{2.4}$$

As stated in Allen et al. (2005), K_c values vary during the growing season as the crop is developing, maturing and aging, as well as changes in the vegetative canopy. This change can be simplified into three different K_c values; K_c initial, K_c mid, and K_c end. Figure 2.1 depicts the three K_c values. There are four major plant stages within the K_c curve. Prior to the transition from K_c initial to K_c mid is stage one, the initial period. The transition period between K_c initial and K_c mid is the crop development period followed by the mid-season period, which constitutes the entire time span within K_c mid. The transition between K_c mid and K_c end is the fourth and final plant stage, the late season period (Allen et al., 2005).

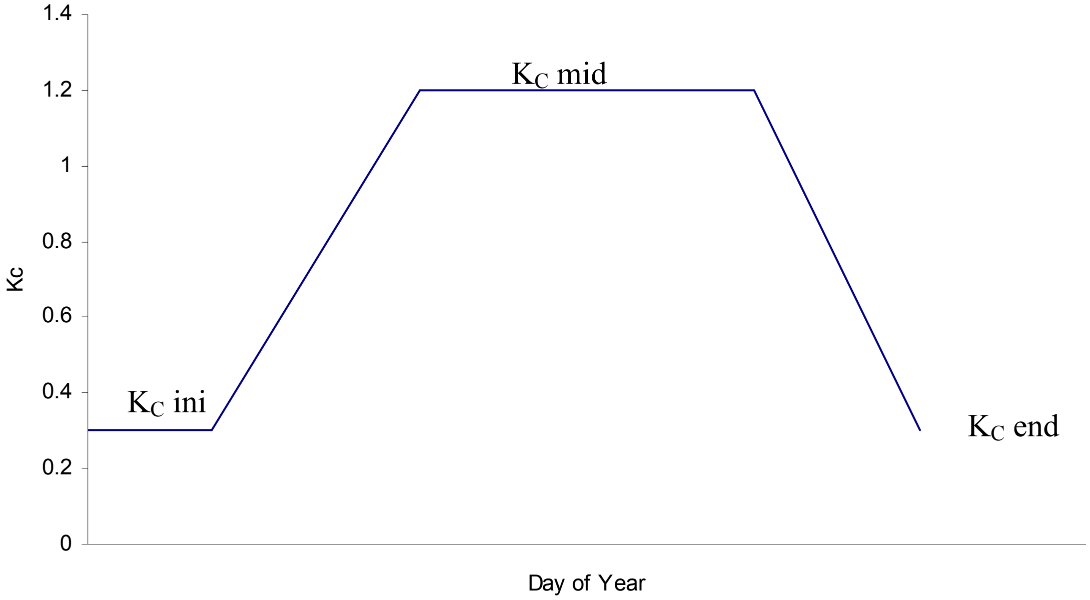

Figure 2.1: Schematic of the general shape of the FAO-56 K_c curve (after Allen et al., 2005).

According to Henggeler (2010), the use of any irrigation scheduling is no more accurate than the crop coefficient values and their corresponding coefficient curve. FAO-56 utilized basic standards to determine recommended crop coefficients, based on a wind speed of 2 m-s^{-1} at a height of 2 m and a relative humidity of 45% (Allen et al. 1998). The climatic characteristics utilized in the FAO-56 procedure are not applicable for all parts of the United States, and thus make irrigation scheduling based on them somewhat uncertain. Using default values which are not characteristic to the local climate can result in over- or under-irrigation (Henggeler et al., 2010).

Limited research has been conducted to modify the crop coefficient used in eq. 2.3 to account for differences in local climatic conditions. Previous research methods used heat units as a method for determining the maturity and water requirement for a crop in a given climate. Gilmore and Rogers (1958) improved the heat units method for measurement by correcting for temperatures below the minimum and above the maximum temperature for growth, 10°C and 30°C respectively. In Henggeler (2010) and Henggeler et al. (2010) simple charts have been devised to enable the modification of FAO-56 crop coefficients and their applicable time spans to local climatic conditions based on the historical weather data from 300 cities across the United States. To modify the K_c value for local climatic conditions, the K_c from FAO-56, mean value for daily wind speed, mean value for daily minimum relative humidity, and mean plant height are used to adjust the K_c in eq. 2.5 (Henggeler et al., 2010).

$$K_{c\text{-}Adj} = K_{c\text{-}FAO\text{-}56} + [0.04(U_2 - 2) - 0.004(RH_{min} - 45)](H / 3)^{0.3} \tag{2.5}$$

where:
$K_{c\text{-}Adj}$ = adjusted K_c
$K_{c\text{-}FAO\text{-}56}$ = K_c from FAO – 56
U_2 = mean daily wind speed
RH_{min} = mean daily minimum relative humidity
H = mean plant height

Henggeler (2010) devised a four step process to modify the growth periods using the adjusted K_c values from eq. 2.5.

1) Determine the average FAO-56 growth period for a desired crop as a percent value of the total season.
2) Determine the local expected growing season length in days based on the plant variety and the expected planting date.
3) Multiply the percent value obtained from the average FAO-56 growth period by the local expected growing season length to obtain your local growth stage lengths.

4) Adjust your results based on local knowledge of growing season length and crop growth periods.

Henggeler (2010) concluded the K_c values must be adjusted to prevent large discrepancies in irrigation for crops, and used soybeans as a prime example. Figure 2.2 shows how different forms of planting lead to changes in K_c values at different times of the year for soybeans (Henggeler, 2010).

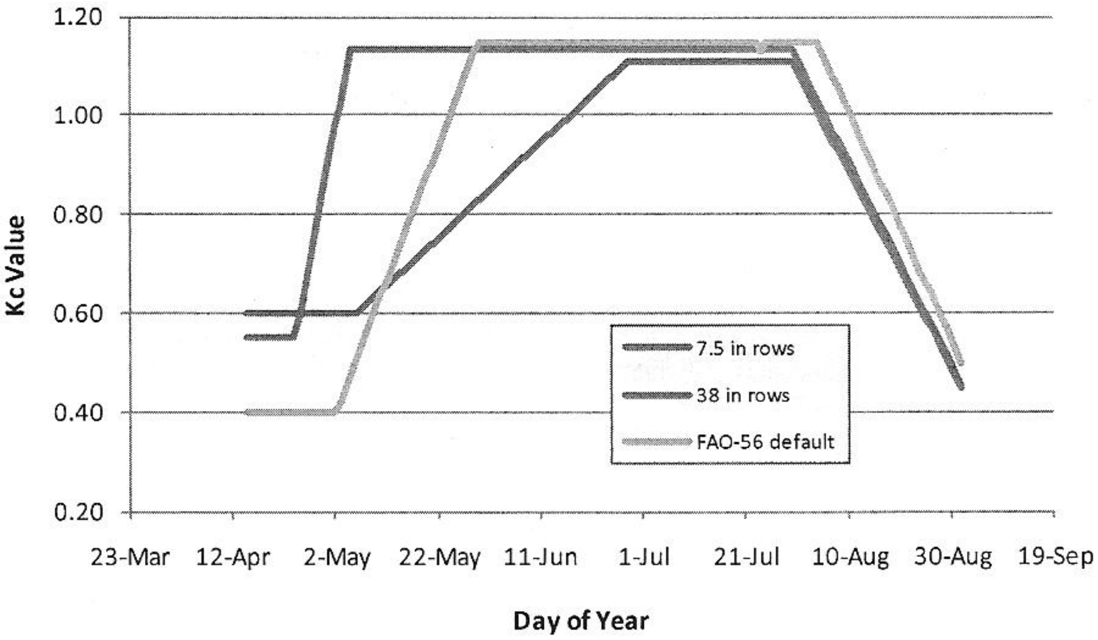

Figure 2.2: Observed changes in K_c values and applicable time periods based on eq. 2.4 (Henggeler, 2010).

2.2 Center-pivot irrigation and modifications

Center-pivot irrigation differs from gravity flow or flood irrigation in many ways, but most notably in its water use efficiency and area of coverage. According to Evans (2006), the efficiency of the water distribution can be decreased by wind, and evaporation losses can be high due to water resting on plant foliage instead of in the soil near the root system where it can be used by the crop. These losses are relatively minute when compared to the inefficiency of gravity flow or flood irrigation (large water surface area subject to evaporation and large quantities of water required to reach distant furrow ends). Sprinkler units are often installed on top of the supply pipe, which is supported by a steel truss system to carry the water a distance up to 400 m, irrigating an area up to 50 hectares (Evans, 2006). The use of center-pivots has enabled the development of croplands unsuitable for gravitational irrigation, but where the local climate does not provide sufficient rainfall to support the growth of crops.

Modifications to the sprinkler system on center-pivots have enabled the inefficiencies observed due to wind and evaporation from current center-pivot sprinkler designs to be decreased. According to Lyle and Bordovsky (1983), one such system is the Low Energy Precision Application (LEPA) method. The LEPA method utilizes a drop tube design with emitters, where the sprinkler is attached to a tube extended from the supply pipe in the direction of the soil surface (typically to a height of 5 cm to 10 cm above the soil surface). The height of the sprinkler above the soil surface can be adjusted depending on the type of crop typically grown under the center-pivot. This system minimizes distribution discrepancies by keeping the irrigated water close to the ground as well as reducing evaporation losses by keeping the water off the foliage of the growing crop (Lyle and Bordovsky, 1983).

2.3 Site specific irrigation

According to Evans (2006) "…75% of the leaching occurs in about 25% of the area in many center-pivot irrigated fields," indicating the need to precisely manage irrigation on small areas of a field. This would prevent the loss of nutrients due to leaching and runoff as well as protecting surface and ground water supplies. To accomplish this, Camp et al. (1998) modified a commercial center-pivot system to enable the independent control of water and chemical application to 100 m^2 areas beneath the center-pivot irrigation system. Nozzles of one, two and four times the normal application rate at a specified tower speed were varied down the supply pipe and controlled by manifolds. A controller was used to switch on the appropriate valves to enable irrigation on a controlled basis over a designated area (Camp et al., 1998). The system was limited to fixed sprinkler zones, but according to Camp et al. (1998) the system showed acceptable application results.

According to the study conducted in Omary et al. (1998), for irrigated areas near the pivot point, angular increment was small, requiring nozzles with lower discharge rates, while at the end of the pivot the irrigated areas were much larger, requiring nozzles with larger discharge rates. This enabled extended variable application depths along the length of the pivot, which allowed the system to operate at eight different application rates at any given tower velocity. The downside of this system (as addressed by Omary et al. (1998)) was chemical and nutrient application through the water of the center-pivot was also applied at varying rates, which was not desired, especially for nutrient application, where uniform application across the entire field is desired to ensure maximum yields.

2.4 Variable rate irrigation

Variable rate irrigation management plans have been devised as a means of conserving water while successfully allocating limited water resources. According to Stone et al. (2010), water savings is becoming more important as other sectors of human society compete with agriculture for available water resources. Stone et al. (2010) conducted experiments from 2007 to 2009 using variable rate irrigation for peanut production which consisted of a center pivot system modified to permit variable applications to individual areas consistent with Camp et al. (1998). The variable rate irrigation was devised as separate treatments based on a whole plot, irrigation of different soil types within a plot and rainfed systems. Utilizing the plot layout as seen in fig. 2.3, the rate of irrigation was varied based on an azimuth reading and the distance down the pivot system.

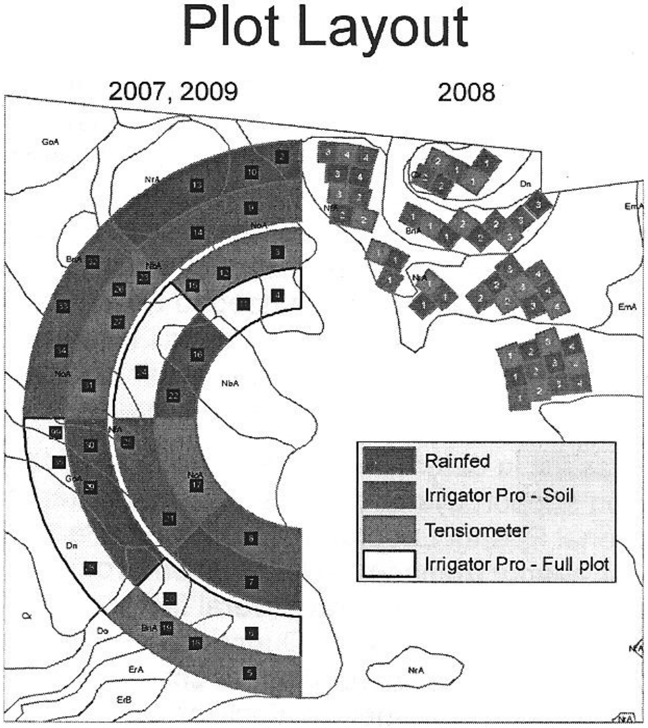

Figure 2.3: Plot layout for irrigated and non-irrigated peanut treatments (Stone, 2010).

Stone et al. (2010) concluded the yields among the different treatments for the two years of the study could be attributed to the extended drought conditions observed in the second half of the growing season in 2007. Based on the irrigation program used, the total amount of water applied was significantly greater than what was needed for optimal plant growth indicating the over-irrigation tendencies of irrigation schedulers (Stone et al., 2010).

The University of Georgia Precision Ag team (UGA) partnered with Farmscan of Australia to devise a user-friendly variable rate irrigation system that could be easily operated by private crop producers. According to Perry and Milton (2006), this cooperative agreement came about as the "water wars" between the states in the southeastern United States began to take on a more prominent role in the political and media circles. The system derived by UGA/Farmscan would vary the amount of water applied to the field as a percent of the application depth. The computer program was designed to open the valves of the sprinklers in a given section of the pivot for a desired amount of time, creating a cycling pattern (Perry and Milton, 2006). The sprinklers in each designated section are controlled on or off by a pneumatically-actuated, normally open, flow control valve (Perry and Milton, 2006). The valves are grouped into "banks" which are physically set down the length of the pivot. The banks cannot vary around the field.

Perry and Milton (2006) reported positive results for the evaluation of their variable rate irrigation system. The system was able to achieve targeted application rates in all the sprinkler banks. It was also noted that the cycling of the sprinklers on and off did not affect the uniformity of the water application.

2.5 Sprinkler irrigation for rice

Center-pivot irrigation is beginning to be considered a viable option for sprinkler irrigation in the production of rice due to the extensive genome changes being made to different sub-species of rice. Prior to genetic adjustments, many scientific studies determined rice was not capable of producing yields under center-pivots comparable to yields produced by flood irrigation.

An investigation into sprinkler irrigation for rice production was conducted by Westcott and Vines (1985). Tests were conducted comparing sprinkler irrigation to flood irrigation for a two year study (1983 to 1984) with sprinkler irrigation consisting of three weekly applications of 38 mm of water in 1983 and a similar irrigation schedule in 1984 to ensure soil water moisture tension was maintained above 30 kPa. Nitrogen application was also considered and was applied as a single application of 101 kg-ha^{-1}. The study conducted by Westcott and Vines (1985) resulted in an average yield of 4448 kg-ha^{-1} for sprinkler irrigation in comparison to 7139 kg-ha^{-1} for flood irrigation in 1983. The reduction in yield under sprinkler irrigation was attributed to sheath blight. In 1984, chemical applications controlled sheath blight but yields for sprinkler irrigation remained less than yields for flood irrigation (5901 kg-ha^{-1} vs 7846 kg-ha^{-1}). Westcott and Vines concluded split application of nitrogen fertilizer may benefit yields under sprinkler irrigation, but flood irrigation remains a more viable option for rice production.

A second comparison of flood to sprinkler irrigation was conducted in the rice growing region of Texas during a three year period (1982 to 1984). In the study conducted by McCauley (1989), total water was applied through sprinkler irrigation and ranged from 931 mm – 1171 mm. The resulting yields from sprinkler irrigation were reduced by 20% when compared to flood irrigation. It was concluded by McCauley (1989) that the reduction in yield could not be attributed to weeds, diseases or water availability because proper herbicides and fungicides were applied to prevent bias from such factors.

Comparing the production of rice under sprinkler irrigation to conventional flood irrigation through replacement of water lost to evapotranspiration since the previous irrigation was conducted in inland southeast Australia for three irrigation schedules (once, twice and three times per week) (Muirhead et al., 1989). The irrigation schedule utilized by Muirhead et al. (1989) resulted in a 50% reduction in yield for all sprinkler irrigation treatments when compared to conventional flood irrigation. Nitrogen fertilizer was applied in sufficient quantities but a phosphorous deficiency could have been present as indicated by the reduced phosphorous concentration in the plant tops of the sprinkler irrigated rice. However, water stress was considered the main factor in the reduction in yield for sprinkler irrigated rice due to the arid climate associated with southeast Australia (Muirhead, et al. 1989).

2.6 Physical properties of soils

The soil stores the water utilized by the plant for physical growth. The storage of water is maintained by the adsorptive forces and capillary forces of the soil and the water molecules. Adsorptive forces hold the water because of the attraction of the negatively charged particles of soil and the positively charged dipole of the water molecule. The capillary forces hold the water because of the surface tension created between the water molecules (James, 1988).

The storage of water within the soil profile can be quantified by four values: saturated soil (θ_{sat}), soil field capacity (θ_{fc}), critical water content (θ_{crit}) and permanent wilting point (θ_{pwp}) (James, 1988). Only the water between θ_{fc} and θ_{pwp} in the soil profile is available for plant use; however water between θ_{crit} and θ_{pwp} is often unavailable for plant use due to the attraction between the water and the soil particles. If the available water is below θ_{crit} the plant can be significantly impacted; whether it is by limiting the physical development of the plant, or (should the plant produce fruit) by decreasing plant yield. Figure 2.4 depicts the quantifiable values of water in the soil and the areas that are available to a plant: readily available water (RAW) and available water (AW). Any amount of water between field capacity and saturation is not available for the plant to use because it passes through the soil profile too quickly. The AW is any water located between field capacity and permanent wilting point. Of this AW, water between field capacity and critical water content is referred to as RAW. If the water content of the soil falls below the critical water content, a crop producing plant will experience a decrease in yield production, and should the water content fall to the permanent wilting point, the plant will die. The ideal water content for plant growth is θ_{fc} and is the water content of the soil desired from irrigation practices.

Different soil textures often have different values for water contents of AW and RAW. Smaller pore space between soil particles and soil particle gradation results in larger water contents for AW and RAW. Pore space between soils increases as soil particle size increases. The three types of soil are listed in increasing particle size: clay, silt and sand. Soil textures are often described in terms of clay, silt, sand and loam. A loam soil is a soil that has a composition of equal parts clay, silt and sand. Table 2.1 shows the field capacity, permanent wilting point, and AW for six different soil textures as stated in Hansen et al., (1979).

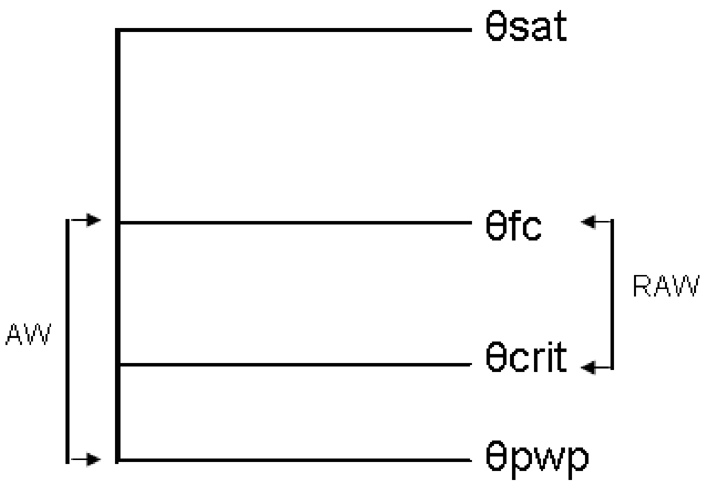

Figure 2.4: Depiction of the four quantifiable water content points (as a point analysis); the available water (AW) and readily available water (RAW) within the soil water balance.

Table 2.1: Infiltration rate, available water (AW), field capacity, and permanent wilting point for different soil textures (after Hansen et al., 1979)

Soil Texture	Infiltration rate ($mm-h^{-1}$)	AW ($mm-cm^{-1}$)	Field Capacity (% by Vol)	Permanent Wilting Point (% by Vol)
Sandy	50	0.8	15	7
Sandy Loam	25	1.2	21	9
Loam	12	1.7	31	14
Clay Loam	8	1.9	36	18
Clay	5	2.3	44	21

The amount of water that can be used from the soil profile without adversely affecting the plant, as defined by James (1988), is the maximum allowable deficiency (MAD). The MAD can be calculated from eq. 2.6. James et al., (1982) calculated the MAD and the maximum root depth of a crop when not limited by the soil texture or depth. A typical root depth for corn is 120 cm and the MAD is 0.65, but it should be noted that both values do vary with soil texture and depth (James et al., 1982).

$$MAD = RAW / AW \tag{2.6}$$

where: MAD = maximum allowable deficiency
RAW = readily available water
AW = available water

2.7 Soil electrical conductivity and soil properties

Apparent soil electrical conductivity (EC_a) is a sensor based measurement, which can be used to provide an indirect measurement of various soil properties. Such soil properties consist of soil salinity, clay content, soil pore size and distribution, clay mineralogy, soil moisture content, and cation exchange capacity. The indirect measurement of EC_a can be used to determine one of the above soil properties if the measurement of the remaining properties can be measured or are known. In addition, if the changes of a given property are greater than the remaining properties, then EC_a can be calibrated and quantified as a direct measurement of the principal contributing factor (Sudduth et al., 2003).

Soil electrical conductivity has been modeled through three conductance pathways: salts contained in soil water, cation exchange capacity of clay minerals, and the direct continuous contact between soil particles. Equation 2.7 was developed to model EC (Cowin and Lesch, 2003):

There are currently two types of in-field portable EC_a measuring devices used in agriculture. A non-direct contact sensor measures electromagnetic inductance (EM), while a direct contact sensor uses electrode based sensors. Both modes of measuring EC_a have advantages and disadvantages. The non-direct contact EM sensor is lightweight and can be pulled by an all-terrain vehicle, allowing it to be used on wet and dry soils or previously planted fields. However, the EM sensor requires frequent calibration as drift is often observed in the EC_a results. In contrast, the direct contact EC_a sensor requires no calibration, but due to its size and soil disruption characteristics, the system cannot be used on saturated soils and must be pulled by a tractor (Sudduth et al., 2003).

$$EC_a = (\theta_{SS} + \theta_{WS})^2(EC_{WS}EC_{SS}) / (\theta_{SS}EC_{WS} + \theta_{WS}EC_S) + (\theta_{SC}EC_{SC}) + (\theta_{WC}EC_{WC}) \tag{2.7}$$

where: EC_a = apparent soil electrical conductivity

θ_{WS} = volumetric soil water content in the soil water pathway

θ_{WC} = volumetric soil water content in the continuous liquid pathway

θ_{SS} = volumetric content of the surface conductance solid phase

θ_{SS} = volumetric content of the indurated solid phase

EC_{WS} = specific EC_S of the soil water pathway

EC_{WC} = specific EC_S of the continuous liquid pathway

EC_{SS} = EC_S of the surface conductance solid phase

EC_{SC} = EC_S of the indurated solid phase

The usefulness of EC_a to determine the texture of a soil is derived from the fact that clays have a high conductivity (10 to 1000 mS-m^{-1}), silts have a medium conductivity (5 to 20 mS-m^{-1}) and sands have a low conductivity (< 5 mS-m^{-1}). Therefore, conductivity has a strong correlation to grain size and texture of a soil (Lund et al., 1999).

A study conducted by Lesch et al. (2005) accurately determined the texture of an arid zone soil by determining the EC_a of the soil. Two soil series were present in the study area (Casa Grande and Mohall). Using an EM system, the percentage of sand, silt, and clay was determined for the field. Table 2.2 shows the mean, minimum and maximum percentage of each soil type calculated from the EC_a from the field, and the mean percentage for the Casa Grande and Mohall soil series. When the EC_a and soil property percentages are mapped, the low conductivity zones correspond with lower clay (higher sand) areas, and high conductivity zones correspond with higher sand (lower clay) areas (Lesch et al., 2005).

Table 2.2: Statistical values for soil properties calculated for a field classified as Casa Grande and Mohall (after Lesch et al. 2005).

Soil Property	Minimum	Maximum	Mean	Casa Grande Mean	Mohall Mean
Clay (%)	10.6	32.3	23.0	24.5	16.4
Sand (%)	51.9	84.9	65.9	64.2	72.6
Silt (%)	4.5	15.8	11.1	11.3	11.0

Chapter 3:

CORN PRODUCTION

3.1 Methodology

3.1.1 Project description

This research was conducted on the East Marsh Pivot field (Marsh Pivot) at the University of Missouri Delta Research Center in Portageville, MO (fig. 3.1). From the United States Department of Agriculture (USDA) web soil survey, the Marsh Pivot was located on soils with the Hayti-Portageville-Cooter classification. According to the USDA web soil survey the Hayti classification "consists of very deep slowly permeable soils," the Portageville classification "consists of deep moderately well drained soils," and the Cooter classification "consists of very deep poorly draining soils" (www.soils.usda.gov).

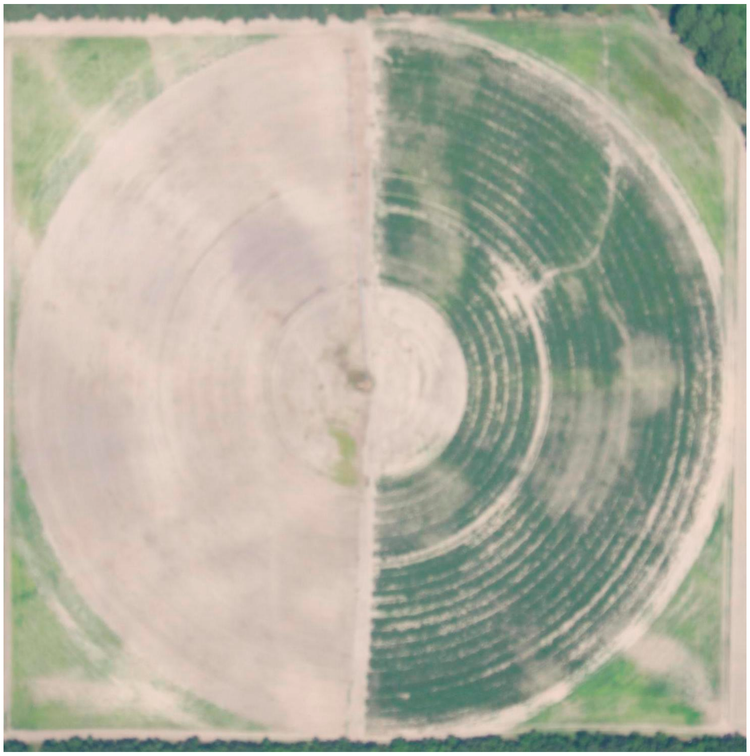

Figure 3.1: Aerial photograph of the East Marsh Pivot field (Marsh Pivot) located in Portageville, MO.

The variability in soil texture on this field is extensive, and was quantified using Veris Technologies' Soil Electrical Conductivity (EC) 3100 system in 2002 to determine the sand content within the soil. Two readings were taken to determine the relative sand content; a shallow reading (0 cm to 30 cm) and a deep reading (0 cm to 91 cm) (Veris Technologies, 2011). The field was divided into separate halves (east and west) with the pivot road being used to define north-south and act as a dividing line between the field halves. However, the road does not lie directly north-south but rather is 4^o off from true north, with the northern end of the road at 4^o and the southern end of the road at 184^o. Variable rate irrigation by azimuth was utilized for this study.

3.1.2 Soil analysis

For the 2009 growing season, the east half of the Marsh Pivot was planted in corn and divided into nine (unequal) sectors for studying different irrigation depths, beginning at 4^o and continuing clockwise to 184^o. For the 2010 growing season, the west half of the Marsh Pivot was planted in corn and divided into six equal 30^o areas beginning at 184^o and continuing clockwise to 4^o. The transition to the west side of the pivot was made to accommodate the production of rice on the east side of the pivot using variable rate irrigation during the 2010 growing season. Soil texture was calculated from the calibration of the electrical conductivity (EC_a) of the soil obtained during the 2002 Veris 3100 survey. The Veris 3100 determined the EC_a for two depths simultaneously by using three pairs of electrodes. One set injects current into the soil, and the remaining sets measured thee voltage potential for a "shallow" and a "deep" reading. Per Veris 3100 manual specifications, electrodes were to be maintained between 2.5 cm and 5.0 cm below ground surface (bgs), and the system was operated at a constant speed through out each sampling run which varied between 13 kph and 19 kph. Data were collected on a 1-s interval and 10 m north-south transects resulting in a 4 m to 6 m data spacing (fig. 3.2). Soil cores for the Marsh Pivot were collected during 2002 for calibration between the Veris EC_a data and field sand content (fig. 3.3). Twelve cores were collected and divided into five 15 cm segments for a total depth of 76 cm bgs. The soil cores were analyzed for texture by the standard sieve-pipette method (results of this method can be seen in Appendix A) (ASTM, 2011).

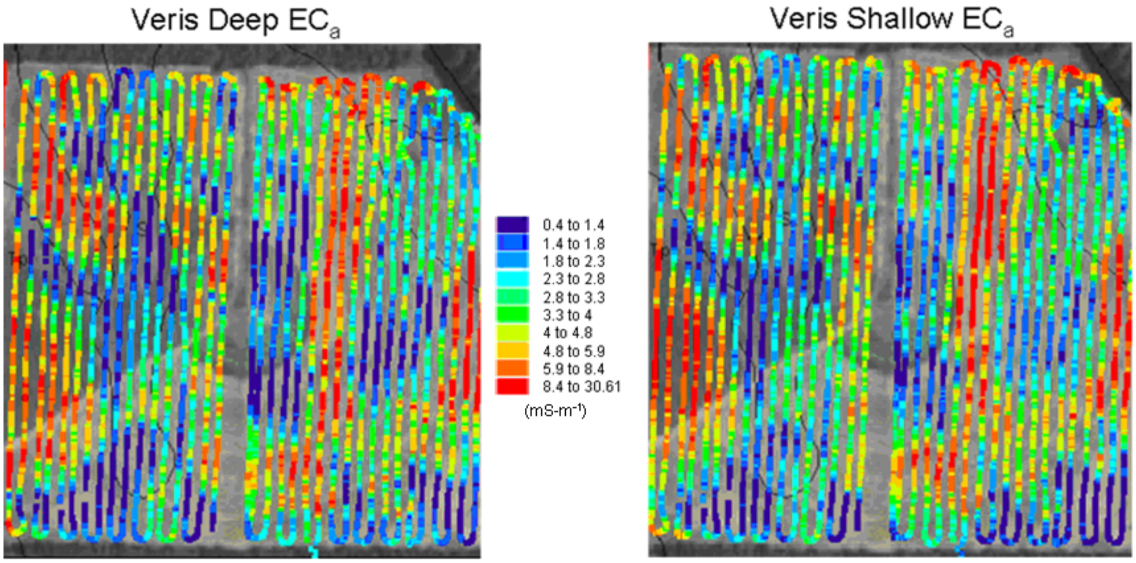

Figure 3.2: Veris 3100 soil EC_a output for deep and shallow readings on the Marsh Pivot (2002).

Table 3.1 shows the percent sand of each 15 cm segment for each soil core based on the results of the standard sieve-pipette method analysis. The average percent sand from the soil core analysis from segments 0 cm to 31 cm at each sample location was used to represent the soil layer sensed by the Veris shallow reading, while the average of all 5 sample segments was used to represent the soil layer sensed by the Veris deep reading.

Figure 3.3: Location of soil sample cores collected for calibration of Veris EC_a data (2002).

Table 3.1: Summary of the standard sieve-pipette soil analysis results (2002).

		Soil Core and Percent Sand					
Segment	Depth (cm)	1	2	3	4	5	6
A	0 to 15	16	92	92	64	77	75
B	15 to 31	36	92	84	58	84	77
C	31 to 46	28	90	94	22	67	48
D	46 to 61	23	96	97	18	51	40
E	61 to 76	22	94	99	25	49	34
Segment	Depth (cm)	7	8	9	10	11	12
A	0 to 15	92	74	81	78	54	90
B	15 to 31	90	68	80	76	35	89
C	31 to 46	92	47	56	65	26	92
D	46 to 61	66	35	44	59	20	92
E	61 to 76	61	34	39	41	26	95

The average percent sand for each calibration point was plotted to determine the profile average for the shallow and deep readings (fig. 3.4). The linear best fit line for the Veris deep reading resulted in the greatest R^2 value (0.83), indicating a high correlation between EC_a and percent sand from the analysis of the soil core samples. The linear best fit line from the Veris deep reading in fig. 3.4 was used to calculate the percent sand for each measurement point. The best fit line was solved for 'x'. This enabled the input of each EC reading to be used in the equation for 'y' and resulted in calculated percent sand. The modified equation for calculating percent sand is:

$$x = 94.16 - 3.76y \tag{3.1}$$

where:

x = percent sand
y = Veris deep EC_a reading

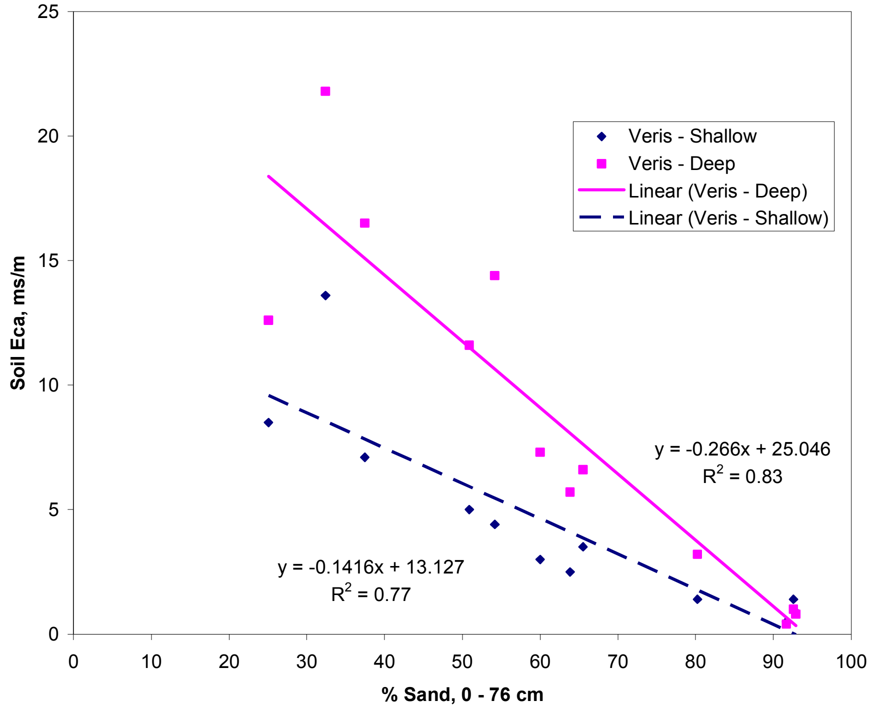

Figure 3.4: Average soil core percent sand versus EC_a for Veris shallow and deep readings used to develop the calibration equation for field percent sand.

Statistical Analysis Software (SAS) was used to calculate the relative frequency of each sand percentage. The histogram in fig. 3.5 illustrates the wide variability of soil textures present in the west half of the Marsh Pivot. The percent sand in the west half of the Marsh Pivot ranges from less than 10% to greater than 95% sand (fig. 3.5). The relative frequency (the ratio of the number of observations for each sand percentage to the total number of observations) brings forth not only the variability in the soil texture (as represented by sand content), but also whether the sand content is weighted toward greater or lesser sand percentages. From fig. 3.5, it can be extrapolated that greater sand percentages occurred more frequently than lesser sand percentages. The mean percent sand was also determined (on a 95% confidence _interval) for each azimuth from 184^o to 4^o and plotted in fig. 3.6. Figure 3.6

provided insight as to the location on the field where greater or lesser sand percentages occurred.

Variable rate irrigation was applied to evaluate how the differeing soil textures would respond to various irrigation amounts. High sand content indicated high drainage capabilities and low water storage capacities of a soil. A histogram of each 30^{o} sector was developed using SAS to determine if each irrigation treatment was being applied to the full range of sand percentages (figs 3.7 to 3.12). The relative frequency analysis was conducted in 1% increments. Figures 3.7 to 3.12 were analyzed for of any potential bias in the yield data should the sand content in any particular sector be weighted toward greater or lesser sand percentages.

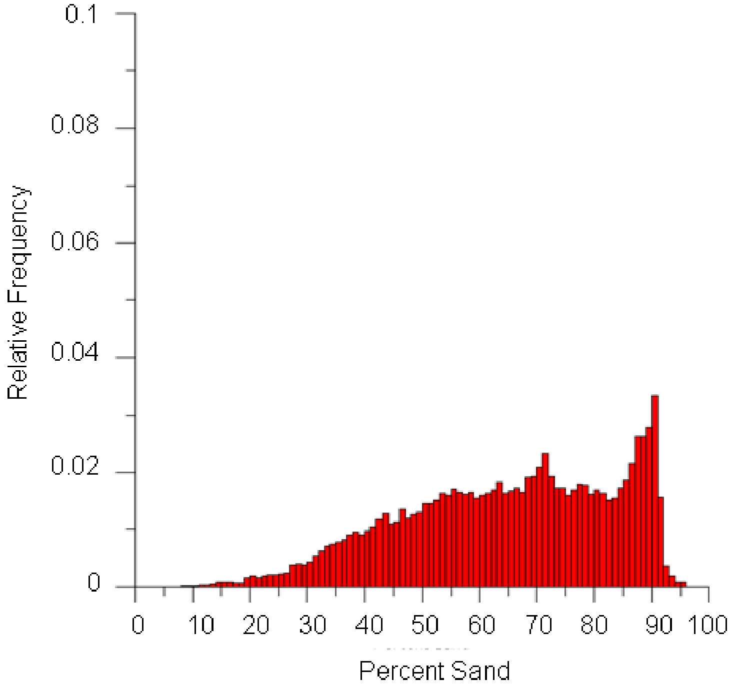

Figure 3.5: Relative frequency for sand percentages, west half of the Marsh Pivot (irrigated corn 2010).

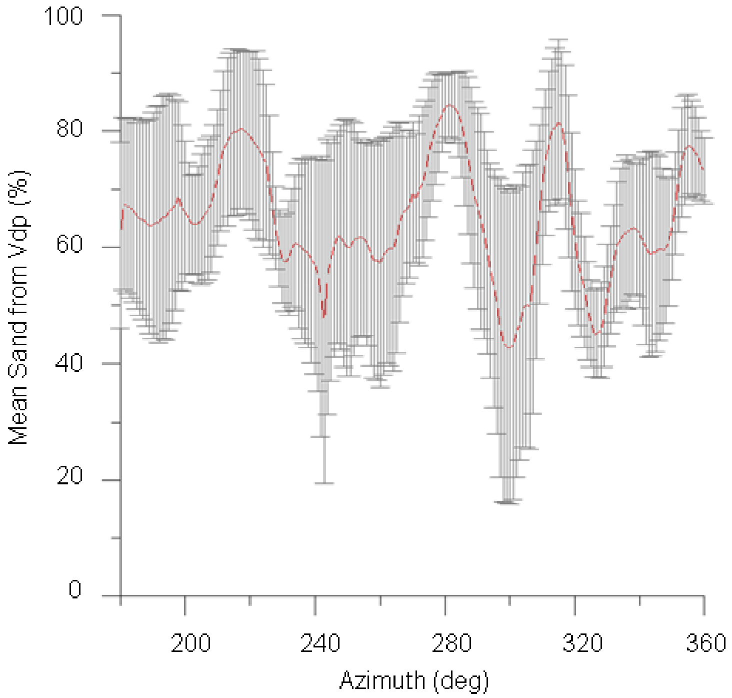

Figure 3.6: Mean percent sand content for each azimuth from 184° to 4°.

The calculated mean percent sand of the soil profile from the 2002 Veris EC study does not extend below the root zone of a mature corn plant. The calibration data for the 2002 Veris EC study went to 76 cm bgs. The root structure of corn can extend beyond 120 cm bgs. Based on available data from the 2002 Veris EC study, it is assumed the sand profile remained constant below the calibration depth and included the root zone of a mature corn plant.

The potential for biased results exists for all sectors because the full range of sand percentages does not occur equally. Sectors 2 (214° to 244°) and 4 (274° to 304°) have increased frequencies of sand percentages approaching to and greater than 90% (fig. 3.8 and 3.10) while sectors 3 (244° to 274°) and 5 (304° to 334°) have sand distributions which range from 10% to 90%, but with relative frequencies less than 0.04 for all percentages (figures 3.9 and 3.11). Sectors 1 (184° to 214°) and 6 (334° to 4°) do not have a given percentage with a greater frequency, but also do not possess the full range of sand percentages (figures 3.7 and 3.12). There were no sand fractions less than 30% for sectors 1 and 6.

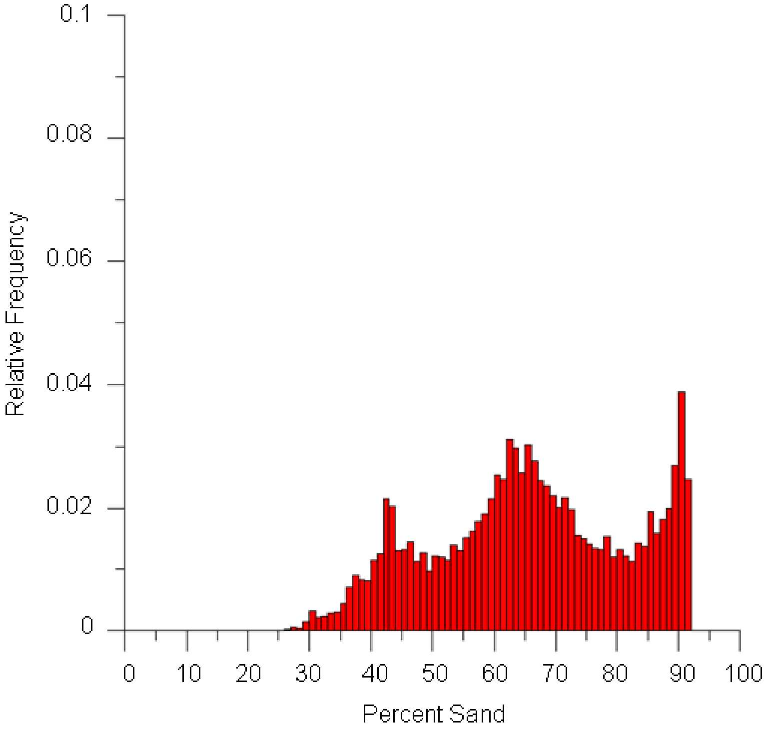

Figure 3.7: Relative frequency for sand percentages on sector 1, 184° to 214°, (irrigated corn 2010).

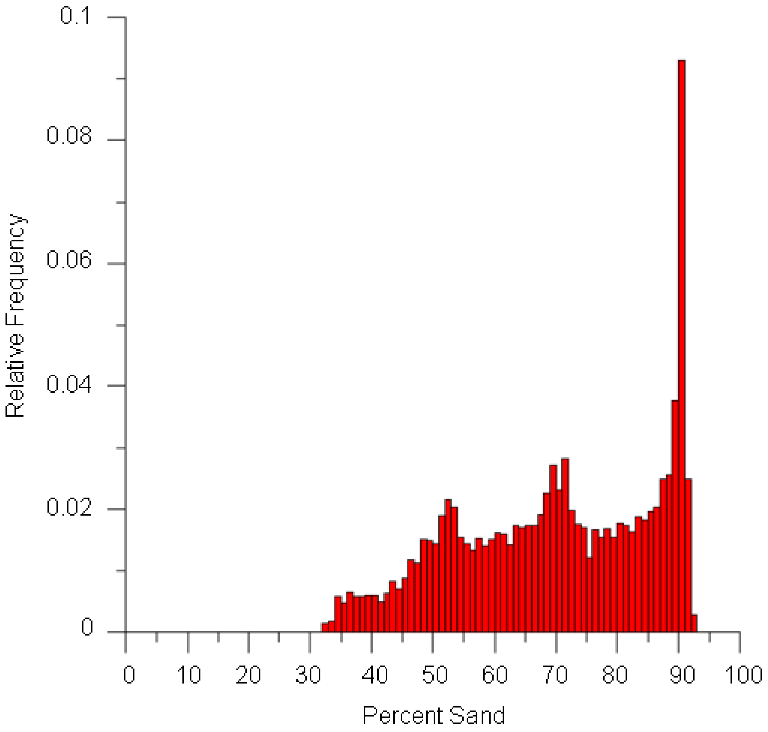

Figure 3.8: Relative frequency for sand percentages on sector 2, 214° to 244° (irrigated corn 2010).

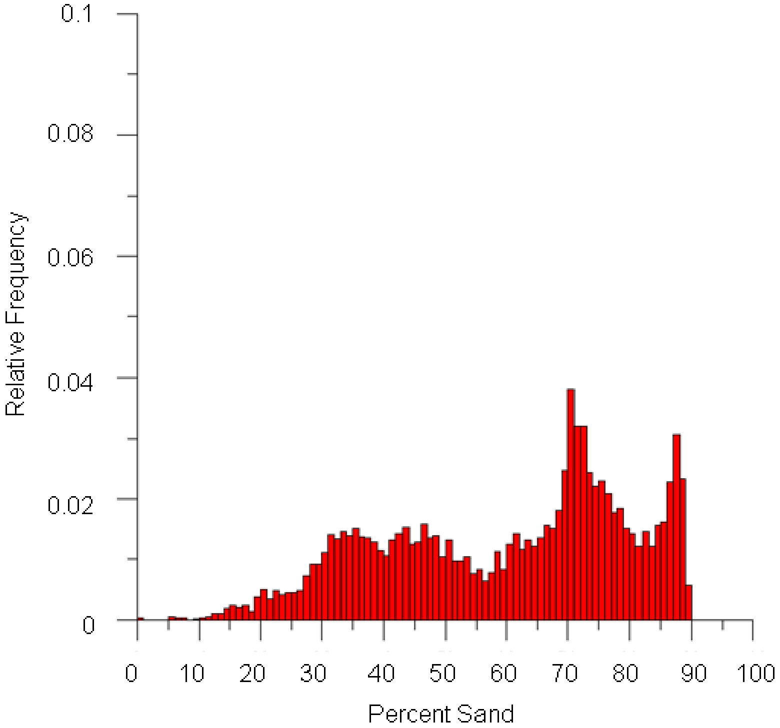

Figure 3.9: Relative frequency for sand percentages on sector 3, 244° to 274°, (irrigated corn 2010).

