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Irrigation Management, Environment, and Profits: Who Wins?

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IRRIGATION MANAGEMENT, ENVIRONMENT, AND PROFITS: WHO WINS?

By

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IRRIGATION MANAGEMENT, ENVIRONMENT, AND PROFITS: WHO WINS?

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The impact of irrigation technology on farmers' management strategies and resulting environmental benefits depends upon agronomic properties and market forces. We evaluate the role of deficit irrigation using soil moisture probe technology on corn yield and evapotranspiration, which is a measure of water use efficiency. Evapotranspiration represents the water that transits through the plant during planting to harvest (transpiration) and the evaporation from the soil into the environment, or the displaced water in the production process. We develop yield and evapotranspiration response functions to inform a constrained profit maximization model used to identify the optimal irrigation level across a variety of input and output prices, expected rainfall and government policy limiting irrigation scenarios. Our results indicate that when including irrigation and output costs, farmers' profit is maximized at full irrigation across average observed output and input prices. When increasing input prices and/or decreasing output prices, profit maximization changes as well as the optimal amount of irrigation. Limiting irrigation by constraining evapotranspiration by a small amount has a large negative effect on farmers' profit. The technology evaluated in this study is not widely used by farmers, making our results helpful in understanding the implications of deficit irrigation and soil moisture probes.

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Abbreviations

AEU-Agro-ecological units

BW-Blue water (irrigation)

CWR- Crop water requirement

CWUE- Crop water use efficiency

ET- Evapotranspiration

ET_a- Actual crop evapotranspiration

ETWUE- Actual crop evapotranspiration water use efficiency

GW- Green water (precipitation)

FAO- Food and Agriculture of the United Nations

FIT- Fully irrigated treatment

GAMS- General Algebraic Modeling System

IRRETUE-Irrigation-evapotranspiration use efficiency

ISWC- Initial soil water content

IWUE-irrigation water use efficiency

LRP- Linear response plateau

MLE- Maximum likelihood estimation

OLS- Ordinary least squares

SWC- Soil water content

TWA- Total water applied

VWT- Virtual water trade

WUE- Water use efficiency

Y_a- Actual yield

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Chapter 1: Introduction

Nebraska is the fourth largest user of irrigated groundwater in the United States behind California, Texas, and Arkansas (Johnson et al., 2011) and has the largest number of irrigated cropland acres (USDA, 2013). The High Plains Aquifer (also known as the Ogallala Aquifer) is very important to Nebraska farmers since rainfall during the growing season may not be adequate or as predictable as it is in other large farming states. Over time, the stress of droughts has increased demand for irrigation resources, causing groundwater levels to decline (McGuire, 2004 and Young et al., 2013). Irrigation in one location can reduce the amount of water in another and limit what is available for irrigation and other uses. In 2006, Nebraska faced a lawsuit by Kansas on the grounds that less water was delivered to Kansas than had been agreed upon in an earlier Compact because of irrigation by Nebraska farmers in the Republican River during a four-year long drought from 2002-2006 (The Supreme Court of the United States, 2014). There is some evidence suggesting that it was an intensive margin issue due to the drought and farmers needing more water to irrigate existing acres. There is some evidence suggesting that it was also an extensive margin issue due to Nebraska adding 934,000 irrigated acres from 2002-2007 (Johnson et al., 2011).

In 2012, the state of Nebraska faced its worst drought since 1940 leading to greater uses of irrigation and increasing farmers' reliance on crop insurance. Prices for corn reached as high at $8.13 per bushel in Hastings, Nebraska during July of 2012 (Johnson and Walters, 2014). Nebraska corn farmers received over $363 million dollars from crop insurance to cover revenue shortfalls during the drought (Smith, 2012). Since Nebraska is one of the largest exporters of corn in the United States, efficient use of its water resources is of particular importance. Greater efficiency can be achieved by effectively managing water resources and working on continuous improvement in crop water productivity (Kelly, 2011). Nebraska's Natural Resources Districts (NRDs) have established irrigation restrictions limiting the expansion of irrigated acres, controlling the allocation of groundwater, setting moratoria on well drilling, and requiring water usage reports (Bathke et al., 2014). The Nebraska's NRDs have also implemented projects to maintain natural water resources by controlling pumping rates, managing canals and reservoirs to encourage recharge of the aquifer, and implementing new irrigation strategies that will allow water savings to rise (Bathke et al., 2014; Edson, 2017). Such new irrigation policies will impact farmers' overall farm management practices.

Irrigation water has a small variable cost for farmers unless external restrictions on its use are being imposed by policy makers. However, environmentalists and economists recognize that there are opportunity costs as well as depletion costs associated with water use.

The necessary increase in food production may not be possible with fixed resources like water (Amado, 2014). Excessive pumping has caused underground water resources to be at risk of being over-exploited. Water in aquifers is replenished by the natural precipitation and surface water that seeps into the aquifer but the rate of recharge is generally lower than the rate at which the water is being consumed. One can think of groundwater as similar to bank account in which deposits are made and from which withdrawals are taken out. If more water is withdrawn than is being replenished, water tables will fall and the water may eventually become inaccessible or exhausted completely. Increased groundwater pumping reduces surface water flows in lakes, streams, and rivers, as well as lowers ground water levels in wetlands. These issues can lead to lawsuits and loss of available water for irrigation and can negatively impact vegetation and wildlife habitat (USGS, 2003). As well as water shortages, over-pumping can lead to land subsidence and lowered water tables. If land subsidence occurs, the soil will collapse into the empty aquifer and destroy the aquifer and limit the possibility of recharge. The water table is the point at which the well can reach the groundwater. If the water table is lowered, the water cannot be pumped and the well would have to be deepened (The Groundwater Foundation, 2017). Maintaining groundwater resources is crucial to continuous access to fresh water for irrigation in the years to come.

In this research, we evaluate how farmers could adjust their irrigation strategy in a profitable way when facing different input and output prices, weather, and potential constraints on irrigation. Measuring evapotranspiration (ET) can be useful in evaluating how much water was used by the plant. ET represents the water that transits through the plant during planting to harvest (transpiration) and the evaporation from the soil into the atmosphere (Irmak, 2015a; and 2015b; Hoekstra and Hung, 2002). The amount of ET observed reflects how efficiently irrigation was used. Total water applied (TWA) is the sum of rainfall, irrigation applied to a field, and the initial stock of water in the soil. The relation between ET and total water applied distinguishes between water used through ET and water that is not being used by the plant. ET has been used by many researchers to examine the relation between water application and plant growth (Hoekstra and Hung; 2002; Irmak, 2015a; and 2015b; Lovelli et al., 2007, among others). Farmers are concerned with having reliable water resources because without water it is not possible to achieve high yields and profit. We analyze the role of water applied on yield and ET and the role of economics given specific water management practices. We also analyze the marginal value of irrigation on yield by separating TWA into green water (GW, represented in this research by the sum of rainfall and initial soil water content) and blue water (BW, represented in this research by irrigation) to further investigate the relation between irrigation, yield, and profit. Economic variables such as input and output costs as well as fixed costs associated with managing a farm and owning an irrigation center pivot are used in a constrained optimization model. This model computes the best irrigation strategy under different irrigation and evapotranspiration restrictions when considering the response of yield and evapotranspiration have to total water applied as well as the response yield has to irrigation at the average green water value during the years of our study.