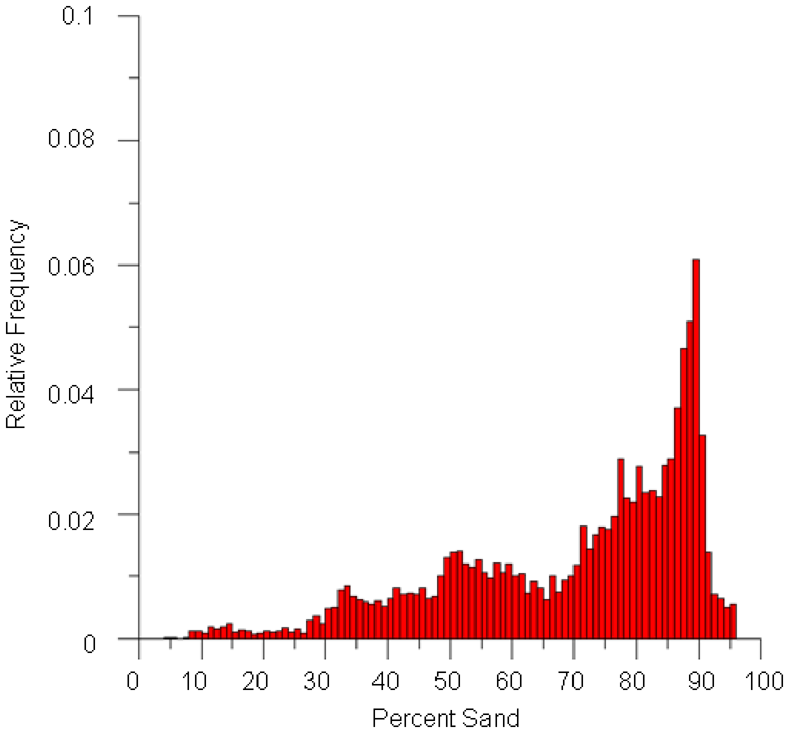

Figure 3.10: Relative frequency for sand percentages on sector 4, 274° to 304°, (irrigated corn 2010).

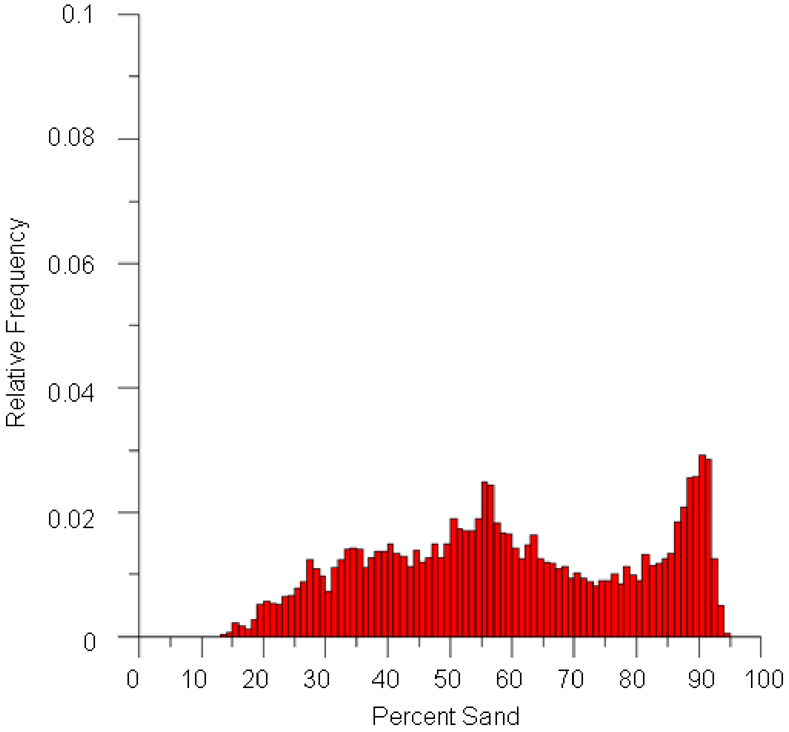

Figure 3.11: Relative frequency for sand percentages on sector 5, 304° to 334°, (irrigated corn 2010).

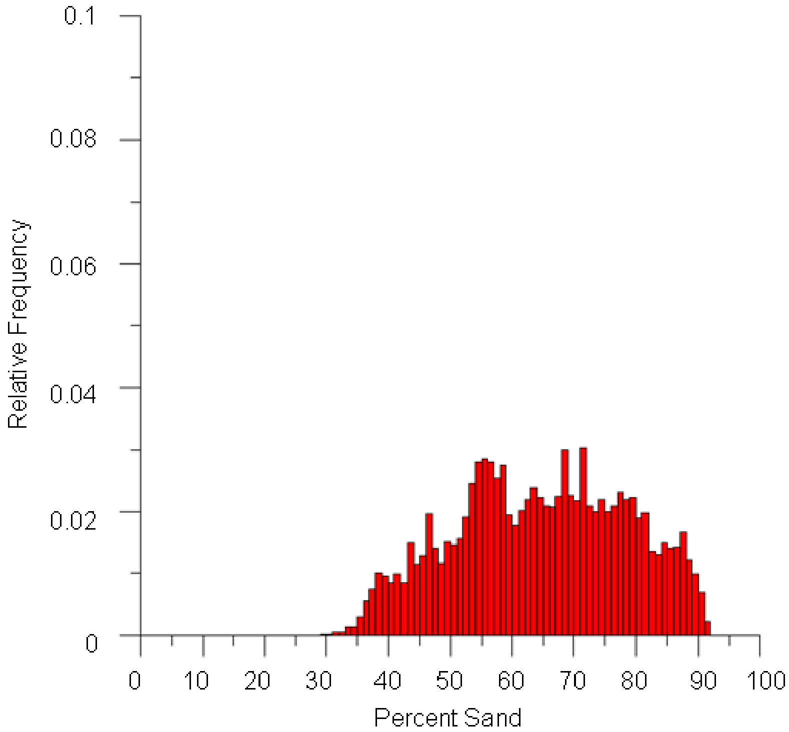

Figure 3.12: Relative frequency for sand percentages on sector 6, 334° to 4°, (irrigated corn 2010).

Figures 3.7, 3.9, and 3.11 show a wide range of percent sand (20 to 90%) with relatively high frequencies. The 70% variation indicates the presence of lower sand percentages. The Cooter association soils consist of clayey soils (0 to 36 cm) over sandy soils (36 to 152 cm). Portageville association soils consist of silty clay soils (0 to 38 cm) over clay soils with silty clay lenses (38 to 152 cm). Hayti association soils consist of silty clay loam soils (0 to 15 cm) over silty clay loam soils with fine sandy loam lenses (15 to 152 cm). Lower sand percentages indicate greater portions of silts or clays in the soil profile which have increased water holding capacities. The greater water holding capacities suggest a greater irrigation depth can be applied with a lower chance of water loss due to percolation down the soil profile.

A map of the soil percent sand content within the Marsh Pivot is shown in fig. 3.13. An attempt was made to balance the areal extent of the sand content of the soil into four classes, or quartiles. A summary of these four sand classes is listed in tab. 3.2, followed by tab. 3.3, which depicts the percentage of each sand class and mean percentage irrigated by each treatment with respect to the west half of the Marsh Pivot. The entire half of the field was analyzed for texture but the analysis did not account for the removal of alleyways between irrigation sectors (9 m) to remove uncertainty from overlapping treatments.

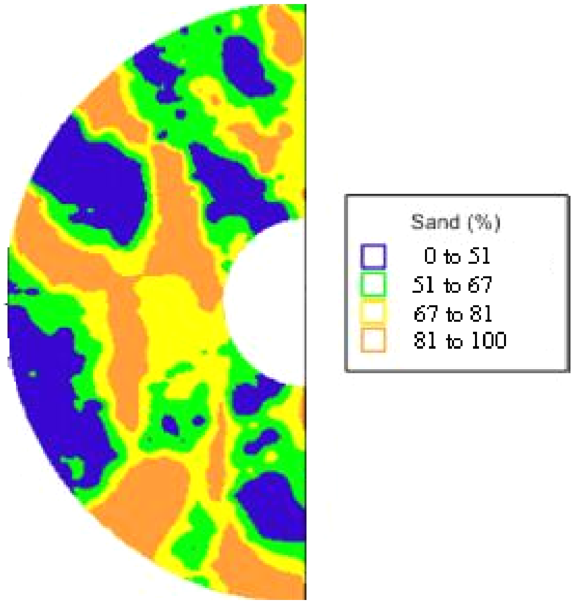

Figure 3.13: Sand content of the west half of the Marsh Pivot in four sand classes.

Table 3.2: Summary of each sand class (quartile) and respective sand content ranges on the west half of the Marsh Pivot.

Sand Class	% Sand
SC_L (low)	0 – 51
SC_M (medium)	51 – 67
SC_H (high)	67 – 81
SC_{VH} (very high)	81 - 100

Table 3.3: Mean sand percentage for each treatment and percentage of each sand class for the west half of the Marsh Pivot.

Treatment	Application depth (mm)	Mean (%)	Standard Deviation (%)	SC_L (%)	SC_M (%)	SC_H (%)	SC_{VH} (%)
1	8	60	8	19	26	26	29
2	15	58	19	31	17	20	32
3	23	64	12	22	34	30	14
4	30	61	13	26	30	24	20
5	38	72	10	41	23	14	21
6	46	76	4	44	18	25	13
West Side	--	--	--	36	22	20	22

The sand classes on the east half of the Marsh Pivot were divided at slightly different intervals than the west side to ensure equal land areas were within each of the four sand classes (tab. 3.4). The histogram in fig. 3.14 illustrates the wide variability of soil textures present in the east half of the Marsh Pivot. As shown in fig. 3.14, the variability of percent sand in the east half of the Marsh Pivot ranges from less than 5% to greater than 95% sand. Table 3.5 indicates the percent of land irrigated by each treatment under each sand class for the east half of the Marsh Pivot.

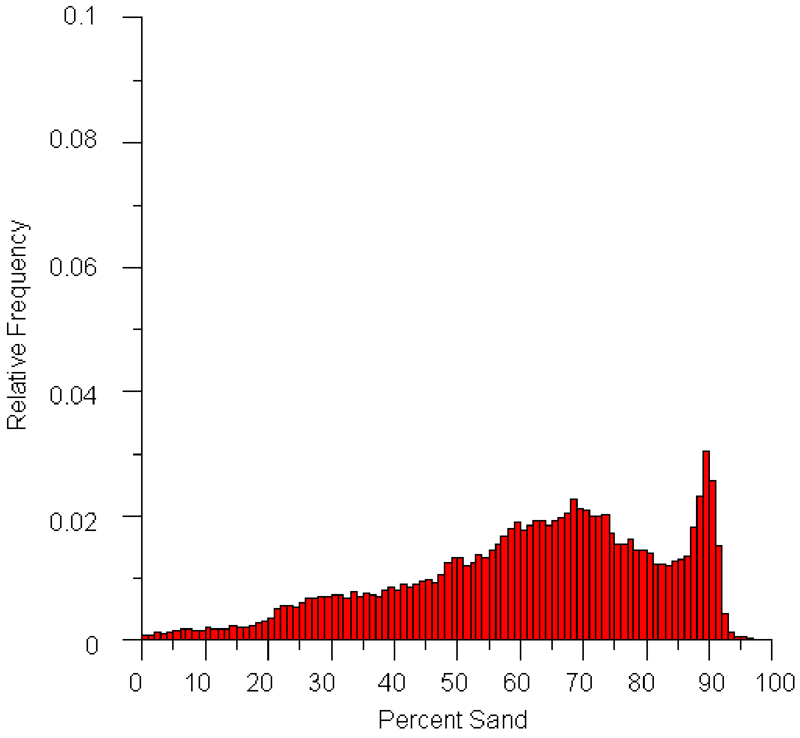

Figure 3.14: Relative frequency for sand percentages on the east half of the Marsh Pivot (irrigated corn 2009).

Table 3.4: Summary of each sand class (quartile) and respective sand content ranges on the east half of the Marsh Pivot.

Sand Class	% Sand
SC_L (low)	0 - 48
SC_M (medium)	48 - 64
SC_H (high)	64 - 77
SC_{VH} (very high)	77 - 100

Table 3.5: Percentage of each sand class beneath each treatment and as a percentage of the east half of the Marsh Pivot.

Treatment	Application depth (mm)	SC_L (%)	SC_M (%)	S_{CH} (%)	SC_{VH} (%)
1	15	34	17	18	30
2	30	34	12	21	34
3	46	30	20	31	18
4	8	32	28	22	18
5	38	35	22	16	27
6	23	25	27	23	24
East Side	--	32	21	21	26

From tables 3.2, 3.3, 3.4 and 3.5; it is shown the four sand classes were not exact quartiles during the study. The discrepancies between sand classes were the result of the removal of buffer zones between irrigation sectors to remove any uncertainty from overlapping treatment zones on each side of the pivot.

3.1.3 Irrigation depths & sector selection

In 2009 the study utilized up to nine different sectors, varying irrigation amounts of 8, 15, 23, 30, 38, and 46 mm across one half of the pivot (east side of the Marsh Pivot in 2009). Table 3.6 details the irrigation depth applied to each sector. In addition, fig. 3.15 shows the layout of the irrigation sectors on the east half of the Marsh Pivot. Nine sectors (while not equal in area) were utilized to ensure each irrigation depth was applied to each sand class in sufficient quantities to allow for a sufficient number of yield data points for each irrigation treatment.

Table 3.6: Summary of each treatment with its associated application depth, application frequency and azimuth range (corn, 2009).

Treatment	Application Depth (mm)	Azimuth Range
0	0	--
1	8	104^o to 124^o
2	15	84^o to 104^o
3	23	59^o to 84^o, 168^o to 184^o
4	30	44^o to 59^o, 124^o to 138^o
5	38	138^o to 168^o
6	46	4^o to 28^o, 28^o to 44^o

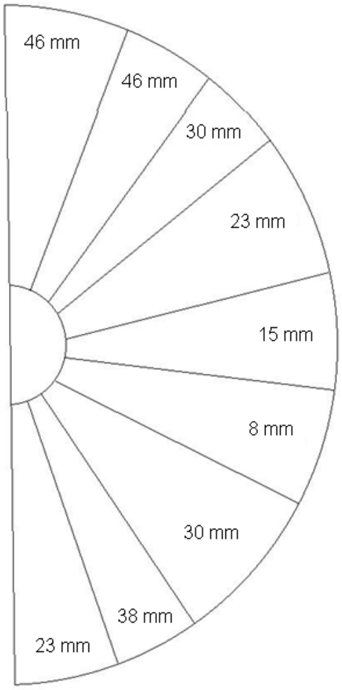

Figure 3.15: Layout of the nine irrigation sectors utilized during 2009 for corn production on the east half of the Marsh Pivot.

In 2010, six different irrigation sectors using one irrigation depth per sector. This layout reduced the area of eliminated data between overlapping irrigation treatments The number of alleyways cut in the crop field for 2009 and 2010 was equal; however the total area of removed crop in 2009 was greater than 2010. Each alleyway removed 9 m of overlap between irrigation treatments. In 2009 the alleyways we cut just prior to harvest and in 2010 the alleyways were cut during the growing season. The reduction in removed area was beneficial on a three tower center-pivot system which had a reduced irrigated area in comparison to center-pivot systems with more towers.

The irrigation treatment depths were assigned to each sector based on the relationship between infiltration rate and soil texture. Assuming a deep or uniform soil profile, the greater the sand content of the soil, the greater the infiltration rate. As a best management practice for water conservation, sectors with relatively low sand contents warranted greater irrigation depths and sectors with relatively high sand contents warranted shallower irrigation depths. The sand content of each sector was described in detail in **3.1.2 Soil analysis**. Figure 3.16 indicates which irrigation depth was assigned to each sector.

In selecting the range of irrigation treatments it was assumed corn will use approximately 8 mm of water for growth per day, and six irrigation treatments in multiples of 8 mm were selected for this study based on the study conducted by Howell et al., (1996) which recorded the ET values for short and long season corn hybrids for three growing seasons (1989, 1990 and 1994). Due to system limitations, exact multiples of 8 mm were not applied to the system. (The system would irrigate 8 mm as 7.9 mm and 16 mm as 15.4 mm. Therefore each actual irrigation depth applied by the system was rounded to the nearest millimeter.) Varying application intervals were also selected for each treatment (tab. 3.7). The range in treatment depths selected were those typically applied by growers on a per set basis (8 mm and 15 mm) with the combination of additional treatments to evaluate the practice of variable rate irrigation on soils with wide ranges of textures such as those on the Marsh Pivot. Actual applied irrigation depths are shown in tab. 3.7.

Table 3.7: Summary of each treatment with its associated application depth, sector, and azimuth range (corn 2010).

Treatment	Application Depth (mm)	Sector	Azimuth Range
0	0	--	--
1	8	1	184^o to 214^o
2	15	4	274^o to 304^o
3	23	6	334^o to 4^o
4	30	2	214^o to 244^o
5	38	5	304^o to 334^o
6	46	3	244^o to 274^o

Table 3.7 provides a summary of each treatment and its associated application depth, frequency, sector, and azimuth range. Any corn planted at a distance greater than 163 m from the pivot point was not irrigated, and only received water through rainfall, acting as the control for baseline comparison purposes (i.e. dryland)

Irrigation was scheduled using the AS for each application depth (Cahoon et al., 1990). The AS can be used to calculate the ET for a given crop based on a user entered parameter (ET_o or maximum daily temperature). For this study, the maximum daily temperature was used to calculate ET for corn. The calculated ET for corn within the AS was subtracted from the available water balance in the soil specified by the user at the beginning of the growing season. The continuous water balance was maintained by the additions of Rainfall and irrigation and the subtraction of crop ET. Appendix F includes each rainfall and irrigation event which occurred during the 2010 growing season. When the cumulative ET_c of the corn was within 8 mm of the depth to be irrigated, that treatment would be irrigated on the following day. The K_c values utilized in the AS are 0.3, 1.15, and 0.3 for K_c initial, K_c mid, and K_c end, respectively (Cahoon et al., 1990). Utilizing the AS for irrigation scheduling includes using the assumptions programmed into the AS. The assumptions include 10% water loss due to application inefficiencies of irrigation equipment and the prediction of crop ET based on the maximum daily temperature.

The Penman-Montieth (PM) method was used to compare calculated ET_c for corn with that calculated using the AS. It was not used for irrigation scheduling. Equation 2.1 was used to calculate the $ET_{o,}$ which was adjusted using K_c factors adjusted for the local climatic conditions as instructed by Henggeler et at. (2010), 0.75, 1.15, and 0.75 for K_C initial, K_C mid, and K_C end, respectively. The ET_c for the season was summed then subtracted from the total applied water for the season (rainfall and irrigated water). This provided a comparison of the efficiency of the AS to schedule irrigation, with the ET calculated using the PM method. The PM method calculated a reference ET (grass), which was used in eq. 2.4 to calculate the evapotranspiration rate of corn (ET_c). The ET_c calculated was based on the hourly wind speed, relative humidity, solar radiation, temperature, and precipitation. The PM method was not used for irrigation scheduling because the weather recording equipment required was not installed until July 2010.

Irrigation scheduling in 2009 was not done solely by the AS. Rather, the AS was used to calculate the ET for corn each day. The calculated ET was subtracted from the continuously running soil water balance for each irrigation treatment. When the water balance was below the field capacity of the soil profile, irrigation occurred.

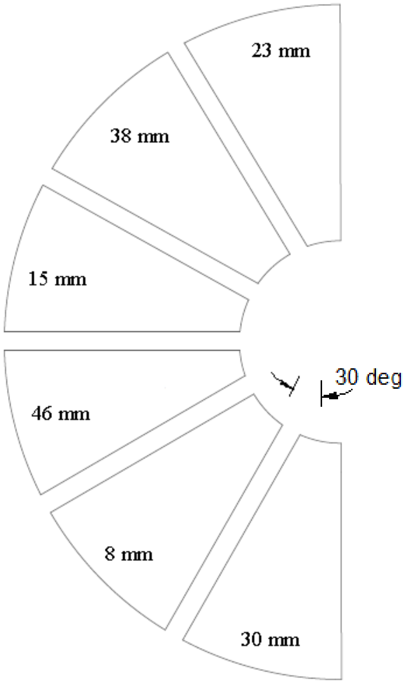

Figure 3.16: Irrigation treatment depths on corn for each sector on the west half of the Marsh Pivot.

3.1.4 Yield acquisition and processing

Field corn was planted in a circular pattern on the east side of the Marsh Pivot in 2009 and the west side in 2010. Corn was harvested in October 2009 and 2010 in a circular pattern and recorded using an AgLeader PF3000 yield monitor on a one-second interval. The AgLeader PF3000 is a universal GPS compatible crop monitor. The monitor is capable of recording the following harvest parameters in real time: acres, moisture, grain weight, bushels and yield (AgLeader, 2002). Only yields between the first and third towers (distance of 50 m to 156 m from the pivot point) were usable in the study due to equipment limitations. The AgLeader PF3000 required a 20 m or greater harvest length for accurate recording of the harvest parameters previously stated. A distance of 9 m was removed from the analysis of each treatment prior to statistical analysis at the boundary of each treatment because of irrigation overlap by one-half of a sprinkler's wetted diameter (4.5 m). Wetted area outside of tower 3 was also removed from analysis to ensure the dry-land sample was not compromised by irrigation. The removal of 9 m between irrigation treatments did not provide the required harvest length for the yield monitor within tower one.

The yield monitor raw data were screened for errors using the Yield Editor program (developed by Sudduth and Drummond, 2007). Yield Editor simplifies the process of applying filters to remove yield data outliers for entire data sets, and allows for manual selection of individual points or regions of data for investigation or possible removal (Sudduth and Drummond, 2007). Yields were then kriged to a 3-m grid corresponding with sand content data (fig. 3.17). This process resulted in over 2400 gridded data points for analysis.

Figure 3.17: Yield data from 2010 kriged to a 3-m grid corresponding with sand content data from 2002.

Using SAS, three analyses were performed on the acquired yield data. The first analysis was the analysis of variance (ANOVA) for each sand class. This analysis generated a mean yield for each treatment, to enable the comparison of yields from each treatment on each sand class. The second analysis was the analysis of covariance (ANCOVA) across all sand classes using sand percentage as a covariant. This analysis generated a mean yield for each treatment across all sand classes. Covariance combines the features of a variance analysis with regression. The regression occurs on a continuous variable (sand percentage) and the variance analysis occurs on a class variable (treatment). This allows for the effects of each irrigation treatment on the dependent variable (yield) to be adjusted for differences in sand directly, rather than through many analyses for each sand quartile. This method reduces the 95% confidence interval, making each mean yield more representative of the treatment mean yield. The final analysis was a regression analysis for both treatment and sand percentage. This analysis generated a mean yield with treatment and sand percentage as independent variables. The SAS code used for each analysis can be seen in Appendix B.

3.2 Results & discussion

3.2.1 Yield summary (2009)

All irrigated sectors resulted in yields significantly greater (at the 95% confidence interval) than dry-land yields. Over all sand classes, a treatment of 15 mm resulted in the greatest yields; with SC_M and 15 mm producing the greatest yield, 11,620 kg-ha^{-1}. However, for all sand classes, treatment 8 mm was not significantly different from 15 mm (the greatest yield from an 8 mm treatment also occurred on SC_M, 10,740 kg-ha^{-1}) (tab. 3.8).

For SC_L the 46 mm treatment was not significantly different from the 8 mm treatment, but was significantly different from 15 mm. The low sand content of the soil correlates to a lower infiltration rate, which would reduce the likelihood of water percolating through the root zone, allowing the crop more time to utilize the water over a given time period. Application depths of 8, 15, and 46 mm resulted in the greatest crop yields for SC_L. Mean yields from irrigation depths of 23, 30 and 38 mm were significantly less and significantly different from depths of 8, 15 and 46 mm for the SC_L sand class (fig. 3.18).

For SC_M, mean yields from irrigation depths greater than 15 mm were significantly less and significantly different than 8 mm and 15 mm; however they were not significantly different from each other (fig. 3.19). For $SC_{H,}$ a treatment of 23 mm was not significantly different from 8 mm or 15 mm. All other treatments were significantly less than 8, 15, and 23 mm treatments (fig. 3.20).

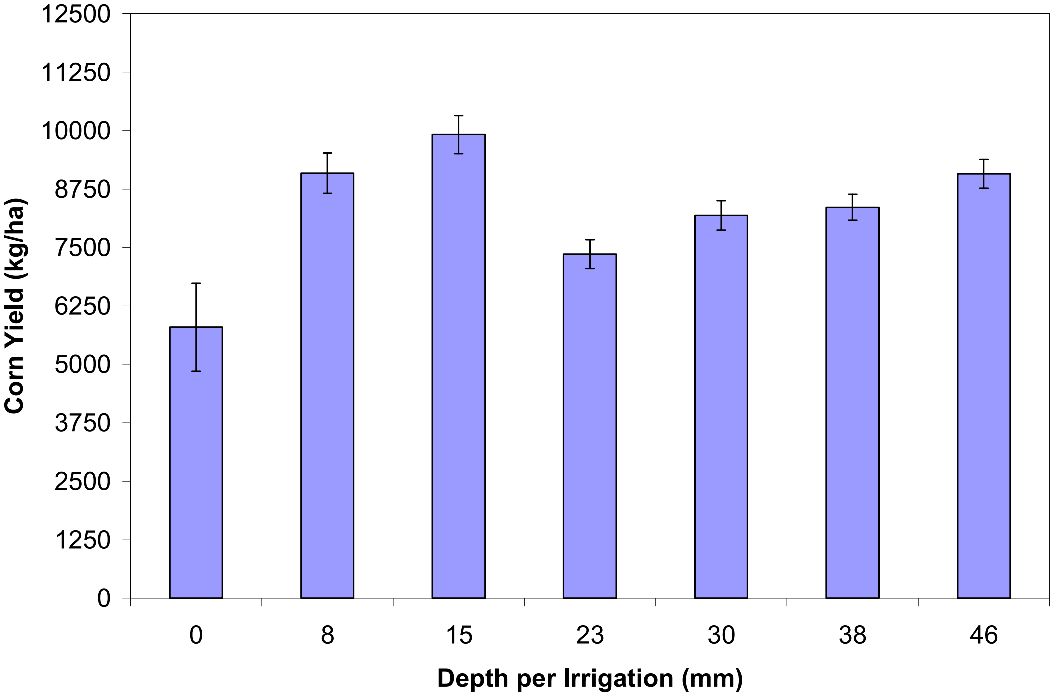

Figure 3.18: Mean yield for each treatment on SC_L (0 to 48%); error bars represent the 95% confidence interval, 2009.

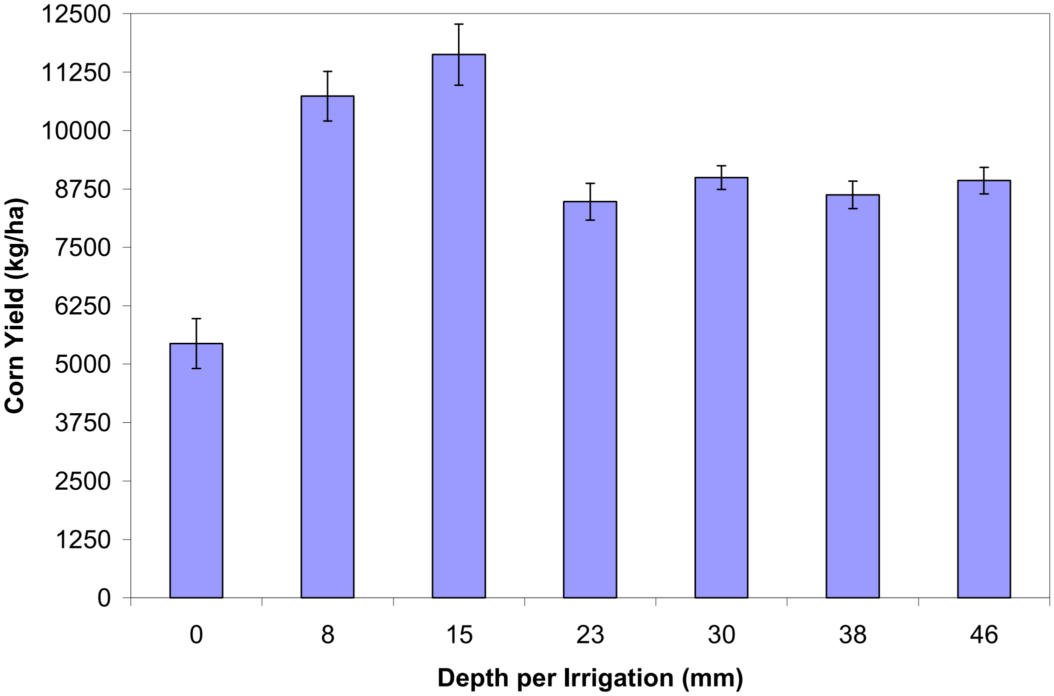

Figure 3.19: Mean yield for each treatment on SC_M (48 to 64%); error bars represent the 95% confidence interval, 2009.

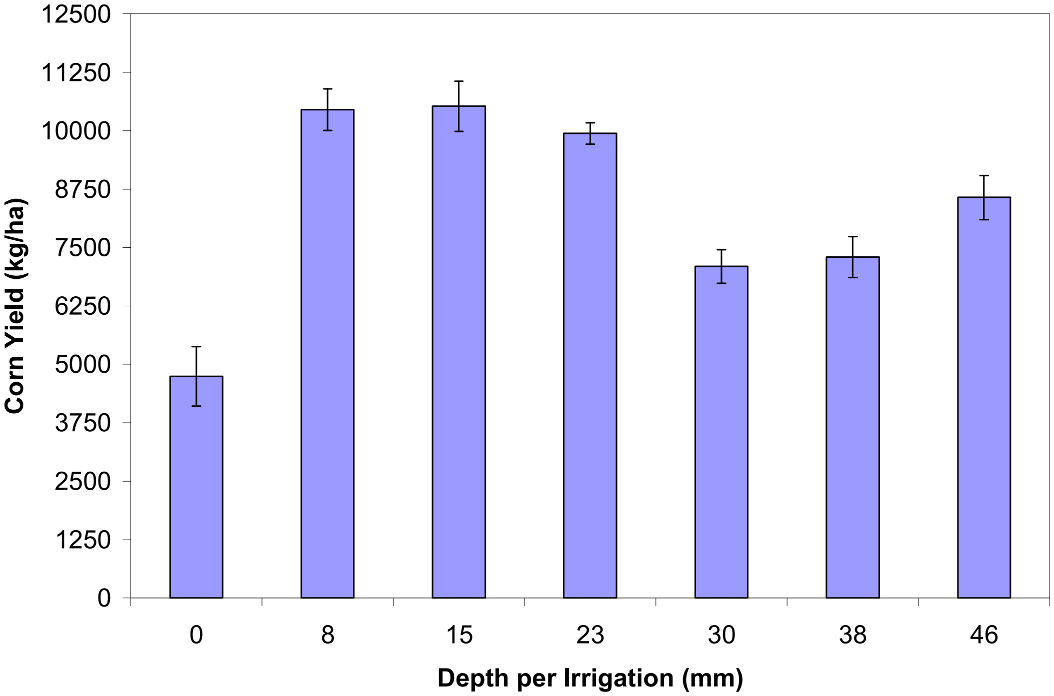

Figure 3.20: Mean yield for each treatment on SC_H (64-77%); error bars represent the 95% confidence interval, 2009.

Sand class, very high (SC_{VH}) supported the greatest mean yield for 15 mm but it was not significantly different from the 23 mm treatment. For SC_{VH}, (percent sand greater than 77%) the soil does not have a high water holding capacity, and because of this greater irrigation amounts will percolate through the soil profile before the water can be utilized by the crop. Figure 3.21 indicates this, as yields for irrigation depths greater than 23 mm were significantly less than yields from irrigation depths 15 and 23 mm.

Based on the covariance analysis, an irrigation treatment of 15 mm resulted in the greatest mean yield (9500 kg-ha^{-1}) and was significantly different from all other yields. In addition, an irrigation treatment of 38 mm resulted in least mean yield (7480 kg-ha^{-1}) but was not significantly different than yields from irrigation treatment

31 mm (tab. 3.8). Dry-land yields remained significantly less than all irrigation treatments (fig. 3.22).

The irrigated water use efficiency (IWUE) for all irrigated treatments is based on the difference between irrigated mean yields (from the covariance analysis) and dry-land mean yields. It is calculated by taking the difference between irrigated and dry-land yields divided by the total irrigated water. The 15 mm treatment had the greatest IWUE followed by treatments 8 mm and 23 mm (tab. 3.8). The 15 mm treatment had an IWUE of 26.8 kg-ha^{-1}mm^{-1} but the IWUE for 8 mm and 23 mm treatments differed by only 0.3 kg-ha^{-1}mm^{-1}. Because 23 mm received less irrigated water than 8 mm, its lower yield does not result in a lower IWUE but rather a greater one, 22.4 kg-ha^{-1}mm^{-1} (8 mm had an IWUE of 22.1 kg-ha^{-1}mm^{-1}).

To use IWUE efficiently in an analysis, each treatment should have as close an equal water balance as possible. The value of IWUE can be limited unless each treatment has nearly equal water balances, because if the water balance for each treatment is not nearly equal for two yield samples the IWUE will be biased higher for a decrease in the water balance or lower for an increase in the water balance. The Irrigation water use efficiency values in tab. 3.8 increase as irrigation depth increases but then decrease after an irrigation depth of 15 mm. The values for IWUE begin to increase again after an irrigation treatment of 38 mm. This is the same pattern present in the mean yields for a covariance analysis (fig. 3.22).

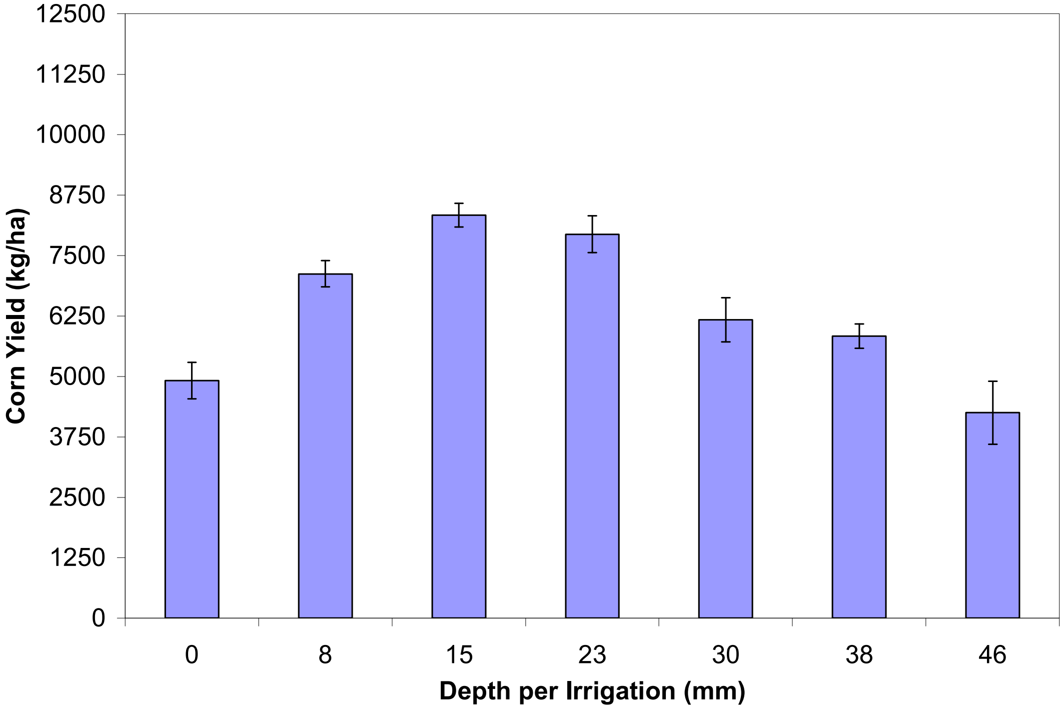

Figure 3.21: Mean yield for each treatment on SC_{VH} (77 to 100%); error bars represent the 95% confidence interval, 2009.

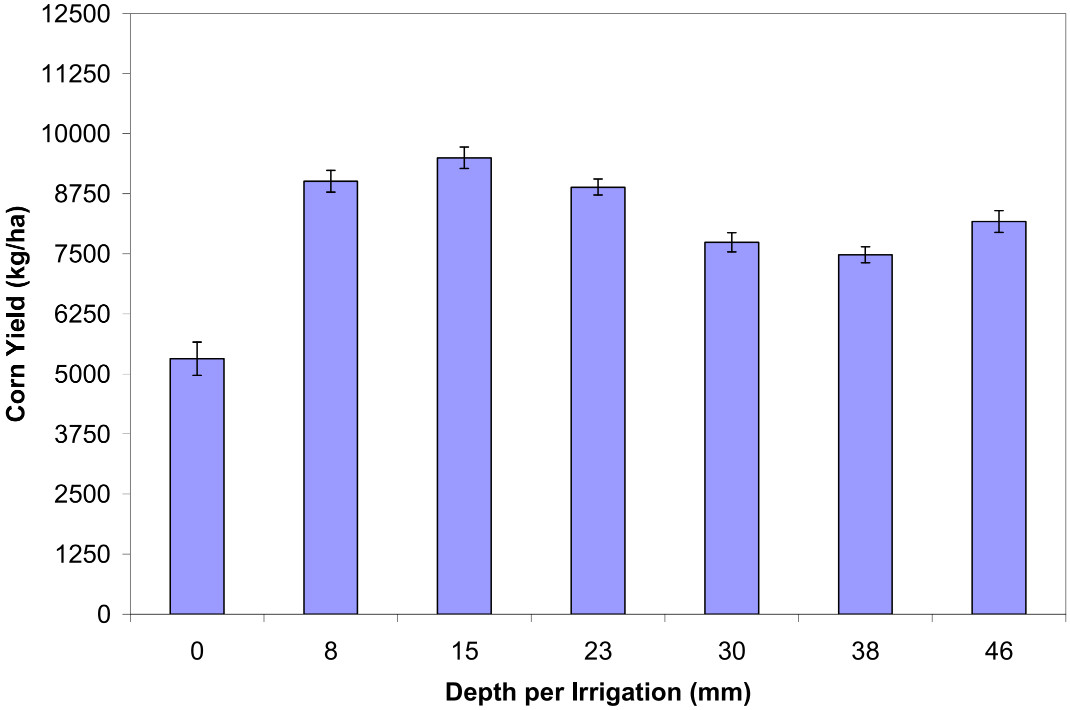

Figure 3.22: Mean yield for each treatment where percent sand was treated as a covariate in the analysis; error bars represent the 95% confidence interval, 2009.

Table 3.8: Mean yield (kg-ha^{-1}) for each sand class and the resulting IWUE for mean yield covariance (corn, 2009).

		Analysis of Variance					
Treatment (mm)	Analysis of Covariance	Sand Class L	Sand Class M	Sand Class H	Sand Class VH	Total Irrigated Water Depth (mm)	IWUE (kg-ha^{-1}mm^{-1})
0 (dry-land)	5320^a	5790^a	5440^a	4740^a	4910^a	0	---
8	9010^b	9090^b	10740^b	10450^b	7120^b	167	22.1
15	9500^c	9920^b	11620^b	10520^b	8330^b	167	26.8
23	8890^b	7360^c	8480^c	9940^b	7940^b	160	22.4
31	7740^d	8190^d	8990^c	7100^c	6170^c	182	13.3
38	7480^d	8360^d	8630^c	7300^c	5830^c	190	11.4
46	8170^e	9070^b	8930^c	8570^d	4250^d	182	15.7

Lettering indicates significant difference on a 95% confidence interval

3.2.2 Yield summary (2010)

Yields for 2010 followed a few of the same patterns as 2009 yields. All irrigated sectors resulted in yields significantly greater (at the 95% confidence interval) than dry-land yields and SC_M produced the greatest yield. However, over all sand classes, a treatment of 46 mm resulted in the greatest yield; with SC_M and 46 mm producing the greatest yield, 9,620 kg-ha^{-1}. In addition, for all sand classes treatments 8 mm and 46 mm were not significantly different from each other, with the greatest yield from an 8 mm treatment occurring on SC_H, 9,020 kg-ha^{-1} (tab. 3.9).

For SC_L, yields from treatments 8 mm and 46 mm were not significantly different from each other, but were significantly greater than yields from all other treatments. Irrigation treatments between 8 mm and 46 mm, while significantly less than yields from 8 mm and 46 mm treatments, remained significantly greater than dry land yields. All yields from irrigation treatments other than 15 mm followed the same pattern seen in 2009. An observed significant increase in yield from dry land to irrigation treatment 8 mm, followed by an immediate drop in yield for treatments up to 23 mm, after which mean yields continuously rose (fig. 3.18). In 2010, 15 mm did not result in an increase in yield but rather showed a decrease in yield (fig. 3.23).

Similar to SC_L, mean yields for irrigation treatments 8 mm and 46 mm were not significantly different from one another, but were significantly greater than all other treatments (tab. 3.9). The same pattern was observed for all mean yields on SC_M as on SC_L, and the mean yields for all treatments were greater on SC_M than on SC_L except for treatments 30 mm and 38 mm (fig. 3.24).

For SC_H, treatments 8 mm and 46 mm resulted in nearly identical yields separated by only 0.9%. The pattern for all irrigation treatments observed on SC_L and SC_M was present on SC_H (fig. 3.25). All mean yields for treatments between 8 mm and 46 mm were not significantly different from each, but were significantly less than yields from treatments 8 mm and 46 mm.

The yield pattern for SC_{VH} followed the same trend as the previous three sand classes with treatments 8 mm and 46 mm resulting in mean yields not significantly different from one another, but still significantly greater than all other irrigation treatments. In contrast to previous mean yield patterns, mean yields for treatments between 8 mm and 46 mm were significantly different and irrigation treatment 38 mm was significantly greater than 15 mm and 30 mm. The overall pattern for SC_{VH} was not similar to the 2009 pattern. In 2009, the mean yields for all treatments on SC_{VH} resulted in a convex parabolic shape while in 2010 mean yields resulted in a concave parabolic shape (figures 3.21 and 3.26). The yield results from 2010 do not support the theory that greater sand content should result in less yield for increased irrigation treatments due to water loss through percolation. A potential source for this discrepancy (greater mean yields for irrigation treatment 46 mm) was the location of treatment 46 mm. Treatments 8 mm and 46 mm resided next to each other on the Marsh Pivot. The potential for overlap beyond the 9 m buffer zone or the potential for pooling of irrigation water from 8 mm within the 46 mm treatment zone, could have provided additional water for crop use within the 46 mm treatment zone throughout the growing season (8 mm was irrigated every day rainfall was not received while 46 mm was irrigated every 6th day) (fig. 3.26).

For the covariance analysis, treatments 8 mm and 46 mm supported yields not significantly different from one another, but which were significantly greater than all other treatments (tab. 3.9). This is the same pattern observed during the variance analysis for each sand class. Dry-land yields remained significantly less and significantly different from all treatments (fig. 3.27).

The irrigated water use efficiency (IWUE) for irrigated treatments was based on the difference between irrigated mean yields (by analysis of covariance) and dry-land mean yields. It was calculated by taking the difference between irrigated and dry-land yields divided by the total irrigated water depth. Based on the greatest mean yield and the intent to apply the same amount of irrigated water with each treatment, it would be expected an application depth of 46 mm would have the greatest IWUE followed by an application depth of 8 mm.

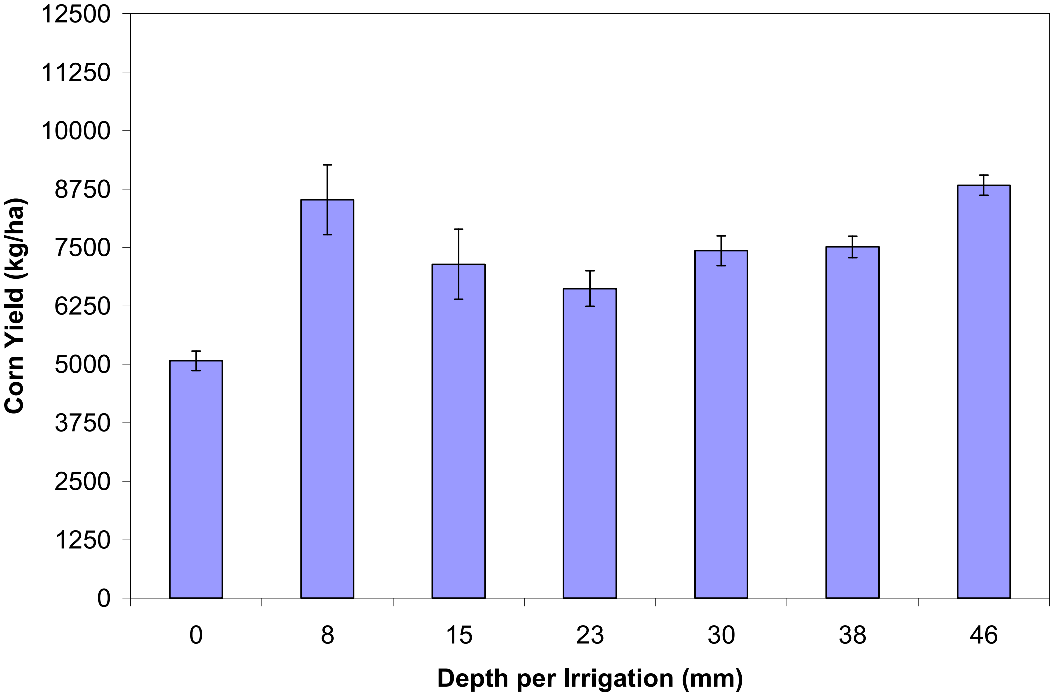

Figure 3.23: Mean yields for each treatment on SC_L (0 to 51%); error bars represent the 95% confidence interval, 2010.