Water goes through a cycle which makes it possible to reuse it again. Water applied on fields can take many forms. Water can go through ET and be taken into the atmosphere where it is stored in the clouds. These clouds eventually move across the globe and fall from the sky as precipitation (Richter, 2012). Precipitation can come in multiple forms and falls over oceans, mountains, lakes, and land. Water that falls on mountains in the form of snow or rain will slowly flow into streams and rivers as surface runoff. This surface runoff will enter rivers, land, or oceans and has the potential to be used for irrigation. Water that is applied to the field can also seep into the ground and recharge aquifers. It can also immediately become runoff and not be used by the plant but may enter a river or lake from which it can be used to irrigate at a later time. Not all water that goes through the cycle can be used again due to contamination (Richter, 2012).

The concept of measuring how much water is used to produce crops is known as the water footprint.

Hoekstra and Hung (2002) used the water footprint concept to measure how much water was used to grow agricultural commodities by a region, country, or industry. Hoekstra and Hung (2002) suggested that studying water footprints can determine which places are using water efficiently and identify weaknesses in farm management, especially in countries that with less advanced irrigation technologies. Hoekstra advised countries that are water abundant to produce water-intensive goods, which are goods that require more water (rice, meat, chocolate, etc.). Countries that are water scarce should import water intensive goods and export goods or services that require less water. Other research shows that many countries are not following this advice (Zhang et al., 2014; Kumar and Sing, 2005; and Wichelns, 2009). Our research considers economic factors as well as water to evaluate farmers' production behavior.

Our results show that full irrigation is the most profitable strategy for farmers under all reasonable input/output costs, various levels of rainfall, and no limitations on ET. [1] We examine the possibility that governments could impose restrictions on water use which may impact farmers' profits and management strategy. If ET is reduced by a small amount from the profit maximizing value, production will be greatly restricted and therefore profits will be lower.

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[1] Full irrigation is defined as fully irrigated treatment (FIT) which is irrigating the crop until soil water depletion is at 40-45% of the total water holding capacity of the soil.

Chapter 2: Literature Review

The motivation for this research is the need to understand the relation between water scarcity, water-use efficiency, and profit. A common practice among irrigation and water-use specialists is to distinguish among precipitation, known as "green water," surface and ground water, referred to as "blue water," and fresh water that carries pollutants from urban and industrial sources known as "grey water" (Hoekstra et al., 2011). When blue and green water (BW and GW respectively) are used for some human purpose such as agricultural production, the amount of water used is referred to as the water footprint of that human activity. Avoiding over-exploiting water can help prevent potential water shortages. One approach to ensure water security is for countries to be aware of their water footprint and attempt to reduce it, especially their blue water footprint since that indicates how much water was used for irrigation, of which producers have control unlike rainfall. According to Hoekstra et al. (2011), water footprint measurements can be used to analyze how efficiently both types of water resources were used to produce goods and services by an individual or country over a certain period of time.

Water Footprint

The concept of the water footprint was developed by Hoekstra and numerous collaborators who have set up the Water Footprint Network (http://waterfootprint.org/en/) and published an extensive manual to calculate water footprints (Hoekstra et al., 2011; and Hoekstra and Hung, 2002). The water footprint can be measured for particular individuals, industries, economic sectors, or geographic regions. Because the greatest use of water is for agricultural production, there have been many studies of the water footprint of particular crops under different management techniques (Chukalla et al., 2015; Jin and Huang, 2016; and Tsakmakis et al., 2018). The objective of these studies was to determine which management practices make the most efficient use of water with a view toward reducing the impact of agricultural production on water supplies. Water footprints have been used to describe how different commodities require different amounts of water and how countries producing the same commodity can have different water footprints for that commodity.

Hoekstra and Mekonnen (2012) used water footprint estimates to analyze how much water goes into production of agriculture commodities. They defined the water footprint of an intermediate or final good as the aggregate of the water footprints of the various steps in the production of the product. Water footprints can vary greatly between commodities. As a global average, the water footprint for beef is very high at 15,500 liter/kg compared to corn at 900 liter/kg (Mekonnen and Hoekstra, 2012). Animal products have a large water footprint because the water required to grow feed is included in the water footprint along with the water consumed by the animal. Hoekstra advised countries that are water abundant to produce and trade meat since pressure on global freshwater resources is rising with increasing demands for water-intensive products such as beef. This approach to managing potential water scarcities is addressed through accounting and managing production through virtual water trading.

Virtual Water

Allan (1998) coined the term “virtual water” which is the water content of traded goods. This concept has been used to describe the potential for countries with limited water resources to enhance their water supplies through importing water-intensive goods from countries that are water-abundant. In subsequent years, a substantial literature has been produced to measure and analyze virtual water trade of different countries or regions within countries. For example, Mubako et al. (2013) found that California was a net exporter of virtual water despite the fact that water is often in short supply in the state. An important aspect of this problem is that water is often underpriced or not priced at all leading to its over-use. A shortcoming of using the virtual water concept to make trade policy recommendations is that water availability is not the only factor driving production and trade.

Hoekstra et al. (2011) argued that global virtual water trade can help reduce overall water consumption when countries that are water-abundant specialize in water-intensive products. The reason for this result is that the amount of water used to produce commodities varies across countries. For example, Renault (2003) found that France trading 1 kg of corn with Egypt saves $0.52m^3$ of water because the water footprint of corn in France is $0.6m^3$/kg compared to$1.12m^3$/kg in Egypt. The difference in water-use efficiency in these two countries may be due to multiple variables such as: different types of soil, access to technology, irrigation management, government regulation and quality of infrastructure, climate, etc. The government can help sustain natural resources by controlling groundwater abstractions, subsidizing farmers to grow commodities that require less water, and giving them access to better farming technology. If countries trade based on advantage in water-use efficiency, global water consumption will decrease (Sadras et al., 2009; Hoekstra and Karandish, 2017). It is likely that trade based on water availability could hurt both countries since it may not be the optimal trade strategy. Countries trade based on comparative advantage in production, which depends on many factors beyond water availability such as opportunity costs of producing one commodity over another, cost of labor, and arable land.

Virtual water trade (VWT) has been analyzed by Hoekstra and Hung (2002) who created a trade flow model to compare virtual water trade among countries:

$$1)\ VWT[n_e, n_i, c, t] = CT[n_e, n_i, c, t]\ X\ SWD[n_e, c],$$

where VWT represents the trade flow from the exporting country (n_e) to the importing country (n_i) in year *t* for crop *c;* CT represents the crop trade from n_e to n_i in year *t* for crop *c; SWD* represents the water demand of crop c in n_e. When water abundant-countries export water intensive goods, this equation will be minimized since their water demand for crop *c* should be lower than it would be in the countries they are exporting to. Based on this trade equation, optimal specialization in production is based on the amount of water resources in importing and exporting countries as well as how water efficient they are. This production strategy has been criticized by Wichelns (2009), Zhang et al., (2014), and Kumar and Singh (2005) in that focusing only on water endowments would indicate absolute advantage rather than comparative advantage. This trade model does not incorporate total opportunity costs of production, which is why optimal virtual water trading is not seen in practice.

Water footprint researchers (Zhang et al., 2014; Kumar and Singh, 2005) have used the VWT model to analyze where water intensive goods should be produced and where they should be exported. Virtual water trade models can also be used to examine domestic trade. Zhang et al. (2014) conducted a study to analyze China's VWT among provinces in China to see if trade within China was based on absolute advantage of water resources. They used the virtual water trade model to measure how much water was being traded within China. They noticed that the demand for agricultural products has increased due to urbanization and growing income as measured by Gross Domestic Product (GDP). The provinces that account for large percentages of China's GDP also have larger water footprints per-capita and rely on importing water-intensive goods from other provinces. Water-scarce regions in the western part of the country are also less populated and turned out to be large water exporters to eastern provinces closer to the coast. It was concluded that the discrepancy is because availability of water resources is not the only factor that goes into production considerations. Kumar and Singh (2005) found that many water-abundant countries are actually net importers of virtual water and water-scarce countries are net exporters. Zhang et al. concluded that the most influential variables driving VWT are crop productivity, arable land, economic development, and access to fuel resources. These variables drive trade much more than water scarcity. In line with these observations, our research assumes profitability is the most important factor farmers consider when making decisions about irrigation.

Analytical Methods to Quantify Water Efficiency

Water footprints have been analyzed further using ET to see how much water is used by the plant. The water applied to a field can either be incorporated into the plant, become runoff, percolate to groundwater, or be consumed through ET (Hoekstra and Hung, 2002). Runoff is water that was not absorbed by the plant or soil and flows out of the field into rivers, lake, or drainage. Water that percolates to groundwater (deep percolation) is water that falls on the soil and seeps into the ground and has the potential to recharge an aquifer. ET represents the water that transits through the plant during planting to harvest (transpiration) and the evaporation from the soil or the displaced water in the production process (Irmak, 2015a). A certain level of ET is required for maximum plant growth, but watering past the point where ET is optimal is considered waste (Hoekstra et al., 2011).

ET is difficult and costly to measure which is why many researchers use models like AquaCrop and CROPWAT to calculate it (Hoekstra and Mekonnen, 2012; Surendran et al., 2015; Etissa, 2016; and Greaves and Wang, 2016). AquaCrop and CROPWAT were developed by the Land and Water Division of the United Nations (2018). AquaCrop simulates yield response functions to water used throughout the planting and growing processes as well as to calculate ET. CROPWAT calculates crop water requirements based on soil, climate, and crop planted. CROPWAT develops irrigation schedules under different management practices while estimating crop performance under different irrigation strategies as well as for rainfed crops.

AquaCrop and CROPWAT generate results based on data entered by the user on climate, crop, soil type, water stress, and other simple inputs (United Nations, 2018). Compared to AquaCrop, CROPWAT requires less input data. CROPWAT is a convenient way to get a quick approximation of ET and yield under different water application strategies. Previous research has found limitations on reporting accurate yield responses to water (Popova et al., 2006; Lovelli et al., 2007). CROPWAT does not account for the initial water content of soil that carries over from year to year (Vote et al., 2015). AquaCrop is a more evolved version of CROPWAT. It is similar in that users enter input data to run the program. It is less complex than other models (Steduto et al., 2012) and more accurate because it requires the user to enter more complex data on soil and ground water characteristics (United Nations, 2018). Both models can only account for a few external impacts and are incapable of incorporating all climate types in all the regions on which they report. Because of these limitations, Steduto et al. (2012) recommend that these models be used only for quick estimations of ET and yield.

CROPWAT and AquaCrop have been used in previous research to calculate water footprints, ET, and yield. Surendran et al. (2015) conducted a study in Kerala, India that used CROPWAT to compute the water requirements for rice, coconuts, and bananas. The authors used CROPWAT to calculate ET by entering data related to climate, rainfall, irrigation, crop and soil conditions. Another experiment done by Etissa (2016) analyzed the optimal irrigation strategy for tomato production in Ethiopia. Etissa (2016) used CROPWAT to calculate the yield response of tomatoes to soil water by entering information such as soil type, climate, irrigation treatment, and crop grown and then noted how closely CROPWAT's predictions of yield with different irrigation strategies matched the actual results. CROPWAT seemed to underestimate yield reduction when using less irrigation but was overall considered a valid tool to help farmers decide on optimal irrigation management (Etissa, 2016).

Greaves and Wang (2016) used AquaCrop to simulate corn production under different irrigation strategies in an experiment in Taiwan. They used the model to measure ET which is used in the calculation of water use efficiency (WUE), calculated as the actual yield (Y_a) under different irrigation strategies divided by ET (Y_a/ET). The calculated WUE was compared to actual measurements of ET and WUE. They found that when water stress increased, the accuracy of AquaCrop's results declined for ET and therefore for WUE. They concluded that AquaCrop is useful in predicting WUE and ET when limiting irrigation slightly but using it in cases of high water stress will result in inaccurate predictions. Due to these limitations, it is best to directly measure ET if possible to get the accurate results regarding WUE and other variables that depend on ET.

ET can be estimated by collecting data on water that has become runoff and run-on from irrigation and precipitation, water that has descended into the aquifer through deep percolation, water that is stored in the soil profile, and the upward flux of soil moisture. Irmak (2015a; 2015b) conducted field experiments and collected accurate data on ET. In this thesis, these more precise data are used to examine the economic effects of alternative irrigation management strategies. Irmak's corn production experiment was conducted in a University of Nebraska-Lincoln agricultural laboratory in south-central Nebraska from 2005-2010. He used different irrigation treatments to see how they impact yield, ET, and water use efficiency (WUE). Four irrigation treatments were conducted: full irrigation (FIT) and limited irrigation treatments (75% FIT, 60% FIT, and 50% FIT). FIT is defined as irrigating the crop until soil water depletion is at 40-45% of the total water holding capacity of the soil. Irmak used a soil moisture probe to measure the soil water content and irrigated the plot based on treatment and the soil water holding capacity. Irrigation is reduced by 25% of what was used to irrigate at full for the plots that were 75% FIT. The same strategy was applied for plots with 60% FIT (40% reduction) and 50% FIT (50% reduction). Irmak concluded that FIT was the best irrigation method to maximize yield for all years.