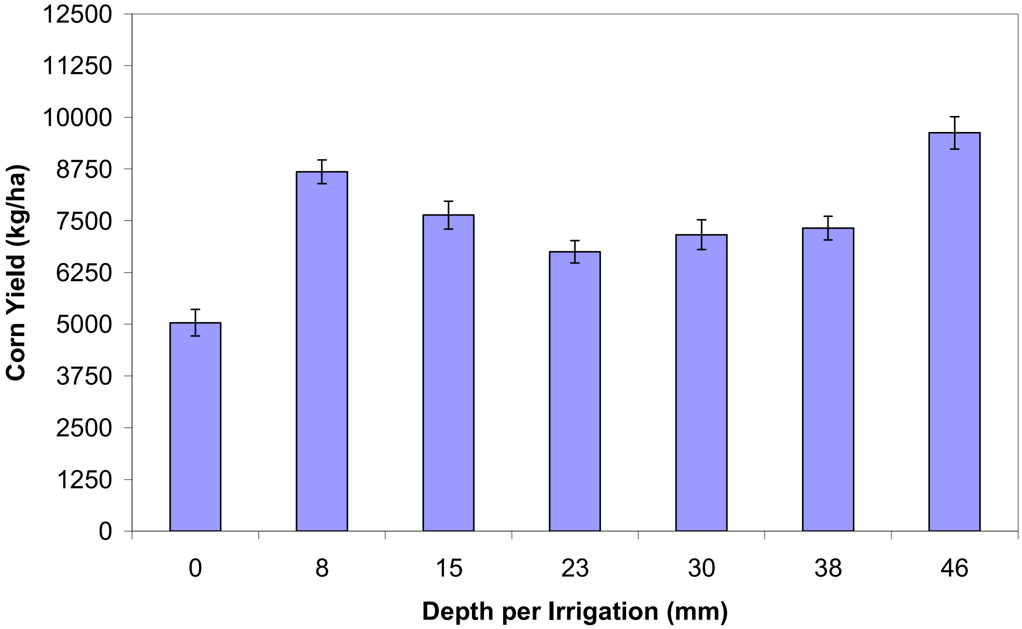

Figure 3.24: Mean yields for each treatment on SC_M (51 to 67%); error bars represent the 95% confidence interval, 2010.

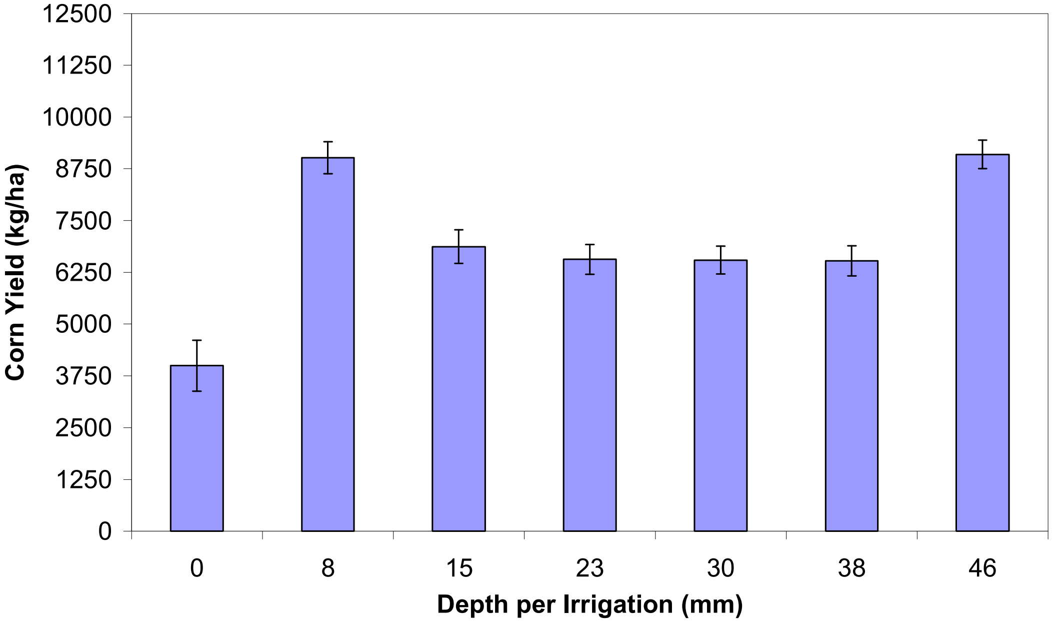

Figure 3.25: Mean yields for each treatment on SC_H (67 to 81%); error bars represent the 95% confidence interval, 2010.

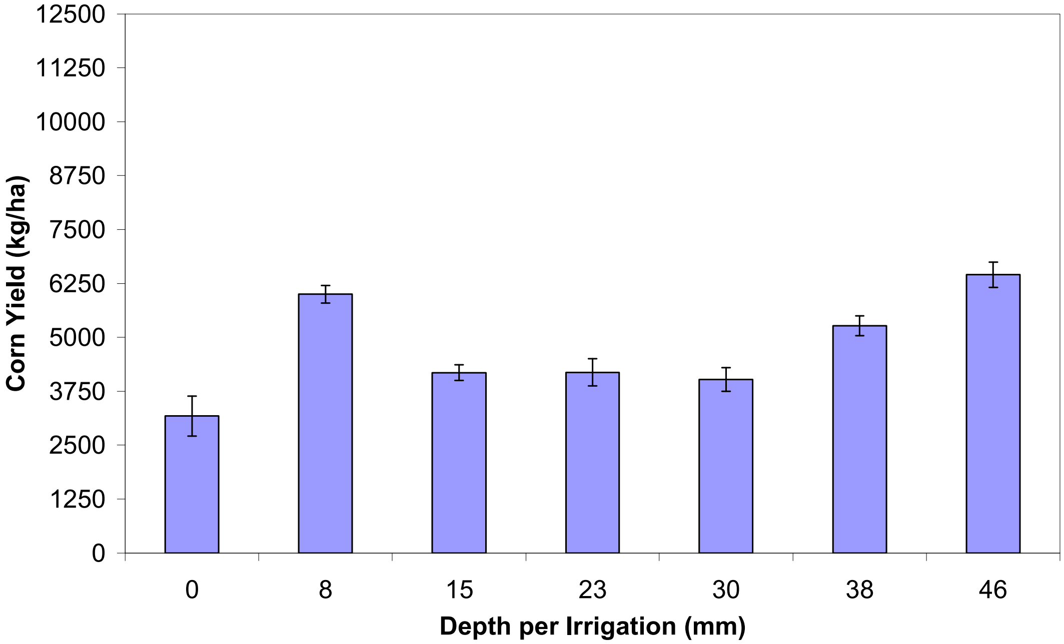

Figure 3.26: Mean yields for all treatments on SC_{VH} (81 to 100%); error bars represent the 95% confidence interval, 2010.

Table 3.9 confirms this assumption with 46 mm having an IWUE of 13.5 kg-ha^{-1}mm^{-1}, followed by 8 mm with an IWUE of 11.6 kg-ha^{-1}mm^{-1}, and also serves as a summary of all mean yields for each treatment and each sand class. (Please refer to the previous description for the value of IWUE within the discussion of the yield results from 2009.) The IWUE pattern of decrease then increase is the same pattern for mean yields from the covariance analysis (fig. 3.27).

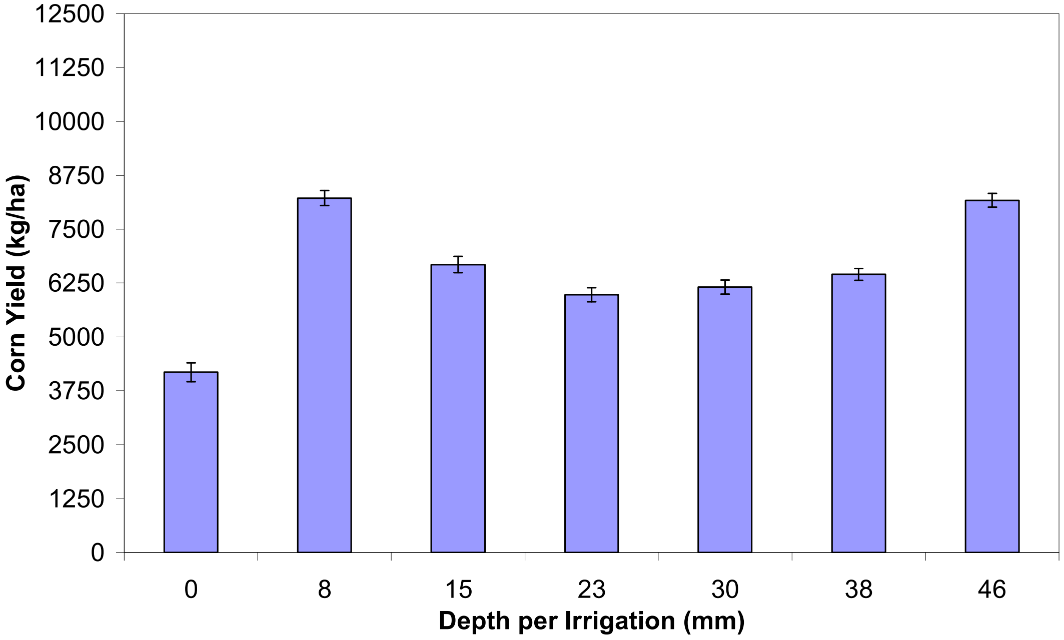

Figure 3.27: Mean yields for each treatment as a covariance over all sand classes; error bars represent the 95% confidence interval, 2010.

Table 3.9: Mean yield (kg-ha^{-1}) for each sand class and the resulting IWUE for mean yield covariance (corn, 2010).

Treatment (mm)	Analysis of Covariance	Analysis of Variance				Total Irrigated Water Depth (mm)	IWUE (kg-ha^{-1}mm^{-1})
		Sand Class L	Sand Class M	Sand Class H	Sand Class VH		
0	4180^{a}	5080^{a}	5040^{a}	4000^{a}	3180^{a}	0	--
8	8220^{b}	8520^{e}	8690^{b}	9020^{b}	6000^{b}	348	11.6
15	6680^{c}	7140^{c}	7640^{c}	6870^{c}	4180^{c}	340	7.3
23	5980^{d}	6620^{c}	6750^{d}	6560^{c}	4190^{c}	340	5.3
30	6160^{d}	7430^{d}	7170^{cd}	6550^{c}	4030^{c}	340	5.8
38	6450^{c}	7510^{d}	7330^{c}	6530^{c}	5270^{d}	295	7.7
46	8170^{b}	8830^{e}	9620^{b}	9100^{b}	6460^{b}	295	13.5

Lettering indicates significant difference on a 95% confidence interval

3.2.3 Water application depths and analysis in 2010

A calculated water deficit was used as a pre-scheduling tool to determine when irrigation should begin in 2010. Irrigation began on June 8, 2010 when the calculated water balance, as determined by the AS, was 1.5 mm and the water used by the corn plant the following day would result in a deficit. Rather than beginning the scheduled irrigations using the AS, an irrigated depth of 19 mm was applied over each sector of the corn field because the installation of the control panel's software was not complete. Variable rate irrigation began on June 12, 2010 with depths 8, 15, 23, and 30 mm being applied to their respective sectors. Irrigation following the AS continued until June 14 and 15, 2010 when software malfunctions within the control panel erased the weekly programmed schedule. Irrigation applications of 19 mm and 20 mm were applied over all sectors to prevent the soil water content from falling below critical water content and causing water stress on the corn while the software malfunctions were resolved and the control panel was re-programmed. The software malfunctions were determined to be the result of incorrect system programming by system operators. Variable rate irrigation began again on June 20, 2010 and continued until July 27, 2010 (reproductive stage R2). Lightning strikes in the area associated with a severe thunderstorm damaged the global positioning equipment. Repairs could not be completed until August 3, after which site specific irrigation began again (reproductive stage R3) and continued until August 6, 2010 (reproductive stage R4) with each treatment being irrigated its respective depth. Water use by the corn was assumed to continue until September 20, 2010 (reproductive stage R5), at which point the effective water use by the plant was minimal and the plant was entering the black layer formation phase. Appendix F lists the date of each irrigation application for each treatment.

An analysis of the dry-land corn showed the water shortage stress as expected because of the lack of water during the reproductive stages. Water from rainfall was available prior to crop emergence but was deficient during the reproductive stages of the crop. Total rainfall depth was 213 mm between May 7 and August 20. Figure 3.28 shows the total ET_c of the corn plant for the PM method and the AS (back-calculated using the PM method for comparison purposes only), compared to the amount of water available through rainfall only during the 2010 growing season. The back-calculated ET_c curve from the PM method was used because it is the most widely studied equation for determining ET. The difference in the depth required for the growing season calculated as the sum of the daily result from eq. 2.4 was 397 mm, indicating the need for irrigation. Combined rainfall and irrigation exceeded ET_c for the entire growing season for four of the six irrigation treatments (fig. 3.29). Table

3.10 shows an excess water application, which ranged from 33 mm for the 8 mm treatment to a deficit of 15 mm for 38 mm and 46 mm treatments.

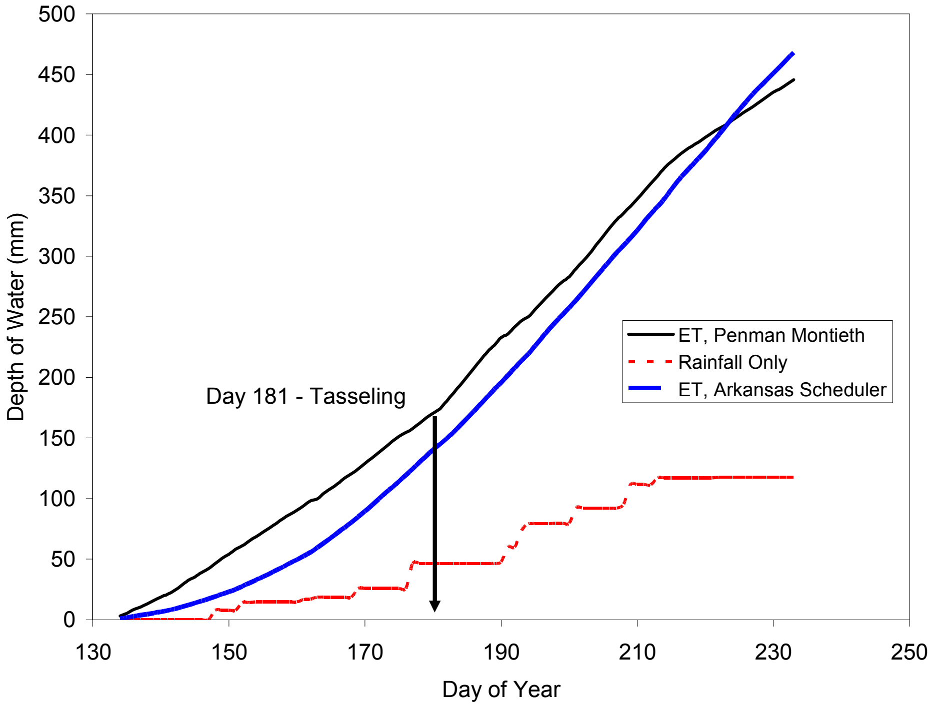

Figure 3.28: Total ET_c for corn as calculated using the Penman-Montieth method and the Arkansas Scheduler with rainfall depth on a daily basis (beginning May 13, 2010).

Table 3.10 summarizes the total amount of water applied (irrigated and rainfall), the amount of water applied through irrigation, and the water surplus experienced by the corn crop. An under-application of water is indicated by '-'for the surplus.

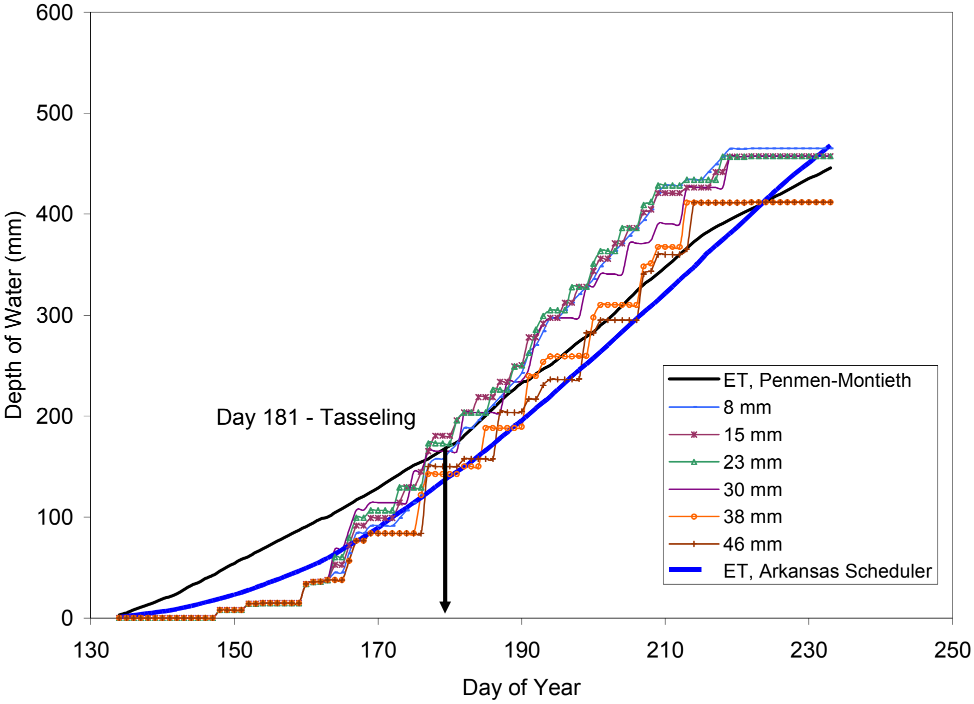

Figure 3.29: Total water applied and ET_c for corn on a daily basis (beginning May 13, 2010).

Table 3.10: Total water applied, irrigated water applied, and deficit versus calculated ET_c for corn.

Irrigation Treatment Depth (mm)	Irrigation & Rainfall (mm)	Irrigated Water (mm)	Surplus (mm)	Total ET_c Corn (PM Method)
8	430	313	33	397
15	423	306	26	397
23	423	306	26	397
30	423	306	26	397
38	382	265	-15	397
46	382	265	-15	397

3.2.4 Irrigation & rainfall analysis

Rainfall for the 2009 growing season (May 15 to September 15, 2009) was timely and adequate for sufficient crop growth, except for the period between days 170 to 190 (fig. 3.30). This range spans the vegetative growth stage (tasseling) and the R1 stage for corn (silking), based on interpolation from field observations in 2010.

Rapid phosphorous, nitrogen and water uptake occurred during these growth stages and a limitation in any of these three necessities could have caused significant yield reduction. The applicable rainfall for crop production in 2009 was 367 mm. A priority for 2009 was to apply the same irrigation depth to each division, but with the abundant rainfall divisions scheduled to receive greater treatments received slightly more total irrigated water than those with small scheduled treatments.

Rainfall for the 2010 growing season was insufficient to support corn production without irrigation. After May 20, 2010 rainfall was recorded on average every 3.2 days with a depth often less than 5 mm or greater than 12 mm. Even for rainfall events greater than 12 mm, 3.2 days is too infrequent. Depending on the intensity and infiltration rate, rainfall events with depths greater than 12 mm, a portion of the rainfall may be lost to runoff or post-rainfall evaporation. For rainfall events less than 8 mm, the depth applied is insufficient to replace the amount of water used by the crop (approximately 8 mm-d^{-1}). During rainfall events of high intensity, the force of droplets when impacting the surface of the soil may compact the soil particles, effectively sealing the soil surface by reducing the pore spaces between soil particles and preventing infiltration. Figure 3.31 depicts the daily rainfall depth for a given day of the year between May 15 and September 15, 2010. Rainfall prior to May 20 was likely not utilized by the plants, and thus not included in the total effective precipitation because the crop had only emerged seven days prior and was not fully established in the soil media. An applicable rainfall depth for crop production was thus 174 mm for 2010. There was also an increase in the average time interval between rainfall events from 2009 to 2010. In 2009, rainfall occurred on average every 2.3 days; but in 2010, rainfall occurred on average every 3.2 days. The maximum number of days between rainfall events was 7 and 12 for 2009 and 2010 respectively. Appendix F provides a summation of each rainfall event between May 15 and September 15, 2009 and 2010.

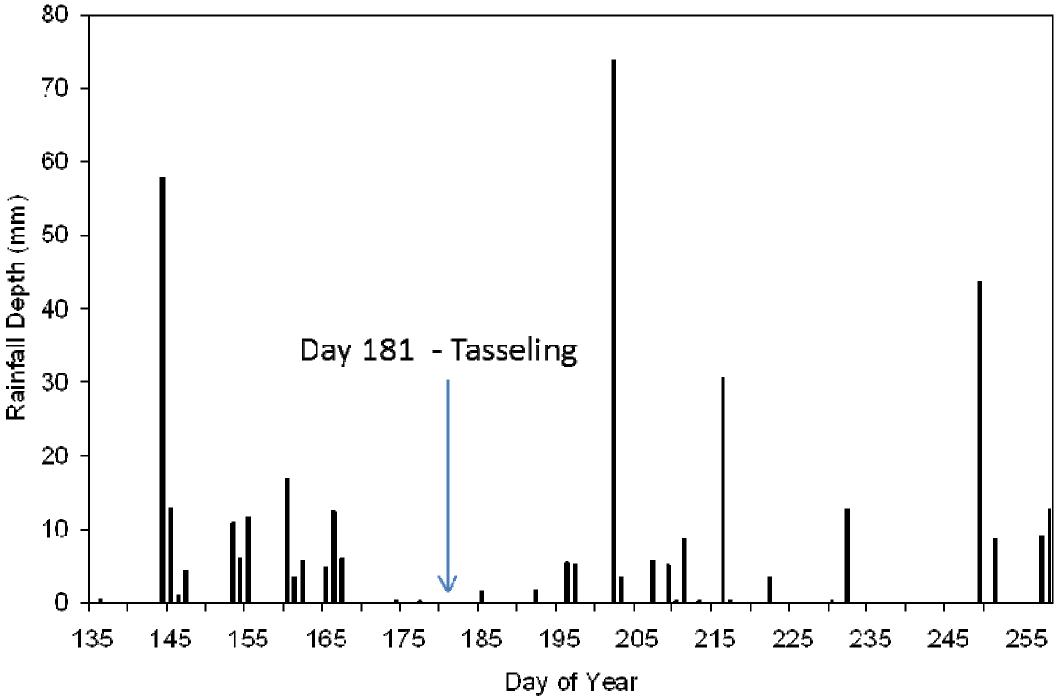

Figure 3.30: Rainfall depth for day of year 135 (May 15, 2009) through 258 (September 15, 2009).

A reduction of approximately 193 mm of rainfall from 2009 to 2010 (day 135 to 255) resulted in a decrease in the water balance and required an increase in irrigated water. An average increase of 114 mm of irrigated water was required to supplement the reduction in rainfall. To compare the IWUE for 2009 to 2010, water balances for each irrigation treatment needed to be as equal as possible to ensure the yield for each treatment was determining the IWUE and not differences in the water balance. This increase in irrigated water resulted in decreases in IWUE.

Irrigation efficiency (IE) is used to compare the benefits of irrigation during periods when rainfall is not available (2010) to periods when rainfall is available (2009). Irrigation efficiency is calculated by dividing the yield from irrigation (covariance) practices by the yield from dry-land practices, and multiplying the result by 100. Table 3.11 shows the IE for each irrigation treatment for 2009 and 2010.

Surface runoff occurs when rainfall intensity is greater than the infiltration rate of the soil. When operating at maximum system speed, 2 mm is applied at an intensity of 22.9 mm-hr^{-1}. The average rainfall intensity for day 135 to 255 from 2010 was 2.9 mm-hr$^{-1,}$ with a maximum and minimum intensity of 19.8 mm-hr^{-1} and 0.3 mm-hr^{-1} respectively, based on hourly recordings. During 2010, personnel observations indicated no surface runoff during irrigation operations; therefore there would not be surface runoff from rainfall based on the maximum rainfall intensity recorded. There are no personnel observations for surface runoff from 2009. However, based on the observations from 2010 and the equipment utilized for the 2009 study, it is assumed the system operated with an application intensity of 22.9 mm-hr^{-1}. Average rainfall intensity for 2009 was 2.7 mm-hr^{-1} with a maximum and minimum intensity of 30.2 mm-hr^{-1} and 0.3 mm-hr^{-1} respectively. Rainfall intensities greater than the application intensity of the pivot system occurred only once during the day 135 to 255 of year period in 2009. Therefore surface runoff during 2009 was minimal and may have only occurred on one occasion.

As previously speculated, subsurface runoff could occur if percolating water in an irrigated sector came into contact with a consistent tight clay layer. The clay layer could potentially result in horizontal flow of water within the soil profile The results from the Veris EC study indicate there is unlikely to be a consistent clay seam within the analyzed soil profile, because no soil core segment from the laboratory analysis of the calibration cores resulted in a "clay" soil classification.

Any applied water was therefore available for the crops to use, unless it passed through soil profile at a rate greater than the up-take rate for each plant. Soil classifications from the calibration core analysis ranged from loam to sandy soils. From tab. 2.1 the infiltration rates for sandy, sandy loam and loam soils are 50, 25, and 12 mm-hr^{-1}, respectively. With application intensities much less than the infiltration rates for the soil textures in question, it is possible portions of each rainfall and irrigation application passed through the soil profile before being utilized by the crops.

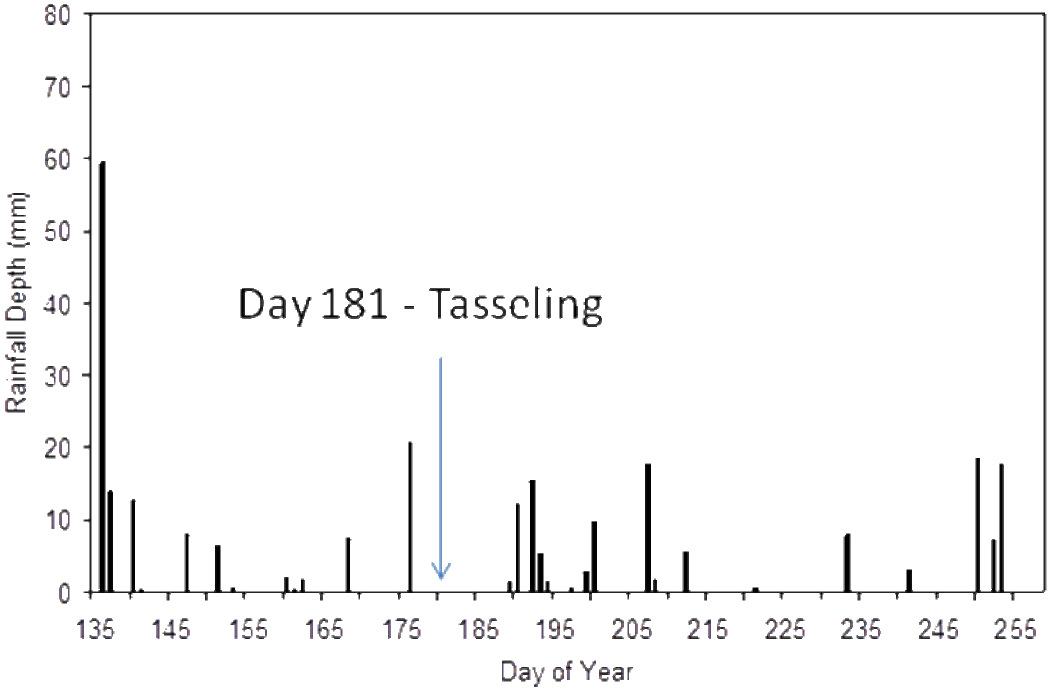

Figure 3.31: Rainfall depth for day of year 135 (May 15, 2010) through 258 (September 15, 2010).

Table 3.11: Comparison of covariance analysis mean yields and irrigation efficiency for 2009 and 2010 corn.

Treatment (mm)	Yield 2009 (kg-ha^{-1})	Yield 2010 (kg-ha^{-1})	IE, 2009	IE, 2010
0 (dry-land)	5320	4180	--	--
8	9010	8220	169.5	196.7
15	9500	6680	178.7	159.8
23	8890	5980	167.2	143
31	7740	6160	145.5	147.3
38	7480	6450	140.7	154.3
46	8170	8170	153.7	193

3.2.5 Yield study summary

Dry-land yields for field corn were collected from outside the last sprinkler of the center-pivot on the west half during 2010 and the east half in 2009. The dry-land yields were used as a control to evaluate irrigation impact on grain yields. To make this determination the IE and IWUE were calculated for both 2009 and 2010, and can be seen in tables 3.8, 3.10 and 3.11.

Yields for 2010 were less than 2009. Yield patterns for 2009 and 2010 had similarities and differences. Both years observed an increase in mean yields from dry-land to irrigation for variance and covariance analyses. After an initial rise in mean yield, a reduction was observed for sand classes SC_L, SC_M, and SC_H during the variance analysis as well as for the covariance analysis. For both study years, mean yields (shown as a smoothed line graph in figures 3.32 and 3.33) followed a pattern of slight increase after the observed decrease previously described (fig. 3.32). The resulting mean yields from a covariance analysis for an irrigation treatment of 46 mm were the same for both years of study (fig. 3.33 and tab. 3.11)

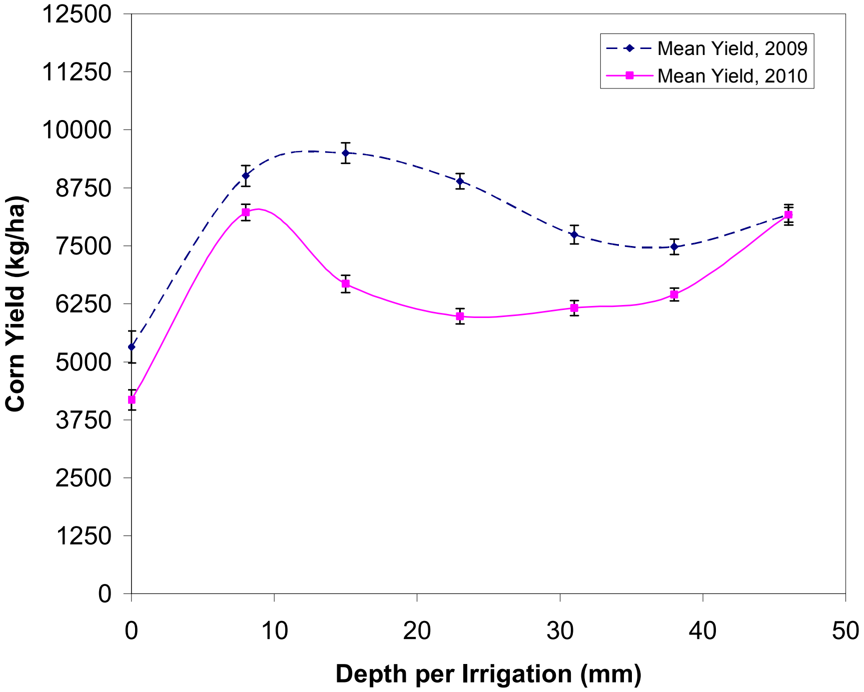

Figure 3.32: Trend for mean yields from covariance analysis for 2009 and 2010; error bars represent a 95% confidence interval.

This trend did not hold true for mean yields from the variance analysis for SC_{VH}. During 2009 all mean yields decreased for irrigation depths greater than 15 mm, while in 2010 the increasing pattern observed after the reduction in mean yields for SC_L, SC_M, and SC_H was present (Fig 3.33).

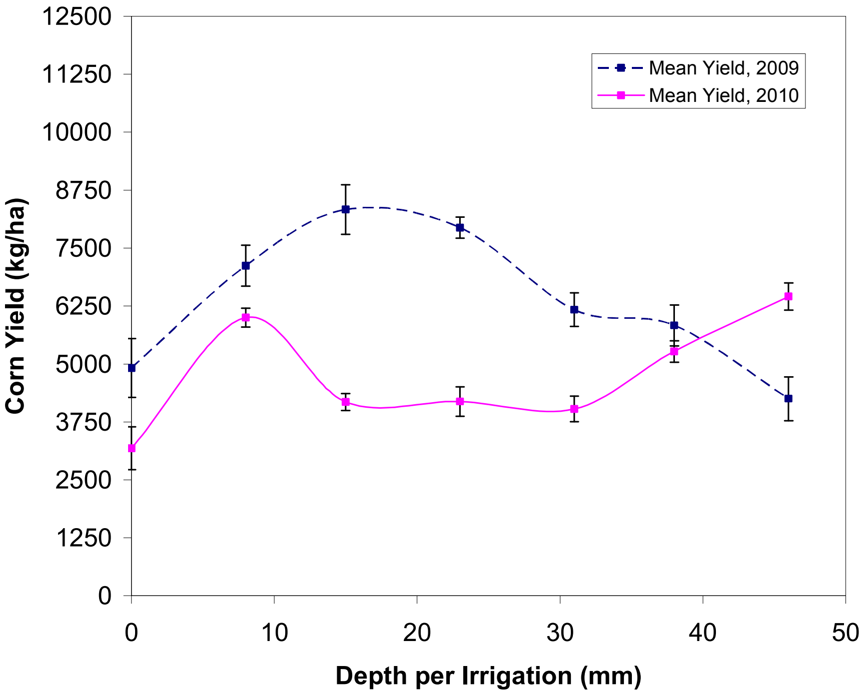

Figure 3.33: Trend for mean yields from variance analysis on SC_{VH} for 2009 and 2010; error bars represent a 95% confidence interval.

Using a regression analysis, the best fit line for 2009 and 2010 yield versus irrigation treatment was a 3rd order quadratic equation (eqs 3.2 and 3.3, respectively). (In these equations, x is the treatment depth in mm and y is the mean yield in kg-ha^{-1}.) By differentiating these equations and finding the roots, an irrigation depth which produced the minimum and maximum yields was obtained.

$$y = 6161.8x^3 - 19056x^2 + 16236x + 5223.2 \tag{3.2}$$

$$y = 3411.9x^3 - 7893.8x^2 + 4822x + 5488.7 \tag{3.3}$$

(The R^2 value for equations 3.2 and 3.3 were 0.15 and 0.19 respectively. This indicates a low correlation in each data set.) The minimum root from the regression analysis was the minimum irrigation depth to be used to produce the greatest yields. The results of this analysis can be used when deciding which irrigation depth and frequency to use for a soil texture, if all other variables remain constant (all though this assumption is unlikely outside of a controlled environment). For 2009, the maximum yield was produced with an irrigation depth of 15 mm and the minimum yield was produced with an irrigation depth of 38 mm. For 2010, the maximum yield was produced with an irrigation depth of 10 mm and the minimum yield was produced with an irrigation depth of 33 mm.

Many variables were different for 2009 and 2010; the location of each irrigation treatment and rainfall (frequency, duration, and intensity) being the most prominent. To reduce the impact of these changes, a regression analysis was performed on the combined yields for 2009 and 2010. The resulting 3rd order quadratic equation (eq. 3.4) was differentiated and solved. The resulting minimum and maximum irrigation depths were 15 mm and 33 mm. (The R^2 value for equation 3.4 was 0.11, indicating a low correlation in the combined data set.)

$$y = 4159.3x^3 - 11675x^2 + 9262.7x + 5387.5 \tag{3.4}$$

Location within the field was also considered because differences in yield could be attributed to the distribution of sand texture within each half of the Marsh Pivot. As indicated by tables 3.2 and 3.4, the sand classes vary for each half of the field. This variation occurred because the sand texture was quantified into four classes for each half of the field to attempt to have equal number of data points within each sand class. The percentage of sand within the textures of each half of the pivot was not dependent on the other half of the field, therefore the sand class breaks were not equal. By conducting a covariance analysis the impact of variation in the sand class divisions between the two halves of the field was eliminated.

Additional years of study are needed to definitively state the appropriate irrigation depth and frequency for non-uniform soil textures, but based on the two year study from 2009 and 2010, it is inferred that during dry years or years with ample precipitation, an irrigation depth of 8 mm results in yields greater than or within 95% of any other irrigation depth when applied on an every day basis. However, for energy conservation through limiting the run time of the system 15 mm should be irrigated every 2nd day (per the regression analysis and eq. 3.3).

For irrigation depths between 15 mm and 38 mm, it can be inferred that irrigation depth and frequency of irrigation do not significantly impact the yield production of corn. However, some factors other than soil texture caused a reduction in yield, as indicated by the continuous increase in yield for treatment 46 mm on all sand classes both years (not including SC_{VH} for 2009) (figs. 3.18 to 3.22 and figs. 3.23 to 3.27).

Changes in soil texture and irrigation treatment simultaneously affected the yield for the Marsh Pivot. The three dimensional surface generated by a regression analysis of yield as a function of depth per irrigation and percent sand for 2009 in fig. 3.34 showed a convex curve. An increase in sand content produced a greater impact on yield reduction than treatment depths, as indicated by the tilt in the generated surface toward greater sand depths for all irrigation depths in fig. 3.34.

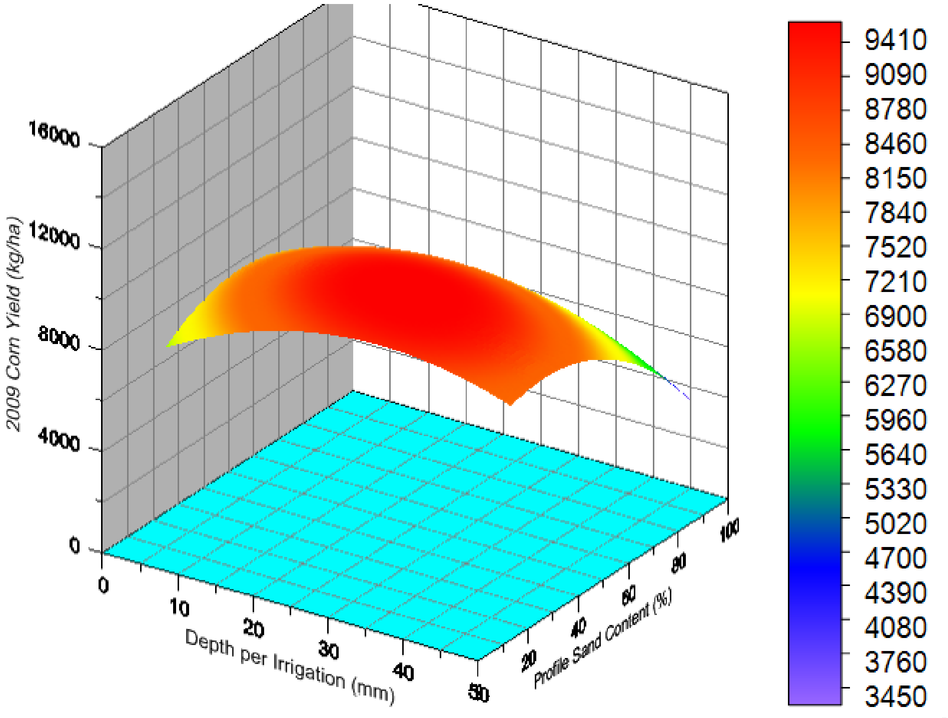

Figure 3.34: Three dimensional surface plot for the interaction between yield, irrigation depth, and percent sand (2009). Surface equation: $y = 85.188 + 82.406x - 32.414x^2 + 2.35z - 0.0213z^2 - 0.395zx$ (where x is the depth per irrigation, y is the mean yield, and z is the profile percent sand). Color scale units are for mean yield (kg-ha^{-1}).

The maximum sand percentage to produce the greatest yield was calculated from the differentiation of the best fit second order quadratic equation fit (through a regression analysis) to the yield data in fig. 3.35 for 2009. From this mathematical analysis, 45% was determined to be the maximum percent sand in the soil profile before a decrease in yield was observed. It was noted the data points had a low R^2 value (0.1214), indicating a low correlation between percent sand and yield.

A maximum yield with the minimum irrigation depth occurred at 15 mm with a sand content of 45%. For treatments and sand contents less than or greater than this combination, yields decreased. The peak sand percentage and irrigation depth are confirmed in fig. 3.36.

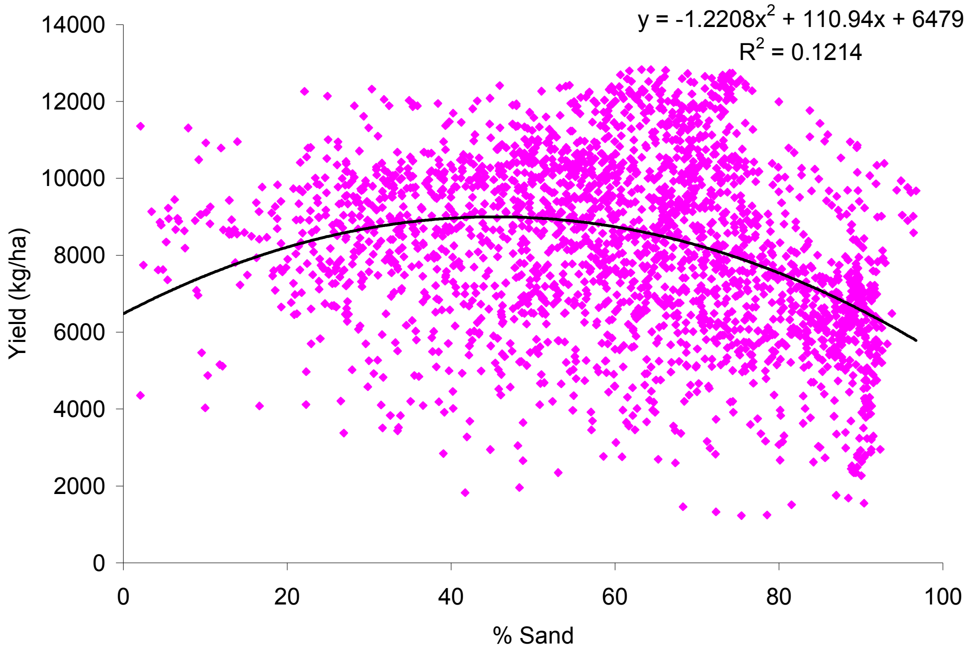

Figure 3.35: Relationship between percent sand and corn yield on the Marsh Pivot (2009).

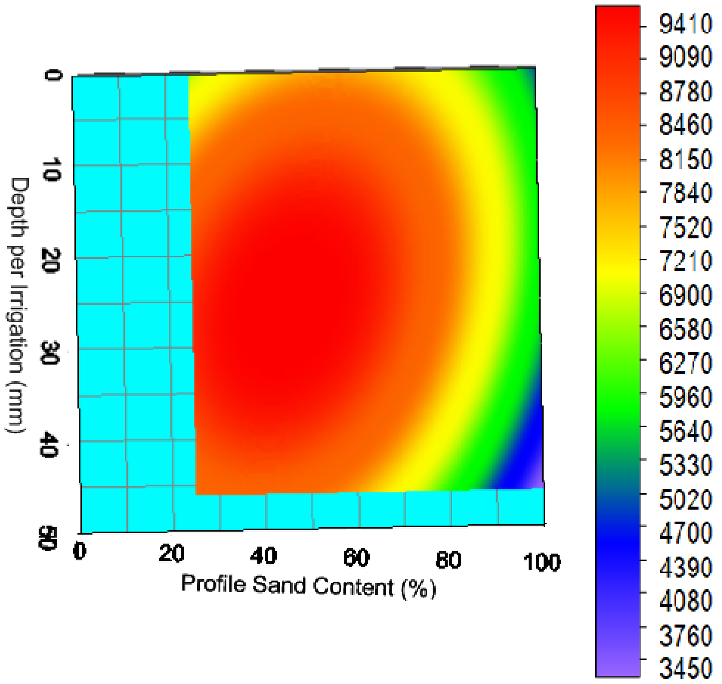

Figure 3.36: Surface plot for the change in yield as irrigation depth and sand content change (2009). Color scale units are for mean yield (kg-ha^{-1})

Changes in soil texture and irrigation treatment simultaneously affected the yield for the Marsh Pivot in 2010 as well. The three dimensional surface generated by the regression analysis between yield and treatment and sand for 2010 in fig. 3.37, showed a concave curve as irrigation depth increased and a convex curve as sand percentage increased. For yields during 2010, soil textures with a greater proportion of sand resulted in lower yields regardless of treatment depth. While there did appear to be a slightly lower yield for treatments between 8 and 46 mm, the difference was minimal and appeared to only be in the range of 630-940 kg/ha (fig. 3.37). This same pattern did not hold true for soil textures with low sand contents. The maximum sand percentage to produce the greatest yield was calculated by differentiating second order quadratic equation fit (through a regression analysis) to the yield data in fig. 3.38 for 2010. From this mathematical analysis, 46% was determined to be the maximum percent sand in the soil profile before a decrease in yield was observed. It was noted the data points had a low R^2 value (0.2767) indicating a low correlation between percent sand and yield.

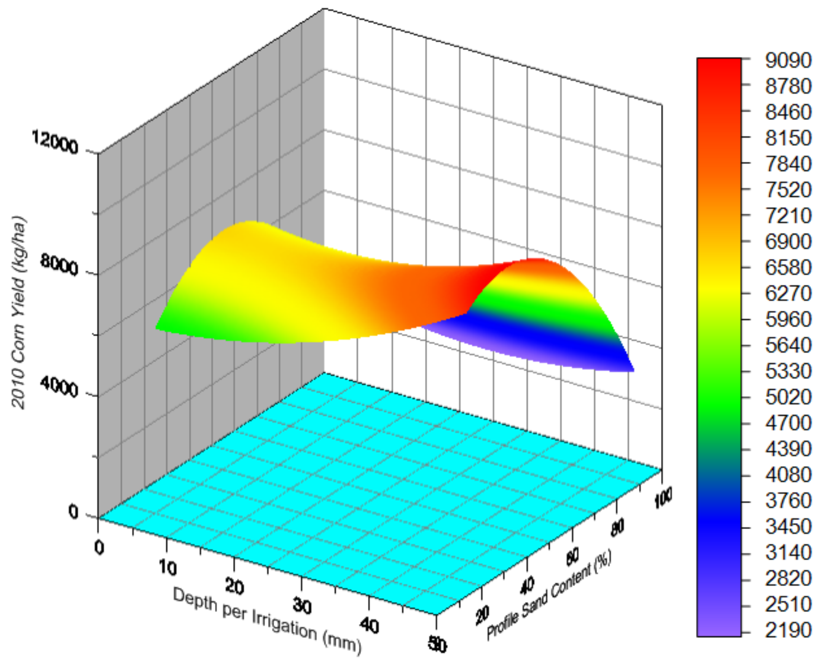

Figure 3.37: Three dimension surface plot for the interaction between yield, irrigation depth, and percent sand (2010). Surface equation:
$y = 13.33 + 15.067x + 14.477x^2 + 3.436z - 0.031z^2 - 0.426zx$,
(where x is the depth per irrigation, y is the mean yield, and z is the profile percent sand). Color scale units are for mean yield (kg-ha^{-1}).