Under these different irrigation treatments, Irmak measured actual crop evapotranspiration ($\mathrm{ET_a}$) by using a soil water balance equation:

$$2)\ P + I + U + Runon = Runoff + DP \pm \Delta SWS + ET_a,$$

where P = precipitation (millimeters, mm); I = irrigation water applied (mm); U = upward soil moisture flux (mm); $Runon$ = surface run-on within the field (mm); $Runoff$ = surface runoff (mm); ΔSWS = change in soil water storage in the soil profile (mm) measured at the beginning and end of the growing season; DP = deep percolation (mm) below the crop root zone. Surface run-on within the field and upward soil moisture flux were found to be negligible so they were dropped from the equation. Rearranging terms, ET_a is calculated as:

$$3)\ ET_a = P + I - Runoff - DP \pm \Delta SWS.$$

Irmak (2015a) estimated deep percolation independently. Runoff was estimated using rainfall, initial abstraction, and maximum potential soil moisture retention to solve for runoff (Irmak, 2015a; USDA, 1986).

Hoekstra et al. (2011) used ET to measure irrigation efficiency. The authors stated that there is potential for ET to be unproductive. ET consists of water that transits through the plant (transpiration) and evaporates from the soil. A high amount of ET indicates the water that was applied was not thoroughly used by the plant. Transpiration contributes to plant growth, which is why some amount of ET is required for output. According to Hoekstra et al. (2011 pp. 131): “The crop water requirement (CWR) is the water needed for evapotranspiration under ideal growth conditions, measured from planting to harvest. ‘Ideal conditions’ means that adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield…It is assumed that the crop water requirements are fully met, so that ET will be equal to the crop water requirement: ET = CWR.” If these two variables are equal to each other, then all water applied was directly used in plant growth or the unavoidable evaporation from the soil and no water applied became runoff or deep percolation. (Hoekstra et al., 2011; Irmak, 2015a; 2015b).

Irmak (2015b) used ET to measure water-use efficiency in a similar way. He calculated crop water use efficiency (CWUE) which is the ratio of yield to ET (Y/ ET_a). Irmak has also measured ET_a water use efficiency (ETWUE) which separates ET_a from CWUE:

$$4)\ \text{ETWUE}= [(Y_i - Y_r)/(ET_{ai} - ET_{ar})]\ x\ 100,$$

where Y_i is yield under irrigation level i; Y_r is yield under rainfed; ET_{ai} is actual ET for irrigation level $i;$ and ET_{ar} is the actual ET for the rainfed treatment. ETWUE is an effective measure of how irrigation affected crop water productivity. If water application decreases, the difference between ET_{ai} and ET_{ar} should get smaller making ETWUE larger. Irmak found evidence that ETWUE increases when water application decreases. Yield was highest at FIT and CWUE was optimized at 75% FIT which suggests transpiration was maintained at the same level as FIT, but soil surface evaporation was reduced indicating an increase in water-use efficiency.

Irmak (2015b) introduced the concept irrigation-ET use efficiency (IRRETUE) which evaluates how efficiently irrigation was used with respect to actual crop ET (%):

$$5)\ \text{IRRETUE}= [(ET_{ai} - ET_{ar})/(Ii)]\ x\ 100,$$

where Ii is irrigation applied under irrigation level $i;$ and ET_{ai} and ET_{ar} are as defined earlier. $ET_{ai},$ $ET_{ai},$ and Ii are measured in the same units, therefore, 100% IRRETUE would indicate all irrigation applied either was transpired through the plant or was evaporated from the soil so no irrigation water was wasted in runoff and ET_{ai} is equal to

CWR. IRRETUE over 100% implies that some of the irrigation applied was not used through ET_{ai} and the farmer over irrigated while under 100% implies under irrigation.

Agricultural production relies on water. The decision about what to produce and how much water to apply depends on expected profit with some consideration of water availability. This research combines environmental and economic factors to investigate optimal irrigation management decisions. If farmers are able to adjust their irrigation strategies when faced with different scenarios surrounding climate, government intervention, and input and output costs, they can make the optimal decision and keep their farms profitable. Using data from Irmak (2015a; 2015b) research, we are able to combine environmental and economic factors to inform farmers on how marginal water application impacts yield, how changes in rainfall and input and output costs affect irrigation strategies, how limiting ET will impact attainable yield, and how a combination of these factors can change profitability.

Chapter 3: Research Methodology

We begin the research methodology section with an overview of the experiment conducted by Irmak (2015a; 2015b) to describe the irrigation study that was used in our research. Using data from Irmak (2015a; 2015b), we develop response functions to estimate the relation between yield and total water applied as well as ET and water applied. We are also interested in the marginal value of irrigation, consequently, we develop a yield response function in which total water applied is separated into irrigation (blue water, BW) and the sum of initial soil water content and rainfall (green water, GW). We use the results from these response functions in a constrained optimization profit maximization model to identify the optimal amount of water applied given economic and agronomic variables such as: output prices, factor prices, irrigation expenses, rainfall, and potential ET restrictions.

Data

The data come from a corn production experiment conducted by Irmak (2015a; 2015b) at the University of Nebraska-Lincoln South Central Agricultural Laboratory near Clay Center, Nebraska, between the years 2005-2010. Irmak recorded the irrigation applied, rainfall, weather, and yield obtained and was also able to measure actual crop evapotranspiration (ET_a). Irmak (2015a; 2015b) experiment was done on a 40.77 acres field separated into 12 different plots of around 2.5 acres each subjected to five different irrigation treatments: fully irrigated (FIT), limited irrigation treatments (75% FIT, 60% FIT, and 50% FIT) and rainfed. The soil type for the entire field is Hastings silt loam, a well-drained upland soil. All plots were planted with the same corn hybrid and planting direction was north-south over the entire course the experiment. The field was irrigated using a four-span hydraulic and continuous move center pivot-irrigation system. The experimental plots were placed in the third span of the center pivot and were irrigated based on the treatment type. Through the years of 2006-2008, we controlled for the two different planting populations, low and high. For 2005, 2009-2010 only high plant population was used in the experiment. Each year all plots were fertilized equally and nitrogen and herbicide applications were consistent on all plots though type of fertilizer and herbicide changed year to year.

Irrigation under FIT depended on the soil water content (SWC) with irrigation used to maintain available soil water in the top 1.5 m profile at between approximately 90% of the field capacity and a maximum allowable depletion set to approximately 40-45% of the total available water holding capacity. Deficit irrigation for each plot was based on how much irrigation FIT required that year. Under 75% FIT, the irrigation was reduced by 25% relative to the amount used for 100% FIT. The same strategy was applied for plots with 60% FIT (40% reduction) and 50% FIT (50% reduction). No irrigation was applied to the rainfed control group. As expected, for years that had more rainfall, less irrigation was needed under FIT to reach optimal SWC.

We estimate yield and ET response functions to total water applied (TWA), and an additional yield response function to blue water (BW) and green water (GW). TWA is the sum of rainfall, irrigation, and initial soil water content (ISWC, which averaged 4.725 inches per each year). ISWC is the moisture content of the soil, which depends on precipitation that happened outside the growing season. We calculate the average of rainfall during the growing season (May 1- September 30) from 2005 to 2010. BW represents irrigation and GW represents ISWC plus rainfall. Figures C1 to C6 in

Appendix C show the relation between irrigation and rainfall for each year in the experiment.

Data for the constrained optimization and response functions for yield and ET came from Irmak (2015a; 2015b) which included initial soil water content, irrigation, precipitation, yield, ET, and variable input and farm production costs. Fixed irrigation costs that were also included in the constrained optimization model came from the U.S. Department of Agriculture. Tables A1 and A2 in Appendix A show the list of variable and fixed costs used to calculate the fixed costs per acre. The model focuses on the variable costs associated with irrigation to analyze the profit strategy based on the marginal cost and return of irrigation. Rainfall data collected outside the time frame of our experiment came from the High Plains Regional Climate Center in Clay Center, Nebraska (2018). Corn prices for the period of our experiment and 2012 came from Nebraska Extension (Johnson and Walters, 2014). Table A3 in Appendix A shows the average, high, and low corn price, irrigation price, and rainfall for the relevant periods. Corn prices from 1940 and 1993 are from USDA (2018). Table A4 in Appendix A includes rainfall and corn prices for years outside the time frame of our experiment (1940, 1993, 2002, and 2012).

Yield and ET Response Functions

We develop response functions to evaluate the effect of TWA on yield and ET, and BW and GW on yield, controlling for repetition, and seeding population. We evaluate two different functional forms for the yield response function to TWA, with each response function representing a particular type of producer behavior. The first model is a linear response model with a stochastic plateau (LRP), which represents the behavior of producers who irrigate the same amount each year unless output and factor prices differ greatly from the expected range.[2] The second model is a quadratic function allowing for curvature in the amount of total water applied, which represents producers who make irrigation decisions based upon output and factor prices.

For the ET response function, we use a quadratic functional form because it was a better fit for the biological process and the data. To analyze the marginal value of irrigation we develop a quadratic response model with a stochastic plateau (QRP) separating TWA into BW and GW. We did not estimate ET as a function of BW and GW separate from TWA because we cannot differentiate ET due to BW from ET due to GW. The quadratic response functions are estimated using ordinary least squares (OLS) whereas the LRP and QRP functions are estimated using maximum likelihood estimation (MLE).

Tembo et al. (2008) proposed that a LRP function's dependent variable will respond linearly to an additional unit of an input until it reaches a certain level known as the "knot point." The knot point is defined as the point where the linear response function and the flat plateau function are splined, indicating that an additional unit of an input will neither increase or decrease yield (Tembo et al., 2008; Berck and Helfand, 1990). Several papers have analyzed how a LRP yield response function responds to nitrogen (Boyer and Borsen, 2013; Liu et al., 2013; Tumusiime et al., 2010; Boyer et al., 2013), but little recent research has been done on yield response to TWA. Grimm et al. (1987) hypothesized that a LRP function would be a strong fit to represent a corn yield response

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[2] For the linear plateau model, very low output prices or very high input prices would cause the decision maker to not apply any irrigation. For all other price combinations, the decision maker irrigates at the 'knot point' or the intersection of the linear response and plateau.

to water as well as nitrogen application. Their results showed that the LRP functional form could not be rejected for both water and nitrogen inputs. We estimate a LRP equation for yield (Y_{it}) for each treatment *i* (*i*=FIT, 75% FIT, 60% FIT, 50% FIT, and Rainfed) in year *t* (*t*= 2005,…,2010):

$$6)\ Y_{it} = \min(\beta_0 + \beta_1 \mathrm{TWA_{it}} + \eta X, P + v_t) + u_t + \varepsilon_{it},$$

where β_0 and β_1 are parameters to be estimated; TWA_{it} is the total water applied; η is the vector of coefficients; X is the vector of control variables (repetition and plant population); P is the expected plateau yield; v_t~ N(0, σ_v^2) is the plateau year random effect which shifts the plateau; u_t~ N(0, σ_u^2) is the year random effect; and ε_{it}~ N(0, σ_ε^2) is the random error term (Tembo et al., 2008). Table 1 describes our results.

To allow for producers who adjust input levels based upon output and factor prices we also consider a quadratic response following an irrigation response study that used a quadratic response function (Kipkorir et al., 2002) The quadratic response equation for estimating yield (Y_{it}) for each treatment *i* (*i*=FIT, 75% FIT, 60% FIT, 50% FIT, and Rainfed) in year *t* (*t*= 2005,…,2010) is :

$$7)\ Y_{it} = \gamma_0 + \gamma_1 \mathrm{TWA_{it}} + \gamma_2 \mathrm{TWA_{it}^2} + \psi X + \varepsilon_{it},$$

where γ_0, γ_1, and γ_2 are the parameters to be estimated; $\mathrm{TWA_{it}}$ is the total water applied; ψ is the vector of coefficients; X is the vector of control variables (repetition and plant population); and ε_{it} is the error term. Table 1 describes our results.

ET is estimated as a function of TWA. We use a quadratic functional form because it represents the biological process more accurately and provided the best fit for the data. Because irrigation and ET are directly related, we use limits on ET in the optimization model to reflect the effects of policies constraining water use. Policies to restrict pumping or well-drilling, for example, will lead to reduced ET and the impact of the restricted ET on profits provides information on the impact of such policies on farm profitability. The quadratic response function for estimating the dependent variable expected evapotranspiration (ET_{it}) for each treatment *i* (*i*=FIT, 75% FIT,…,Rainfed) in year *t* (*t*= 2005,…,2010) is:

$$8)\ ET_{it} = \phi_0 + \phi_1 \mathrm{TWA_{it}} + \phi_2 \mathrm{TWA_{it}^2} + \zeta X + \varepsilon_{it},$$

where ϕ_0, ϕ_1 and ϕ_2 are the parameters to be estimated; $\mathrm{TWA_{it}}$ is the total water applied; ζ is the vector of coefficients; X is the vector of control variables: repetition and plant population; and ε_{it} is the error term. Table 1 describes our results.

To analyze the marginal value of irrigation we build upon Tembo et al. (2008) to separate TWA into BW and GW and include a quadratic term for both BW and GW. We estimate a QRP equation for yield (Y_{it}) for each treatment *i* (*i*=FIT, 75% FIT, 60% FIT, 50% FIT, and Rainfed) in year *t* (*t*= 2005,…,2010):

$$9)\ Y_{it} = \min(\alpha_0 + \alpha_1 BW_{it} + \alpha_2 BW_{it}^2 + \alpha_3 GW_{it} + \alpha_4 GW_{it}^2 + \omega X,\ P + v_t) + u_t + \varepsilon_{it},$$

where α_0, $\alpha_1, \alpha_2, \alpha_3$ and α_4 are the parameters to be estimated; BW_{it} is the total of blue water applied (irrigation); GW_{it} is the total of green water applied (ISWC plus rainfall); ω is the vector of coefficients; X is the vector of control variables (repetition and plant population); and ε_{it} is the error term. Table 1 describes our results.