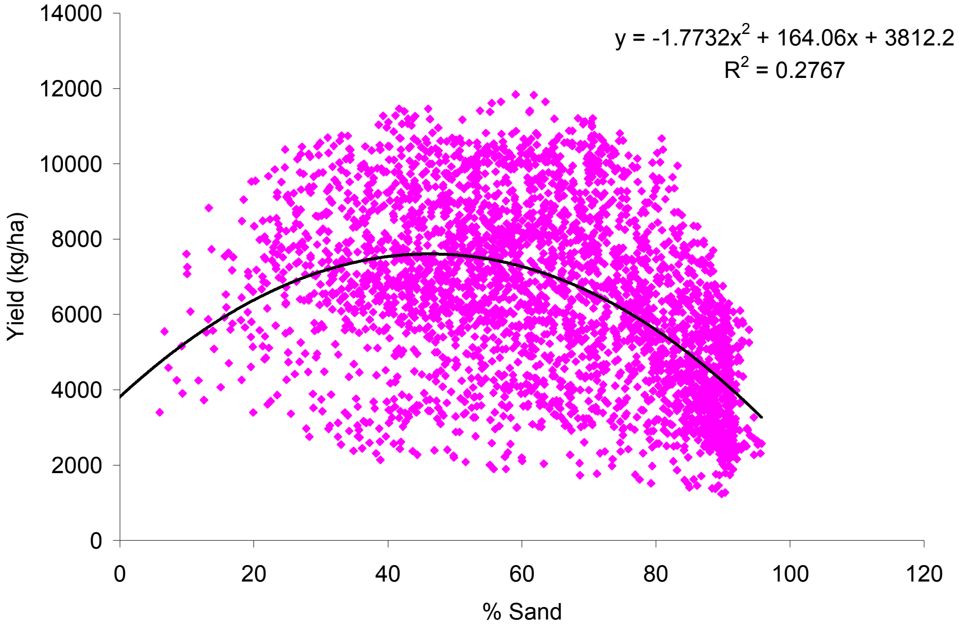

Figure 3.38: Relationship between percent sand and corn yield on the Marsh Pivot (2010).

A maximum yield with the minimum irrigation depth occurred at 10 mm with a sand content of 46%. This treatment was not directly tested. To confirm or refute this statistical analysis, further studies using an irrigation depth of 10 mm should be utilized.

A possible explanation for the previously stated observations concerning the yields produced during 2009 and 2010 could be related to the water holding capacity of the soil. Regardless of treatment depth, for soils with sand contents greater than 45% the yield decreased. This was potentially due to the greater pore space and reduced adsorptive capability of the sandier soil. For soils with greater proportions of sand, there were decreased proportions of negatively charged clay particles, which attract the positively charged dipole of water molecules. These factors may have resulted in an increase in percolation below the root zone of the crop.

However, for greater irrigation depths and lower sand contents, it appeared too much water was beginning to become a limiting factor for plant growth. A potential reason for this conclusion was that the volume of applied water was greater than the combination of the uptake rate of the plant and percolation rate of the soil, resulting in saturated soil conditions.

3.3 Conclusion

For the production of corn on non-uniform soils, it is possible to use variable rate irrigation by sector using conventional center-pivot systems. Based on a two year study, an irrigation depth of 8 mm on an every day basis will result in a mean yield within 95% of any other irrigation depth less than 46 mm on the non-uniform soils at the Marsh Pivot. However, to ensure the best use of equipment, energy, and water resources, an irrigation depth of 15 mm should be applied every 2nd day (eq. 3.4) for the soil texture on the Marsh Pivot and the sub-humid climate. Weather patterns vary, but average rainfall for the Marsh Pivot from May 15 to September 15 is 324 mm (from years 2000 to 2010).

The soil textures being used for this study were divided into four sand classes. Sand class SC_L for each half of the Marsh Pivot has a range of 0 to 48% (east) and 0 to 51% (west). Each sand class division was selected to have equal portions of sand per sand class. The greater sand contents indicate greater infiltration rates and decreased water holding capacities of the soils. For both years of the study, regardless of irrigation depth, sand contents of 45 to 46% produced the greatest yields and as sand content increased beyond 45 to 46%, yields decreased for all sand class (figures 3.35 and 3.38).

During 2009, the Marsh Pivot received a substantially greater depth of water from rainfall than 2010, and this study indicates 15 mm should be irrigated on an every other day basis. However, during 2009, irrigation depths of 8 mm and 46 mm resulted in yields similar to those during 2010, using the same irrigation treatments. An irrigation treatment of 15 mm did not result in similar results during 2009 and 2010, but rather in 2010 yields were less than those during 2009.

The application of greater irrigation depths to soils with greater percentages of sand produced an increase for variance analysis on SC_L, SC_M, and SC_H and for the covariance analysis. For these sand classes, soil texture does not appear to limit the yield production for greater irrigation depths but rather yield production benefits from the greater irrigation depths. The variance analysis on SC_{VH} did not reflect this same pattern for both years. Rather, in 2009, yields continued to decrease for greater irrigation depths potentially indicating the importance of the water holding capacity of the soil. For 2010, the same rise in mean yields observed for variance and covariance analyses was present for greater irrigation depths on SC_{VH}. A potential explanation for this is the location of the 46 mm sector. This irrigation treatment resided next to an irrigation treatment of 8 mm which was irrigated every day. Any water applied through localized surface flow, wind dispersion, or sprinkler overlap could be biasing the mean yields for the 46 mm treatment.

There remains some uncertainty in the results due to equipment malfunctions throughout the study. System malfunctions resulted in deviations from the irrigation schedule during the critical reproductive period for the crop which could have potentially reduced the resulting yields (see section 3.2.3 for a description of the malfunctions). Additional uncertainty can be attributed to experimental design flaws. The two treatments with the greatest yields were applied to adjacent sectors indicating a potential for error associated with overlap of irrigated water (8 mm was irrigated everyday which could have provided water to the 46 mm treatment zone if the 9 m buffer was not adequate to remove all overlap). The presence of soil moisture readings could determine the effectiveness of the 9 m buffer, but were not available during this study. A field slope study between sectors was not performed to verify or refute the potential for overland flow between sectors. Personnel observations only indicated there was not overland flow leaving the Marsh Pivot. Future research should include soil moisture sensors at the edge of each buffer zone, rain gauges at the boundaries of each treatment and a full survey of the Marsh Pivot should be conducted to remove these sources of uncertainty.

The application of this study outside a research setting could be practical for cultivated fields with non-uniform soils. For this study, yields increased as sand percentage increased up to 45%. If the soil texture of a field is known to be near 45%, an application depth of 15 mm irrigated every 2nd day would be recommended. As the percentage of sand decreases for a soil the irrigation depth can be decreased because the soil will have increased portions of silts and clays, which possess a greater water holding capacity. As the percentage of sand increases for a soil, the irrigation depth should be increased because the water holding capacity of the soil will have decreased due to the reduction in silts and clays within the soil. A soil EC study with calibration data should be used to determine the soil texture of the field. If a soil EC study is not practical, a representative number of soil samples should be collected to determine the relative sand content of the soil.

Chapter 4:
RICE PRODUCTION

4.1 Methodology

4.1.1 Project description

This research was conducted on the East Marsh Pivot field (Marsh Pivot) at the University of Missouri Delta Research Center in Portageville, MO (fig. 4.1). From the United States Department of Agriculture (USDA) web soil survey, the Marsh Pivot was located on soils with the Hayti-Portageville-Cooter classification. According to the USDA web soil survey the Hayti classification "consists of very deep slowly permeable soils," the Portageville classification "consists of deep moderately well drained soils," and the Cooter classification "consists of very deep poorly draining soils" (www.soils.usda.gov). Please see section 4.1.2 for an analytical analysis of the percent sand on the Marsh Pivot.

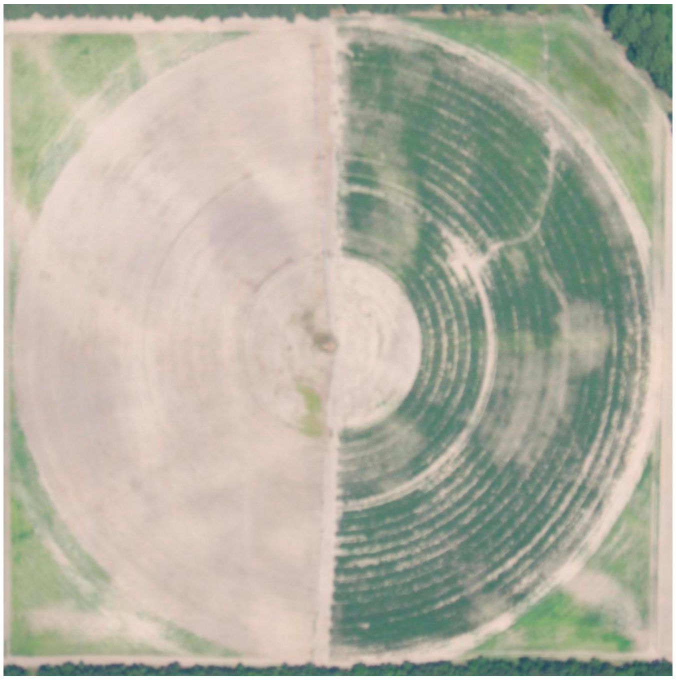

Figure 4.1: Aerial photograph of the East Marsh Pivot field (Marsh Pivot) located in Portageville, MO.

The variability in soil texture on this field is extensive and was quantified using Veris Technologies' Soil Electrical Conductivity (EC) 3100 system in 2002, to determine the sand content within the soil. Two readings were taken to determine the relative sand content; a shallow reading (0 cm to 30 cm) and a deep reading (0 cm to 91 cm) (Veris Technologies, 2011). The field was divided into separate halves (east and west), with the pivot road being used to define north-south and act as a dividing line between the field halves. However, the road does not lie directly north-south but rather is 4^{o} off from true north, with the northern end of the road at 4^{o} and the southern end of the road at 184^{o}. Variable rate irrigation by azimuth and annulus was utilized for this study.

4.1.2 Soil analysis

For the 2010 growing season, the east half of the Marsh Pivot was planted in rice in a circular pattern and divided into six equal sectors every 30^{o} beginning at 4^{o} and continuing clockwise to 184^{o}. The 30^{o} sectors were further divided into seven approximately equal areas along the length of the pivot forming 42 separate irrigation plots. The 42 irrigation plots were used to test the effectiveness and applicability of variable rate irrigation (VRI) technology provided by Valley Manufacturing Inc. Six treatments were applied once within each concentric ring, creating seven repetitions of each irrigation treatment.

Determination of soil texture was calculated from the calibration of the electrical conductivity (EC_a) of the soil obtained during the 2002 Veris Technologies study. The Veris 3100 determined the EC_a for two depths simultaneously by using three pairs of electrodes. One set injects current into the soil, and the remaining sets measured the voltage potential for a "shallow" and a "deep" reading. Per Veris 3100 specifications, electrodes were to be maintained between 2.5 cm and 5.0 cm below ground surface (bgs), and the system was operated at a constant speed through out each sampling run which varied between 13 kph and 19 kph. Data were collected on a 1-s interval and with a 10 m spacing between north-south transects resulting in a 4 m to 6 m data spacing (fig. 4.2). Soil cores for the Marsh Pivot were collected during 2002 for calibration between the Veris EC$_a$ data and field sand content (fig. 4.3). Twelve cores were collected and divided into five 15 cm segments for a total depth of 76 cm bgs. The soil cores were analyzed for texture by the standard sieve-pipette method (results of this method can be seen in Appendix A) (ASTM, 2011).

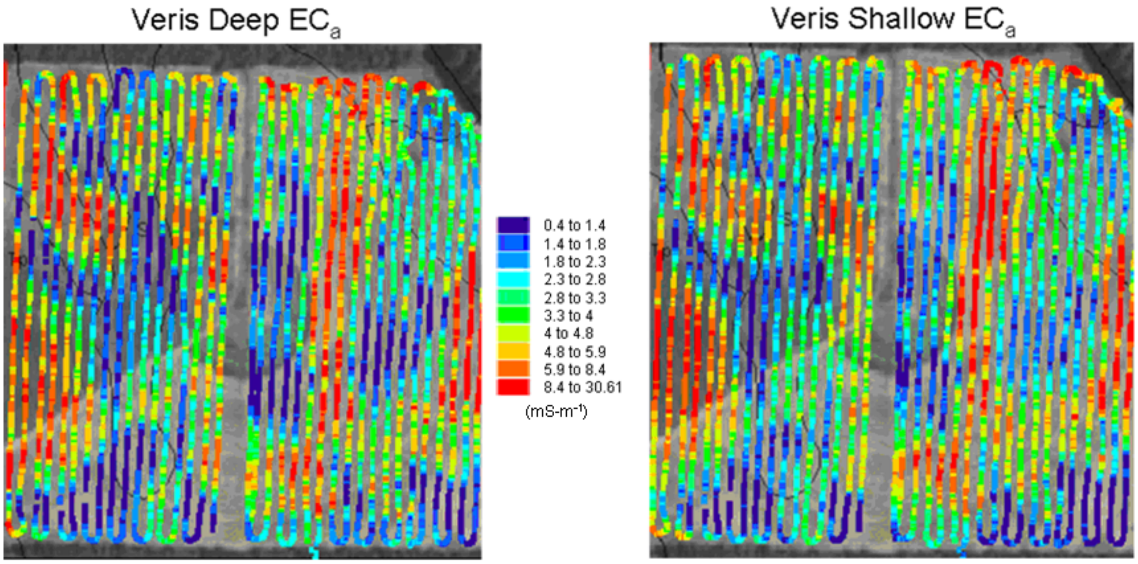

Figure 4.2: Veris 3100 soil EC$_a$ output for deep and shallow readings on the Marsh Pivot (2002).

Table 4.1 shows the percent sand of each 15 cm segment for each soil core based on the results of the standard sieve-pipette method analysis. The average percent sand from the soil core analysis from segments 0 cm to 31 cm at each sample location was used to represent the soil layer sensed by the Veris shallow reading, while the average of all 5 sample segments was used to represent the soil layer sensed by the Veris deep reading.

Figure 4.3: Location of soil sample cores collected for calibration of Veris EC$_a$ data (2002).

Table 4.1: Summary of the standard sieve-pipette soil analysis results (2002).

		Soil Core and Percent Sand					
Segment	Depth (cm)	1	2	3	4	5	6
A	0 to 15	16	92	92	64	77	75
B	15 to 31	36	92	84	58	84	77
C	31 to 46	28	90	94	22	67	48
D	46 to 61	23	96	97	18	51	40
E	61 to 76	22	94	99	25	49	34
Segment	Depth (cm)	7	8	9	10	11	12
A	0 to 15	92	74	81	78	54	90
B	15 to 31	90	68	80	76	35	89
C	31 to 46	92	47	56	65	26	92
D	46 to 61	66	35	44	59	20	92
E	61 to 76	61	34	39	41	26	95

The average percent sand for each calibration point was plotted to determine the profile average for the shallow and deep readings (fig. 4.4). The linear best fit line for the Veris deep reading resulted in the greatest R^2 value (0.83), indicating a high correlation between EC_a and percent sand from the analysis of the soil core samples. The linear best fit line from the Veris deep reading in Fig 4.4 was used to calculate the percent sand for each measurement point. The best fit line was solved for 'x'. This enabled the input of each EC reading into the equation for 'y' and resulted in calculated percent sand. The modified equation for calculating percent sand is:

$$x = 94.16 - 3.76y \tag{4.1}$$

where:

x = percent sand
y = Veris deep EC_a reading

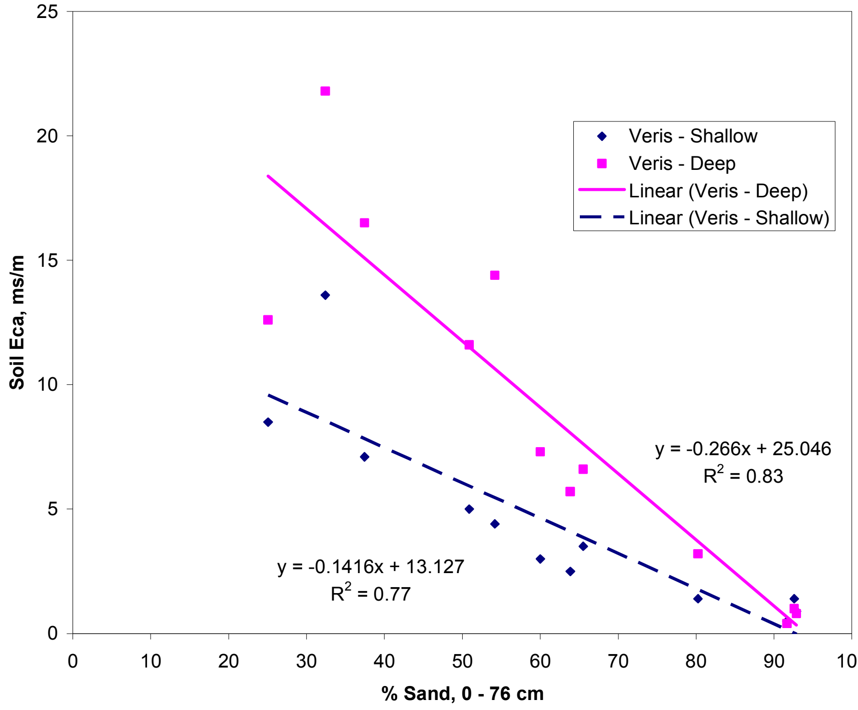

Figure 4.4: Average soil core percent sand versus EC_a for Veris shallow and deep readings used to develop the calibration equation for field percent sand.

Statistical Analysis Software (SAS) was used to calculate the relative frequency of each sand percentage. The histogram in fig. 4.5 illustrates the wide variability of soil textures present in the east half of the Marsh Pivot. The percent sand in the west half of the Marsh Pivot ranges from less than 5% to greater than 95% sand (Fig 4.5). The relative frequency (the ratio of the number of observations for each sand percentage to the total number of observations) brings forth not only the variability in the soil texture (as represented by sand content), but also whether the sand content is weighted toward greater or lesser sand percentages. From Fig 4.5, it can be extrapolated that greater sand percentages occurred more frequently than lesser sand percentages.

Variable rate irrigation was applied to evaluate how the differing soil textures would respond to various irrigation amounts. High sand content indicated high drainage capabilities and low water storage capacities of a soil. A histogram of the soils beneath each irrigation treatment was created using SAS, to determine if each irrigation treatment was being applied to the full range of sand percentages (Fig 4.7 to 4.12). Figures 4.5 to 4.11 were analyzed for any potential bias in the statistical analysis of the yield data should the sand content in any particular sector be weighted toward greater or lesser sand percentages.

Each irrigation treatment was located arbitrarily within each concentric ring to ensure each treatment was applied to all possible soil textures. An attempt was made to apply each irrigation treatment to equal areas of each sand class. With a maximum root zone of 15 cm to 30 cm, non-uniform soils with significant areas of sand and sandy loam textures must be irrigated more frequently due to greater infiltration rates and lower water holding capacity compared to silty or clayey soils. .

Although an attempt was made to maintain the full range of sand percentages for each sector, because of the soil variability this was not possible. Treatment 1 (50%, 8 mm) percent sand frequencies were weighted toward sand contents between 50% and 80% (fig. 4.6). Treatment 2 (60%, 10 mm) percent sand frequencies were weighted toward sand percentages between 60% and 70% (fig. 4.7). Treatment 3 (70%, 11 mm) sand percentages were heavily weighted greater than 60%, with sand percentages near 90% having a relative frequency greater than 0.6 (fig. 4.8). Treatment 4 (80%, 13 mm) had a relatively even distribution of sand percentages with increased frequencies of sand percentages approaching to, and greater than 90% (fig. 4.9). Treatment 5 (90%, 14 mm) sand percentages were weighted greater than 40%, and percentages less than 30% were minimal (fig. 4.10). Treatment 6 (100%, 16 mm) sand percentages were relatively evenly distributed across all sand percentages (fig. 4.11).

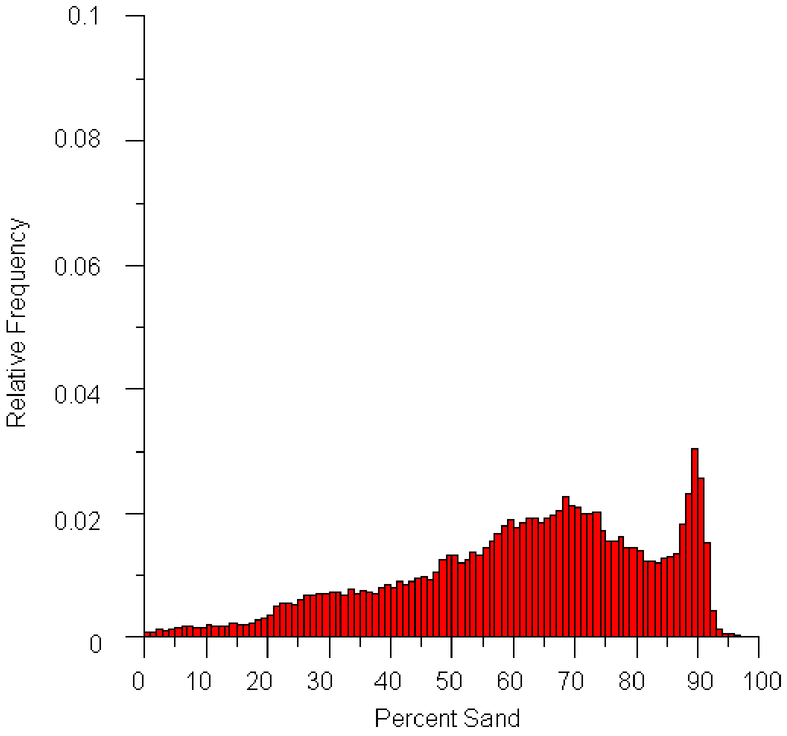

Figure 4.5: Relative frequency of sand percentages on the east half of the Marsh Pivot (irrigated rice, 2010).

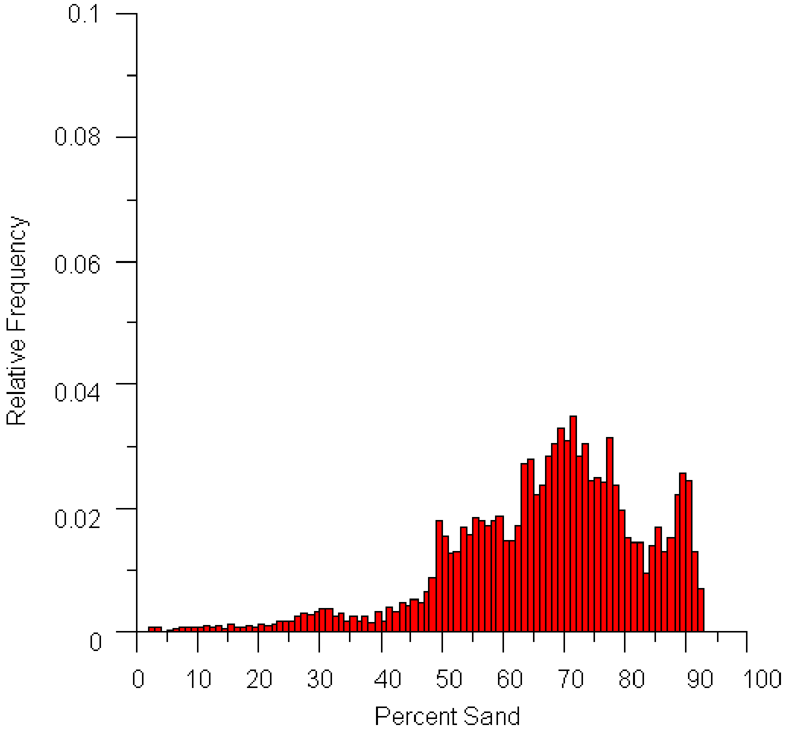

Figure 4.6: Relative frequency of sand percentages on treatment 1 (8 mm), (irrigated rice 2010).

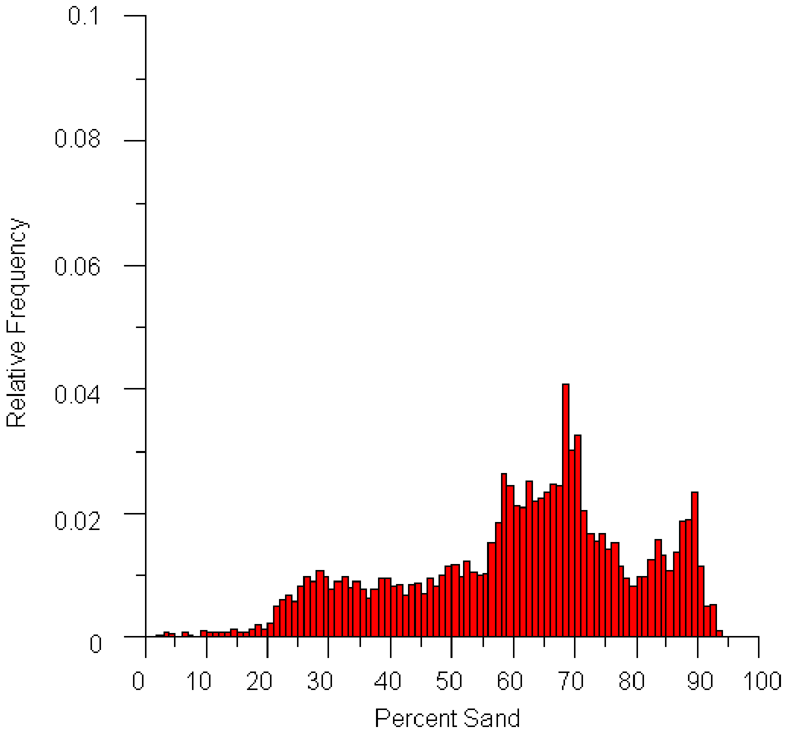

Figure 4.7: Relative frequency for sand percentages on treatment 2 (10 mm), (irrigated rice 2010).

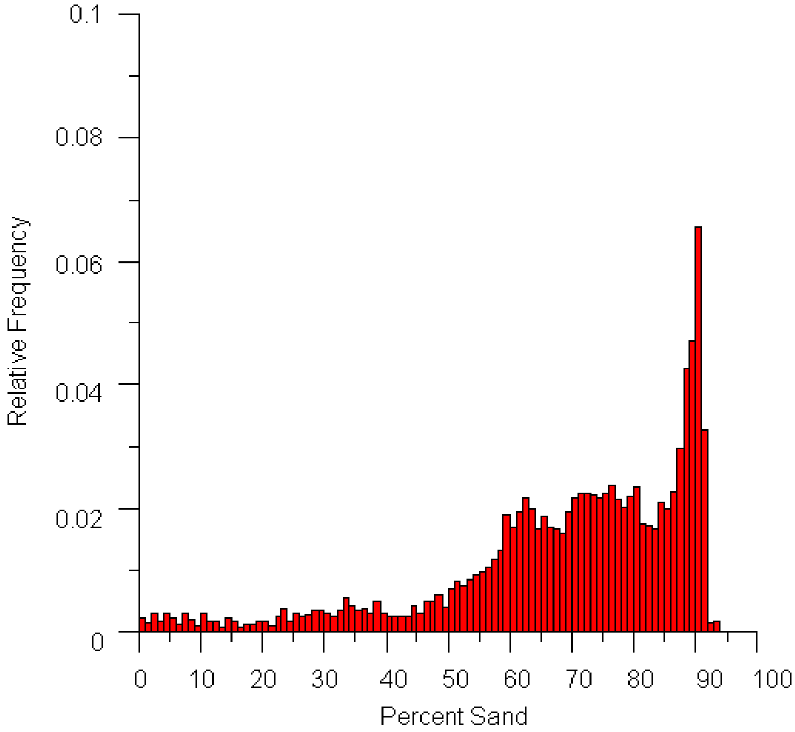

Figure 4.8: Relative frequency for sand percentages on treatment 3 (11 mm), (irrigated rice 2010).

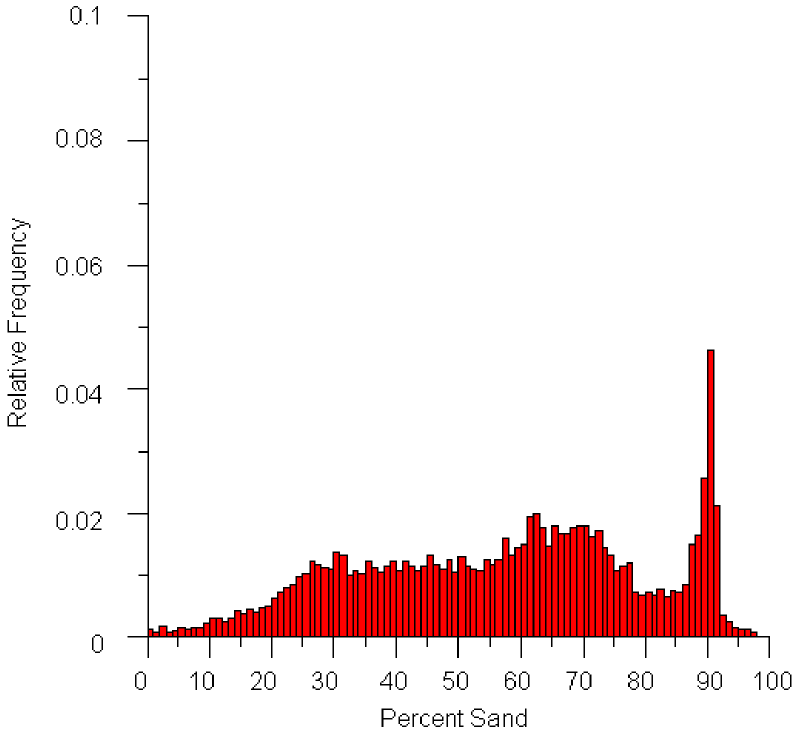

Figure 4.9: Relative frequency for sand percentages on treatment 4 (13 mm), (irrigated rice 2010).

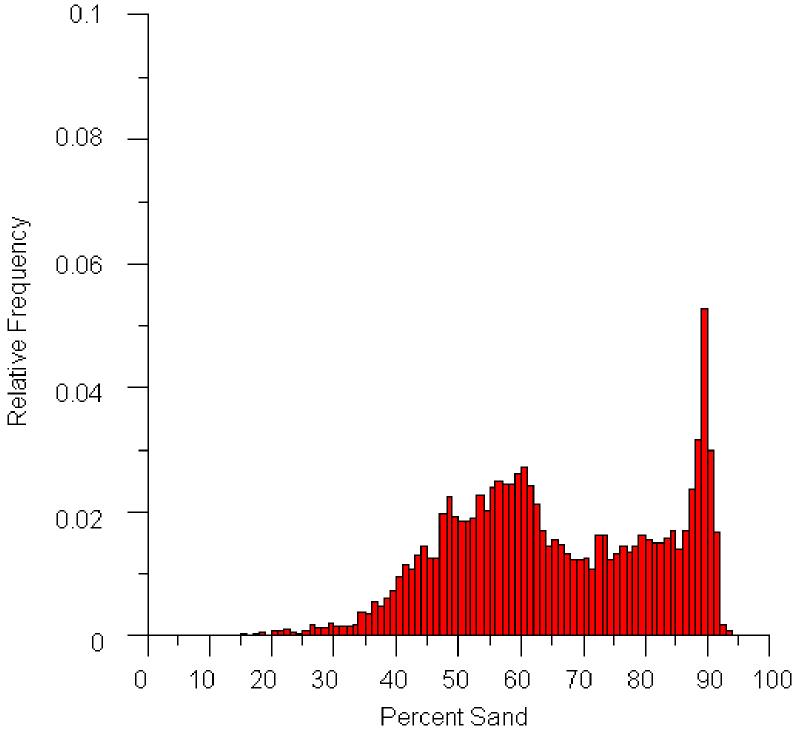

Figure 4.10: Relative frequency for sand percentages on treatment 5 (14 mm), (irrigated rice 2010).

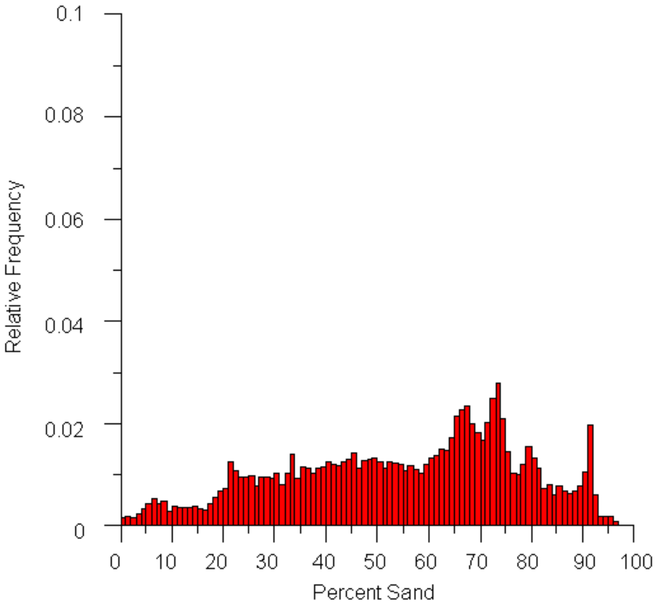

Figure 4.11: Relative frequency for sand percentages on treatment 6 (16 mm), (irrigated rice 2010).

A map of the soil percent sand content within the Marsh Pivot is shown in fig. 4.12. An attempt was made to balance the areal extent of the sand content of the soil into four classes, or quartiles. A summary of these four sand classes is listed in tab. 4.2, followed by tab. 4.3, which depicts the percentage of each sand class and mean percentage irrigated by each treatment with respect to the east half of the Marsh Pivot. From tab. 4.3, except for irrigation treatments 13 mm and 16 mm, approximately 50% of the area irrigated for each treatment was greater than 64%. The division into quartiles was based on data from the entire half of the field but the analysis did not account for the removal of alleyways between irrigation treatments (9 m) to remove uncertainty from overlapping treatments. The variability of the soil texture was accommodated through the randomization of six irrigation treatments within seven concentric rings on the east half of the Marsh Pivot. Each irrigation treatment was applied to near equal areas of each sand class (prior to removal of data from overlapping treatments).

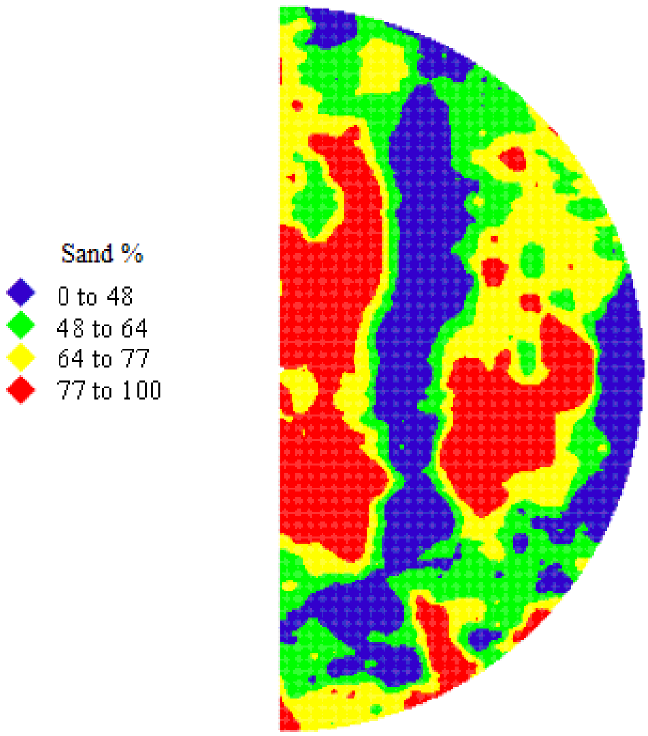

Figure 4.12: Sand content of the east half of the Marsh Pivot in four sand classes.

Table 4.2: Summary of each sand class and its respective sand content range for the east half of the Marsh Pivot .

Sand Class	% Sand
SC_L (low)	0 - 48
SC_M (medium)	48 - 64
SC_H (high)	64 - 77
SC_{VH} (very high)	77 - 100

Table 4.3: Percentage of each sand class beneath each treatment and as a percentage of the east half of the Marsh Pivot.

Treatment	Application depth (mm)	SC_L (%)	SC_M (%)	SC_H (%)	SC_{VH} (%)	% Sand > 64%
1	8	28	21	28	23	51
2	10	31	24	26	19	45
3	11	30	16	21	33	54
4	13	44	20	16	20	36
5	14	27	27	18	28	56
6	16	41	27	15	17	32
East Side	--	33	22	18	27	45

4.1.3 Irrigation depths & location

Center-pivot irrigation was utilized in lieu of conventional flood irrigation. In conventional flood irrigation there is a constant water supply for the root zone of the rice plant, but there are high losses of water to evaporation and infiltration. In addition to reducing water loss, center-pivot irrigation allows for the application of fertilizers (fertigation), pesticides and fungicides (chemigation) to stimulate yield production. Application of fertilizers and chemicals when using conventional flood irrigation would require draining the field, applying the desired products, then re-flooding post application. The draining and re-flooding practices result in increased water usage. The use of a VRI system enables the user to vary the irrigation depth, depending on any number of factors. The irrigation rates in this study were varied based on the estimated evapotranspiration rate of rice (6.5 mm-d^{-1}, 80% for corn), and it was attempted to apply each irrigation treatment to the full range of sand percentages.

Each irrigation plot received one of six different irrigation treatments every two days, equaling seven repetitions of each irrigation depth. The depth applied to each sector was based on a percentage of ET_c for rice. The reduction in ET_c for rice was attributed to the reduction in plant size and root system. The daily ET_c for rice was back calculated, using the Penman-Montieth (PM) method for sub-humid climates, with adjusted crop coefficients for K_c initial, K_c mid, and K_c end taken from Tyagi et al. (1999) to determine if the total water applied through the selected irrigation schedule and rainfall exceeded, or was less than the seasonal total requirement for the rice crop.

The variable rate program used to control the irrigation system (Valley Manufacturing, Inc.) limited water application to increments of 10% with 100% being the maximum depth applied. An irrigation frequency of every other day was selected due to system limitations. The VRI software can store one irrigation layout (fig. 4.13). Changing the irrigation layout within the software required design software supplied by Valley Manufacturing, Inc. and hardware to transfer the layout from a portable CPU to the irrigation panel. This limitation required a singular irrigation frequency, which would not require persistent layout changes. An every-other-day irrigation frequency required an application depth of 13 mm to be applied as a baseline, to ensure one treatment was applying as close to the estimated daily water requirement for rice, 6.5 mm-d^{-1}. To acquire one treatment of 13 mm, 16 mm was selected as the 100% application depth. Table 4.4 lists the application percentage and the corresponding depth for each irrigation treatment applied to the rice using VRI.

To ensure each irrigation treatment was applied to nearly equal percentages of each sand class, a spreadsheet was created to sort and randomize the treatments across each concentric ring using the random number generator in Microsoft Excel. Each sand class was summed to determine the number of data points for each sand class within each treatment. The spreadsheet was randomized until each treatment was applied to approximately equal percentages of each sand class. Figure 4.13 shows the layout produced from the randomization spreadsheet for each irrigation treatment on the east half of the Marsh Pivot.

Table 4.4: Application percent and corresponding irrigation depth for each variable rate irrigation treatment, Marsh Pivot.

Treatment	Application (%)	Irrigation Depth (mm)
1	50	8
2	60	10
3	70	11
4	80	13
5	90	14
6	100	16

The sprinkler zones of equal areas were laterally divided along the length of the pivot and are non-adjustable. Table 4.5 lists the distance from the pivot point to the beginning and end of each sprinkler zone. In an attempt to limit the impacts of mechanical malfunctions with individual sprinkler heads, each sprinkler zone contains one area for each treatment (fig. 4.13). With this arrangement, should there be a mechanical issue with an individual sprinkler, each treatment within the zone will be subjected to the resulting change in application depth, and any biased yields toward one treatment or another from such a malfunction should be minimized (fig. 4.13). The equipment and system parameters determining the radial irrigation zones are found in Appendix H (Valley Manufacturing Inc.).

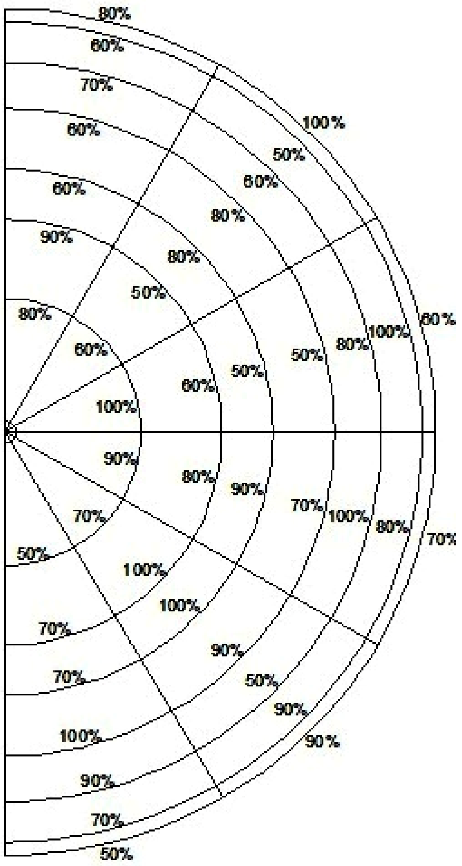

Figure 4.13: Variable rate irrigation treatment layout for the east side of the Marsh Pivot.

Table 4.5. Beginning and ending distance from the center-pivot for each sprinkler zone (equal areas).

Sprinkler Zone	Beginning Distance From Pivot (m)	End Distance From Pivot (m)
1	4.2	48.7
2	51.5	79.3
3	82.1	98.8
4	101.4	122.2
5	124.8	140.0
6	142.6	155.6
7	158.0	163.2

4.1.4 Yield acquisition and processing

Rice was planted in a circular pattern and was harvested in October 2010 in a circular pattern, and recorded using an AgLeader PF3000 yield monitor on a one-second interval. The AgLeader PF3000 is a universal GPS compatible crop monitor. The monitor is capable of recording the following harvest parameters in real time: acres, moisture, grain weight, bushels and yield (AgLeader, 2002). Yields outside of the third tower (distance of 156 m from the pivot point) were unusable in the study. A distance of 9 m was removed from the analysis of each treatment prior to statistical analysis at the boundary of each treatment because of irrigation overlap by one-half of a sprinkler's wetted diameter (4.5 m). The area within the annulus outside of the third tower was too small after the removal of the 9 m buffer zone to provide enough yield data points for statistical analysis.

The yield monitor raw data were screened for errors using the Yield Editor program (developed by Sudduth and Drummond, 2007). Yield Editor simplifies the process of applying filters to remove yield data outliers for entire data sets and allows for manual selection of individual points or regions of data for investigation or possible removal (Sudduth and Drummond, 2007). Yields were then kriged to a 3-m grid corresponding with sand content data (fig. 4.14). This process resulted in over 2400 gridded data points for analysis.

Figure 4.14: Yield data from 2010 kriged to a 3-m grid corresponding with sand content data from 2002.

Using SAS, three analyses were performed on the acquired yield data. The first analysis was the analysis of variance (ANOVA) for each sand class. This analysis generated a mean yield for each treatment to enable the comparison of yields from each treatment on each sand class. The second analysis was the analysis of covariance (ANCOVA) across all sand classes, using sand percentage as a covariant. This analysis generated a mean yield for each treatment across all sand classes. Covariance combines the features of a variance analysis with regression. The regression occurs on a continuous variable (sand percentage), and the variance analysis occurs on a class variable (treatment). This allows for the effects of each irrigation treatment on the dependent variable (yield) to be adjusted for differences in sand directly, rather than through many analyses for each sand quartile. This method reduces the 95% confidence interval making each mean yield more representative of the treatment mean yield. The final analysis was a regression analysis for both treatment and sand percentage. This analysis generated a mean yield with treatment and sand percentage as independent variables. The SAS code used for each analysis can be seen in Appendix B.

4.2 Results & discussion

4.2.1 Water application depths & analysis

Irrigation began on May 27, 2010, during the vegetative growth stage with an application depth of 8 mm to prevent crop burn up due to limited rainfall during the end of May. An application depth of 8 mm was selected because it was estimated to be the daily ET for rice. All sectors received the same irrigation depth due to the late implementation of the variable rate irrigation control system. Irrigation continued to be applied to all sectors at 100% until June 21, 2010; at which point the variable rate irrigation control program was installed (Valley Manufacturing, Inc.).

A depth of 22 mm was selected as the panel irrigation value and was irrigated every other day. At 22 mm, irrigated every other day, the ET for rice was being applied between application percentages 70% and 80 %, 15 mm and 17 mm respectively. After consulting with Dr. Earl Vories, with the United States Department of Agriculture (USDA), it was determined the ET requirement for rice was approximately 20% less than 8 mm-d^{-1}. The new ET value for rice was estimated at 6.5 mm-d^{-1} (or 13 mm every other day). To apply a range of irrigation depths both greater than and less than 13 mm, 16 mm was selected as the panel value for the irrigation schedule. As shown in tab. 4.4, 13 mm was irrigated as 80% of the panel value. A depth 16 mm was used as the panel value until July 27, 2010. On July 27, 2010, lighting strikes in the area associated with a severe thunderstorm damaged the global positioning equipment. The system malfunction was first recorded on July 28,

2010. The global positioning equipment was first observed reporting the pivot position an additional 60° clockwise from the actual pivot position (i.e. when located at 0° the global positioning system was reporting a position of 60°). Procedures were taken to adjust the system to account for the 60° discrepancy, to enable irrigation to continue for the rice on July 29. On July 29, subsequent observations indicated the global positioning equipment was reporting a pivot position an additional 130° clockwise from the actual position. The variable rate system was then shut down to limit any uncertainty being injected into the irrigation schedule. The pivot was split with corn in 2010, and to prevent any water shortage damage occurring to the corn or rice, the ET for corn was used to irrigate the entire pivot on July 31 and August 2. The ET value for corn was selected because it was greater than the ET for rice. Repairs could not be completed until August 3, 2010 (the system malfunction occurred between the booting and heading phases within the reproductive stage for rice), after which VRI continued until September 6, 2010.

Conventional flood irrigation for rice requires the drainage of the flood waters to facilitate the application of fertilizers and fungicides during the growing season. Using center-pivots to irrigate rice allows for irrigation to continue while applying any chemigation or fertigation required to support the rice crop. Using an injection pump, chemicals (fertilizers or fungicides) were injected into the water stream from a portable holding tank. A constant irrigation depth was used to select the injection rate required to apply the desired volume of chemical to the rice field. Chemigation (injecting fungicides into the water stream of the center-pivot) was applied once through an application depth of 3 mm non-VRI on July 27, 2010. Fertilizer was applied through fertigation, (injecting liquid ammonia into the water stream of the center-pivot) through an application depth of 5 mm non-VRI. After fertigation a second pass was made across the field using a panel depth of 10 mm using VRI. This practice ensured the crop received its required every other day water requirement, but allowed for uniform fertilizer application. This occurred five times during the growing season (June 29, July 7, July 14, July 19 and July 23) to ensure the rice crop was receiving the recommended nitrogen to support proper plant functions. A series of fertigations (five) was utilized for nitrogen application during the grain filling stages, because during this growth stage any reduction in nutrients or water can significantly impact yields. Appendix G details the date of each rainfall event, fertigation, chemigation and irrigation applied to the east half of the Marsh Pivot in 2010 to support the production of rice.

Irrigation is required to meet the water requirements of rice. Based on the PM method, total ET_c for rice during 2010 was 666 mm and rainfall was 147 mm. Two treatments exceeded the ET_c requirement for rice (100% and 90%), one treatment supplied the ET_c for rice (80%) and three treatments (70%, 60% and 50%) were insufficient to supply the required water for ET_c (fig. 4.15). The range for irrigation depths and deficits for each treatment percentage can be seen in tab. 4.6. The combination of irrigated water and rainfall created a surplus of applied water for two treatments, but a deficit remained for three treatments.

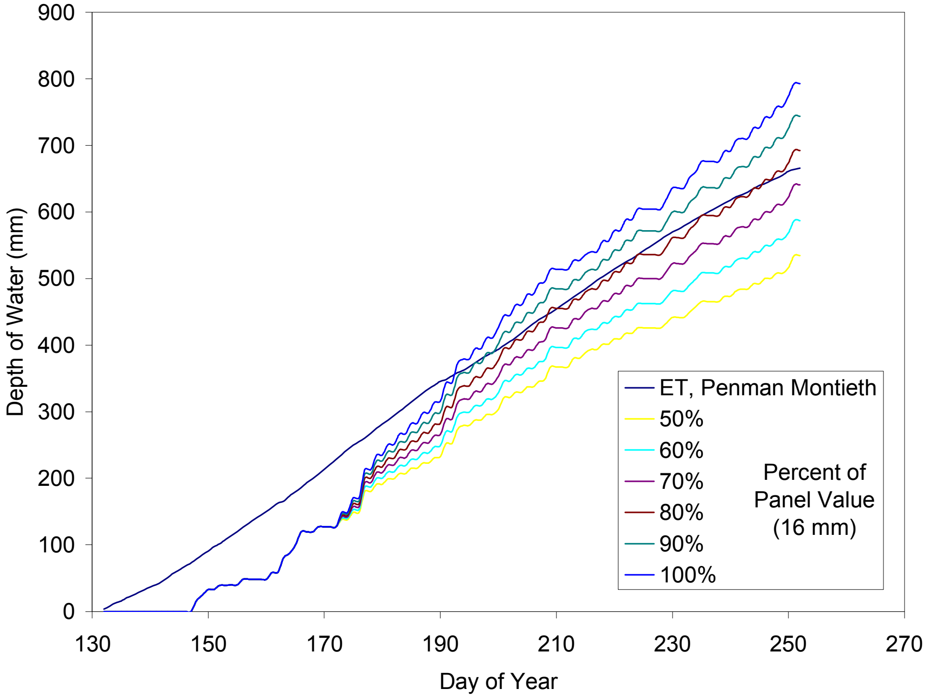

Figure 4.15: Irrigation and rainfall water for each treatment and its relationship with ET_c for rice (beginning May 13, 2010).

Table 4.6: Irrigation and rainfall, irrigated water applied, and water surplus versus ET_c for rice, 2010.

Irrigation Treatment Depth (%)	Irrigation and rainfall (mm)	Irrigated water (mm)	Surplus (mm)	Total ET rice
50	535	388	-131	666
60	587	440	-79	666
70	640	493	-26	666
80	692	545	26	666
90	744	597	78	666
100	793	646	127	666

4.2.2 Yield summary (2010)

Over all sand classes an irrigation treatment of 16 mm resulted in the greatest yields; with SC_H and 16 mm producing the greatest yield, 12290 kg-ha^{-1}. However, through a variance and covariance analysis there was always another irrigation treatment not significantly different from the 16 mm irrigation treatment (tab. 4.7).

The overall mean yield for each irrigation treatment, without dependence on sand class, showed a linear increase in mean yield as irrigation depth increased. From this analysis, it is likely the most efficient irrigation depth was not tested because a plateau in yield is not observed. As irrigation depths increase, the mean yields should reach a plateau if all other variables remain constant. However, this is unlikely to happen due to the uncontrolled environment of the study area. Through this analysis, a treatment of 16 mm resulted in the greatest mean yield (10150 kg-ha^{-1}) and was significantly different from all other treatments (fig. 4.16 and tab. 4.7).

For SC_L an irrigation treatment of 16 mm resulted in the greatest mean yield, but it was not significantly different from irrigation treatments 8, 10, or 14 mm. Because of the low sand content for $SC_{L,}$ the water holding capacity of the soil should have been acceptable for all irrigation treatments. However, because treatments 8 mm and 10 mm provided less water than the ET requirement for rice, these treatments should have produced yields significantly less than and different than treatment 16 mm. Some factor other than water availability and soil texture either elevated the yields for treatments 8 mm and 10 mm or decreased yields for the 16 mm treatment (fig. 4.17).

For SC_M, irrigation treatment 16 mm resulted in the greatest yield, but was not significantly different from irrigation treatment 13 mm. The least productive irrigation treatment was 11 mm, which was also significantly different from all other irrigation depths (fig. 4.18). An analysis of the yield map for rice (fig. 4.19) showed one location, in sector 1 (4^o to 34^o) zone 5, 11 mm (70%) resulted in a low yield with a major portion of SC_M. This sample of yield may be skewing the mean yield down, as indicated by the greater 95% confidence interval for a treatment of 11 mm. An explanation for this anomaly was not apparent, but may be a combination of weed pressure and an unknown factor. (Weed pressure was present throughout the rice field but individual weed locations were not recorded). Because of the major portion of SC_M in this location and the surrounding zones do not show an indication of sprinkler malfunction, these two factors were eliminated.

The greatest yield occurred on SC_H with an irrigation treatment of 16 mm. A maximum yield of 12,290 $kg\text{-}ha^{-1}$ was recorded; however, this mean yield was not significantly different from the mean yield with treatment 13 mm. Irrigation treatments between 8 mm and 11 mm resulted in mean yields not significantly different from each other, but which were significantly less than all other treatments. On a high sand class there was an increase in percolation. Irrigation depths 8 mm to 11 mm may not have provided enough water to counter the plant uptake rate and percolation rate of the water (fig. 4.20).

Sand class very high (SC_{VH}) resulted in varying mean yields. The greatest mean yield for SC_{VH} resulted from an irrigation depth of 16 mm, but was not significantly different from treatment 13 mm. The least mean yield was also reported on $SC_{VH,}$ and it occurred with an irrigation depth of 8 mm. However, it was not significantly different than mean yields from treatment 10 mm (tab. 4.7 and fig. 4.21). An analysis of the yield map for rice (fig. 4.19) showed one location, in sector 1 (4^o to 34^o) zone 5, 11 mm (70%) resulted in a low yield with a major portion of SC_M.

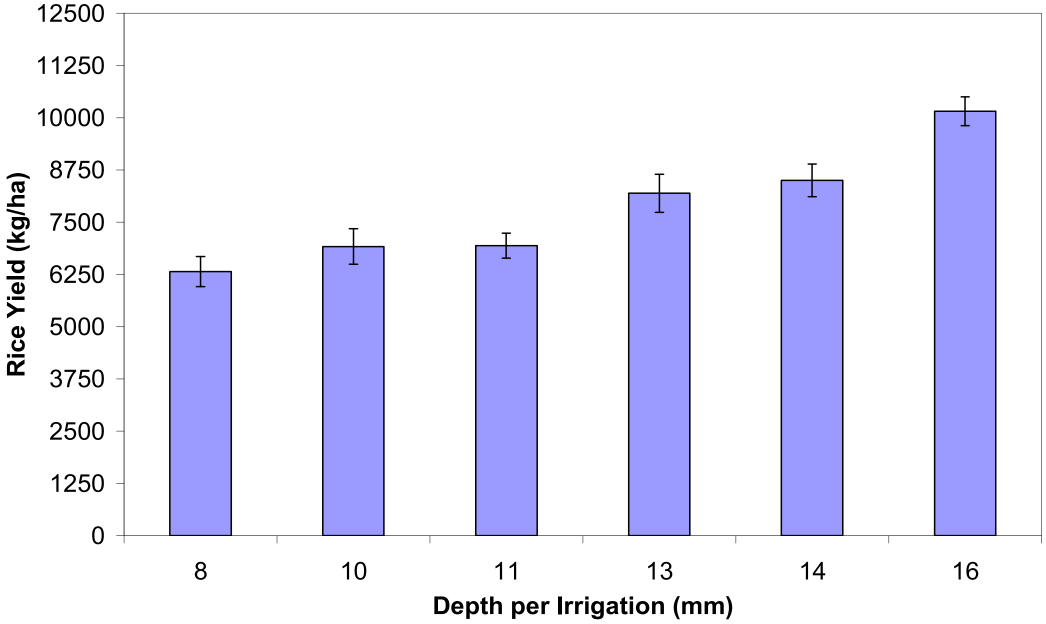

Figure 4.16: Mean yield for each treatment not dependent on sand class; error bars represent the 95% confidence interval, 2010.

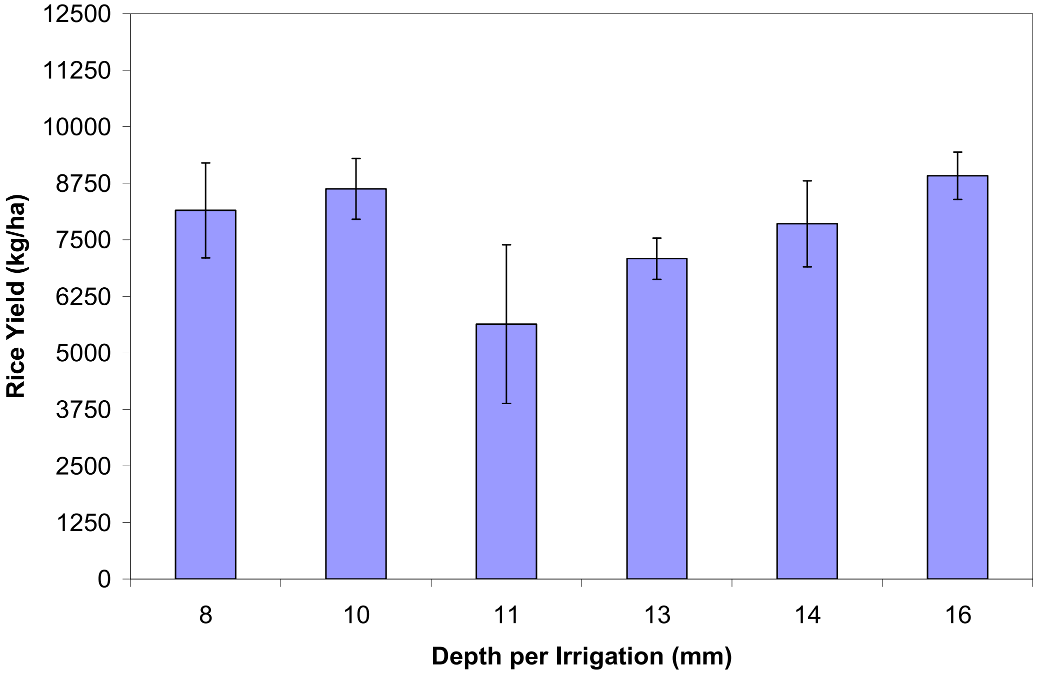

Figure 4.17: Mean yield for each treatment on SC_L (0 to 48%); error bars represent the 95% confidence interval, 2010.

For the covariance analysis, treatments 13 mm and 16 mm resulted in the greatest mean yields and were significantly greater than all other treatments. Irrigation treatments less than 13 mm were significantly less than all other treatments (tab. 4.7). Table 4.7 summarizes the mean yield for each treatment on each sand class, as well as the water use efficiency (WUE) for each treatment as it pertains to the overall yield mean of each treatment.

Water use efficiency was calculated by dividing the mean yield from the covariance analysis for a given treatment by the total irrigated water for that treatment. The water use efficiency for all treatments was low (approximately 1 kg-ha^{-1}mm^{-1}). However, irrigation treatment 13 mm (equal to the ET for rice, 6.5 mm-d^{-1}) did produce the greatest WUE, 1.3 kg-ha^{-1}mm^{-1}. The resulting water use efficiencies were expected, due to the high water requirement for the production of rice. The WUE pattern follows the mean yield pattern observed in fig. 4.22 for an analysis of covariance. When mean yields decreased, WUE decreased and when mean yields increased, WUE increased.

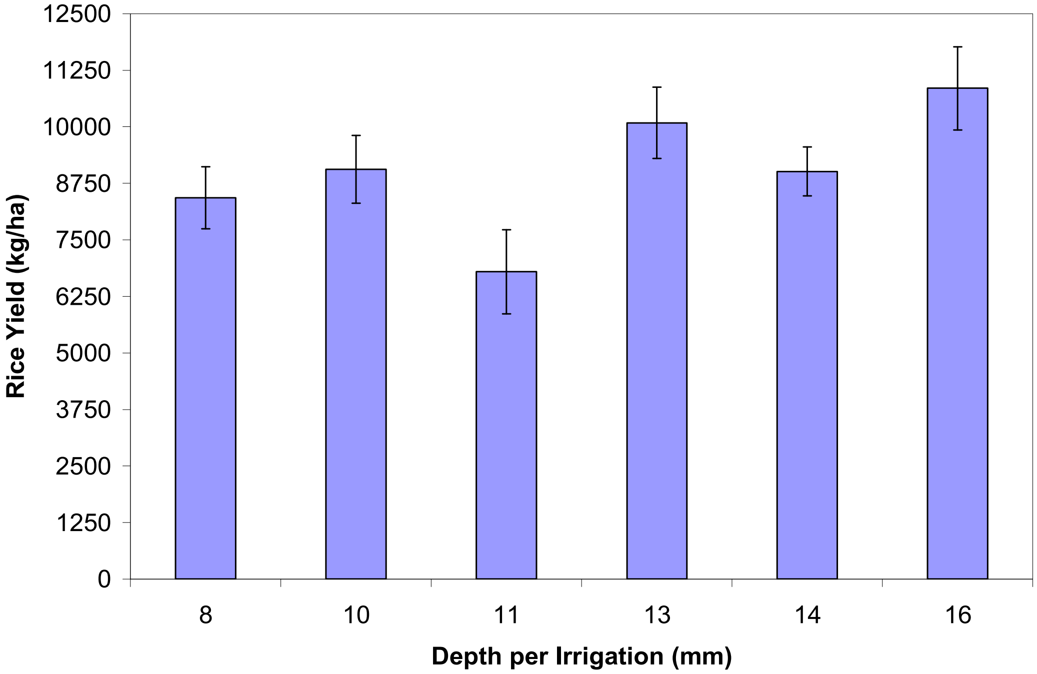

Figure 4.18: Mean yield for each treatment on SC_M (48 to 64%); error bars represent the 95% confidence interval, 2010.

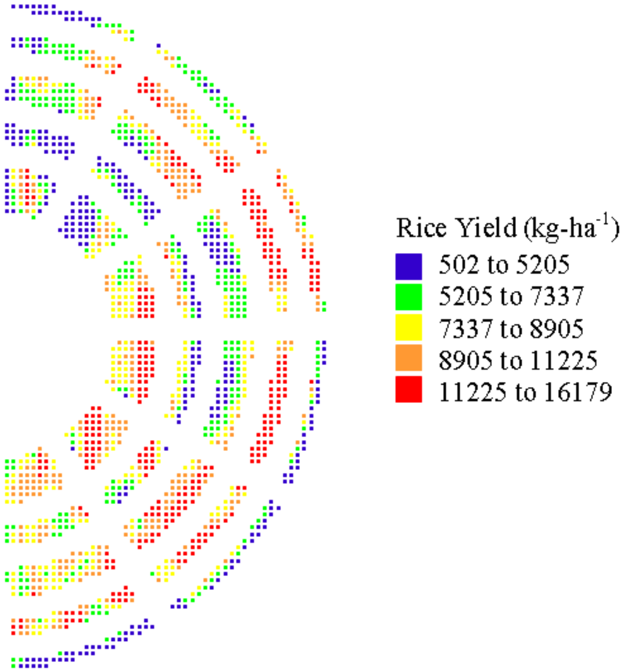

Figure 4.19: Yield map for rice cultivation on the east half of the Marsh Pivot, 2010.

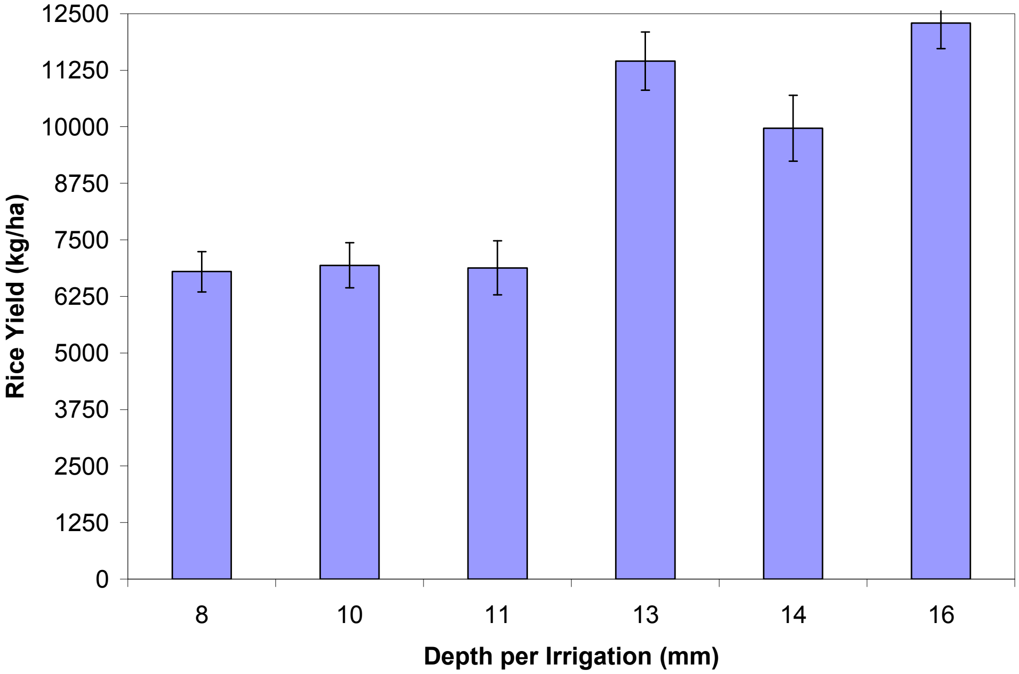

Figure 4.20: Mean yield for each treatment on SC_H (64 to 77%); error bars represent the 95% confidence interval, 2010.

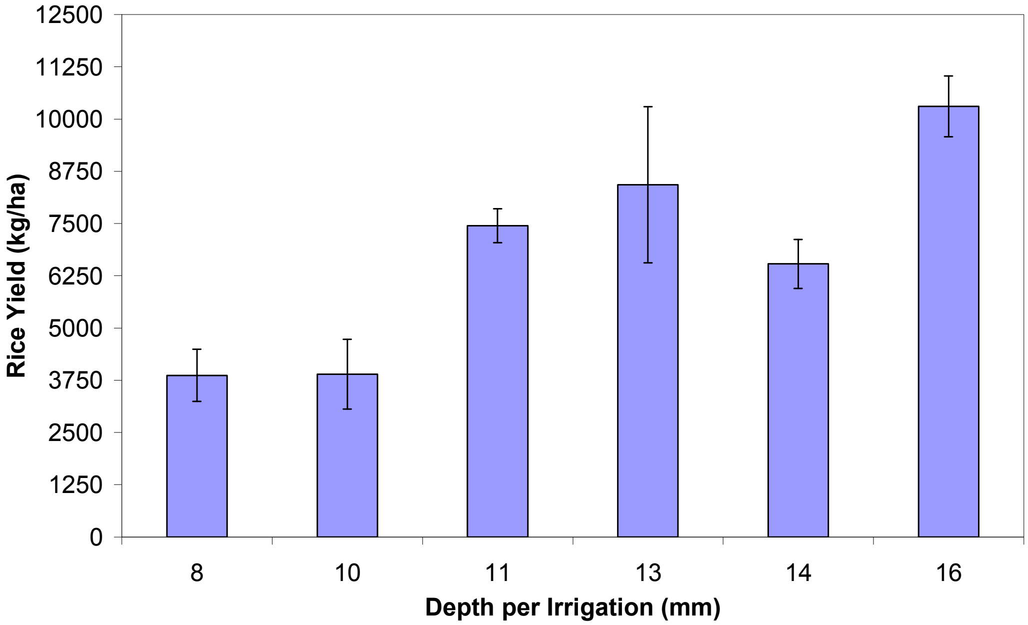

Figure 4.21: Mean yield for each treatment on SC_{VH} (77 to 100%); error bars represent the 95% confidence interval, 2010.

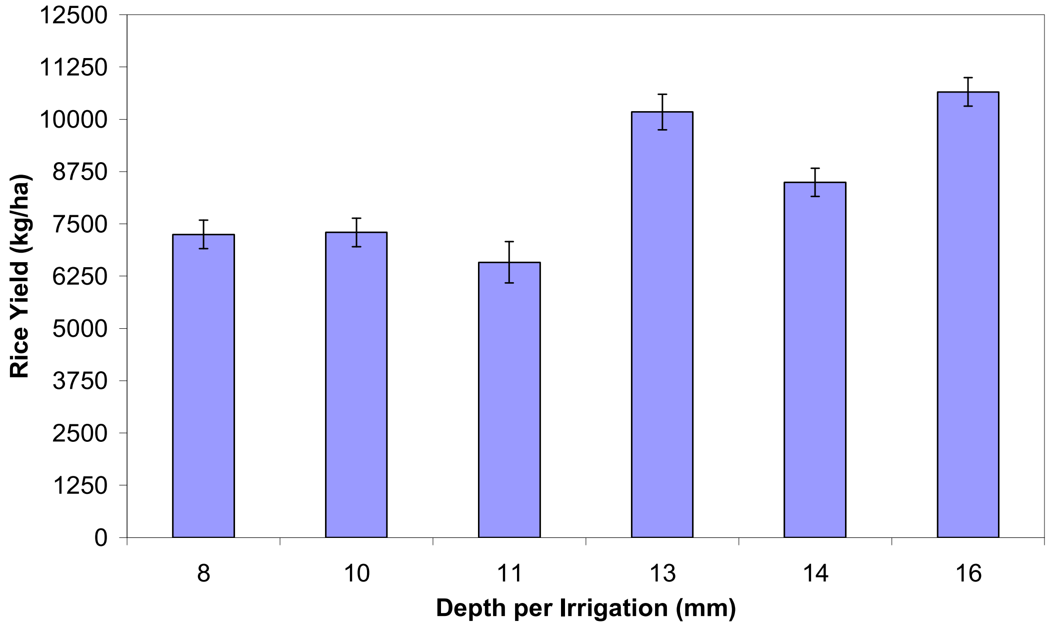

Figure 4.22: Mean yield for each treatment as a covariance over all sand classes; error bars represent the 95% confidence interval, 2010.

Table 4.7: Mean yield (kg-ha^{-1}) for each sand class and the resulting WUE for mean yield (analysis of covariance).

Treatment (mm)	Analysis of Covariance	Analysis of Variance					Total Water Depth (mm)	WUE (kg-ha^{-1}mm^{-1})
		Overall Mean	Sand Class L	Sand Class M	Sand Class H	Sand Class VH		
8	7240^{a}	6310^{a}	8150^{ac}	8420^{a}	6800^{a}	3870^{a}	622	1.2
10	7290^{a}	6910^{a}	8620^{s}	9060^{ab}	6930^{a}	3890^{a}	672	1.1
11	6580^{a}	6930^{a}	5640^{b}	6790^{c}	6880^{a}	7450^{b}	725	0.9
13	10170^{b}	8190^{b}	7080^{bc}	10080^{bd}	11450^{bc}	8430^{bc}	777	1.3
14	8490^{c}	8490^{b}	7850^{ac}	9010^{ab}	9960^{b}	6530^{b}	829	1.0
16	10650^{b}	10150^{c}	8920^{a}	10850^{d}	12290^{c}	10300^{c}	880	1.2

Lettering indicates significant difference on a 95% confidence interval

4.2.3 Applied water & yield analysis summary

Rainfall for the 2010 growing season was insufficient to support rice production without irrigation. After May 20, 2010, rainfall was recorded on average every 3.2 days with a depth often less than 5 mm or greater than 12 mm; even for rainfall events greater than 12 mm, 3.2 days is too infrequent. Depending on the intensity and infiltration rate, rainfall events with depths greater than 12 mm, a portion of the rainfall may be lost to runoff or post-rainfall evaporation. For rainfall events less than 6.5 mm, the depth applied is insufficient to replace the amount of water used by the crop (approximately 6.5 mm-d^{-1}). During rainfall events of high intensity, the force of droplets when impacting the surface of the soil may compact the soil particles, effectively sealing the soil surface by reducing the pore spaces between soil particles and preventing infiltration. Figure 4.23 depicts the daily rainfall depth for a given day of the year between May 15 and September 15, 2010. Rainfall prior to May 20 was likely not utilized by the plants, and thus not included in the total effective precipitation because the crop had only emerged seven days prior and was not fully established in the soil media. An applicable rainfall depth for crop production was thus 174 mm for 2010. The maximum number of days between rainfall events was 12 for 2010. Appendix H provides a summation of each rainfall event between May 15 and September 15, 2010.

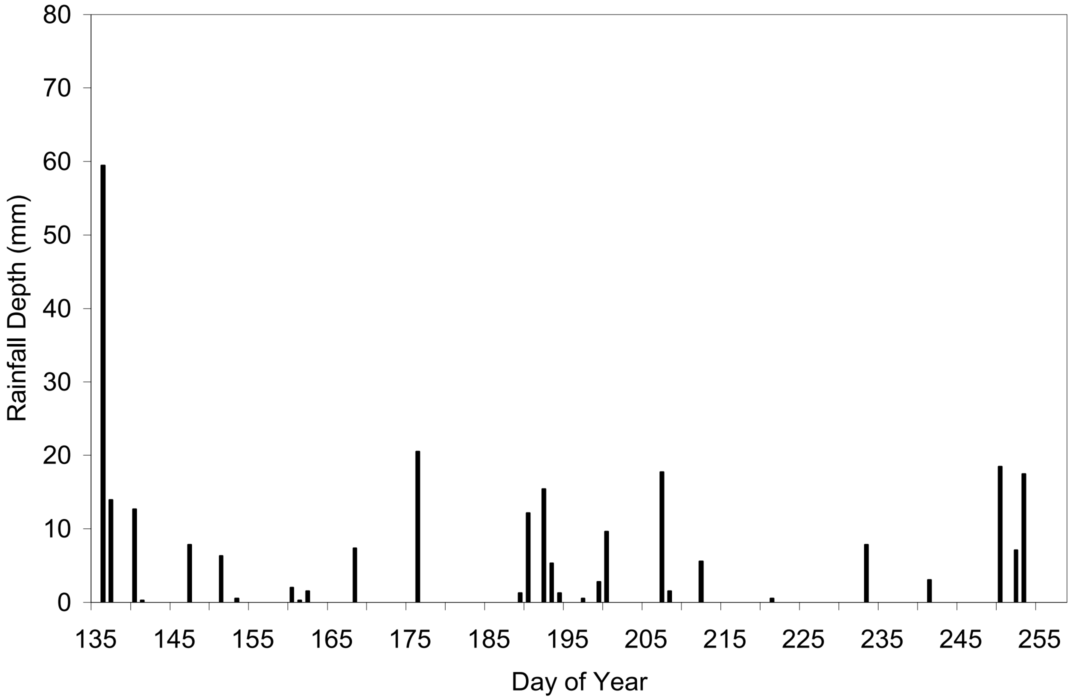

Figure 4.23: Rainfall depth for day of year 135 (May 15, 2010) through 258 (September 15, 2010).

The goal of this study was to determine the applicability of center-pivot irrigation on rice as a means of conserving water in comparison to flood irrigation. A secondary goal was to determine the irrigation depth to be applied to rice through center-pivot irrigation to produce the greatest yield possible on a non-uniform soil.

To adjust the depth of water applied, the center-pivot used pulsating sprinkler heads to reduce the volume of water being applied to all irrigation zones less than 100%. The pivot speed was determined by the pivot panel depth (100%). When applying larger volumes of water, a slower speed forced water to be applied for a longer duration but not at an increased intensity. The longer duration may have kept water in the root zone of the rice (maximum of 40 cm to 100 cm) even with losses to percolation, allowing the plant more time to utilize the water. The infiltration rate was possibly great enough to allow infiltration to prevent evaporation of a large volume of applied water, but slow enough to allow the rice to utilize the water.

Mean yields for the variance analysis on each sand class and the covariance analysis tended to follow a similar pattern. A rise in mean yields was observed for irrigation treatments 8 mm to 13 mm, followed by a decrease in mean yields for irrigation treatment 14 mm, and completed by another rise in mean yields for irrigation treatment 16 mm for all analyses except for the variance analysis on SC_L (fig. 4.24) (as shown as a grouped bar graph for each mean yield data point). Sand class low shows a decrease in mean yields for an increase in irrigation depth from 10 mm to 11mm every other day. Following the decrease a consistent rise in yield was observed as irrigation treatment depth increased.

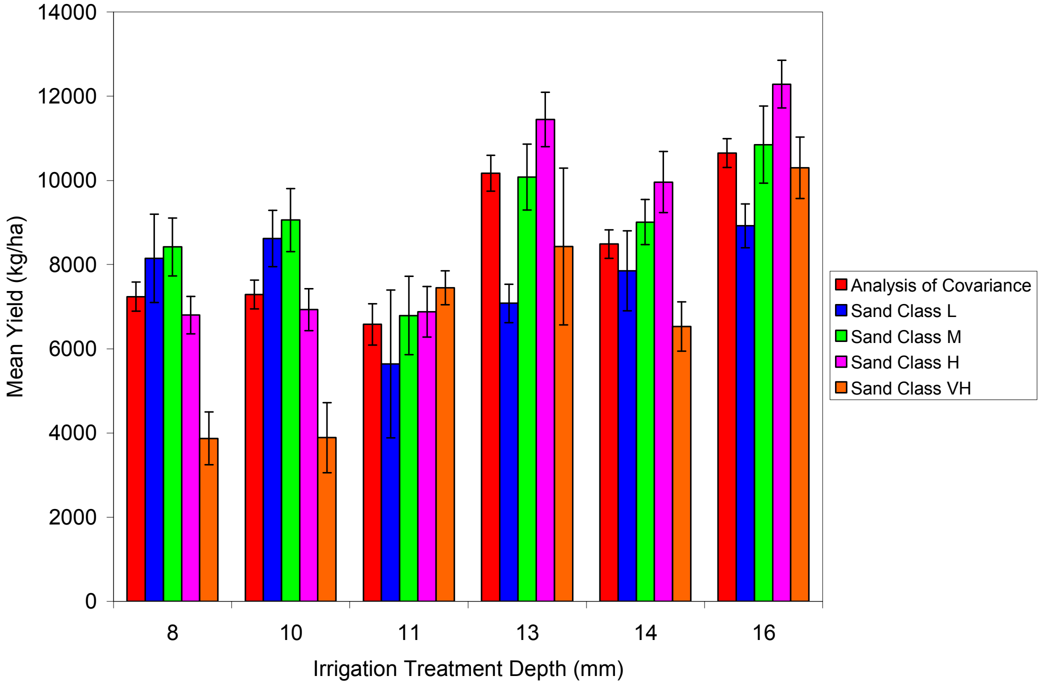

Figure 4.24: Trend for mean yields from variance and covariance analyses for 2010 rice production.

However, mean yields for irrigation treatment 11 mm tended to vary greatly between sand classes. A second anomaly was the increase in mean yields for irrigation treatment 13 mm. For sand classes SC_M, SC_H, and $SC_{VH,}$ mean yields for treatment 13 mm were not significantly different from mean yields for irrigation treatment 16 mm. A potential explanation for this anomaly is the location of each 13 mm and 16 mm treatment within the irrigation layout. All but 2 repetitions for 13 mm and 16 mm resided next to each other with a major congregation along the 90^o azimuth (fig. 4.13). This region is also encompassed by a large portion of the three sand classes indicated above. Due to the location of the irrigation treatments, it was possible for irrigated water to have been transferred between treatments (either by wind dispersion, localized surface flow, or sprinkler overlap not removed by the 9 m buffer zone).

Using a regression analysis, the best fit line for 2010 yields versus irrigation treatment was a 2^{nd} order quadratic equation (eq. 4.2). By differentiating this equation and finding the root, the percentage of 16 mm to produce mean yields following the above patterns was obtained. (In these equations, x is the treatment depth in mm and y is the mean yield in $kg\text{-}ha^{-1}$.) (The R^2 value for equation 4.2 and was 0.13. This indicates a low correlation in the data set.)

$$y = 11538x^2 - 10099x + 8578.4 \qquad (4.2)$$

The results of this analysis can be used when determining a minimum irrigation depth required for the variable rate system to produce similar mean yields. For mean yields from 2010, this percentage of 16 mm was 44%, or 7 mm.

To determine the impacts of the sand content of the soil on the yield, the kriged sand and yield data points are charted and fitted with a best fit second order quadratic equation (fig. 4.25). By differentiating the equation and finding its root a maximum of 49%, sand will produce the greatest mean yield. For sand contents greater than 49%, yields decreased regardless of irrigation depth. This peak may shift for individual sand classes, but for non-research applications it would be easier to irrigate an entire field based on a single mean sand percentage and irrigation treatment. While the R^2 for the relationship between yield and percent sand is low ($R^2 = 0.1363$), it is acceptable for data outside of a laboratory controlled setting. Further, additional years of study may be able to refine this value.

For soil textures with sand greater than 49%, water was unlikely to be maintained in the root zone long enough for crop utilization due to greater infiltration rates for soils with textures higher in sand. This would result in significant yield reductions of treatments 8, 10, and 11 mm, when compared to treatments 13, 14, and 16 mm. For the three former treatments, the supplied volume of water may not have been great enough to counteract the percolation of water through the soil profile.

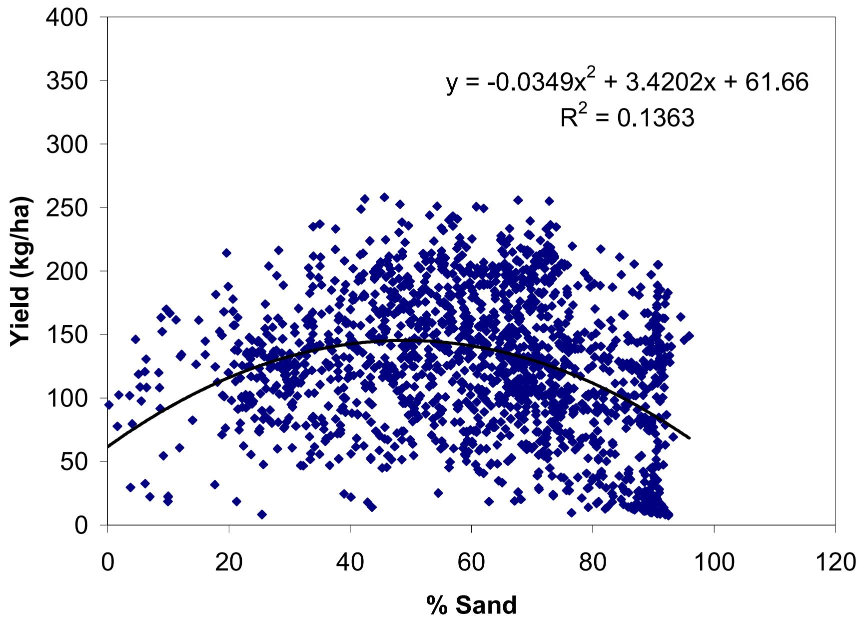

Figure 4.25: Relationship between percent sand and rice yield on the Marsh Pivot (2010).

In comparison to the mean yields from conventional flood irrigation (average of 7040 kg-ha^{-1}) resulting from the three year study conducted by Vories et al. (2002), this study resulted in mean yields greater than those for conventional flood irrigation for irrigation depths greater than 11 mm irrigated every-other-day for a non-uniform soil texture. The required water to ensure proper crop growth under center-pivot irrigation was significantly reduced to produce mean yields equal to, or greater than conventional flood irrigation (666 mm vs 1200 to 1600 mm). However, the results from this study indicate the optimum irrigated depth to be applied on an every other day frequency for the production of rice was not tested during the 2010 growing season. An over application of water will be indicated by a decrease or plateau in yield following a significant increase in yield. As indicated by fig. 4.16, the peak irrigation treatment had not been reached since a plateau or decrease in yield was not present in the mean yield regardless of sand class.

Figure 4.14 indicates an over irrigation for 90% (14 mm) and 100% (16 mm) of ET_c based on crop coefficients from Tyagi et al. (1999) and ET_o from the PM method. However, because there was not a plateau or decrease in yield from over irrigation, two possible scenarios arise to account for the over irrigation. A first possibility is the crop coefficients from Tyagi et al. (1999) are not accurate for local climatic conditions in southeastern Missouri. Larger crop coefficients will increase the ET_c curve in fig. 4.14. An equal increase of 0.22 for each crop coefficient would be required to indicate under irrigation (fig. 4.26).

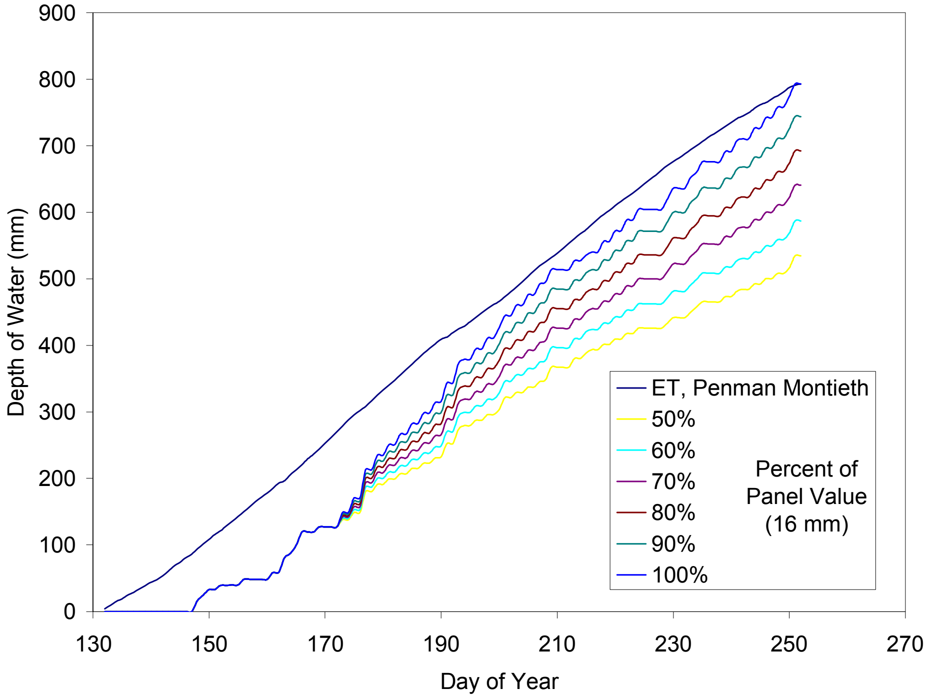

Figure 4.26: Total applied water and its relationship with ET_c for rice with crop coefficients increased by 0.22 (ET_T = 793 mm).

The second possibility to explain the presence of over irrigation in fig. 4.14 was the non-uniform soil textures on the east half of the Marsh Pivot. For the east side of the pivot, 67% of the soils have a sand content of 48% or greater (tab. 4.3). Table 2.1 indicated infiltration rates of 25 and 50 mm-hr^{-1} for sandy and sandy loam soils, respectively. The pivot operates at an application rate of 23 mm-hr^{-1}. The pivot application rate indicated water from treatment 100% would only be available for plant utilization for 0.9 hr (55 min) for a sandy loam soil and 0.5 hr (30 min) for sandy soils, assuming all applied water drains freely through the profile if it is not used by the plant. This assumption is not correct because of the attraction between the negatively charged soil particles and the positively charged dipole of the water molecule. However, outside of a laboratory setting, the volume of water maintained in the profile remained unknown.

Changes in soil texture and irrigation treatment simultaneously affected the rice yield for the Marsh Pivot. However, there were several observations made from the surface function generated by the yield, treatment, and soil sand content on the Marsh Pivot (fig. 4.27).

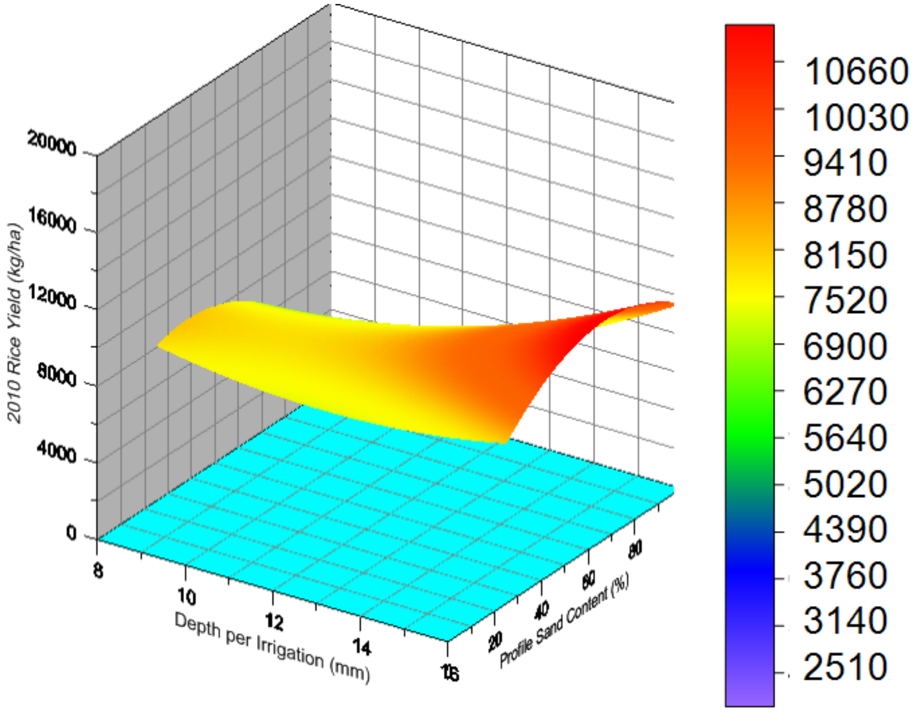

Figure 4.27: Three dimensional surface plot for the interaction between yield, irrigation depth, and percent sand (2010). Surface equation: $y = 239.51 - 400.78x + 219.83x^2 + 0.5944z - 0.02707z^2 + 3.0zx$. (Where x is the depth per irrigation, y is the mean yield, and z is the profile percent sand). Color scale units are for mean yield ($kg\text{-}ha^{-1}$).

The first prominent observation was the minimal change in yield for an increase in treatment depth for low sand contents. There appeared to be very little deviation or tilting of the surface map for low sand contents. The opposite was observed for the greatest sand contents on the Marsh Pivot. Depreciation in yield was observed for greater sand contents and shallower irrigation depths. However, the effect of the greater sand content appeared to be reduced for greater irrigation depths when the surface was observed from above the yield axis (fig. 4.28).

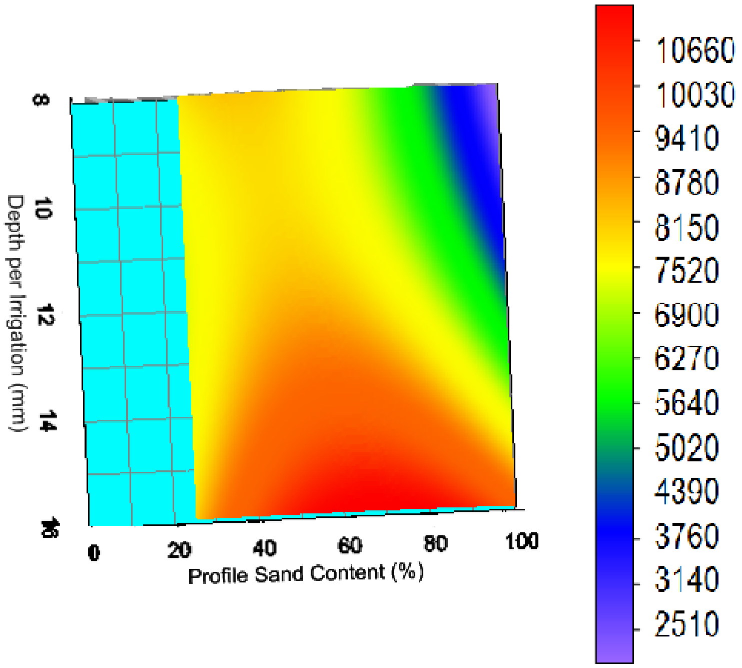

Figure 4.28: Surface plot for the change in yield as irrigation depth and sand content change (2010). Color scale units are for mean yield (kg-ha^{-1}).