Constrained Optimization Model to Compute Profit

For the constrained optimization model, we include variable and fixed costs of production in the profit equation to determine the optimal water application given expenses with the objective to maximize profit. We include all production costs allowing us to identify profitability, which influences decision making.

The optimization model is solved using GAMS (General Algebraic Modeling System, see programs B1, B2, and B3 in Appendix B for code). We use the cost information and both yield response functions to find the amount of TWA to maximize profit under average conditions over input and output prices and rainfall. Equation (10) shows the constrained profit equation for an LRP yield response function:

$$10)\pi_t = \underbrace{(Pc_t * (\beta_0 + \beta_1\, TWA_{it}))}_{\boxed{\text{Revenue: price multiplied by yield function}}} - \underbrace{(C_{it} * (TWA_{it} - Rain_t - ISWC_t)) - FC_t}_{\boxed{\text{Cost: variable and fixed}}}$$

$$s.t.(\beta_0 + \beta_1 \mathrm{TWA_{it}}) \leq PL_{LRP},$$

$$s.t.\ (\phi_0 + \phi_1 \mathrm{TWA_{it}} + \phi_2 \mathrm{TWA_{it}^2}) \leq\ U,$$

where π is profit; Pc_t is the price of corn per bushel; β_0 is the constant from the LRP yield equation; $\beta_1$is the parameter estimate for TWA_{it} from the LRP yield equation; $C_{it}$is the variable cost of irrigation applied per inch; $Rain_t$ is the rainfall that occurred during the growing season; $ISWC_t$ is the initial water content of the soil before the growing season begins; and FC_t is the fixed costs per acre associated with running a farm and an irrigation sprinkler system. The profit equation is constrained by the yield equation in that yield cannot be more than the plateau yield, PL_{LRP}. TWA is also constrained by, U, the maximum acceptable ET that will vary by potential government restrictions. The optimization model also included constraints requiring that yields and output and input prices be positive. P_c is multiplied by the LRP yield response function which represents the revenue. Fixed costs and the variable cost of applying irrigation which depends on how much rain there was as well as the initial water content are subtracted from revenue. Equation (11) shows the constrained profit function for a quadratic yield function:

$$11)\ \pi_t = (\underbrace{Pc_t * (\gamma_0 + \gamma_1 TWA_{it} + \gamma_2 TWA_{it}^2)}_{\boxed{\text{Revenue: price multiplied by yield function}}}) - (\underbrace{C_{it} * (TWA_{it} - Rain_t - ISWC_t)) - FC_t}_{\boxed{\text{Cost: variable and fixed}}}$$

$$s.t.\ (\phi_0 + \phi_1 \mathrm{TWA_{it}} + \phi_2 \mathrm{TWA_{it}^2}) \leq\ U,$$

where γ_0 is the constant from the quadratic equation; $\gamma_1$is the parameter estimate for TWA_{it} from the quadratic yield equation; and $\gamma_2$is the parameter estimate for TWA_{it}^2 from the quadratic yield equation. It is constrained by, U, the maximum acceptable ET that will vary by potential government restrictions. The quadratic and LRP functions are similar in that the cost function is the same and they are constrained by U, but the quadratic includes a parameter estimate in TWA_{it}^2 in the yield equation whereas the yield equation under the LRP function is constrained by PL_{LRP}.

A separate analysis is done to examine the optimal amount of BW when considering the impact BW has on yield by separating out GW from TWA. Equation (12) shows the constrained profit function for a QRP function:

$$12)\ \pi_t = (\underbrace{Pc_t * (\alpha_0 + \alpha_1 BW_{it} + \alpha_2 BW_{it}^2 + \alpha_3 GW_{it} + \alpha_4 GW_{it}^2)}_{\boxed{\text{Revenue: price multiplied by yield function}}}) - (\underbrace{C_{it} * BW_{it}) - FC_t}_{\boxed{\text{Cost: variable and}}}$$

$$s.t. (\alpha_0 + \alpha_1 BW_{it} + \alpha_2 BW_{it}^2 + \alpha_3 GW_{it} + \alpha_4 GW_{it}^2) \leq PL_{QRP},$$

$$s.t.\ (\phi_0 + \phi_1 \mathrm{TWA_{it}} + \phi_2 \mathrm{TWA_{it}^2}) \leq\ U,$$

where α_0 is the constant from the QRP yield equation; $\alpha_1$is the parameter estimate for BW_{it} from the QRP yield equation; and α_2 is the parameter estimate for BW_{it}^2 from the QRP yield equation; α_3 is the parameter estimate for $GW_{it}$from the QRP yield equation; and α_4 is the parameter estimate for GW_{it}^2 from the QRP yield equation. The irrigation cost, C_{it}, is multiplied by BW_{it} since irrigation is already solved for. It is constrained by

PL_{QRP}, the maximum achievable yield as well as U, the maximum acceptable ET that will vary by potential government restrictions. See equation (10) for the definition of all variables. Using equations 10, 11, and 12, we calculated the expected profit under normal farming conditions.

In addition to calculating profit under normal farming conditions, we analyze 20 scenarios that increased/decreased expected prices, rainfall, and allowable ET which changed the results of the optimal amount of TWA (or BW when calculating profit with the QRP yield equation) as well as expected ET, yield, and profit. We also include scenarios from years in which Nebraska experienced severe weather conditions outside the timeframe of the experiment. We note how corn prices changed in these extreme years and calculated the change from the lowest to highest price of that year. We then incorporate the percentage change in prices to the average corn price in the time frame of the experiment to get a realistic interpretation of what this price change would do to profit for each scenario.

Chapter 4: Results

Our objective is to solve for the best irrigation strategy when considering the response yield and ET have to TWA as well as including economic costs and prices of inputs and outputs that impact profit. In addition, we analyze the best irrigation strategy when considering the response of yield to BW. Our results solving for the optimal amount of irrigation vary depending on which response function was used. Profit computed in the constrained optimization model varied greatly when variables were slightly changed. Our results can assist farmers in making water management decisions based on normal expectations, as well as unexpected weather and economic conditions. Table 1 reports the estimation results for all the response functions.

Response Functions Results

Figure 1 shows the relation between TWA and yield for the LRP yield response function based on the results in table 1. The constant, β_0, represents the expected yield under no water applied at -349.58 bu/acre, indicating a certain amount of water applied is required for plants to start growing at all. The required amount of water applied under the LRP function is approximately 17 inches. Below this amount there is no output but once this threshold is reached, yield will increase at a linear rate of approximately 20 bu/acre per inch of total water applied until the knot point, *PL* at 242.31 bu/acre with TWA equal to about 29.6 inches, indicating constant returns to water until the knot point.

Figure 2 shows the relation between TWA and yield for the quadratic yield response function based on the results in table 1. The shape of the curve suggests that there are diminishing marginal returns to TWA. The constant, γ_0, represents the expected yield under no water application at -297.58 bu/acre. Both the LRP and quadratic function indicate there must be a large amount of water applied before plant growth is possible. The required amount of water applied under the quadratic function is approximately 11 inches. Beyond this point of water application yield will increase at a decreasing rate because the TWA parameter, γ_1, is positive but the TWA^2 parameter, γ_2, is negative.