From this angle, maximum yields appeared to increase as irrigation depth per set increased, but this was not consistent for a single sand content range. From fig. 4.28, the maximum yield transition was non-linear for a singular sand content. The maximum yield transition appeared to follow a slight increase in sand content as irrigation depth increased. From the second order quadratic equation from the best fit line in fig. 4.24, the maximum sand content of the soil to produce the maximum yield occurred at 49% with an irrigation treatment of 16 mm.

A potential explanation for the increase in yield as treatment depth and sand content increased was the reduction in weed pressure, due to increased water presence in the soil profile. By irrigating every second day, the soil's ability to dry out could have been reduced, thus allowing the water tolerant rice plant to thrive while limiting the growth other plant species. The other potential explanation was the larger irrigation depths reduced the impact of the percolation, due to greater pore space and reduced adsorptive capability of a sandy soil.

The observed consistent yield for low sand contents regardless of irrigation depth could potentially be the result of the soil's water holding capacity. For soils with lesser proportions of sand, there were increased proportions of negatively charged clay particles which attract the positively charged dipole of water molecules. These factors may have resulted in a decrease in percolation below the root zone of the crop. The reduction in yield observed for greater sand contents and shallower irrigation depths can be attributed to the low water holding capacity of the soil, and the total season irrigation depth from shallow irrigation treatment.

4.3 Conclusion

This study showed that VRI can be used to produce rice on non-uniform soils. However, the one year study did not indicate the irrigation treatment required to produce the greatest mean yields under a center-pivot system using an irrigation frequency of every-other-day, because a decrease or plateau from over irrigation was not present in the sample data. This conclusion also indicates the data does not support use of 6.5 mm-d^{-1}as the ET_c for rice. Further research into the ET_c for rice must be done prior to continuing this study to determine an appropriate range of irrigation depths.

For this study, the volume of water required to produce mean yields equal to yields produced via flood irrigation was less than the volume of water required for flood irrigation (from Vories et al., 2002). With a maximum total applied water depth of 788 mm (100% ET_c) for 2010, mean yields (covariance) were equal to or exceeded flood irrigation yields in the same geographic region (MO-AR Mississippi River flood plain). The absolute maximum yield per irrigation treatment was not found based on the irrigation treatments of this study because a plateau in mean yield from over irrigation was not observed. However, it is possible that 16 mm was the most beneficial treatment for rice production, based on the efficiency of the irrigation system utilized. If the most beneficial treatment is not able to be applied to an entire field within 48 hrs (time from the start of one irrigation cycle to the next) then the next best suited irrigation treatment should be utilized. Further research with increased irrigation depths may indicate a plateau in yield thus indicating the most beneficial irrigation depth.

The extended period of time (47 hrs or greater) between irrigations likely had an impact on the yields. Irrigating daily to determine the crop water requirements would reduce the time between irrigations on the sandy loam to sandy soils; increasing the time the crop root zone has available water. Further investigation is needed to determine the water requirements for rice under center-pivot irrigation with a focus on irrigation frequency.

For the Marsh Pivot, it was concluded from the best fit second order quadratic equation, the maximum yield can be produced on sand percentages up to 49%. For sand contents greater than 49%, yield reductions were recorded. It was also observed that for sand contents greater than 49%, irrigation depth must be increased to provide enough water to compensate for the increase in percolation.

There remains some uncertainty in the results due to agronomic and mechanical issues during the study. Field observations indicated variable weed pressure throughout the field due to ragweed. On one occasion, the attempted removal of weeds by hand reduced a portion of the weed population but was unsuccessful at eradication. Equipment malfunctions during the study may lead to some uncertainty in the yield results as well. As noted previously errors in the global positioning system from lightning strikes resulted in deviations from the selected irrigation schedule and may have influenced some yield results.

Chapter 5:

FUTURE RESEARCH

There are several opportunities for additional research in the areas of site specific or variable rate irrigation that do not fall within the scope of this project. These research topics of this study are explained in detail in Chapters 3 and 4. Additional opportunities for research are listed here:

1) Additional in-field study of variable rate irrigation may resolve inconsistencies in yields for individual treatments (greater than 8 mm) for the two year study for corn production under the center-pivot system.
2) Additional in-field study of variable rate irrigation to determine the irrigation treatment to produce the greatest yield for rice under a center-pivot system.
3) Utilizing varying frequencies for variable rate irrigation (ex: every day or every third day rather than every other day) may enable the determination of the most economical irrigation schedule (depth and frequency) for a non-research setting.

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
1A	29.63	1.9026	2.000	0.00	16.28	21.31	Si. Loam
	83.72	0.11	1.400	0.00			
	46.65	0.0613	0.500	8.28			
	34.93	0.0459	0.150	48.97			
	21.16	0.0278	0.053	42.76			
	21.31	0.028	remains				
		3.0780					
		5.2536					
1B	30.04	1.4689	2.000	0.00	36.15	14.63	Si. Loam
	63.85	0.0781	1.400	0.34			
	54.45	0.0666	0.500	5.39			
	38.83	0.0475	0.150	60.61			
	19.13	0.0234	0.053	33.67			
	14.63	0.0179	remains				
		3.1880					
		4.8904					
1C	25.85	1.4763	2.000	0.00	27.74	11.13	Si. Loam
	72.26	0.1032	1.400	0.00			
	59.45	0.0849	0.500	6.17			
	41.80	0.0597	0.150	50.66			
	8.61	0.0123	0.053	43.17			
	11.13	0.0159	remains				
		3.9580					
		5.7103					
1D	13.74	0.6389	2.000	0.00	23.39	20.89	Si. Loam
	76.61	0.0891	1.400	0.00			
	65.09	0.0757	0.500	3.39			
	50.38	0.0586	0.150	22.03			
	30.61	0.0356	0.053	74.58			
	20.89	0.0243	remains				
		3.7280					
		4.6502					
1E	19.01	0.9764	2.000	0.00	21.76	16.82	Si. Loam
	78.24	0.1005	1.400	0.00			
	53.56	0.0688	0.500	3.03			
	47.72	0.0613	0.150	39.90			
	22.66	0.0291	0.053	57.07			
	16.82	0.0216	remains				
		3.8780					
		5.1357					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
2A	91.15	6.1421	2.000	0.00	91.93	2.37	Sand
	8.07	0.0136	1.400	1.55			
	6.94	0.0117	0.500	31.46			
	1.66	0.0028	0.150	61.57			
	3.56	0.006	0.053	5.42			
	2.37	0.004	remains				
		0.5580					
		6.7382					
2B	91.26	14.2773	2.000	0.07	91.51	4.37	Sand
	8.49	0.0332	1.400	2.95			
	7.77	0.0304	0.500	36.96			
	7.13	0.0279	0.150	54.60			
	5.09	0.0199	0.053	5.41			
	4.37	0.0171	remains				
		1.2380					
		15.6438					
2C	88.94	12.895	2.000	0.00	89.63	2.90	Sand
	10.37	0.0376	1.400	1.18			
	8.96	0.0325	0.500	33.31			
	7.94	0.0288	0.150	59.19			
	4.63	0.0168	0.053	6.31			
	2.90	0.0105	remains				
		1.4780					
		14.4992					
2D	95.75	13.0648	2.000	0.00	96.06	0.88	Sand
	3.94	0.0135	1.400	1.30			
	3.21	0.011	0.500	30.88			
	2.66	0.0091	0.150	62.61			
	1.58	0.0054	0.053	5.21			
	0.88	0.003	remains				
		0.5380					
		13.6448					
2E	99.23	9.3083	2.000	0.00	93.86	4.86	Sand
	6.14	0.0144	1.400	3.61			
	5.97	0.014	0.500	40.71			
	5.54	0.013	0.150	52.93			
	5.07	0.0119	0.053	2.75			
	4.86	0.0114	remains				
		0.0080					
		9.381					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
3A	89.51	10.9608	2.000	0.00	91.64	1.76	Sand
	8.36	0.0256	1.400	0.18			
	5.42	0.0166	0.500	27.18			
	4.18	0.0128	0.150	62.99			
	2.08	0.0064	0.053	9.64			
	1.76	0.0054	remains				
		1.2180					
		12.2456					
3B	89.40	5.5097	2.000	0.00	83.52	1.30	L. Sand
	16.48	0.0254	1.400	0.26			
	18.23	0.0281	0.500	20.16			
	5.71	0.0088	0.150	68.92			
	0.58	0.0009	0.053	10.66			
	1.30	0.002	remains				
		0.5880					
		6.1629					
3C	91.31	11.5239	2.000	0.00	93.54	1.71	Sand
	6.46	0.0204	1.400	0.26			
	4.66	0.0147	0.500	30.69			
	3.55	0.0112	0.150	61.38			
	2.18	0.0069	0.053	7.67			
	1.71	0.0054	remains				
		1.0380					
		12.6205					
3D	96.17	13.7911	2.000	0.00	96.83	0.67	Sand
	3.17	0.0114	1.400	0.29			
	2.22	0.008	0.500	35.00			
	1.86	0.0067	0.150	60.57			
	0.95	0.0034	0.053	4.14			
	0.67	0.0024	remains				
		0.5180					
		14.341					
3E	98.03	11.2096	2.000	0.00	98.85	0.00	Sand
	1.15	0.0033	1.400	0.36			
	0.87	0.0025	0.500	29.95			
	0.56	0.0016	0.150	65.95			
	0.00	9.78E-16	0.053	3.74			
	0.00	-1E-15	remains				
		0.2180					
		11.435					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
4A	58.34	8.1432	2.000	0.00	63.58	7.91	S. Loam
	36.42	0.1275	1.400	0.25			
	28.51	0.0998	0.500	11.93			
	20.85	0.073	0.150	77.39			
	11.25	0.0394	0.053	10.43			
	7.91	0.0277	remains				
		5.4480					
		13.9586					
4B	53.98	5.5887	2.000	0.00	58.13	7.70	S. Loam
	41.87	0.1084	1.400	0.00			
	30.09	0.0779	0.500	9.36			
	22.21	0.0575	0.150	66.85			
	8.46	0.0219	0.053	23.78			
	7.70	0.02	remains				
		4.4780					
		10.3524					
4C	18.27	1.8096	2.000	0.00	22.12	21.03	Si. Loam
	77.88	0.1929	1.400	0.65			
	62.86	0.1557	0.500	6.45			
	47.96	0.1188	0.150	43.23			
	26.69	0.0661	0.053	49.68			
	21.03	0.0521	remains				
		7.5080					
		9.9032					
4D	13.88	0.6962	2.000	0.00	18.12	23.68	Si. Loam
	81.88	0.1027	1.400	0.00			
	63.30	0.0794	0.500	3.36			
	49.75	0.0624	0.150	42.95			
	29.10	0.0365	0.053	53.69			
	23.68	0.0297	remains				
		4.0080					
		5.0149					
4E	15.73	0.7738	2.000	0.00	25.31	21.46	Si. Loam
	74.69	0.0919	1.400	0.00			
	54.45	0.067	0.500	4.29			
	45.84	0.0564	0.150	22.86			
	37.55	0.0462	0.053	72.86			
	21.46	0.0264	remains				
		3.8580					
		4.9197					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
5A	79.43	7.6619	2.000	0.00	76.83	4.31	L. Sand
	23.17	0.0559	1.400	0.76			
	14.13	0.0341	0.500	24.24			
	9.66	0.0233	0.150	63.13			
	5.02	0.0121	0.053	11.87			
	4.31	0.0104	remains				
		1.8480					
		9.6457					
5B	77.74	4.4223	2.000	0.00	84.19	4.22	L. Sand
	15.81	0.0225	1.400	0.34			
	13.35	0.019	0.500	28.04			
	9.63	0.0137	0.150	57.99			
	4.85	0.0069	0.053	13.63			
	4.22	0.006	remains				
		1.1980					
		5.6884					
5C	63.23	9.2006	2.000	0.00	66.75	7.75	S. Loam
	33.25	0.121	1.400	0.57			
	24.67	0.0898	0.500	16.72			
	18.57	0.0676	0.150	53.13			
	10.11	0.0368	0.053	29.58			
	7.75	0.0282	remains				
		5.0080					
		14.552					
5D	47.58	5.9406	2.000	0.00	51.16	10.25	Loam
	48.84	0.1525	1.400	0.00			
	36.70	0.1146	0.500	5.93			
	26.74	0.0835	0.150	37.78			
	14.15	0.0442	0.053	56.30			
	10.25	0.032	remains				
		6.1180					
		12.4854					
5E	44.33	5.4214	2.000	0.00	48.65	9.39	Loam
	51.35	0.1575	1.400	0.00			
	36.51	0.112	0.500	2.04			
	26.60	0.0816	0.150	33.60			
	13.37	0.041	0.053	64.36			
	9.39	0.0288	remains				
		6.3880					
		12.2303					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
6A	67.52	5.6107	2.000	0.00	72.48	4.14	S. Loam
	27.52	0.0572	1.400	0.00			
	17.46	0.0363	0.500	3.06			
	13.18	0.0274	0.150	55.32			
	5.82	0.0121	0.053	41.62			
	4.14	0.0086	remains				
		2.5580					
		8.3103					
6B	70.79	4.5906	2.000	0.00	77.25	0.99	L. Sand
	22.75	0.0369	1.400	0.00			
	12.02	0.0195	0.500	4.91			
	8.63	0.014	0.150	60.58			
	2.47	0.004	0.053	34.51			
	0.99	0.0016	remains				
		1.8180					
		6.4846					
6C	43.64	5.2131	2.000	0.00	47.57	15.65	Loam
	52.43	0.1571	1.400	0.00			
	40.05	0.12	0.500	1.57			
	31.54	0.0945	0.150	76.47			
	18.99	0.0569	0.053	21.96			
	15.65	0.0469	remains				
		6.2580					
		11.9465					
6D	32.69	1.9507	2.000	0.00	39.90	17.96	Loam
	60.10	0.0897	1.400	0.00			
	50.39	0.0752	0.500	1.28			
	38.26	0.0571	0.150	39.30			
	19.97	0.0298	0.053	59.42			
	17.96	0.0268	remains				
		3.7380					
		5.9673					
6E	29.05	3.5175	2.000	0.00	33.62	16.97	Si. Loam
	66.38	0.201	1.400	0.00			
	47.16	0.1428	0.500	0.34			
	36.92	0.1118	0.150	18.09			
	21.47	0.065	0.053	81.57			
	16.97	0.0514	remains				
		8.0180					
		12.1075					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
7A	89.25	12.6307	2.000	0.16	92.31	1.38	Sand
	7.69	0.0272	1.400	1.68			
	5.51	0.0195	0.500	31.57			
	4.04	0.0143	0.150	56.35			
	1.89	0.0067	0.053	10.23			
	1.38	0.0049	remains				
		1.4480					
		14.1513					
7B	88.21	12.7215	2.000	0.00	90.41	1.49	Sand
	9.59	0.0347	1.400	0.52			
	5.83	0.0211	0.500	20.55			
	3.90	0.0141	0.150	67.76			
	1.94	0.007	0.053	11.18			
	1.49	0.0054	remains				
		1.6180					
		14.4218					
7C	90.72	11.4794	2.000	0.00	91.50	1.74	Sand
	8.50	0.0269	1.400	1.50			
	5.12	0.0162	0.500	40.37			
	6.00	0.019	0.150	51.77			
	2.88	0.0091	0.053	6.36			
	1.74	0.0055	remains				
		1.0980					
		12.6541					
7D	61.92	6.2652	2.000	0.00	66.02	7.43	S. Loam
	33.98	0.086	1.400	0.87			
	24.07	0.0609	0.500	21.45			
	17.55	0.0444	0.150	46.19			
	9.80	0.0248	0.053	31.49			
	7.43	0.0188	remains				
		3.6180					
		10.1181					
7E	55.80	6.6527	2.000	0.00	60.93	7.81	S. Loam
	39.07	0.1165	1.400	0.82			
	27.40	0.0817	0.500	18.60			
	19.42	0.0579	0.150	39.80			
	10.80	0.0322	0.053	40.78			
	7.81	0.0233	remains				
		4.9580					
		11.9223					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
8A	65.67	7.7954	2.000	0.00	70.70	6.82	S. Loam
	29.30	0.087	1.400	0.39			
	22.70	0.0674	0.500	12.70			
	17.48	0.0519	0.150	64.79			
	10.31	0.0307	0.053	22.12			
	6.82	0.0203	remains				
		3.8180					
		11.8707					
8B	64.47	6.6225	2.000	0.00	68.12	7.05	S. Loam
	31.88	0.0819	1.400	0.31			
	23.43	0.0602	0.500	14.09			
	17.40	0.0447	0.150	66.00			
	10.20	0.0262	0.053	19.60			
	7.05	0.0181	remains				
		3.4180					
		10.2716					
8C	40.71	2.8225	2.000	0.00	47.01	11.88	Loam
	52.99	0.0919	1.400	0.00			
	36.10	0.0626	0.500	7.88			
	23.30	0.0404	0.150	61.93			
	10.32	0.0179	0.053	30.20			
	11.88	0.0206	remains				
		3.8780					
		6.9339					
8D	30.28	3.5208	2.000	0.00	34.94	13.79	Si. Loam
	65.06	0.1892	1.400	0.00			
	48.45	0.1409	0.500	8.10			
	35.94	0.1045	0.150	48.60			
	18.26	0.0531	0.053	43.30			
	13.79	0.0401	remains				
		7.5780					
		11.6266					
8E	29.13	3.6537	2.000	0.00	33.69	14.21	Si. Loam
	66.31	0.2086	1.400	0.00			
	51.27	0.1613	0.500	7.69			
	37.38	0.1176	0.150	54.73			
	18.75	0.059	0.053	37.57			
	14.21	0.0447	remains				
		8.2980					
		12.5429					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
9A	78.26	9.6857	2.000	0.00	81.42	3.72	L. Sand
	18.58	0.0575	1.400	0.32			
	12.95	0.0401	0.500	18.52			
	9.14	0.0283	0.150	64.97			
	5.01	0.0155	0.053	16.19			
	3.72	0.0115	remains				
		2.5380					
		12.3766					
9B	76.18	9.3227	2.000	0.00	79.83	3.78	L. Sand
	20.17	0.0619	1.400	0.44			
	12.80	0.0393	0.500	17.11			
	9.48	0.0291	0.150	64.25			
	5.05	0.0155	0.053	18.20			
	3.78	0.0116	remains				
		2.7580					
		12.2381					
9C	48.49	2.908	2.000	0.00	56.39	11.40	S. Loam
	43.61	0.0654	1.400	0.78			
	57.94	0.0869	0.500	6.98			
	23.07	0.0346	0.150	36.43			
	11.13	0.0167	0.053	55.81			
	11.40	0.0171	remains				
		2.8680					
		5.9967					
9D	38.83	5.8033	2.000	0.00	43.79	9.74	Loam
	56.21	0.2101	1.400	0.00			
	37.59	0.1405	0.500	2.26			
	25.90	0.0968	0.150	45.39			
	13.32	0.0498	0.053	52.35			
	9.74	0.0364	remains				
		8.6080					
		14.9449					
9E	34.58	3.7802	2.000	0.00	38.62	13.20	Loam
	61.38	0.1683	1.400	0.00			
	43.73	0.1199	0.500	2.12			
	30.38	0.0833	0.150	39.39			
	17.18	0.0471	0.053	58.48			
	13.20	0.0362	remains				
		6.6980					
		10.933					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
10A	74.77	5.913	2.000	0.00	78.01	4.40	L. Sand
	21.99	0.0435	1.400	0.00			
	13.30	0.0263	0.500	8.15			
	9.30	0.0184	0.150	63.15			
	0.10	0.0002	0.053	28.70			
	4.40	0.0087	remains				
		1.8980					
		7.9081					
10B	71.00	10.0242	2.000	0.00	76.04	5.10	S. Loam
	23.96	0.0846	1.400	0.10			
	16.45	0.0581	0.500	7.27			
	12.09	0.0427	0.150	65.40			
	6.63	0.0234	0.053	27.23			
	5.10	0.018	remains				
		3.8680					
		14.119					
10C	58.56	7.8023	2.000	0.00	65.13	5.61	S. Loam
	34.87	0.1162	1.400	0.00			
	22.81	0.076	0.500	1.61			
	15.85	0.0528	0.150	41.53			
	8.58	0.0286	0.053	56.85			
	5.61	0.0187	remains				
		5.2280					
		13.3226					
10D	52.75	6.0732	2.000	0.00	59.13	9.66	S. Loam
	40.87	0.118	1.400	0.00			
	29.68	0.0857	0.500	0.69			
	21.44	0.0619	0.150	67.76			
	13.16	0.038	0.053	31.54			
	9.66	0.0279	remains				
		5.1080					
		11.5127					
10E	35.13	3.6912	2.000	0.00	40.98	18.06	Loam
	59.02	0.1551	1.400	0.00			
	43.27	0.1137	0.500	0.63			
	32.46	0.0853	0.150	23.42			
	21.33	0.0562	0.053	75.95			
	18.06	0.0476	remains				
		6.3580					
		10.5071					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
11A	49.67	6.3658	2.000	0.00	54.33	8.31	S. Loam
	45.67	0.1468	1.400	0.00			
	32.88	0.1057	0.500	5.26			
	23.55	0.0757	0.150	42.81			
	11.79	0.0379	0.053	51.93			
	8.31	0.0267	remains				
		6.0580					
		12.8166					
11B	36.12	1.905	2.000	0.00	35.33	7.05	Si. Loam
	64.67	0.0853	1.400	0.28			
	38.14	0.0503	0.500	4.42			
	32.07	0.0423	0.150	51.10			
	2.58	0.0034	0.053	44.20			
	7.05	0.0093	remains				
		3.1780					
		5.2736					
11C	19.36	2.093	2.000	0.00	26.06	20.23	Si. Loam
	73.94	0.1999	1.400	0.00			
	58.08	0.157	0.500	2.79			
	43.21	0.1168	0.150	17.32			
	25.67	0.0694	0.053	79.89			
	20.23	0.0547	remains				
		8.1180					
		10.8088					
11D	14.83	1.41	2.000	0.00	19.97	21.36	Si. Loam
	80.03	0.1903	1.400	0.00			
	61.90	0.1472	0.500	3.51			
	46.09	0.1096	0.150	39.77			
	26.03	0.0619	0.053	56.73			
	21.36	0.0508	remains				
		7.5380					
		9.5078					
11E	24.82	3.4116	2.000	0.00	26.37	22.20	Si. Loam
	73.63	0.2531	1.400	0.00			
	59.52	0.2046	0.500	1.35			
	45.65	0.1569	0.150	10.31			
	26.94	0.0926	0.053	88.34			
	22.20	0.0763	remains				
		9.5480					
		13.7431					

Appendix A – Standard sieve-pipette soil core analysis results

Sample	% Finer	Net Wt (g)	Size (mm)	Sand Fraction	Sand (%)	Clay (%)	Soil Class
12A	87.23	5.5272	2.000	0.00	90.22	1.33	Sand
	9.78	0.0155	1.400	1.18			
	3.34	0.0053	0.500	17.01			
	3.09	0.0049	0.150	69.95			
	2.33	0.0037	0.053	11.87			
	1.33	0.0021	remains				
		0.7780					
		6.3367					
12B	86.70	12.3053	2.000	0.00	88.82	2.22	Sand
	11.18	0.0397	1.400	0.65			
	8.14	0.0289	0.500	23.88			
	6.14	0.0218	0.150	66.39			
	3.20	0.0114	0.053	9.08			
	2.22	0.0079	remains				
		1.7780					
		14.193					
12C	90.90	8.0404	2.000	0.00	92.27	1.54	Sand
	7.73	0.0171	1.400	0.99			
	5.42	0.012	0.500	25.12			
	4.07	0.009	0.150	68.84			
	2.35	0.0052	0.053	5.04			
	1.54	0.0034	remains				
		0.7580					
		8.8451					
12D	96.87	6.2152	2.000	0.00	92.40	2.93	Sand
	7.60	0.0122	1.400	0.80			
	7.10	0.0114	0.500	27.84			
	9.04	0.0145	0.150	68.04			
	6.42	0.0103	0.053	3.32			
	2.93	0.0047	remains				
		0.1480					
		6.4163					
12E	93.38	13.7307	2.000	0.00	94.67	1.36	Sand
	5.33	0.0196	1.400	1.02			
	3.75	0.0138	0.500	24.95			
	2.99	0.011	0.150	69.58			
	1.71	0.0063	0.053	4.45			
	1.36	0.005	remains				
		0.9180					
		14.7044					

Appendix B – Statistical Analysis Software Code

2009 Corn SAS Analysis of Variance code

```
DATA one;
infile 'c:\data\vories\corn thompson 09\3mgrid_CLN_SAS.csv' delimiter="," ls=20000;
INPUT e n vsh vdp sand yield std azi trt amt;
if sand < 0 then sand = 0;
if sand < 46.7 then sandCLASS = 1;
if sand >= 46.7 and sand < 62.2 then sandCLASS = 2;
if sand >= 62.2 and sand < 74.42 then sandCLASS = 3;
if sand >= 74.42 then sandCLASs = 4;
run;

proc sort' by sandCLASS trt;

PROC GLM; by sandCLASS;
        class trt;
        model Yield = trt;
        LSmeans trt \ CL tdiff;
run;
quit;
```

2009 Corn SAS Analysis of Covariance code

```
DATA one;
infile 'c:\data\vories\corn thompson 09\3mgrid_CLN_SAS.csv' delimiter="," ls=20000;
INPUT e n vsh vdp sand yield std azi trt amt;
if sand < 0 then sand = 0;
if sand < 46.7 then sandCLASS = 1;
if sand >= 46.7 and sand < 62.2 then sandCLASS = 2;
if sand >= 62.2 and sand < 74.42 then sandCLASS = 3;
if sand >= 74.42 then sandCLASs = 4;
run;

proc sort' by sandCLASS trt;

PROC GLM;
        class trt;
        model Yield = trt sand trt*sand;
        LSmeans trt \ CL tdiff;
run;
quit;
```

Appendix B – Statistical Analysis Software Code

2010 Corn SAS Analysis of Variance code

```
DATA one;
infile 'c:\data\vories\harvest2010\3mgridWEST_CLN_SAS.csv' delimiter="," ls=20000;
INPUT e n sand yield std azi trt sector;
if sand < 0 then sand = 0;
if sand < 46.7 then sandCLASS = 1;
if sand >= 46.7 and sand < 62.2 then sandCLASS = 2;
if sand >= 62.2 and sand < 74.42 then sandCLASS = 3;
if sand >= 74.42 then sandCLASS = 4;
if sector = 4 and trt = 0 then delete;
dist = sqrt((e - 258217.7)*(e - 258217.7)+(n-4032942.5)*(n-4032942.5));
if dist < 167.64 and dist > 163 then delete;
if trt = 0 and azi < 270 then delete;
RUN;

proc sort; by trt sandCLASS;

PROC GLM; by sandCLASS;
  class trt;
  model Yield = trt;
  LSmeans trt / CL tdiff;
run;
quit;
```

2010 Corn SAS Analysis of Covariance code

```
DATA one;
infile 'c:\data\vories\harvest2010\3mgridWEST_CLN_SAS.csv' delimiter="," ls=20000;
INPUT e n sand yield std azi trt sector;
if sand < 0 then sand = 0;
if sand < 46.7 then sandCLASS = 1;
if sand >= 46.7 and sand < 62.2 then sandCLASS = 2;
if sand >= 62.2 and sand < 74.42 then sandCLASS = 3;
if sand >= 74.42 then sandCLASS = 4;
if sector = 4 and trt = 0 then delete;
dist = sqrt((e - 258217.7)*(e - 258217.7)+(n-4032942.5)*(n-4032942.5));
if dist < 167.64 and dist > 163 then delete;
if trt = 0 and azi < 270 then delete;
RUN;

proc sort; by trt sand;

PROC GLM;
  class trt;
  model Yield = trt sand trt*sand;
  LSmeans trt / CL tdiff;
run;
quit;
```

Appendix B – Statistical Analysis Software Code

2010 Rice SAS Analysis of Variance code

```
DATA one;
infile 'c:\data\vories\harvest2010\cleaned rice buffered.csv' delimiter="," ls=20000;
INPUT e n vsh vdp sand yield std azi trt sector segment;
if sand < 0 then sand = 0;
if sand < 46.7 then sandCLASS = 1;
if sand >= 46.7 and sand < 62.2 then sandCLASS = 2;
if sand >= 62.2 and sand < 74.42 then sandCLASS = 3;
if sand >= 74.42 then sandCLASS = 4;
RUN;

proc sort; by sandCLASS trt;

PROC GLM; by sandCLASS;
  class trt;
  model Yield = trt;
  LSmeans trt / CL tdiff;
run;
quit;
```

2010 Rice SAS Analysis of Covariance code

```
DATA one;
infile 'c:\data\vories\harvest2010\cleaned rice buffered.csv' delimiter="," ls=20000;
INPUT e n vsh vdp sand yield std azi trt sector segment;
if sand < 0 then sand = 0;
if sand < 46.7 then sandCLASS = 1;
if sand >= 46.7 and sand < 62.2 then sandCLASS = 2;
if sand >= 62.2 and sand < 74.42 then sandCLASS = 3;
if sand >= 74.42 then sandCLASS = 4;
RUN;

proc sort; by trt sand;

PROC GLM;
  class trt;
  model Yield = trt sand trt*sand;
  LSmeans trt / CL tdiff;
run;
quit;
```

Appendix C – GLM procedure yield output (corn, 2009)

```
The SAS System     08:35 Wednesday, December 1, 2010  40

------------------------------------------ sandCLASS=1 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 1 2 3 4 5 6


Number of Observations Read         600
Number of Observations Used         600
The SAS System     08:35 Wednesday, December 1, 2010  41

------------------------------------------ sandCLASS=1 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        6     108758.6576      18126.4429      25.87    <.0001

Error                      593     415443.9679        700.5800

Corrected Total            599     524202.6255


R-Square     Coeff Var      Root MSE    yield Mean

0.207474      19.61401      26.46847      134.9468


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     108758.6576      18126.4429      25.87    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     108758.6576      18126.4429      25.87    <.0001
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------------------------------------------ sandCLASS=1 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         92.395000           1
1        144.937544           2
2        158.146094           3
3        117.306881           4
4        130.559623           5
5        133.263121           6
6        144.690811           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|
```

Appendix C – GLM procedure yield output (corn, 2009)

```
Dependent Variable: yield

i/j  1            2            3            4            5            6            7

1             -6.25008     -7.89674     -3.09449     -4.73407     -5.13464     -6.50186
               <.0001       <.0001       <.0001       <.0001       <.0001       <.0001
2  6.250082                  -2.74007     6.386443     3.307225     2.810095     0.057206
    <.0001                    0.0063       <.0001       0.0010       0.0051       0.9544
3  7.896741     2.740066                  9.797802     6.583938     6.237291     3.238892
    <.0001       0.0063                    <.0001       <.0001       <.0001       0.0013
4  3.094488     -6.38644      -9.7978                  -3.67049     -4.72666     -7.67238
    0.0021       <.0001       <.0001                    0.0003       <.0001       <.0001
5   4.73407     -3.30723     -6.58394     3.670488                  -0.79453     -3.93128
    <.0001       0.0010       <.0001       0.0003                    0.4272       <.0001
6  5.134643     -2.81009     -6.23729     4.726661     0.794532                  -3.40252
   <.0001       0.0051       <.0001       <.0001       0.4272                    0.0007
7 6.501859     -0.05721     -3.23889     7.672383     3.931283     3.402517
   <.0001       0.9544       0.0013       <.0001       <.0001       0.0007


trt    yield LSMEAN      95% Confidence Limits

0         92.395000       77.388699   107.401301
1        144.937544      138.052181   151.822907
2        158.146094      151.648175   164.644013
3        117.306881      112.327779   122.285983
4        130.559623      125.510553   135.608692
5        133.263121      128.885333   137.640909
6        144.690811      139.756769   149.624852


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     08:35 Wednesday, December 1, 2010  43

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 1 2 3 4 5 6


Number of Observations Read         592
Number of Observations Used         592
The SAS System     08:35 Wednesday, December 1, 2010  44

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        6     221875.0618      36979.1770      47.26    <.0001

Error                      585     457785.8900        782.5400

Corrected Total            591     679660.9518


R-Square     Coeff Var      Root MSE    yield Mean
```

Appendix C – GLM procedure yield output (corn, 2009)

```
0.326450      19.89012      27.97392      140.6423


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     221875.0618      36979.1770      47.26    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     221875.0618      36979.1770      47.26    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  45

----------------------------------------- sandCLASS=2 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         86.796905           1
1        171.180000           2
2        185.361786           3
3        135.186753           4
4        143.390168           5
5        137.538986           6
6        142.341575           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j   1            2            3            4            5            6            7

1               -13.8233     -14.4419     -9.01774     -11.2719      -10.293       -11.34
                 <.0001       <.0001       <.0001       <.0001       <.0001       <.0001
2   13.8233                  -2.07794      6.707556    5.535003     6.824074     5.887629
    <.0001                    0.0382       <.0001       <.0001       <.0001       <.0001
3   14.44187     2.077937                 8.127634     7.143257     8.247954     7.454184
    <.0001       0.0382                    <.0001       <.0001       <.0001       <.0001
4   9.017736    -6.70756     -8.12763                  -2.00508     -0.59114       -1.816
    <.0001       <.0001       <.0001                    0.0454       0.5547       0.0699
5   11.27189      -5.535     -7.14326     2.005082                  1.672002     0.303515
    <.0001       <.0001       <.0001       0.0454                    0.0951       0.7616
6   10.29302    -6.82407     -8.24795     0.591143       -1.672                  -1.44604
    <.0001       <.0001       <.0001       0.5547       0.0951                    0.1487
7  1.33995     -5.88763     -7.45418     1.815996     -0.30352     1.446036
   <.0001       <.0001       <.0001       0.0699       0.7616       0.1487


trt    yield LSMEAN      95% Confidence Limits

0         86.796905       78.319241    95.274568
1        171.180000      162.702337   179.657663
2        185.361786      174.978811   195.744760
3        135.186753      128.925584   141.447923
4        143.390168      138.353686   148.426651
5        137.538986      132.862051   142.215920
6        142.341575      137.794581   146.888569


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     08:35 Wednesday, December 1, 2010  46
```

Appendix C – GLM procedure yield output (corn, 2009)

```
------------------------------------------ sandCLASS=3 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 1 2 3 4 5 6


Number of Observations Read         582
Number of Observations Used         582
The SAS System     08:35 Wednesday, December 1, 2010  47

------------------------------------------ sandCLASS=3 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        6     383296.8108      63882.8018      80.01    <.0001

Error                      575     459095.3163        798.4266

Corrected Total            581     842392.1271


R-Square     Coeff Var      Root MSE    yield Mean

0.455010      19.90868      28.25644      141.9303


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     383296.8108      63882.8018      80.01    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     383296.8108      63882.8018      80.01    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  48

------------------------------------------ sandCLASS=3 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         75.593667           1
1        166.610645           2
2        167.796190           3
3        158.520378           4
4        113.133548           5
5        116.326984           6
6        136.675185           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield
```

Appendix C – GLM procedure yield output (corn, 2009)

```
i/j  1            2            3            4            5            6            7

1               -14.4833     -13.6504     -15.1481     -6.32739     -6.49863     -9.49315
                  <.0001       <.0001       <.0001       <.0001       <.0001       <.0001
2   14.4833                  -0.20994     2.008025     11.54308      9.94765     5.691571
    <.0001                    0.8338       0.0451       <.0001       <.0001       <.0001
3  13.65037     0.209944                  1.961411     10.40573     9.143874     5.353305
    <.0001       0.8338                    0.0503       <.0001       <.0001       <.0001
4  15.14812     -2.00802     -1.96141                  13.13495     10.53907     5.128995
    <.0001       0.0451       0.0503                    <.0001       <.0001       <.0001
5  6.327395     -11.5431     -10.4057     -13.1349                  -0.69261     -4.86966
    <.0001       <.0001       <.0001       <.0001                    0.4888       <.0001
6  6.498628     -9.94765     -9.14387     -10.5391     0.692612                  -3.88314
    <.0001       <.0001       <.0001       <.0001       0.4888                    0.0001
7  9.493146     -5.69157     -5.35331       -5.129     4.869662     3.883137
    <.0001       <.0001       <.0001       <.0001       <.0001       0.0001


trt    yield LSMEAN      95% Confidence Limits

0         75.593667       65.461086    85.726248
1        166.610645      159.562337   173.658953
2        167.796190      159.232597   176.359784
3        158.520378      154.922949   162.117807
4        113.133548      107.378629   118.888468
5        116.326984      109.334839   123.319129
6        136.675185      129.122805   144.227565


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     08:35 Wednesday, December 1, 2010  49

------------------------------------------ sandCLASS=4 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 1 2 3 4 5 6


Number of Observations Read         633
Number of Observations Used         633
The SAS System     08:35 Wednesday, December 1, 2010  50

------------------------------------------ sandCLASS=4 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                       DF         Squares     Mean Square    F Value    Pr > F

Model                         6     253992.1207      42332.0201      68.67    <.0001

Error                       626     385880.6427        616.4228

Corrected Total             632     639872.7634


R-Square     Coeff Var      Root MSE    yield Mean

0.396942      22.84547      24.82786      108.6774
```

Appendix C – GLM procedure yield output (corn, 2009)

```
Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     253992.1207      42332.0201      68.67    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     253992.1207      42332.0201      68.67    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  51

---------------------------------------- sandCLASS=4 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         78.347385           1
1        113.540682           2
2        132.879810           3
3        126.578923           4
4         98.369111           5
5         92.969795           6
6         67.727273           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j             1            2            3            4            5            6
7

1             -9.35473     -14.9056     -11.0747     -4.15842     -3.94977     1.734196
               <.0001       <.0001       <.0001       <.0001       <.0001       0.0834
2  9.354728                  -6.60563     -3.46569     3.539956       6.8985     8.012928
    <.0001                    <.0001       0.0006       0.0004       <.0001       <.0001
3  14.90556     6.605627                  1.722246     8.226237     14.00267     11.53176
    <.0001       <.0001                    0.0855       <.0001       <.0001       <.0001
4  11.07474     3.465694     -1.72225                  5.859053      9.07841     9.610096
    <.0001       0.0006       0.0855                    <.0001       <.0001       <.0001
5  4.158424     -3.53996     -8.22624     -5.85905                  1.275456      4.74412
    <.0001       0.0004       <.0001       <.0001                    0.2026       <.0001
6  3.949767      -6.8985     -14.0027     -9.07841     -1.27546                  4.445561
    <.0001       <.0001       <.0001       <.0001       0.2026                    <.0001
7   -1.7342     -8.01293     -11.5318      -9.6101     -4.74412     -4.44556
    0.0834       <.0001       <.0001       <.0001       <.0001       <.0001


trt    yield LSMEAN      95% Confidence Limits

0         78.347385       72.299949    84.394820
1        113.540682      109.297018   117.784345
2        132.879810      129.000992   136.758628
3        126.578923      120.531488   132.626358
4         98.369111       91.100998   105.637224
5         92.969795       88.934721    97.004868
6         67.727273       57.332462    78.122083


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.


The SAS System     08:35 Wednesday, December 1, 2010  52
```

Appendix C – GLM procedure yield output (corn, 2009)

```
The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 1 2 3 4 5 6


Number of Observations Read        2407
Number of Observations Used        2407
The SAS System     08:35 Wednesday, December 1, 2010  53

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                       13     1019841.102       78449.316      88.74    <.0001

Error                     2393     2115590.200         884.074

Corrected Total           2406     3135431.302


R-Square     Coeff Var      Root MSE    yield Mean

0.325263      22.67513      29.73339      131.1278


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     607199.8746     101199.9791     114.47    <.0001
sand                         1     170443.8350     170443.8350     192.79    <.0001
sand*trt                     6     242197.3921      40366.2320      45.66    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     198262.0697      33043.6783      37.38    <.0001
sand                         1     120445.8416     120445.8416     136.24    <.0001
sand*trt                     6     242197.3921      40366.2320      45.66    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  54

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         84.774296          1
1        143.695866          2
2        151.481483          3
3        141.736317          4
4        123.377036          5
5        119.240413          6
6        130.294386          7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j 1            2            3            4            5            6            7

1              -17.6069     -20.0112     -18.3128     -11.9025     -11.0757     -13.6037
```

Appendix C – GLM procedure yield output (corn, 2009)

```
                  <.0001       <.0001       <.0001       <.0001       <.0001       <.0001
2  17.60686                  -3.03533     0.864127     8.305065      10.7755     5.191463
    <.0001                    0.0024       0.3876       <.0001       <.0001       <.0001
3  20.01117     3.035327                  4.334247     11.57169     14.32741     8.261526
    <.0001       0.0024                    <.0001       <.0001       <.0001       <.0001
4  18.31276     -0.86413     -4.33425                  8.691647     11.81226     5.046828
    <.0001       0.3876       <.0001                    <.0001       <.0001       <.0001
5  11.90251     -8.30507     -11.5717     -8.69165                   1.95649     -2.82793
    <.0001       <.0001       <.0001       <.0001                    0.0505       0.0047
6  11.07566     -10.7755     -14.3274     -11.8123     -1.95649                  -4.87167
    <.0001       <.0001       <.0001       <.0001       0.0505                    <.0001
7  13.60365     -5.19146     -8.26153     -5.04683     2.827926     4.871666
    <.0001       <.0001       <.0001       <.0001       0.0047       <.0001


trt    yield LSMEAN      95% Confidence Limits

0         84.774296       79.274502    90.274090
1        143.695866      140.115799   147.275933
2        151.481483      147.948418   155.014548
3        141.736317      139.098698   144.373936
4        123.377036      120.183288   126.570783
5        119.240413      116.596584   121.884242
6        130.294386      126.715561   133.873211


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
```

Appendix D – GLM procedure yield output (corn, 2010)

```
The SAS System     08:35 Wednesday, December 1, 2010  28

----------------------------------------- sandCLASS=1 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 0.3 0.6 0.9 1.2 1.5 1.8


Number of Observations Read         748
Number of Observations Used         748
The SAS System     08:35 Wednesday, December 1, 2010  29

----------------------------------------- sandCLASS=1 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        6     215203.4403      35867.2400      45.81    <.0001

Error                      741     580225.2816        783.0301

Corrected Total            747     795428.7219


R-Square     Coeff Var      Root MSE    yield Mean

0.270550      24.30298      27.98267      115.1409


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     215203.4403      35867.2400      45.81    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     215203.4403      35867.2400      45.81    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  30

----------------------------------------- sandCLASS=1 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         97.029091           1
0.3      135.881429           2
0.6      113.850000           3
0.9      105.549630           4
1.2      118.495584           5
1.5      119.789116           6
1.8      140.798383           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|
```

Appendix D – GLM procedure yield output (corn, 2010)

```
Dependent Variable: yield

i/j 1            2            3            4            5            6            7

1               -5.06768     -2.19403     -2.04571     -5.94994     -7.96072     -15.9439
                  <.0001       0.0285       0.0411       <.0001       <.0001       <.0001
2  5.067682                  2.083063     3.614227     2.138431     2.056075     -0.63152
    <.0001                    0.0376       0.0003       0.0328       0.0401       0.5279
3  2.194026     -2.08306                  0.989042      -0.5714     -0.75883      -3.4612
    0.0285       0.0376                    0.3230       0.5679       0.4482       0.0006
4  2.045705     -3.61423     -0.98904                  -2.60646     -3.19788     -8.04662
    0.0411       0.0003       0.3230                    0.0093       0.0014       <.0001
5  5.949936     -2.13843     0.571399     2.606462                   -0.3286     -5.78601
    <.0001       0.0328       0.5679       0.0093                    0.7426       <.0001
6  7.960719     -2.05608     0.758826     3.197883       0.3286                  -6.63856
    <.0001       0.0401       0.4482       0.0014       0.7426                    <.0001
7  15.94387     0.631524     3.461198     8.046621     5.786005     6.638558
    <.0001       0.5279       0.0006       <.0001       <.0001       <.0001


trt    yield LSMEAN      95% Confidence Limits

0         97.029091       93.716400   100.341782
0.3      135.881429      121.199496   150.563362
0.6      113.850000       99.168067   128.531933
0.9      105.549630       98.073955   113.025304
1.2      118.495584      112.235187   124.755982
1.5      119.789116      115.258173   124.320059
1.8      140.798383      136.547404   145.049363


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     08:35 Wednesday, December 1, 2010  31

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 0.3 0.6 0.9 1.2 1.5 1.8


Number of Observations Read         809
Number of Observations Used         809
The SAS System     08:35 Wednesday, December 1, 2010  32

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        6     331023.8674      55170.6446      79.90    <.0001

Error                      802     553812.0712        690.5387

Corrected Total            808     884835.9386


R-Square     Coeff Var      Root MSE    yield Mean
```

Appendix D – GLM procedure yield output (corn, 2010)

```
0.374108      22.65065      26.27810      116.0148


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     331023.8674      55170.6446      79.90    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     331023.8674      55170.6446      79.90    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  33

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         84.277895           1
0.3      138.490469           2
0.6      121.819474           3
0.9      107.639041           4
1.2      114.295476           5
1.5      116.805489           6
1.8      153.448310           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j 1            2            3            4            5            6            7

1            -17.197     -10.9233     -7.67168     -8.40209     -10.4252     -18.3115
              <.0001       <.0001       <.0001       <.0001       <.0001       <.0001
2  17.19704               4.684701     9.695883     6.557045     6.664622     -3.84665
    <.0001                 <.0001       <.0001       <.0001       <.0001       0.0001
3  10.92329      -4.6847               4.093786     1.911743     1.420395     -7.67231
    <.0001       <.0001                 <.0001       0.0563       0.1559       <.0001
4  7.671675     -9.69588     -4.09379               -1.84969      -2.9101     -12.0486
    <.0001       <.0001       <.0001                 0.0647       0.0037       <.0001
5  8.402086     -6.55705     -1.91174     1.849694               -0.68536     -9.24213
    <.0001       <.0001       0.0563       0.0647                 0.4933       <.0001
6  10.42517     -6.66462      -1.4204     2.910095     0.685358               -9.48713
    <.0001       <.0001       0.1559       0.0037       0.4933                 <.0001
7  18.31154     3.846649      7.67231     12.04856     9.242131     9.487129
    <.0001       0.0001       <.0001       <.0001       <.0001       <.0001


trt    yield LSMEAN      95% Confidence Limits

0         84.277895       80.094044    88.461746
0.3      138.490469      133.931223   143.049715
0.6      121.819474      116.527274   127.111673
0.9      107.639041      103.370086   111.907996
1.2      114.295476      108.667421   119.923532
1.5      116.805489      112.332764   121.278214
1.8      153.448310      147.326655   159.569965


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     08:35 Wednesday, December 1, 2010  34
```

Appendix D – GLM procedure yield output (corn, 2010)

```
------------------------------------------ sandCLASS=3 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 0.3 0.6 0.9 1.2 1.5 1.8


Number of Observations Read         596
Number of Observations Used         596
The SAS System     08:35 Wednesday, December 1, 2010  35

------------------------------------------ sandCLASS=3 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        6     339551.0584      56591.8431      76.78    <.0001

Error                      589     434122.4825        737.0501

Corrected Total            595     773673.5409


R-Square     Coeff Var      Root MSE    yield Mean

0.438882      24.02639      27.14867      112.9952


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     339551.0584      56591.8431      76.78    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     339551.0584      56591.8431      76.78    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  36

------------------------------------------ sandCLASS=3 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         65.885556           1
0.3      143.793205           2
0.6      109.579722           3
0.9      104.680000           4
1.2      104.402981           5
1.5      104.058989           6
1.8      145.079703           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield
```

Appendix D – GLM procedure yield output (corn, 2010)

```
i/j  1           2           3           4           5           6           7

1            -16.941      -9.3292     -8.6789     -8.88664    -8.53997     -18.1699
              <.0001       <.0001      <.0001      <.0001      <.0001       <.0001
2  16.94102                7.711107    9.288787     9.68653     9.436267     -0.31437
    <.0001                 <.0001      <.0001      <.0001      <.0001       0.7534
3  9.329204     -7.71111                1.1386     1.243754    1.282911     -8.47781
    <.0001       <.0001                0.2553      0.2141      0.2000       <.0001
4  8.678897     -9.28879     -1.1386               0.070663    0.152592     -10.2355
    <.0001       <.0001      0.2553                0.9437      0.8788       <.0001
5  8.886638     -9.68653     -1.24375    -0.07066               0.087747     -10.725
    <.0001       <.0001      0.2141      0.9437                 0.9301       <.0001
6  8.539967     -9.43627     -1.28291    -0.15259    -0.08775                -10.3928
    <.0001       <.0001      0.2000      0.8788      0.9301                  <.0001
7  18.16995     0.314371     8.477807    10.23549    10.72501    10.39283
    <.0001       0.7534      <.0001      <.0001      <.0001      <.0001


trt    yield LSMEAN      95% Confidence Limits

0         65.885556       59.167870    72.603241
0.3      143.793205      137.755907   149.830503
0.6      109.579722      103.295903   115.863541
0.9      104.680000       99.028094   110.331906
1.2      104.402981       99.174527   109.631434
1.5      104.058989       98.407083   109.710895
1.8      145.079703      139.774167   150.385239


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     08:35 Wednesday, December 1, 2010  37

------------------------------------------ sandCLASS=4 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 0.3 0.6 0.9 1.2 1.5 1.8


Number of Observations Read        1163
Number of Observations Used        1163
The SAS System     08:35 Wednesday, December 1, 2010  38

------------------------------------------ sandCLASS=4 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                     DF         Squares     Mean Square    F Value    Pr > F

Model                       6      301168.523       50194.754      77.61    <.0001

Error                    1156      747631.014         646.740

Corrected Total          1162     1048799.537


R-Square     Coeff Var      Root MSE    yield Mean

0.287155      32.71759      25.43108      77.72905
```

Appendix D – GLM procedure yield output (corn, 2010)

```
Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6     301168.5227      50194.7538      77.61    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6     301168.5227      50194.7538      77.61    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  39

------------------------------------------ sandCLASS=4 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         48.482025           1
0.3       95.680697           2
0.6       66.669536           3
0.9       66.809900           4
1.2       64.202879           5
1.5       84.068730           6
1.8      102.938120           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j  1            2            3            4            5            6            7

1              -14.3375      -5.6593     -4.78778     -4.34581     -10.4448     -14.7048
                <.0001       <.0001       <.0001       <.0001       <.0001       <.0001
2  14.33746                  13.25264     9.561141     11.45586     4.712191     -2.53777
    <.0001                    <.0001       <.0001       <.0001       <.0001       0.0113
3  5.659305     -13.2526                  -0.04784     0.929586     -7.37663     -13.0965
    <.0001       <.0001                    0.9619       0.3528       <.0001       <.0001
4  4.787782     -9.56114     0.047839                  0.773255     -5.48818     -10.4315
    <.0001       <.0001       0.9619                    0.4395       <.0001       <.0001
5  4.345809     -11.4559     -0.92959     -0.77326                  -6.88665     -11.9956
    <.0001       <.0001       0.3528       0.4395                    <.0001       <.0001
6   10.4448     -4.71219      7.37663     5.488183     6.886647                  -6.30749
    <.0001       <.0001       <.0001       <.0001       <.0001                    <.0001
7  14.70484     2.537768      13.0965     10.43145     11.99559     6.307485
    <.0001       0.0113       <.0001       <.0001       <.0001       <.0001


trt    yield LSMEAN      95% Confidence Limits

0         48.482025       42.868260    54.095790
0.3       95.680697       92.486418    98.874976
0.6       66.669536       63.798331    69.540742
0.9       66.809900       61.820276    71.799524
1.2       64.202879       59.859969    68.545789
1.5       84.068730       80.439313    87.698147
1.8      102.938120       98.325211   107.551028


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.


The SAS System     08:35 Wednesday, December 1, 2010  19
```

Appendix D – GLM procedure yield output (corn, 2010)

```
The GLM Procedure

Class Level Information

Class         Levels    Values

trt                7    0 0.3 0.6 0.9 1.2 1.5 1.8


Number of Observations Read        3316
Number of Observations Used        3316
The SAS System     08:35 Wednesday, December 1, 2010  20

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                       13     2114694.827      162668.833     220.75    <.0001

Error                     3302     2433183.332         736.882

Corrected Total           3315     4547878.159


R-Square     Coeff Var      Root MSE    yield Mean

0.464985      26.65322      27.14556      101.8472


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          6      931129.541      155188.257     210.60    <.0001
sand                         1     1001583.752     1001583.752    1359.22    <.0001
sand*trt                     6      181981.534       30330.256      41.16    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          6      290843.365       48473.894      65.78    <.0001
sand                         1     1108974.801     1108974.801    1504.96    <.0001
sand*trt                     6      181981.534       30330.256      41.16    <.0001
The SAS System     08:35 Wednesday, December 1, 2010  21

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

0         73.466561           1
0.3      131.969523           2
0.6      107.561929           3
0.9       95.861353           4
1.2       98.915555           5
1.5      103.264567           6
1.8      130.564827           7


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j   1            2            3            4            5            6            7

1              -28.6202     -16.0502     -11.5049     -13.0838      -16.599     -29.9031
                <.0001       <.0001       <.0001       <.0001       <.0001       <.0001
```

Appendix D – GLM procedure yield output (corn, 2010)

```
2  28.62016                   11.0225     17.66165     16.17881     15.10092     0.699151
    <.0001                    <.0001       <.0001       <.0001       <.0001       0.4845
3  16.05019     -11.0225                  5.507172     4.072214     2.162909     -11.0027
    <.0001       <.0001                    <.0001       <.0001       0.0306       <.0001
4  11.50487     -17.6617     -5.50717                  -1.56995     -4.12311     -18.1714
    <.0001       <.0001       <.0001                    0.1165       <.0001       <.0001
5  13.08378     -16.1788     -4.07221     1.569946                  -2.42427     -16.5851
    <.0001       <.0001       <.0001       0.1165                    0.0154       <.0001
6  16.59896     -15.1009     -2.16291     4.123115     2.424271                  -15.5535
    <.0001       <.0001       0.0306       <.0001       0.0154                    <.0001
7  29.90307     -0.69915     11.00267     18.17136     16.58513     15.55352
   <.0001       0.4845       <.0001       <.0001       <.0001       <.0001


trt    yield LSMEAN      95% Confidence Limits

0         73.466561       70.768311    76.164810
0.3      131.969523      129.006006   134.933039
0.6      107.561929      104.389031   110.734826
0.9       95.861353       93.162167    98.560540
1.2       98.915555       96.220442   101.610668
1.5      103.264567      101.004437   105.524697
1.8      130.564827      127.969523   133.160131


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
```

Appendix E – GLM procedure yield output (rice, 2010)

```
The SAS System     09:09 Thursday, December 16, 2010   1

------------------------------------------ sandCLASS=1 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                6    50 60 70 80 90 100


Number of Observations Read         405
Number of Observations Used         405
The SAS System     09:09 Thursday, December 16, 2010   2

------------------------------------------ sandCLASS=1 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        5      78998.5366      15799.7073       7.84    <.0001

Error                      399     804311.2777       2015.8177

Corrected Total            404     883309.8143


R-Square     Coeff Var      Root MSE    yield Mean

0.089435      35.26601      44.89786      127.3120


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          5     78998.53659     15799.70732       7.84    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          5     78998.53659     15799.70732       7.84    <.0001
The SAS System     09:09 Thursday, December 16, 2010   3

------------------------------------------ sandCLASS=1 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

50       129.910714           1
60       137.506912           2
70        89.855000           3
80       112.933716           4
90       126.738649           5
100      142.730877           6


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|
```

Appendix E – GLM procedure yield output (rice, 2010)

```
Dependent Variable: yield

i/j       1             2             3             4             5             6

1                    -0.75347      2.421732        1.8348      0.282059       -1.3538
                      0.4516        0.0159        0.0673        0.7780        0.1766
2      0.753474                    3.133732      3.735893      1.174034      -0.75936
         0.4516                      0.0019        0.0002        0.2411        0.4481
3      -2.42173      -3.13373                    -1.57322      -2.30494      -3.57087
         0.0159        0.0019                      0.1165        0.0217        0.0004
4       -1.8348      -3.73589      1.573216                    -1.67284      -5.32576
        0.0673        0.0002        0.1165                      0.0951        <.0001
5      -0.28206      -1.17403      2.304943       1.67284                    -1.88256
        0.7780        0.2411        0.0217        0.0951                      0.0605
6      1.353802      0.759357      3.570866      5.325764      1.882557
         0.1766        0.4481        0.0004        <.0001        0.0605


trt    yield LSMEAN      95% Confidence Limits

50       129.910714      113.230022   146.591406
60       137.506912      126.803096   148.210728
70        89.855000       61.942863   117.767137
80       112.933716      105.678302   120.189131
90       126.738649      112.227820   141.249478
100      142.730877      134.464016   150.997739


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     09:09 Thursday, December 16, 2010   4

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                6    50 60 70 80 90 100


Number of Observations Read         372
Number of Observations Used         372
The SAS System     09:09 Thursday, December 16, 2010   5

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                     DF         Squares     Mean Square    F Value    Pr > F

Model                       5     111066.3351      22213.2670      10.29    <.0001

Error                     366     790418.4294       2159.6132

Corrected Total           371     901484.7645


R-Square     Coeff Var      Root MSE    yield Mean

0.123204      31.95811      46.47164      145.4142
```

Appendix E – GLM procedure yield output (rice, 2010)

```
Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          5     111066.3351      22213.2670      10.29    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          5     111066.3351      22213.2670      10.29    <.0001
The SAS System     09:09 Thursday, December 16, 2010   6

------------------------------------------ sandCLASS=2 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

50       134.321765           1
60       144.405088           2
70       108.300541           3
80       160.754808           4
90       146.163043           5
100      175.674651           6


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j           1             2             3             4             5             6

1                          .20824      2.740946      -3.08763      -1.66567      -4.56715
                           0.2277        0.0064        0.0022        0.0966        <.0001
2      1.208238                    3.680004      -1.83463      -0.23353      -3.33124
        0.2277                      0.0003        0.0674        0.8155        0.0010
3      -2.74095         -3.68                    -5.24808      -4.31072       -6.4654
      0.0064        0.0003                      <.0001        <.0001        <.0001
4      3.087626      1.834629      5.248079                    1.878937      -1.55758
      0.0022        0.0674        <.0001                      0.0610        0.1202
5      1.665668       0.23353      4.310715      -1.87894                    -3.55271
        0.0966        0.8155        <.0001        0.0610                      0.0004
6      4.567147      3.331237      6.465396       1.55758      3.552708
       <.0001        0.0010        <.0001        0.1202        0.0004


trt    yield LSMEAN      95% Confidence Limits

50       134.321765      123.239714   145.403815
60       144.405088      132.300858   156.509318
70       108.300541       93.276950   123.324131
80       160.754808      148.081998   173.427617
90       146.163043      137.641355   154.684732
100      175.674651      161.738580   189.610722


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     09:09 Thursday, December 16, 2010   7

------------------------------------------ sandCLASS=3 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values
```

Appendix E – GLM procedure yield output (rice, 2010)

```
trt                6    50 60 70 80 90 100


Number of Observations Read         410
Number of Observations Used         410
The SAS System     09:09 Thursday, December 16, 2010   8

------------------------------------------ sandCLASS=3 -----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        5      564040.723      112808.145      80.03    <.0001

Error                      404      569500.669        1409.655

Corrected Total            409     1133541.392


R-Square     Coeff Var      Root MSE    yield Mean

0.497592      26.98568      37.54537      139.1307


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          5     564040.7228     112808.1446      80.03    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          5     564040.7228     112808.1446      80.03    <.0001
The SAS System     09:09 Thursday, December 16, 2010   9

------------------------------------------ sandCLASS=3 -----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

50       108.355905           1
60       110.576386           2
70       109.660000           3
80       182.566200           4
90       167.577111           5
100      195.055362           6


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j         1             2             3             4             5             6

1                    -0.40267      -0.21231      -11.5033      -8.85271      -14.9006
                      0.6874        0.8320        <.0001        <.0001        <.0001
2      0.402666                    0.142615      -10.7106      -8.20095      -13.8113
        0.6874                      0.8867        <.0001        <.0001        <.0001
3      0.212309      -0.14262                    -10.0623      -7.76519      -12.7678
       0.8320        0.8867                      <.0001        <.0001        <.0001
```

Appendix E – GLM procedure yield output (rice, 2010)

```
4      11.50328      10.71058      10.06225                     1.94289      -1.79107
       <.0001        <.0001        <.0001                      0.0527        0.0740
5      8.852707      8.200952       7.76519      -1.94289                    -3.81954
        <.0001        <.0001        <.0001        0.0527                      0.0002
6      14.90063      13.81128      12.76775      1.791072       3.81954
        <.0001        <.0001        <.0001        0.0740        0.0002


trt    yield LSMEAN      95% Confidence Limits

50       108.355905      101.152914   115.558896
60       110.576386      102.474829   118.677943
70       109.660000       99.968443   119.351557
80       182.566200      172.128074   193.004326
90       167.577111      156.574360   178.579862
100      195.055362      186.169839   203.940885


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
The SAS System     09:09 Thursday, December 16, 2010  10

----------------------------------------- sandCLASS=4 ----------------------------------
---------

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                6    50 60 70 80 90 100


Number of Observations Read         462
Number of Observations Used         462
The SAS System     09:09 Thursday, December 16, 2010  11

----------------------------------------- sandCLASS=4 ----------------------------------
---------

The GLM Procedure

Dependent Variable: yield

Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                        5      548584.747      109716.949      56.81    <.0001

Error                      456      880666.997        1931.287

Corrected Total            461     1429251.744


R-Square     Coeff Var      Root MSE    yield Mean

0.383827      46.78065      43.94641      93.94143


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          5     548584.7473     109716.9495      56.81    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          5     548584.7473     109716.9495      56.81    <.0001
The SAS System     09:09 Thursday, December 16, 2010  12
```

Appendix E – GLM procedure yield output (rice, 2010)

```
----------------------------------------- sandCLASS=4 ----------------------------------
---------

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

50        52.418642           1
60        44.253103           2
70       112.581824           3
80        55.875714           4
90       104.922987           5
100      149.036000           6


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j         1             2             3             4             5             6

1                    1.080216        -10.14      -0.32125      -7.50639      -12.5831
                     0.2806        <.0001        0.7482        <.0001        <.0001
2      -1.08022                    -10.2247      -1.03846       -7.9404      -12.6684
        0.2806                      <.0001        0.2996        <.0001        <.0001
3      10.13999      10.22471                    5.578582      1.268705      -5.34735
       <.0001        <.0001                      <.0001        0.2052        <.0001
4      0.321246      1.038461      -5.57858                     -4.5335      -8.26402
        0.7482        0.2996        <.0001                      <.0001        <.0001
5       7.50639      7.940397      -1.26871      4.533498                    -5.68569
         <.0001        <.0001        0.2052        <.0001                      <.0001
6      12.58306      12.66844      5.347347      8.264024      5.685688
        <.0001        <.0001        <.0001        <.0001        <.0001


trt    yield LSMEAN      95% Confidence Limits

50        52.418642       42.822796    62.014488
60        44.253103       32.913137    55.593070
70       112.581824      105.958114   119.205533
80        55.875714       37.029848    74.721581
90       104.922987       95.081054   114.764920
100      149.036000      137.390868   160.681132


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.

The SAS System     09:09 Thursday, December 16, 2010  13

The GLM Procedure

Class Level Information

Class         Levels    Values

trt                6    50 60 70 80 90 100


Number of Observations Read        1649
Number of Observations Used        1649
The SAS System     09:09 Thursday, December 16, 2010  14

The GLM Procedure

Dependent Variable: yield
```

Appendix E – GLM procedure yield output (rice, 2010)

```
Sum of
Source                      DF         Squares     Mean Square    F Value    Pr > F

Model                       11     1396572.068      126961.097      57.16    <.0001

Error                     1637     3635736.797        2220.975

Corrected Total           1648     5032308.865


R-Square     Coeff Var      Root MSE    yield Mean

0.277521      37.70636      47.12723      124.9848


Source                      DF       Type I SS     Mean Square    F Value    Pr > F

trt                          5     701848.4179     140369.6836      63.20    <.0001
sand                         1      47138.5504      47138.5504      21.22    <.0001
sand*trt                     5     647585.1001     129517.0200      58.32    <.0001


Source                      DF     Type III SS     Mean Square    F Value    Pr > F

trt                          5     379310.9064      75862.1813      34.16    <.0001
sand                         1      95753.3147      95753.3147      43.11    <.0001
sand*trt                     5     647585.1001     129517.0200      58.32    <.0001
The SAS System     09:09 Thursday, December 16, 2010  15

The GLM Procedure
Least Squares Means

LSMEAN
trt    yield LSMEAN      Number

50       111.182318           1
60       108.531730           2
70       103.449334           3
80       140.005965           4
90       137.288086           5
100      166.477199           6


Least Squares Means for Effect trt
t for H0: LSMean(i)=LSMean(j) / Pr > |t|

Dependent Variable: yield

i/j             1             2             3             4             5             6

1                      0.640083      1.513369       -6.3099      -6.31981      -13.1823
                         0.5222        0.1304        <.0001        <.0001        <.0001
2           -0.64008                 1.002347      -6.95714      -7.04453      -13.9739
              0.5222                   0.3163        <.0001        <.0001        <.0001
3           -1.51337      -1.00235                 -6.73878      -6.68467      -12.3236
             0.1304        0.3163                   <.0001        <.0001        <.0001
4           6.309896      6.957144      6.738778                 0.602012       -5.7884
             <.0001        <.0001        <.0001                   0.5472        <.0001
5           6.319813       7.04453      6.684668      -0.60201                 -7.05652
            <.0001        <.0001        <.0001        0.5472                   <.0001
6           13.18227      13.97391      12.32364      5.788396      7.056518
            <.0001        <.0001        <.0001        <.0001        <.0001


trt    yield LSMEAN      95% Confidence Limits

50       111.182318      105.372437   116.992199
60       108.531730      102.855814   114.207645
70       103.449334       95.282710   111.615959
80       140.005965      133.185228   146.826702
```

Appendix E – GLM procedure yield output (rice, 2010)

```
90       137.288086      131.640918   142.935254
100      166.477199      160.651755   172.302644


NOTE: To ensure overall protection level, only probabilities associated with pre-planned
comparisons should be used.
```

Appendix F – Corn irrigation and rainfall schedule (2009)

Date	Day of Year	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 1 (8 mm)	Total Water Applied (mm)	Treatment 2 (15 mm)	Total Water Applied (mm)	Treatment 3 (23 mm)	Total Water Applied (mm)	Treatment 4 (30 mm)	Total Water Applied (mm)	Treatment 5 (38 mm)	Total Water Applied (mm)	Treatment 6 (46 mm)	Total Water Applied (mm)
5/4/2009	124	0	0		0		0		0		0		0		0
5/5/2009	125	0	0		0		0		0		0		0		0
5/6/2009	126	11.2	11		11		11		11		11		11		11
5/7/2009	127	0.0	11		11		11		11		11		11		11
5/8/2009	128	14.0	25		25		25		25		25		25		25
5/9/2009	129	5.6	31		31		31		31		31		31		31
5/10/2009	130	8.4	39		39		39		39		39		39		39
5/11/2009	131	0.3	39		39		39		39		39		39		39
5/12/2009	132	0.0	39		39		39		39		39		39		39
5/13/2009	133	0.0	39		39		39		39		39		39		39
5/14/2009	134	12.4	52		52		52		52		52		52		52
5/15/2009	135	0.0	52		52		52		52		52		52		52
5/16/2009	136	0.5	52		52		52		52		52		52		52
5/17/2009	137	0.0	52		52		52		52		52		52		52
5/18/2009	138	0.0	52		52		52		52		52		52		52
5/19/2009	139	0.0	52		52		52		52		52		52		52
5/20/2009	140	0.0	52		52		52		52		52		52		52
5/21/2009	141	0.0	52		52		52		52		52		52		52
5/22/2009	142	0.0	52		52		52		52		52		52		52
5/23/2009	143	0.0	52		52		52		52		52		52		52
5/24/2009	144	58.2	110		110		110		110		110		110		110
5/25/2009	145	13.0	123		123		123		123		123		123		123
5/26/2009	146	1.0	124		124		124		124		124		124		124
5/27/2009	147	4.3	129		129		129		129		129		129		129
5/28/2009	148	0.0	129		129		129		129		129		129		129
5/29/2009	149	0.0	129		129		129		129		129		129		129
5/30/2009	150	0.0	129		129		129		129		129		129		129

6/25/2009	176	0.0	208	8	240		238	23	254		238	246	254
6/26/2009	177	0.3	208	8	248	15	253		254	30	268	246	254

Appendix F – Corn irrigation and rainfall schedule (2009)

Appendix F – Corn irrigation and rainfall schedule (2009)

Date	Day of Year	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 1 (8 mm)	Total Water Applied (mm)	Treatment 2 (15 mm)	Total Water Applied (mm)	Treatment 3 (23 mm)	Total Water Applied (mm)	Treatment 4 (30 mm)	Total Water Applied (mm)	Treatment 5 (38 mm)	Total Water Applied (mm)	Treatment 6 (46 mm)	Total Water Applied (mm)
6/27/2009	178	0.0	208	8	256		253		254		268	38	284		254
6/28/2009	179	0.0	208		256		253		254		268		284		254
6/29/2009	180	0.0	208	8	264	15	268	23	277		268		284	46	300
6/30/2009	181	0.0	208	8	272		268		277	30	298		284		300
7/1/2009	182	0.0	208	8	280	15	283		277		298		284		300
7/2/2009	183	0.0	208	8	288		283	23	300		298	38	322		300
7/3/2009	184	0.0	208	8	296	15	298		300		298		322		300
7/4/2009	185	1.5	209	8	305		299		301	30	329		323		301
7/5/2009	186	0.0	209	8	313	15	314	23	324		329		323	46	347
7/6/2009	187	0.0	209	8	321		314		324		329		323		347
7/7/2009	188	0.0	209	8	329	15	329		324		329	38	361		347
7/8/2009	189	0.0	209	8	337		329	23	347	30	359		361		347
7/9/2009	190	0.0	209	8	345	15	344		347		359		361		347
7/10/2009	191	0.0	209												
7/11/2009	192	1.8	211												
7/12/2009	193	0.0	211												
7/13/2009	194	0.0	211												
7/14/2009	195	0.0	211												
7/15/2009	196	5.6	217												
7/16/2009	197	5.3	222												
7/17/2009	198	0	222												
7/18/2009	199	0	222												
7/19/2009	200	0	222												
7/20/2009	201	0	222												
7/21/2009	202	74.2	296												
7/22/2009	203	3.6	300												
7/23/2009	204	0.0	300												

Appendix F – Corn irrigation and rainfall schedule (2009)

Date	Day of Year	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 1 (8 mm)	Total Water Applied (mm)	Treatment 2 (15 mm)	Total Water Applied (mm)	Treatment 3 (23 mm)	Total Water Applied (mm)	Treatment 4 (30 mm)	Total Water Applied (mm)	Treatment 5 (38 mm)	Total Water Applied (mm)	Treatment 6 (46 mm)	Total Water Applied (mm)
7/24/2009	205	0.0	300												
7/25/2009	206	0.0	300												
7/26/2009	207	5.8	306												
7/27/2009	208	0.0	306												
7/28/2009	209	5.1	311												
7/29/2009	210	0.3	311												
7/30/2009	211	8.6	320												
7/31/2009	212	0.0	320												
8/1/2009	213	0.0	320												
8/2/2009	214	0.0	320												
8/3/2009	215	0.0	320												
8/4/2009	216	30.7	350												
8/5/2009	217	0.3	351												
8/6/2009	218	0.0	351												
8/7/2009	219	0.0	351												
8/8/2009	220	0.0	351												
8/9/2009	221	0.0	351												
8/10/2009	222	3.6	354												
8/11/2009	223	0.0	354												
8/12/2009	224	0.0	354												
8/13/2009	225	0.0	354												
8/14/2009	226	0.0	354												
8/15/2009	227	0.0	354												
8/16/2009	228	0.0	354												
8/17/2009	229	0.0	354												
8/18/2009	230	0.3	354												
8/19/2009	231	0.0	354												

Appendix F – Corn irrigation and rainfall schedule (2009)

Date	Day of Year	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 1 (8 mm)	Total Water Applied (mm)	Treatment 2 (15 mm)	Total Water Applied (mm)	Treatment 3 (23 mm)	Total Water Applied (mm)	Treatment 4 (30 mm)	Total Water Applied (mm)	Treatment 5 (38 mm)	Total Water Applied (mm)	Treatment 6 (46 mm)	Total Water Applied (mm)
8/20/2009	232	12.7	367												
			Total Precipitation to Date (mm)	**Treatment 1 (8 mm)**	**Total Water Applied (mm)**	**Treatment 2 (15 mm)**	**Total Water Applied (mm)**	**Treatment 3 (23 mm)**	**Total Water Applied (mm)**	**Treatment 4 (30 mm)**	**Total Water Applied (mm)**	**Treatment 5 (38 mm)**	**Total Water Applied (mm)**	**Treatment 6 (46 mm)**	**Total Water Applied (mm)**
Totals:			**367**												

*Previous study data for irrigation was not available for July 10, 2009 through August 20, 2009.

**Rainfall amounts from historical weather data from agebb.missouri.edu.

6/9/2010	161	94.26	2.0	16.764	35.814	35.814	35.814	35.814	35.814	35.814

Appendix G – Corn irrigation and rainfall schedule (2010)

7/10/2010	192	238.89	0	59.944	7.62	270.256	277.876	22.86	285.496	30.48	277.876	239.776	216.916

Appendix G – Corn irrigation and rainfall schedule (2010)

8/10/2010	223	381.87	0	117.602	465.074	457.454	457.454	457.454	411.734	411.734

Appendix G – Corn irrigation and rainfall schedule (2010)

Appendix G – Corn irrigation and rainfall schedule (2010)

Date	Day of Year	Total Et - Corn (mm)	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 1 (8 mm)	Total Water Applied (mm)	Treatment 2 (15 mm)	Total Water Applied (mm)	Treatment 3 (23 mm)	Total Water Applied (mm)	Treatment 4 (30 mm)	Total Water Applied (mm)	Treatment 5 (38 mm)	Total Water Applied (mm)	Treatment 6 (46 mm)	Total Water Applied (mm)
8/11/2010	224	383.43	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/12/2010	225	384.96	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/13/2010	226	386.46	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/14/2010	227	387.87	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/15/2010	228	389.48	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/16/2010	229	391.08	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/17/2010	230	392.57	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/18/2010	231	393.77	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/19/2010	232	395.25	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
8/20/2010	233	396.76	0	117.602		465.074		457.454		457.454		457.454		411.734		411.734
		Total Et - Corn (mm)		**Total Precipitation to Date (mm)**	**Treatment 1 (8 mm)**	**Total Water Applied (mm)**	**Treatment 2 (15 mm)**	**Total Water Applied (mm)**	**Treatment 3 (23 mm)**	**Total Water Applied (mm)**	**Treatment 4 (30 mm)**	**Total Water Applied (mm)**	**Treatment 5 (38 mm)**	**Total Water Applied (mm)**	**Treatment 6 (46 mm)**	**Total Water Applied (mm)**
Totals:		**396.76**		**117.602**	**347.472**	**465.074**	**339.852**	**457.454**	**339.852**	**457.454**	**339.852**	**457.454**	**294.132**	**411.734**	**294.132**	**411.734**

* August 20, 2010 the black layer formed within the kernel signal the cessation of water use

** June 30, 2010 liquid ammonia applied through fertigation because of observed plant stress. Tasseling occurred

Appendix H – Rice irrigation and rainfall schedule (2010)

Date	Day of Year	Total ET Rice (mm)	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 100% (16.0 mm)	Total Water Applied (mm)	Treatment 90% (14.3 mm)	Total Water Applied (mm)	Treatment 80% (12.7 mm)	Total Water Applied (mm)	Treatment 70% (11.1 mm)	Total Water Applied (mm)	Treatment 60% (9.5 mm)	Total Water Applied (mm)	Treatment 50% (7.9 mm)	Total Water Applied (mm)
5/11/2010	132	3.64	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/12/2010	133	8.01	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/13/2010	134	12.87	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/14/2010	135	15.93	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/15/2010	136	20.71	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/16/2010	137	24.16	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/17/2010	138	28.36	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/18/2010	139	32.43	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/19/2010	140	36.90	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/20/2010	141	40.25	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/21/2010	142	44.91	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/22/2010	143	51.03	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/23/2010	144	57.55	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/24/2010	145	62.15	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/25/2010	146	68.01	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/26/2010	147	72.75	0	0		0.0		0.0		0.0		0.0		0.0		0.0
5/27/2010	148	79.10	7.874	7.874	8.4	16.3	8.4	16.3	8.4	16.3	8.4	16.3	8.4	16.3	8.4	16.3
5/28/2010	149	85.38	0	7.874	8.4	24.6	8.4	24.6	8.4	24.6	8.4	24.6	8.4	24.6	8.4	24.6
5/29/2010	150	90.90	0	7.874	8.4	33.0	8.4	33.0	8.4	33.0	8.4	33.0	8.4	33.0	8.4	33.0
5/30/2010	151	97.20	0	7.874		33.0		33.0		33.0		33.0		33.0		33.0
5/31/2010	152	101.84	6.35	14.224		39.4		39.4		39.4		39.4		39.4		39.4
6/1/2010	153	108.48	0	14.224		39.4		39.4		39.4		39.4		39.4		39.4
6/2/2010	154	114.24	0.508	14.732		39.9		39.9		39.9		39.9		39.9		39.9
6/3/2010	155	120.29	0	14.732		39.9		39.9		39.9		39.9		39.9		39.9
6/4/2010	156	126.61	0	14.732	8.4	48.3	8.4	48.3	8.4	48.3	8.4	48.3	8.4	48.3	8.4	48.3
6/5/2010	157	132.42	0	14.732		48.3		48.3		48.3		48.3		48.3		48.3
6/6/2010	158	139.01	0	14.732		48.3		48.3		48.3		48.3		48.3		48.3
6/7/2010	159	144.75	0	14.732		48.3		48.3		48.3		48.3		48.3		48.3
6/8/2010	160	150.09	0	14.732		48.3		48.3		48.3		48.3		48.3		48.3
6/9/2010	161	156.39	2.032	16.764	8.4	58.7	8.4	58.7	8.4	58.7	8.4	58.7	8.4	58.7	8.4	58.7
6/10/2010	162	162.66	0.254	17.018		58.9		58.9		58.9		58.9		58.9		58.9
6/11/2010	163	165.60	1.524	18.542	20.3	80.8	20.3	80.8	20.3	80.8	20.3	80.8	20.3	80.8	20.3	80.8
6/12/2010	164	173.28	0	18.542	6.4	87.1	6.4	87.1	6.4	87.1	6.4	87.1	6.4	87.1	6.4	87.1
6/13/2010	165	179.51	0	18.542	12.7	99.8	12.7	99.8	12.7	99.8	12.7	99.8	12.7	99.8	12.7	99.8
6/14/2010	166	186.10	0	18.542	19.8	119.6	19.8	119.6	19.8	119.6	19.8	119.6	19.8	119.6	19.8	119.6

Appendix H – Rice irrigation and rainfall schedule (2010)

Date	Day of Year	Total ET Rice (mm)	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 100% (16.0 mm)	Total Water Applied (mm)	Treatment 90% (14.3 mm)	Total Water Applied (mm)	Treatment 80% (12.7 mm)	Total Water Applied (mm)	Treatment 70% (11.1 mm)	Total Water Applied (mm)	Treatment 60% (9.5 mm)	Total Water Applied (mm)	Treatment 50% (7.9 mm)	Total Water Applied (mm)
6/15/2010	167	193.56	0	18.542		119.6		119.6		119.6		119.6		119.6		119.6
6/16/2010	168	199.57	0	18.542		119.6		119.6		119.6		119.6		119.6		119.6
6/17/2010	169	206.07	7.366	25.908		127.0		127.0		127.0		127.0		127.0		127.0
6/18/2010	170	213.40	0	25.908		127.0		127.0		127.0		127.0		127.0		127.0
6/19/2010	171	220.72	0	25.908		127.0		127.0		127.0		127.0		127.0		127.0
6/20/2010	172	228.02	0	25.908		127.0		127.0		127.0		127.0		127.0		127.0
6/21/2010	173	235.50	0	25.908	21.8	148.8	19.7	146.7	17.5	144.5	15.3	142.3	13.1	140.1	10.9	137.9
6/22/2010	174	243.12	0	25.908		148.8		146.7		144.5		142.3		140.1		137.9
6/23/2010	175	249.82	0	25.908	21.8	170.7	19.7	166.3	17.5	162.0	15.3	157.6	13.1	153.2	10.9	148.8
6/24/2010	176	255.13	0	25.908		170.7		166.3		162.0		157.6		153.2		148.8
6/25/2010	177	260.57	20.574	46.482	21.8	213.1	19.7	206.6	17.5	200.0	15.3	193.4	13.1	186.9	10.9	180.3
6/26/2010	178	267.66	0	46.482		213.1		206.6		200.0		193.4		186.9		180.3
6/27/2010	179	275.16	0	46.482	21.8	235.0	19.7	226.2	17.5	217.5	15.3	208.7	13.1	200.0	10.9	191.3
6/28/2010	180	281.49	0	46.482		235.0		226.2		217.5		208.7		200.0		191.3
6/29/2010	181	287.44	0	46.482	15.9	250.8	14.3	240.5	12.7	230.2	11.1	219.8	9.5	209.5	7.9	199.2
6/30/2010	182	293.96	0	46.482		250.8		240.5		230.2		219.8		209.5		199.2
7/1/2010	183	300.72	0	46.482	15.9	266.7	14.3	254.8	12.7	242.9	11.1	231.0	9.5	219.0	7.9	207.1
7/2/2010	184	307.49	0	46.482		266.7		254.8		242.9		231.0		219.0		207.1
7/3/2010	185	314.52	0	46.482	15.9	282.6	14.3	269.1	12.7	255.6	11.1	242.1	9.5	228.6	7.9	215.1
7/4/2010	186	321.61	0	46.482		282.6		269.1		255.6		242.1		228.6		215.1
7/5/2010	187	328.14	0	46.482	15.9	298.5	14.3	283.4	12.7	268.3	11.1	253.2	9.5	238.1	7.9	223.0
7/6/2010	188	334.56	0	46.482		298.5		283.4		268.3		253.2		238.1		223.0
7/7/2010	189	339.89	0	46.482	15.9	314.3	14.3	297.6	12.7	281.0	11.1	264.3	9.5	247.6	7.9	230.9
7/8/2010	190	345.70	1.27	47.752		315.6		298.9		282.2		265.6		248.9		232.2
7/9/2010	191	348.62	12.192	59.944	15.9	343.7	14.3	325.4	12.7	307.1	11.1	288.9	9.5	270.6	7.9	252.3
7/10/2010	192	354.10	0	59.944		343.7		325.4		307.1		288.9		270.6		252.3
7/11/2010	193	358.90	13.716	73.66	15.9	373.3	14.3	353.4	12.7	333.6	11.1	313.7	9.5	293.9	7.9	274.0
7/12/2010	194	362.24	5.588	79.248		378.8		359.0		339.1		319.3		299.4		279.6
7/13/2010	195	367.84	0	79.248		378.8		359.0		339.1		319.3		299.4		279.6
7/14/2010	196	373.49	0	79.248	15.9	394.7	14.3	373.3	12.7	351.8	11.1	330.4	9.5	309.0	7.9	287.5
7/15/2010	197	379.21	0	79.248		394.7		373.3		351.8		330.4		309.0		287.5
7/16/2010	198	384.69	0.508	79.756	15.9	411.1	14.3	388.1	12.7	365.0	11.1	342.0	9.5	319.0	7.9	296.0
7/17/2010	199	389.30	0	79.756		411.1		388.1		365.0		342.0		319.0		296.0
7/18/2010	200	393.56	0	79.756	15.9	427.0	14.3	402.4	12.7	377.7	11.1	353.1	9.5	328.5	7.9	303.9
7/19/2010	201	399.83	12.446	92.202	5.1	444.5		414.8		390.2		365.6		341.0		316.4

Appendix H – Rice irrigation and rainfall schedule (2010)

Date	Day of Year	Total ET Rice (mm)	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 100% (16.0 mm)	Total Water Applied (mm)	Treatment 90% (14.3 mm)	Total Water Applied (mm)	Treatment 80% (12.7 mm)	Total Water Applied (mm)	Treatment 70% (11.1 mm)	Total Water Applied (mm)	Treatment 60% (9.5 mm)	Total Water Applied (mm)	Treatment 50% (7.9 mm)	Total Water Applied (mm)
7/20/2010	202	405.51	0	92.202		444.5		414.8		390.2		365.6		341.0		316.4
7/21/2010	203	411.56	0	92.202	15.9	460.4	14.3	429.1	12.7	402.9	11.1	376.7	9.5	350.5	7.9	324.3
7/22/2010	204	418.38	0	92.202		460.4		429.1		402.9		376.7		350.5		324.3
7/23/2010	205	425.16	0	92.202	15.9	476.3	14.3	443.4	12.7	415.6	11.1	387.8	9.5	360.0	7.9	332.2
7/24/2010	206	431.99	0	92.202		476.3		443.4		415.6		387.8		360.0		332.2
7/25/2010	207	438.29	0	92.202	15.9	492.1	14.3	457.7	12.7	428.3	11.1	398.9	9.5	369.5	7.9	340.2
7/26/2010	208	443.45	3.048	95.25		495.2		460.7		431.3		402.0		372.6		343.2
7/27/2010	209	448.62	16.256	111.506	2.5	514.0	2.5	479.5	2.5	450.1	2.5	420.8	2.5	391.4	2.5	362.0
7/28/2010	210	454.33	0	111.506		514.0		479.5		450.1		420.8		391.4		362.0
7/29/2010	211	460.32	0	111.506		514.0		479.5		450.1		420.8		391.4		362.0
7/30/2010	212	466.42	0	111.506		514.0		479.5		450.1		420.8		391.4		362.0
7/31/2010	213	472.54	5.588	117.094	7.9	527.4	7.9	493.0	7.9	463.6	7.9	434.2	7.9	404.9	7.9	375.5
8/1/2010	214	478.60	0	117.094		527.4		493.0		463.6		434.2		404.9		375.5
8/2/2010	215	483.83	0	117.094	7.9	535.3	7.9	500.8	7.9	471.5	7.9	442.1	7.9	412.7	7.9	383.3
8/3/2010	216	490.72	0	117.094		535.3		500.8		471.5		442.1		412.7		383.3
8/4/2010	217	497.47	0	117.094		535.3		500.8		471.5		442.1		412.7		383.3
8/5/2010	218	502.86	0	117.094	15.9	551.2	14.3	515.1	12.7	484.2	11.1	453.2	9.5	422.2	7.9	391.3
8/6/2010	219	508.27	0	117.094		551.2		515.1		484.2		453.2		422.2		391.3
8/7/2010	220	514.00	0	117.094	15.9	567.1	14.3	529.4	12.7	496.9	11.1	464.3	9.5	431.8	7.9	399.2
8/8/2010	221	519.62	0	117.094		567.1		529.4		496.9		464.3		431.8		399.2
8/9/2010	222	524.69	0.508	117.602	15.9	583.4	14.3	544.2	12.7	510.1	11.1	475.9	9.5	441.8	7.9	407.7
8/10/2010	223	529.84	0	117.602		583.4		544.2		510.1		475.9		441.8		407.7
8/11/2010	224	535.77	0	117.602	15.9	599.3	14.3	558.5	12.7	522.8	11.1	487.1	9.5	451.3	7.9	415.6
8/12/2010	225	541.59	0	117.602		599.3		558.5		522.8		487.1		451.3		415.6
8/13/2010	226	547.28	0	117.602		599.3		558.5		522.8		487.1		451.3		415.6
8/14/2010	227	552.62	0	117.602		599.3		558.5		522.8		487.1		451.3		415.6
8/15/2010	228	558.75	0	117.602		599.3		558.5		522.8		487.1		451.3		415.6
8/16/2010	229	564.82	0	117.602	15.9	615.2	14.3	572.8	12.7	535.5	11.1	498.2	9.5	460.9	7.9	423.5
8/17/2010	230	569.90	0	117.602	15.9	631.1	14.3	587.1	12.7	548.2	11.1	509.3	9.5	470.4	7.9	431.5
8/18/2010	231	573.99	0	117.602		631.1		587.1		548.2		509.3		470.4		431.5
8/19/2010	232	579.02	0	117.602		631.1		587.1		548.2		509.3		470.4		431.5
8/20/2010	233	584.16	0	117.602	15.9	646.9	14.3	601.4	12.7	560.9	11.1	520.4	9.5	479.9	7.9	439.4
8/21/2010	234	589.32	7.874	125.476		654.8		609.2		568.8		528.3		487.8		447.3
8/22/2010	235	594.20	0	125.476	15.9	670.7	14.3	623.5	12.7	581.5	11.1	539.4	9.5	497.3	7.9	455.2
8/23/2010	236	599.36	0	125.476		670.7		623.5		581.5		539.4		497.3		455.2

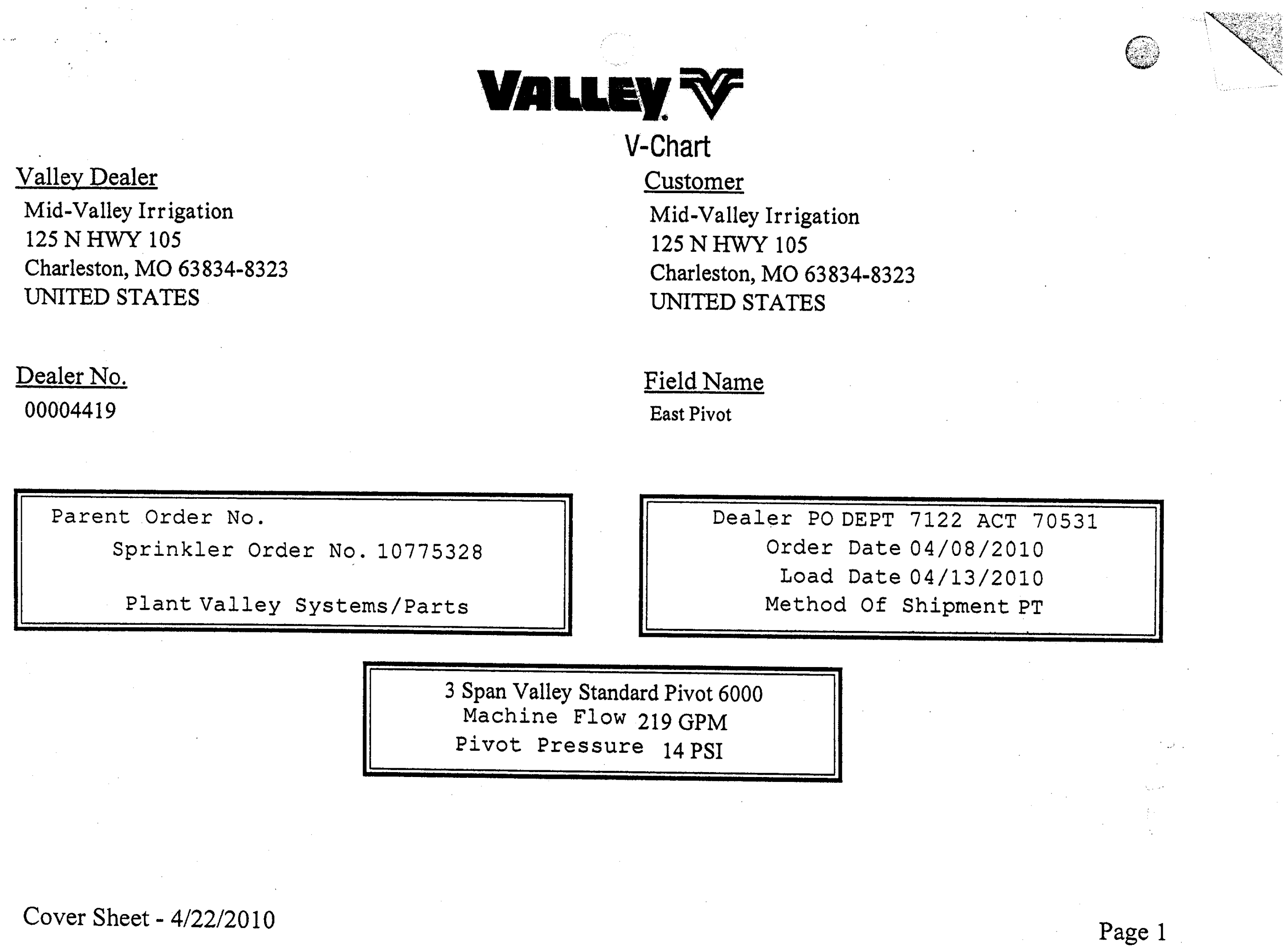
Appendix H – Rice irrigation and rainfall schedule (2010)

Date	Day of Year	Total ET Rice (mm)	Daily Precipitation (mm)	Total Precipitation to Date (mm)	Treatment 100% (16.0 mm)	Total Water Applied (mm)	Treatment 90% (14.3 mm)	Total Water Applied (mm)	Treatment 80% (12.7 mm)	Total Water Applied (mm)	Treatment 70% (11.1 mm)	Total Water Applied (mm)	Treatment 60% (9.5 mm)	Total Water Applied (mm)	Treatment 50% (7.9 mm)	Total Water Applied (mm)
8/24/2010	237	603.89	0	125.476		670.7		623.5		581.5		539.4		497.3		455.2
8/25/2010	238	608.45	0	125.476		670.7		623.5		581.5		539.4		497.3		455.2
8/26/2010	239	613.31	0	125.476	15.9	686.6	14.3	637.8	12.7	594.2	11.1	550.5	9.5	506.8	7.9	463.2
8/27/2010	240	618.05	0	125.476		686.6		637.8		594.2		550.5		506.8		463.2
8/28/2010	241	622.85	0	125.476	15.9	702.4	14.3	652.1	12.7	606.9	11.1	561.6	9.5	516.4	7.9	471.1
8/29/2010	242	625.91	3.048	128.524		705.5		655.2		609.9		564.7		519.4		474.2
8/30/2010	243	629.93	0	128.524		705.5		655.2		609.9		564.7		519.4		474.2
8/31/2010	244	635.25	0	128.524	15.9	721.4	14.3	669.4	12.7	622.6	11.1	575.8	9.5	528.9	7.9	482.1
9/1/2010	245	639.83	0	128.524		721.4		669.4		622.6		575.8		528.9		482.1
9/2/2010	246	642.56	0	128.524	15.9	737.2	14.3	683.7	12.7	635.3	11.1	586.9	9.5	538.5	7.9	490.0
9/3/2010	247	646.82	0	128.524		737.2		683.7		635.3		586.9		538.5		490.0
9/4/2010	248	651.04	0	128.524	15.9	753.1	14.3	698.0	12.7	648.0	11.1	598.0	9.5	548.0	7.9	498.0
9/5/2010	249	655.34	0	128.524		753.1		698.0		648.0		598.0		548.0		498.0
9/6/2010	250	661.00	0	128.524	15.9	769.0	14.3	712.3	12.7	660.7	11.1	609.1	9.5	557.5	7.9	505.9
9/7/2010	251	664.01	18.542	147.066		787.5		730.8		679.2		627.6		576.0		524.4
9/8/2010	252	665.69	0	147.066		787.5		730.8		679.2		627.6		576.0		524.4
		Total ET Rice (mm)		**Total Precipitation to Date (mm)**	**Treatment 100% (16.0 mm)**	**Total Water Applied (mm)**	**Treatment 90% (14.3 mm)**	**Total Water Applied (mm)**	**Treatment 80% (12.7 mm)**	**Total Water Applied (mm)**	**Treatment 70% (11.1 mm)**	**Total Water Applied (mm)**	**Treatment 60% (9.5 mm)**	**Total Water Applied (mm)**	**Treatment 50% (7.9 mm)**	**Total Water Applied (mm)**
Totals:		**665.69**		**147.066**	**640.461**	**787.53**	**583.7809**	**730.85**	**532.1808**	**679.25**	**480.5807**	**627.65**	**428.9806**	**576.05**	**377.3805**	**524.45**

* Fertigation occurred on June 29, July 7, July 14, July19, and July 23 through an application depth of 5.08 mm.