Figure 3 shows the relation between TWA and ET for the quadratic ET response function based on the results from table 1. The curve is relatively flat, indicating that TWA does not have much effect on ET. The constant, ϕ_0, represents the expected ET under no water application at -5.775. The parameter estimate for TWA, ϕ_1, is 1.637. The parameter estimates of ϕ_0 and ϕ_1 indicate that an output of ET should occur when TWA is around 4 inches. The TWA^2 parameter estimate, ϕ_2, has a small negative value of -0.021, indicating diminishing marginal returns. This small parameter estimate would suggest ET begins to decline around 40 inches of TWA, higher than the amount of TWA at full irrigation. Since the value of TWA does not go beyond 35 inches, ET has a positive correlation with TWA in the frame of our data set.

Figure 4 shows the relation between BW and yield for the quadratic plateau yield response function based on the results from table 1. The slope of the curve shows that there are diminishing marginal returns of BW. The summation of the constant, α_0, parameter estimate for GW, α_3, multiplied by the average rainfall plus ISWC, and the parameter estimate for GW^2, α_4, multiplied by the average rainfall plus ISCW squared gives the intercept of the response function shown in figure 4, which is approximately 117 bu/acre. This value indicates that under average conditions, yield should be around 117 bu/acre without any BW applied. Beyond this point, yield increases at a decreasing rate because the parameter estimate for BW, α_1, is positive but the parameter estimate for BW^2, α_2, is negative.

Constrained Optimization Results with Normal Conditions for the LRP and Quadratic Yield Response Functions to TWA

The results for the LRP and the quadratic functions under average prices and rain are presented in table 2. The optimal solution for the LRP yield response function is at the knot point of the graph, which can be seen in figure 1. If the farmer irrigates according to the LRP response function, he/she would either irrigate at the knot point or not at all. The quadratic function results are close to the maximum point as seen in figure 2.

Constrained Optimization Results with Different Variable (Irrigation) Costs for the LRP Yield and Quadratic Yield Response Functions to TWA

We analyze what the most profitable irrigation management strategies are under different irrigations costs, which are reported in table 3. We first investigate the effects of increasing and decreasing the irrigation average cost by 50%. This variation provides a wide range of potential changes in irrigation costs and allowed analysis of how such changes would affect profits.

Under the LRP response function with all different irrigation input prices, the optimal strategy is for the farmer to produce at the knot point, that is, full irrigation with profit ranging from \$59.20 to \$128.85 per acre. We then ask, how much would the cost of irrigation, per acre-inch, have to increase for the farmer’s optimal strategy to be not to irrigate at all? Holding all over variables at the average, we find that irrigation costs would have to increase to \$65.70 per acre inch for the farmer to cease irrigation altogether. Average irrigation costs would have to increase over 700% for this scenario to occur in reality, which is very unlikely. If corn prices were low at $2.34 per bushel, irrigation costs would have to increase to $47.23 per acre inch for the farmer to have no incentive to irrigate. Therefore, it would be quite unlikely for the farmer to never irrigate to the knot point as long as there are no government restrictions on irrigated water.

Under the quadratic response function, the change in irrigation costs affects the optimal amount of irrigation applied. The lower the irrigation costs, the more water the farmer would apply. Since less water was applied with higher irrigation costs, yield decreases by approximately six bu/acre as did profit by $52.88 dollars. Under less expensive irrigation, yield increases by approximately four bu/acre and profit increased by $61.29 dollars. With more expensive irrigation costs, yield was lowered more than when irrigation costs were lower. With higher irrigation costs, marginal return of TWA decreases.

Constrained Optimization Results with Different Corn Prices for the LRP and Quadratic Yield Response Functions to TWA

We investigate the effects of changing the price of corn (results in table 4). The average price of corn was $3.28 per bushel during the period 2005-2010. We calculate farm profits at the highest ($4.22 per bushel) and lowest ($2.34 per bushel) pries during this period (Johnson and Walters, 2014; USDA, 2018). The analysis of farm profitability with this range of variable output prices, holding all other variables constant, allows determination of their impacts on farm profitability and the likely changes in irrigation management strategies induced by these price variations.

If responses are modeled with the LRP function, the optimal irrigation strategy is to irrigate to the knot point regardless of the output price. Profits range from $321.80 per acre at the high average corn price to -$133.75 when corn prices are very low. The variation in profits is far more dramatic when output prices are changed than when input prices are varied. With the quadratic function, per-acre profits also changed dramatically ranging from $294.07 to -$167.62 for high and low average prices respectively. Irrigation water varied around three inches depending on the corn price scenario, which is less than under different irrigation costs.

Constrained Optimization Results with Variable Weather Conditions for the LRP and Quadratic Yield Response Functions to TWA

We are interested in how farmers' irrigation management strategy should change when faced with irregular weather. Results with low and high rainfall during the growing season (High Plains Regional Climate Center, 2018) are presented in table 5. The sample low, high, and average rainfall were taken from the years and location where the experiment was conducted. For the LRP response function, high and low rainfall resulted in the same TWA. Irrigation was adjusted so that TWA would remain at the knot point. These results indicate that the average irrigation cost of $9.12 per inch was still low enough that even the driest year's profit is maximized when the farmer irrigates to the knot point (figure 1). The profit will be lower than the year with high rainfall, since farmers had to increase irrigation which decreased their profit. If yield responses are modeled with the quadratic function, irrigation adjusts so that TWA remains the same under all different weather conditions. The more the farmer needed to irrigate, the lower the profit because of the increase in variable costs.

To examine weather scenarios further, we include extreme weather events in years outside our experimental scope that experienced extreme rainfall (high and low).

Clay Center experienced an excess in rainfall in 1993, a drought in 2002 and 2012, and a severe drought in 1940 (High Plains Regional Climate Center, 2018) (results in table 6). Rainfall associated with these extreme events was used in the constrained optimization model for both LRP and quadratic response functions to investigate the effects of weather events more extreme than was experienced during the period of the experiment (2005-2010). We include these years because since they happened historically, they may occur again sometime in the future. The 1993 flood resulted from excess rainfall of 37.2 inches, which pushed TWA past the knot point and no irrigation would have been needed. Profit would have increase to a total of $163.64 per acre since there were no irrigation costs. With the quadratic function, the extra TWA increased yield by a few bushels from the optimal TWA under normal conditions. For the LRP and quadratic functions in the 2002 and 2012 droughts, TWA would stay the same while irrigation increased to accommodate the low rainfall. Under the LRP function, even with the 1940 severe drought, keeping all other inputs constant, it would have made sense for the farmer to irrigate over 17 inches for a profit of $6.06 per acre. If quadratic responses are assumed, TWA stays the same but the farmer incurs a loss of $26.24 due to the need for an increase in irrigation which increases costs.