** Chemigation occurred on July 27 through an application depth of 2.54 mm

Appendix I – Marsh Pivot mechanical details (Valley Manufacturing, Inc.)



V-Chart

Valley Dealer
Mid-Valley Irrigation
125 N HWY 105
Charleston, MO 63834-8323
UNITED STATES

Dealer No.
00004419

Customer
Mid-Valley Irrigation
125 N HWY 105
Charleston, MO 63834-8323
UNITED STATES

Field Name
East Pivot

Parent Order No.
Sprinkler Order No. 10775328
Plant Valley Systems/Parts

Dealer PO DEPT 7122 ACT 70531
Order Date 04/08/2010
Load Date 04/13/2010
Method Of Shipment PT

3 Span Valley Standard Pivot 6000
Machine Flow 219 GPM
Pivot Pressure 14 PSI

Cover Sheet - 4/22/2010

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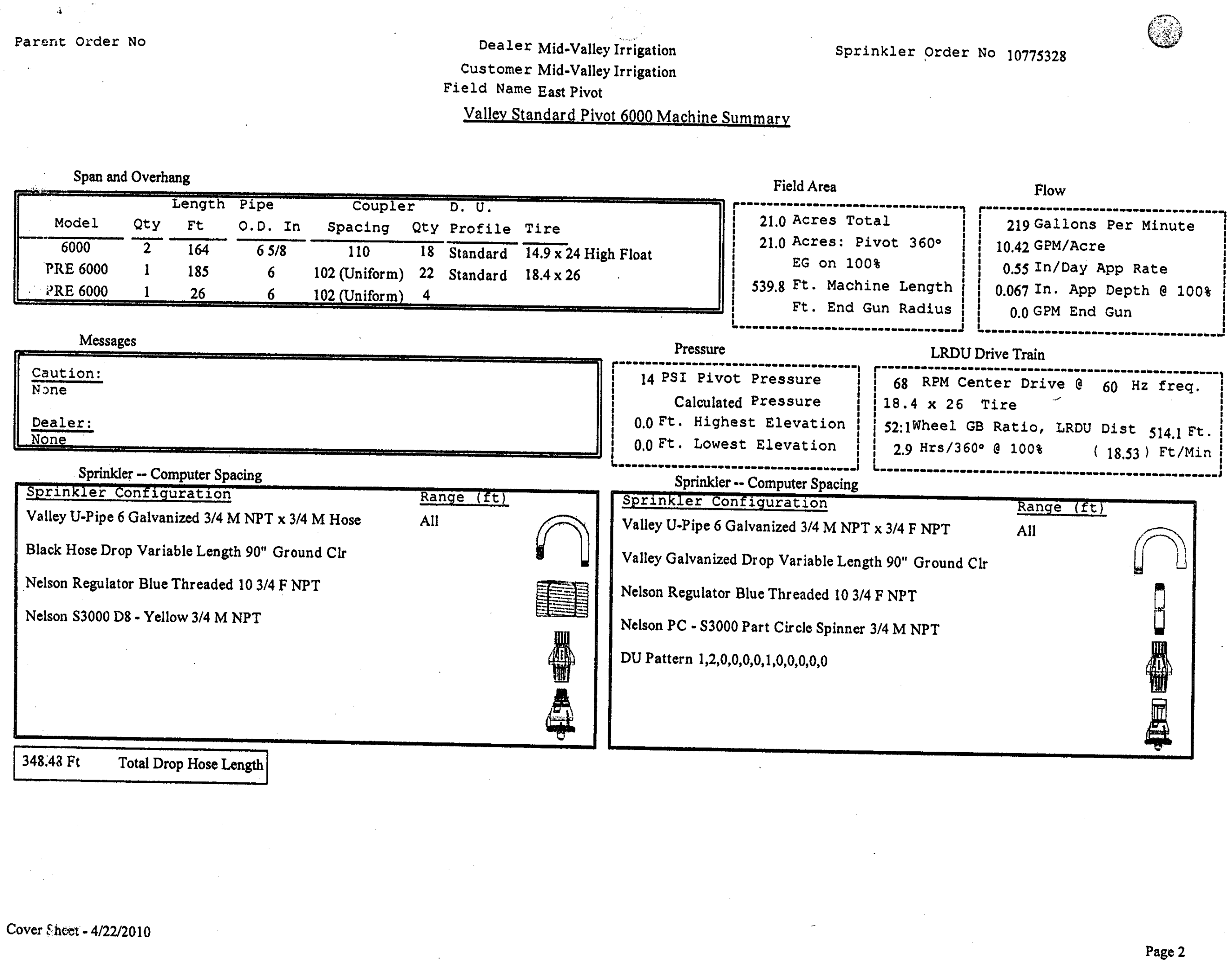
Appendix I – Marsh Pivot mechanical details (Valley Manufacturing, Inc.)



Parent Order No

Dealer Mid-Valley Irrigation
Customer Mid-Valley Irrigation
Field Name East Pivot

Sprinkler Order No 10775328

Valley Standard Pivot 6000 Machine Summary

Span and Overhang

Model	Qty	Length Ft	Pipe O.D. In	Coupler Spacing	Qty	D. U. Profile	Tire
6000	2	164	6 5/8	110	18	Standard	14.9 x 24 High Float
PRE 6000	1	185	6	102 (Uniform)	22	Standard	18.4 x 26
PRE 6000	1	26	6	102 (Uniform)	4		

Field Area

21.0 Acres Total
21.0 Acres: Pivot 360°
EG on 100%
539.8 Ft. Machine Length
Ft. End Gun Radius

Flow

219 Gallons Per Minute
10.42 GPM/Acre
0.55 In/Day App Rate
0.067 In. App Depth @ 100%
0.0 GPM End Gun

Messages

Caution:
None

Dealer:
None

Pressure

14 PSI Pivot Pressure
Calculated Pressure
0.0 Ft. Highest Elevation
0.0 Ft. Lowest Elevation

LRDU Drive Train

68 RPM Center Drive @ 60 Hz freq.
18.4 x 26 Tire
52:1 Wheel GB Ratio, LRDU Dist 514.1 Ft.
2.9 Hrs/360° @ 100% (18.53) Ft/Min

Sprinkler -- Computer Spacing

Sprinkler Configuration	Range (ft)
Valley U-Pipe 6 Galvanized 3/4 M NPT x 3/4 M Hose	All
Black Hose Drop Variable Length 90" Ground Clr	
Nelson Regulator Blue Threaded 10 3/4 F NPT	
Nelson S3000 D8 - Yellow 3/4 M NPT	

348.48 Ft Total Drop Hose Length

Sprinkler -- Computer Spacing

Sprinkler Configuration	Range (ft)
Valley U-Pipe 6 Galvanized 3/4 M NPT x 3/4 F NPT	All
Valley Galvanized Drop Variable Length 90" Ground Clr	
Nelson Regulator Blue Threaded 10 3/4 F NPT	
Nelson PC - S3000 Part Circle Spinner 3/4 M NPT	
DU Pattern 1,2,0,0,0,0,1,0,0,0,0,0	

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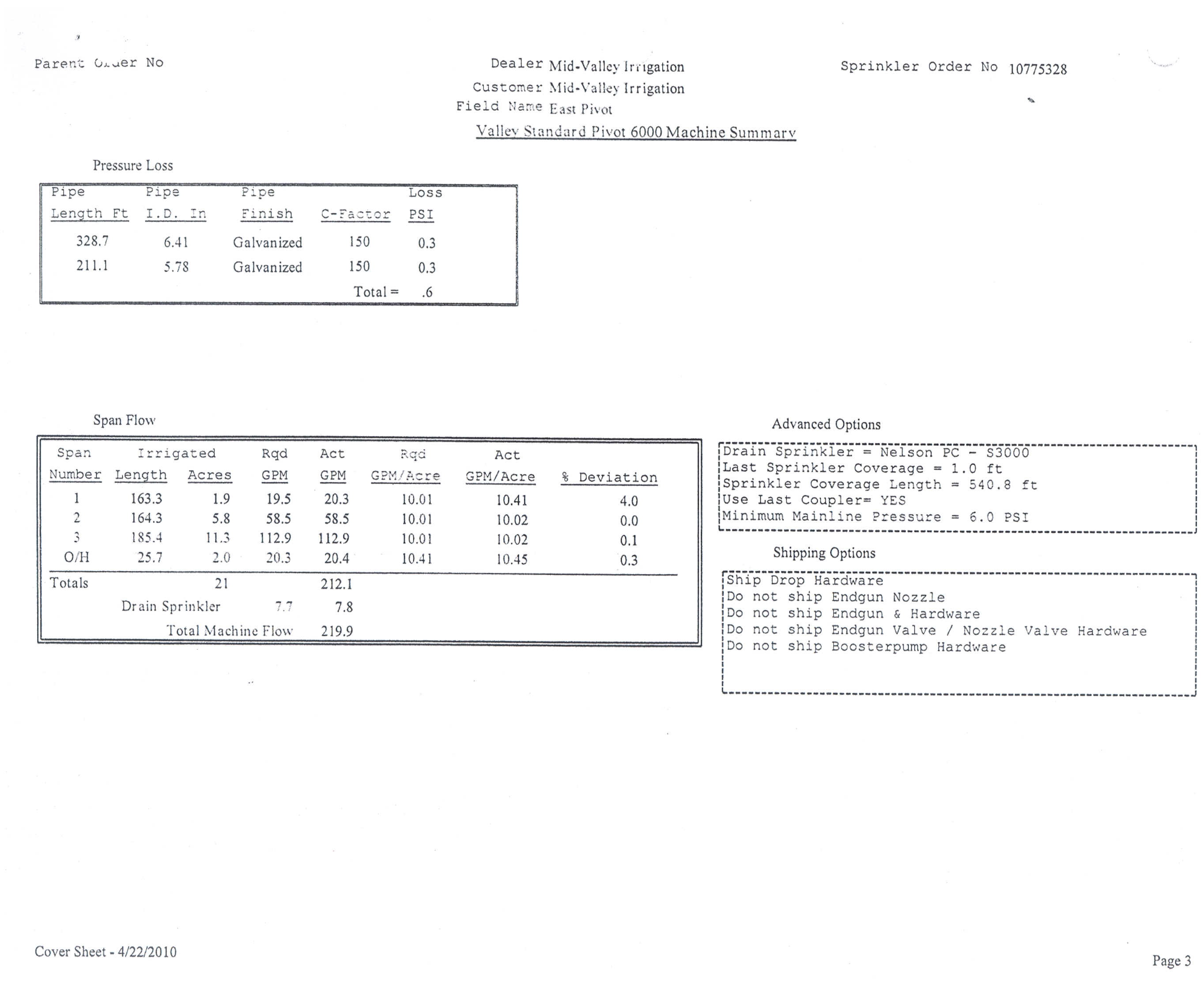
Appendix I – Marsh Pivot mechanical details (Valley Manufacturing, Inc.)



Parent Order No

Dealer Mid-Valley Irrigation
Customer Mid-Valley Irrigation
Field Name East Pivot

Sprinkler Order No 10775328

Valley Standard Pivot 6000 Machine Summary

Pressure Loss

Pipe Length Ft	Pipe I.D. In	Pipe Finish	C-Factor	Loss PSI
328.7	6.41	Galvanized	150	0.3
211.1	5.78	Galvanized	150	0.3
			Total =	.6

Span Flow

Span Number	Irrigated Length	Irrigated Acres	Rqd GPM	Act GPM	Rqd GPM/Acre	Act GPM/Acre	% Deviation
1	163.3	1.9	19.5	20.3	10.01	10.41	4.0
2	164.3	5.8	58.5	58.5	10.01	10.02	0.0
3	185.4	11.3	112.9	112.9	10.01	10.02	0.1
O/H	25.7	2.0	20.3	20.4	10.41	10.45	0.3
Totals		21		212.1			
Drain Sprinkler			7.7	7.8			
Total Machine Flow				219.9			

Advanced Options

Drain Sprinkler = Nelson PC - S3000
Last Sprinkler Coverage = 1.0 ft
Sprinkler Coverage Length = 540.8 ft
Use Last Coupler= YES
Minimum Mainline Pressure = 6.0 PSI

Shipping Options

Ship Drop Hardware
Do not ship Endgun Nozzle
Do not ship Endgun & Hardware
Do not ship Endgun Valve / Nozzle Valve Hardware
Do not ship Boosterpump Hardware

Cover Sheet - 4/22/2010

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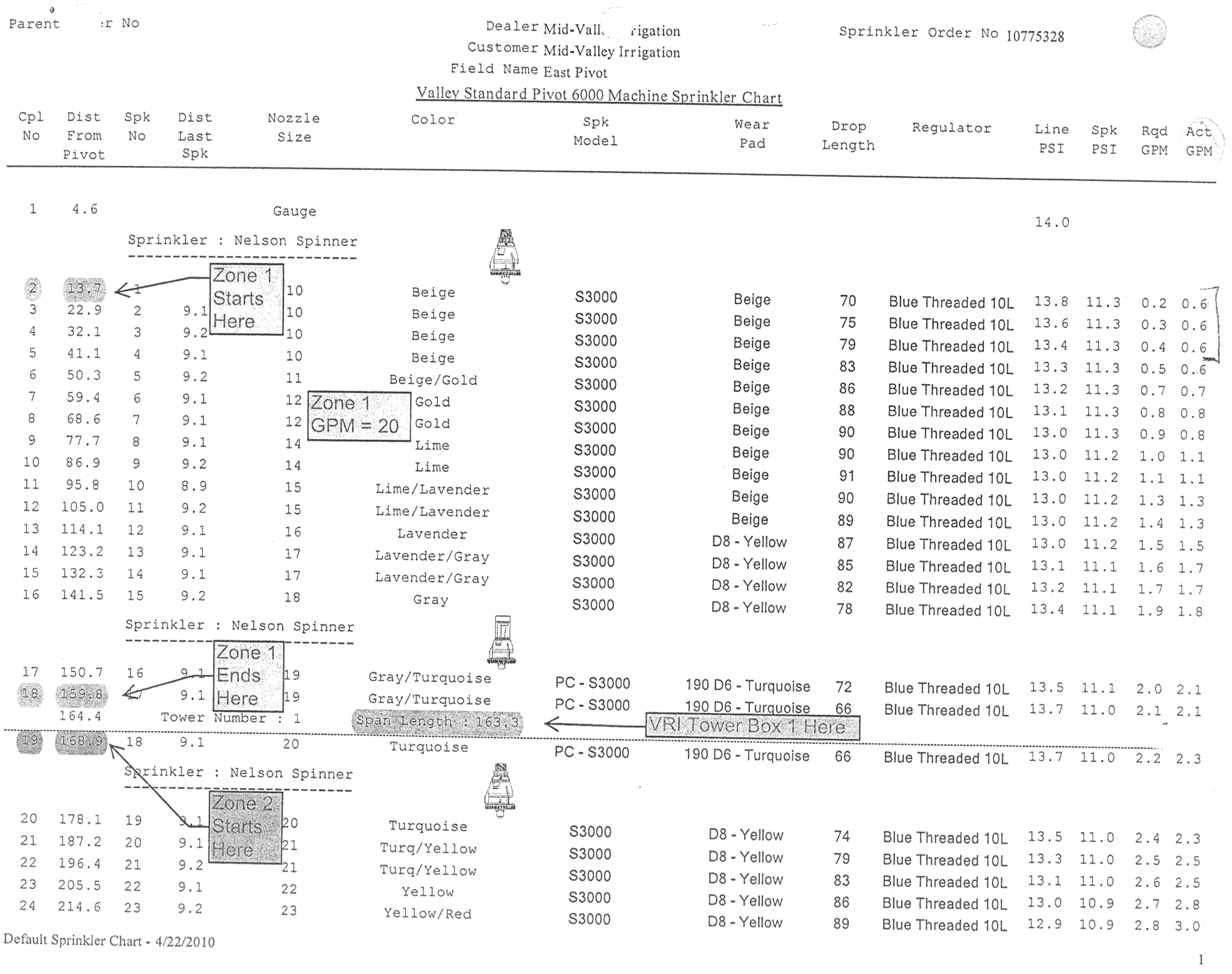
Appendix I – Marsh Pivot mechanical details (Valley Manufacturing, Inc.)



Parent :r No

Dealer Mid-Vall. rigation
Customer Mid-Valley Irrigation
Field Name East Pivot

Sprinkler Order No 10775328

Valley Standard Pivot 6000 Machine Sprinkler Chart

Cpl No	Dist From Pivot	Spk No	Dist Last Spk	Nozzle Size	Color	Spk Model	Wear Pad	Drop Length	Regulator	Line PSI	Spk PSI	Rqd GPM	Act GPM
1	4.6			Gauge						14.0			
		Sprinkler : Nelson Spinner											
2	13.7	1		10	Beige	S3000	Beige	70	Blue Threaded 10L	13.8	11.3	0.2	0.6
3	22.9	2	9.1	10	Beige	S3000	Beige	75	Blue Threaded 10L	13.6	11.3	0.3	0.6
4	32.1	3	9.2	10	Beige	S3000	Beige	79	Blue Threaded 10L	13.4	11.3	0.4	0.6
5	41.1	4	9.1	10	Beige	S3000	Beige	83	Blue Threaded 10L	13.3	11.3	0.5	0.6
6	50.3	5	9.2	11	Beige/Gold	S3000	Beige	86	Blue Threaded 10L	13.2	11.3	0.7	0.7
7	59.4	6	9.1	12	Gold	S3000	Beige	88	Blue Threaded 10L	13.1	11.3	0.8	0.8
8	68.6	7	9.1	12	Gold	S3000	Beige	90	Blue Threaded 10L	13.0	11.3	0.9	0.8
9	77.7	8	9.1	14	Lime	S3000	Beige	90	Blue Threaded 10L	13.0	11.2	1.0	1.1
10	86.9	9	9.2	14	Lime	S3000	Beige	91	Blue Threaded 10L	13.0	11.2	1.1	1.1
11	95.8	10	8.9	15	Lime/Lavender	S3000	Beige	90	Blue Threaded 10L	13.0	11.2	1.3	1.3
12	105.0	11	9.2	15	Lime/Lavender	S3000	Beige	89	Blue Threaded 10L	13.0	11.2	1.4	1.3
13	114.1	12	9.1	16	Lavender	S3000	D8 - Yellow	87	Blue Threaded 10L	13.0	11.2	1.5	1.5
14	123.2	13	9.1	17	Lavender/Gray	S3000	D8 - Yellow	85	Blue Threaded 10L	13.1	11.1	1.6	1.7
15	132.3	14	9.1	17	Lavender/Gray	S3000	D8 - Yellow	82	Blue Threaded 10L	13.2	11.1	1.7	1.7
16	141.5	15	9.2	18	Gray	S3000	D8 - Yellow	78	Blue Threaded 10L	13.4	11.1	1.9	1.8
		Sprinkler : Nelson Spinner											
17	150.7	16	9.1	19	Gray/Turquoise	PC - S3000	190 D6 - Turquoise	72	Blue Threaded 10L	13.5	11.1	2.0	2.1
18	159.8	17	9.1	19	Gray/Turquoise	PC - S3000	190 D6 - Turquoise	66	Blue Threaded 10L	13.7	11.0	2.1	2.1
	164.4	Tower Number : 1			Span Length : 163.3								
19	168.9	18	9.1	20	Turquoise	PC - S3000	190 D6 - Turquoise	66	Blue Threaded 10L	13.7	11.0	2.2	2.3
		Sprinkler : Nelson Spinner											
20	178.1	19	9.1	20	Turquoise	S3000	D8 - Yellow	74	Blue Threaded 10L	13.5	11.0	2.4	2.3
21	187.2	20	9.1	21	Turq/Yellow	S3000	D8 - Yellow	79	Blue Threaded 10L	13.3	11.0	2.5	2.5
22	196.4	21	9.2	21	Turq/Yellow	S3000	D8 - Yellow	83	Blue Threaded 10L	13.1	11.0	2.6	2.5
23	205.5	22	9.1	22	Yellow	S3000	D8 - Yellow	86	Blue Threaded 10L	13.0	10.9	2.7	2.8
24	214.6	23	9.2	23	Yellow/Red	S3000	D8 - Yellow	89	Blue Threaded 10L	12.9	10.9	2.8	3.0

Zone 1 Starts Here

Zone 1 GPM = 20

Zone 1 Ends Here

VRI Tower Box 1 Here

Zone 2 Starts Here

Default Sprinkler Chart - 4/22/2010

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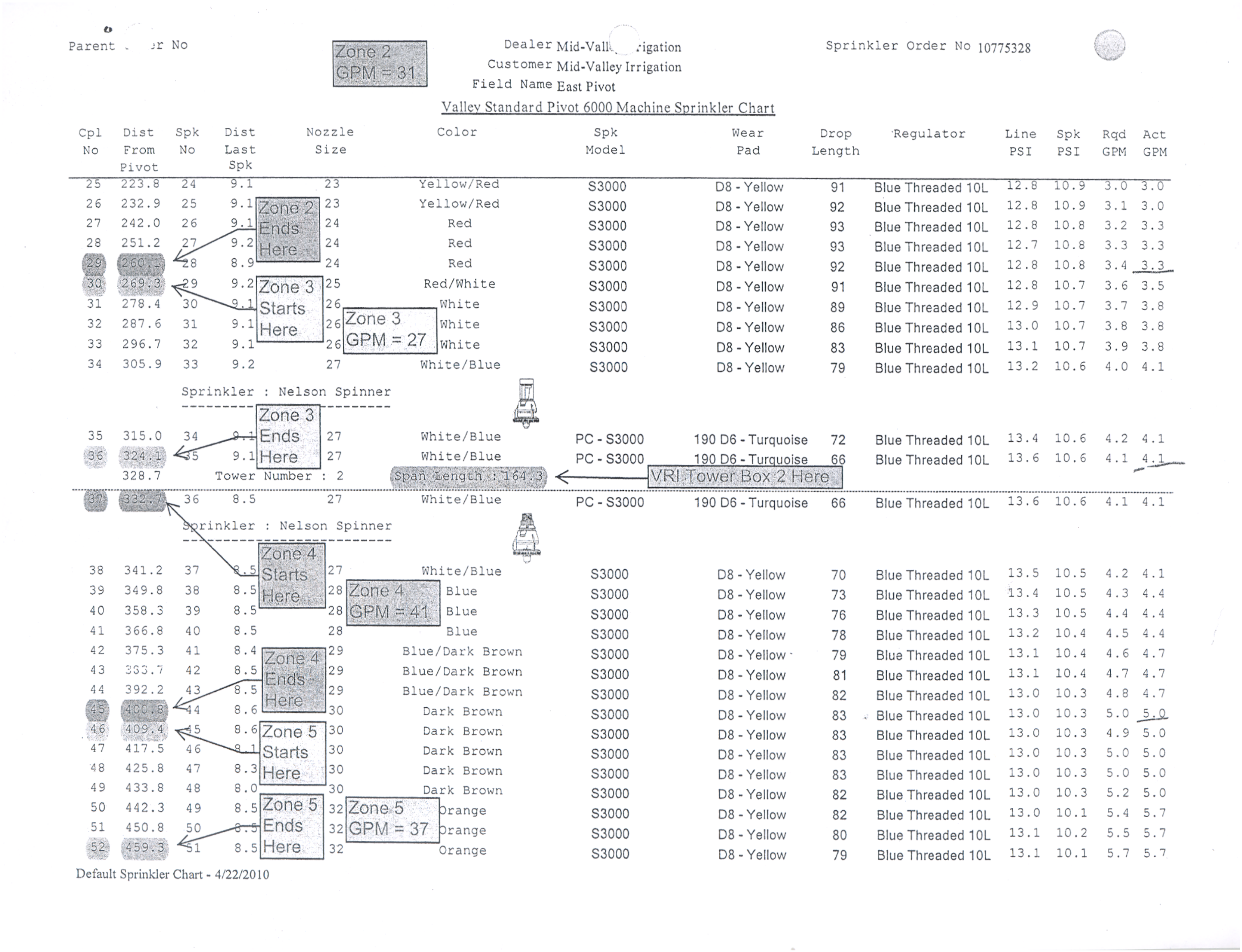
Appendix I – Marsh Pivot mechanical details (Valley Manufacturing, Inc.)



Parent r No

Dealer Mid-Vall [illegible] rigation
Customer Mid-Valley Irrigation
Field Name East Pivot

Sprinkler Order No 10775328

Valley Standard Pivot 6000 Machine Sprinkler Chart

Cpl No	Dist From Pivot	Spk No	Dist Last Spk	Nozzle Size	Color	Spk Model	Wear Pad	Drop Length	Regulator	Line PSI	Spk PSI	Rqd GPM	Act GPM
25	223.8	24	9.1	23	Yellow/Red	S3000	D8 - Yellow	91	Blue Threaded 10L	12.8	10.9	3.0	3.0
26	232.9	25	9.1	23	Yellow/Red	S3000	D8 - Yellow	92	Blue Threaded 10L	12.8	10.9	3.1	3.0
27	242.0	26	9.1	24	Red	S3000	D8 - Yellow	93	Blue Threaded 10L	12.8	10.8	3.2	3.3
28	251.2	27	9.2	24	Red	S3000	D8 - Yellow	93	Blue Threaded 10L	12.7	10.8	3.3	3.3
29	260.1	28	8.9	24	Red	S3000	D8 - Yellow	92	Blue Threaded 10L	12.8	10.8	3.4	3.3
30	269.3	29	9.2	25	Red/White	S3000	D8 - Yellow	91	Blue Threaded 10L	12.8	10.7	3.6	3.5
31	278.4	30	9.1	26	White	S3000	D8 - Yellow	89	Blue Threaded 10L	12.9	10.7	3.7	3.8
32	287.6	31	9.1	26	White	S3000	D8 - Yellow	86	Blue Threaded 10L	13.0	10.7	3.8	3.8
33	296.7	32	9.1	26	White	S3000	D8 - Yellow	83	Blue Threaded 10L	13.1	10.7	3.9	3.8
34	305.9	33	9.2	27	White/Blue	S3000	D8 - Yellow	79	Blue Threaded 10L	13.2	10.6	4.0	4.1
		Sprinkler : Nelson Spinner											
35	315.0	34	9.1	27	White/Blue	PC - S3000	190 D6 - Turquoise	72	Blue Threaded 10L	13.4	10.6	4.2	4.1
36	324.1	35	9.1	27	White/Blue	PC - S3000	190 D6 - Turquoise	66	Blue Threaded 10L	13.6	10.6	4.1	4.1
	328.7	Tower Number : 2			Span Length : 164.3								
37	332.7	36	8.5	27	White/Blue	PC - S3000	190 D6 - Turquoise	66	Blue Threaded 10L	13.6	10.6	4.1	4.1
		Sprinkler : Nelson Spinner											
38	341.2	37	8.5	27	White/Blue	S3000	D8 - Yellow	70	Blue Threaded 10L	13.5	10.5	4.2	4.1
39	349.8	38	8.5	28	Blue	S3000	D8 - Yellow	73	Blue Threaded 10L	13.4	10.5	4.3	4.4
40	358.3	39	8.5	28	Blue	S3000	D8 - Yellow	76	Blue Threaded 10L	13.3	10.5	4.4	4.4
41	366.8	40	8.5	28	Blue	S3000	D8 - Yellow	78	Blue Threaded 10L	13.2	10.4	4.5	4.4
42	375.3	41	8.4	29	Blue/Dark Brown	S3000	D8 - Yellow	79	Blue Threaded 10L	13.1	10.4	4.6	4.7
43	383.7	42	8.5	29	Blue/Dark Brown	S3000	D8 - Yellow	81	Blue Threaded 10L	13.1	10.4	4.7	4.7
44	392.2	43	8.5	29	Blue/Dark Brown	S3000	D8 - Yellow	82	Blue Threaded 10L	13.0	10.3	4.8	4.7
45	400.8	44	8.6	30	Dark Brown	S3000	D8 - Yellow	83	Blue Threaded 10L	13.0	10.3	5.0	5.0
46	409.4	45	8.6	30	Dark Brown	S3000	D8 - Yellow	83	Blue Threaded 10L	13.0	10.3	4.9	5.0
47	417.5	46	8.1	30	Dark Brown	S3000	D8 - Yellow	83	Blue Threaded 10L	13.0	10.3	5.0	5.0
48	425.8	47	8.3	30	Dark Brown	S3000	D8 - Yellow	83	Blue Threaded 10L	13.0	10.3	5.0	5.0
49	433.8	48	8.0	30	Dark Brown	S3000	D8 - Yellow	82	Blue Threaded 10L	13.0	10.3	5.2	5.0
50	442.3	49	8.5	32	Orange	S3000	D8 - Yellow	82	Blue Threaded 10L	13.0	10.1	5.4	5.7
51	450.8	50	8.5	32	Orange	S3000	D8 - Yellow	80	Blue Threaded 10L	13.1	10.2	5.5	5.7
52	459.3	51	8.5	32	Orange	S3000	D8 - Yellow	79	Blue Threaded 10L	13.1	10.1	5.7	5.7

Zone 2 GPM = 31

Zone 2 Ends Here

Zone 3 Starts Here

Zone 3 GPM = 27

Zone 3 Ends Here

VRI Tower Box 2 Here

Zone 4 Starts Here

Zone 4 GPM = 41

Zone 4 Ends Here

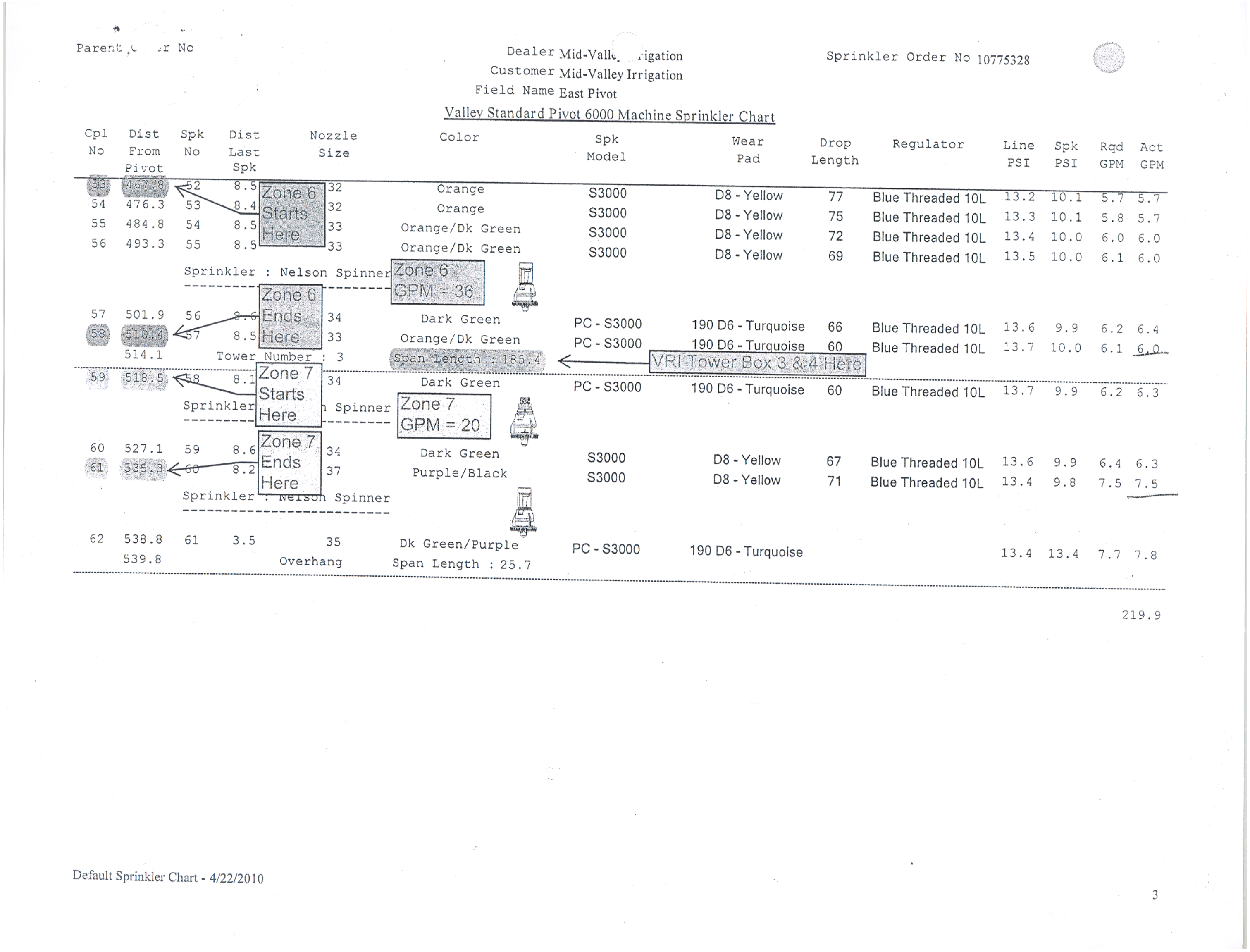
Zone 5 Starts Here

Zone 5 Ends Here

Zone 5 GPM = 37

Default Sprinkler Chart - 4/22/2010

Appendix I – Marsh Pivot mechanical details (Valley Manufacturing, Inc.)



Parent [illegible]r No

Dealer Mid-Vall[illegible]rigation
Customer Mid-Valley Irrigation
Field Name East Pivot

Sprinkler Order No 10775328

Valley Standard Pivot 6000 Machine Sprinkler Chart

Cpl No	Dist From Pivot	Spk No	Dist Last Spk	Nozzle Size	Color	Spk Model	Wear Pad	Drop Length	Regulator	Line PSI	Spk PSI	Rqd GPM	Act GPM
53	467.8	52	8.5	32	Orange	S3000	D8 - Yellow	77	Blue Threaded 10L	13.2	10.1	5.7	5.7
54	476.3	53	8.4	32	Orange	S3000	D8 - Yellow	75	Blue Threaded 10L	13.3	10.1	5.8	5.7
55	484.8	54	8.5	33	Orange/Dk Green	S3000	D8 - Yellow	72	Blue Threaded 10L	13.4	10.0	6.0	6.0
56	493.3	55	8.5	33	Orange/Dk Green	S3000	D8 - Yellow	69	Blue Threaded 10L	13.5	10.0	6.1	6.0
Sprinkler : Nelson Spinner													
57	501.9	56	8.6	34	Dark Green	PC - S3000	190 D6 - Turquoise	66	Blue Threaded 10L	13.6	9.9	6.2	6.4
58	510.4	57	8.5	33	Orange/Dk Green	PC - S3000	190 D6 - Turquoise	60	Blue Threaded 10L	13.7	10.0	6.1	6.0
	514.1	Tower Number : 3			Span Length : 185.4								
59	518.5	58	8.1	34	Dark Green	PC - S3000	190 D6 - Turquoise	60	Blue Threaded 10L	13.7	9.9	6.2	6.3
Sprinkler [illegible]n Spinner													
60	527.1	59	8.6	34	Dark Green	S3000	D8 - Yellow	67	Blue Threaded 10L	13.6	9.9	6.4	6.3
61	535.3	60	8.2	37	Purple/Black	S3000	D8 - Yellow	71	Blue Threaded 10L	13.4	9.8	7.5	7.5
Sprinkler : Nelson Spinner													
62	538.8	61	3.5	35	Dk Green/Purple	PC - S3000	190 D6 - Turquoise			13.4	13.4	7.7	7.8
	539.8			Overhang	Span Length : 25.7								

219.9

Zone 6 Starts Here

Zone 6 GPM = 36

Zone 6 Ends Here

VRI Tower Box 3 & 4 Here

Zone 7 Starts Here

Zone 7 GPM = 20

Zone 7 Ends Here

Default Sprinkler Chart - 4/22/2010

3

Appendix J – Image Permissions

1.1 Frank Zybach first center-pivot system (University of Nebraska, Linclon)

Mr. Rackers: We are pleased to hear of your interest in this photo, and you may feel free to use it without cost for your thesis. Please credit it to the University of Nebraska-Lincoln.

Good luck with the thesis and in your professional future.

Dan

Daniel R. Moser
IANR News
Educational Media
University of Nebraska Institute of Agriculture and Natural Resources
203 ACB
Lincoln, NE 68583-0918
402-472-3007

Appendix J – Image Permissions

1.2 8000 series center-pivot by Valley Manufacturing (www.valleyirrigation.com)

VALLEY

A valmont PRODUCT

April 18, 2011

Andrew Rackers
1904 Green Leaves Ct.
Columbia, MO 65201

Dear Andrew

Per your request and clarification as attached, permission is granted to use the 8000 series Valley Center Pivot photo for educational purposes.

Best regards,

Sara Sims

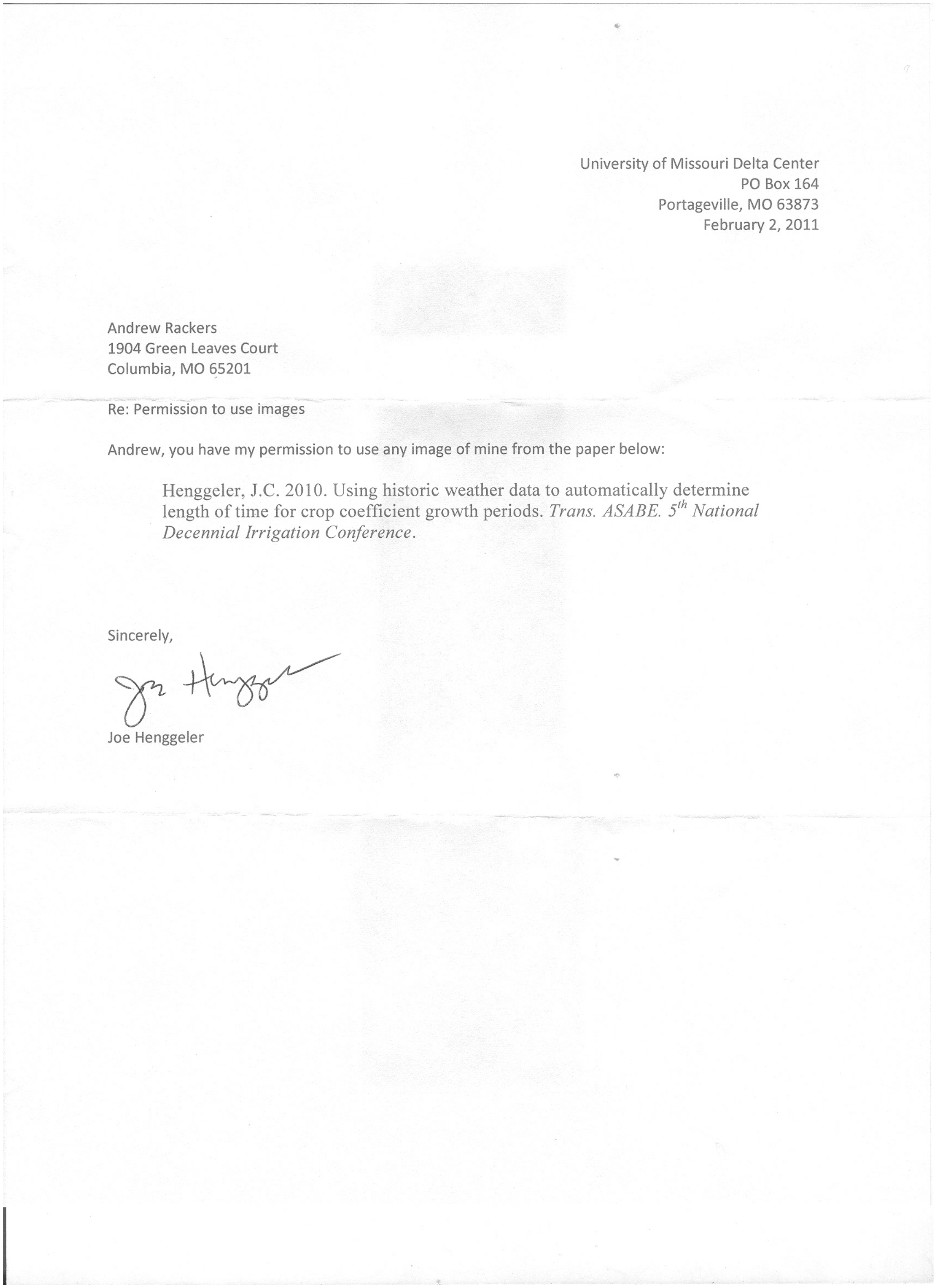
Sara Sims
Marketing Communications Manager
Valmont Irrigation
Valley, NE

Enclosure

Valmont Irrigation, Valmont Industries, Inc.
7002 North 288th Street PO Box 358 Valley, NE 68064-0358 USA
800-825-6668 (800-VAL-MONT) Fax 402-359-4429
irrigation@valmont.com valleyirrigation.com

Appendix J – Image Permissions

2.2 Observed changes in K_c values and applicable time period (Henggeler, 2010).



University of Missouri Delta Center
PO Box 164
Portageville, MO 63873
February 2, 2011

Andrew Rackers
1904 Green Leaves Court
Columbia, MO 65201

Re: Permission to use images

Andrew, you have my permission to use any image of mine from the paper below:

> Henggeler, J.C. 2010. Using historic weather data to automatically determine length of time for crop coefficient growth periods. *Trans. ASABE. 5th National Decennial Irrigation Conference*.

Sincerely,

Joe Henggeler

Joe Henggeler

2.3 Plot layout for irrigated and non-irrigated peanut treatments (Stone, 2010)

Appendix J – Image Permissions

Andrew,

I hereby give you permission to use figure 1 from the following manuscript for use in your Master's Thesis.

Stone, K. C., P. J. Bauer, W. J. Busscher, J. A. Millen, D. E. Evans, E. E. Strickland. 2010. Variable-Rate Irrigation Management for Peanut in the Eastern Coastal Plain. Paper no. IRR10-8977, In Proceedings of the 5th National Decennial Irrigation Conference, 5-8 December 2010, Phoenix Convention Center, Phoenix, Arizona USA. CDROM.

If you need a more formal permission letter, please let me know.

Good luck with your Thesis.

Sincerely,

Kenneth Stone

Kenneth C. Stone, Ph. D., P.E.
Coastal Plains Soil, Water, and Plant Research Center
USDA-ARS
2611 West Lucas St.
Florence, SC 29501
(843) 669-5203 ext. 111
Fax: (843) 669-6970
Email: ken.stone@ars.usda.gov

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