In a realistic situation where there is less rainfall, total output will be lower and we expect output prices to increase which will impact expected profit. To include this effect in the analysis, we drew on the 2017 agricultural census which showed that Nebraska’s planted corn acreage was 57% irrigated, and 43% rainfed in 2017 (USDA, 2017). If there is a significant drought, the total corn supply in Nebraska will be cut by close to 43% since dryland acres would produce little or nothing. Such a decrease in total supply could potentially increase corn prices. In the 2012 drought, prices increased from $5.86 in January to as much as $8.13 per bushel in July in Hastings, Nebraska. This increase in prices will not change the irrigation strategy under the LRP function since the farmer would irrigate to the knot point even with lower prices. Assuming a quadratic function, it would make sense to irrigate more for a small yield increase with such high output prices. The results in tables 7 and 8 illustrate the impact of dramatic price increases as a result of extreme weather conditions. Table 7 shows only the price and profit change and table 8 displays the irrigation, ET, and TWA change based on the price changes showed in table 7.

We include two scenarios that combine changes in more than one of the variables. One scenario includes a high output price of $4.22, which was the highest corn price in our experimental sample from 2005-2010, and rainfall from the 1940 drought. Since demand for irrigation services will be higher in periods of drought, we increase average irrigation costs by 50%. The second scenario was the opposite in which irrigation and output costs decrease during a flood (table 9). Under the LRP function, farmers would irrigate to the full regardless of the increase in both prices so nothing changed but profit. Assuming the quadratic response function, the optimal amount of irrigation under the drought conditions was 21.5 inches with a yield of 244.2 bu/acre and TWA of 33.84 inches. TWA and yield are moderately lower than the irrigation management strategy under all average variables. For both response functions under the flood scenario, irrigation costs did not impact profit since the farmer did not need to irrigate.

Constrained Optimization Results with Observed Farmers' Irrigation Behavior for the LRP and Quadratic Yield Response Functions to TWA

We are interested in how much farmers are currently irrigating and whether they should change their irrigation management strategy based on our results. According to a census survey by the USDA (2013), Nebraska farmers apply an average of 12 inches of irrigation water per acre. Under both response functions, farmers are over-irrigating. However, the USDA survey only had results for the entire state. A survey by Derrel Martin (2012) found that Nebraska farmers in six sites across the state also irrigated on average 12 inches per acre between the years of 1996-2001. Martin separated his results to show how much farmers are irrigating at specific sites. The closest site to Clay Center was Arapahoe where farmers were irrigating 8.1 inches when average rainfall during the growing season was 17.32 inches. Since there is little difference between rainfall levels at these two sites, it is assumed that farmers in the area around Clay Center would also apply about 8 inches of irrigation water. According to the constrained optimization results with the LRP function, farmers are over irrigating; whereas with the quadratic function, farmers are under irrigating (table 10).

Constrained Optimization Results with ET Restrictions for the LRP and Quadratic Yield Response Functions to TWA

The last scenario we analyze is the effect of ET restrictions on profit. Hypothetically, the government could restrict water use for farmers, which will be represented by lower levels of ET. We restrict ET as a proxy for potential government restrictions on water use (for example well-drilling, pumping rates, etc.) as a way to persuade farmers to be more efficient with their water use. ET output was restricted by 5% or 10% from the optimal amount of ET under no restrictions (table 11). For the quadratic yield response function, 5% reduction would decrease ET from 26.16 inches to 24.85. This small reduction decreased profit by $22.65 dollars, yield by 18.8 bu/acre, and irrigation by 4.3 inches (34% decrease). A 10% decrease would decrease profit by $63.53, yield by 39.3 bu/acre, and irrigation by 7.2 inches (57% decrease). For the LRP function, a 5% reduction would decrease ET from 24.61 inches to 23.38 inches. Profit would decrease by $147.29, yield by 52.1 bu/acre, and irrigation by 2.6 inches (34% decrease). A 10% decrease would decrease profit by $269.25, yield 95.3 bu/acre and irrigation by 4.8 inches (62% decrease). These results show that a decrease in ET, even by a small amount would have a large impact on farmers' profitability.

Constrained Optimization Results with Normal Conditions for the QRP Yield Response Function to BW

The results for the quadratic plateau function under average prices and rain are presented in table 12. The optimal solution is to apply BW up until the plateau. After this point of BW application, yield will not increase due to the unlikelihood of obtaining higher yields given our data set. The quadratic plateau function is seen in figure 4.

Constrained Optimization Results with Different Variable (Irrigation) Costs for the QRP Yield Response Function to BW

The irrigation costs we evaluate are the same for all response functions, which is increasing and decreasing the average irrigation cost by 50%. The change in irrigation costs does not affect the optimal amount of BW to apply. Profit is always maximized when BW is applied up until the function plateaus. Profit decreases to $78.35 dollars with higher irrigation costs and profit increases to $145.67 dollars with lower irrigation costs (results in table 13).

Constrained Optimization Results with Different Corn Prices for the QRP Yield Response Function to BW

The corn prices we evaluate are the same for all response functions, which is the high and low price during the scope of our experiment. The optimal BW application strategy does not change with the change in corn prices. It always makes sense to irrigate until the function plateaus given the range of corn prices. Profit ranges from $334.27 per acre at the high average corn price to -$120.25 when corn prices are very low. The variation in profit is more dramatic when output prices change compared to a change in input prices (results in table 14).

Constrained Optimization Results with Observed Farmers' Irrigation Behavior for the QRP Yield Response Function to BW

We also analyze how farmers are currently irrigating with the quadratic plateau response function to see if farmers are over or under irrigating based on the marginal value of irrigation. We use the same results from the USDA census showing that Nebraska farmers across the state are irrigating on average 12 inches of water. Included in the analysis is the survey by Derrel Martin (2012) that stated farmers on a site near Clay Center, Nebraska were irrigating 8.1 inches (results in table 15). Both amounts of irrigation are considered over irrigation with decreased profit due to the increase in irrigation costs with no additional yield gains.

Constrained Optimization Results with ET Restrictions for the QRP Yield Response Function to BW

We include an ET restriction scenario in the quadratic plateau yield response function to see how a reduction of ET would impact profit and how much BW farmers could apply. ET was restricted by 5% or 10% from the optimal amount of ET under no restrictions (table 16). A 5% reduction decreased ET from 24.50 inches to 23.55 inches. A small reduction in ET decreased profit by $60.35 dollars, yield by 34.1 bu/acre, and irrigation by 2.5 inches (34% decrease) . A 10% reduction would decrease profit by $175.23 dollars, yield by 71.2 bu/acre, and irrigation by 4.7 inches (63% decrease). Attempting to reduce ET, even by a small amount would have a large negative impact on farmers' profitability.

Chapter 5: Conclusion

Our primary goal in this thesis is to evaluate how farmers should adjust irrigation management strategies based on profit and water use. We examine profitability by modeling the response function of yield to TWA and yield to BW and use it as our expectation of yield under given values of TWA and BW. These response functions are used in a constrained optimization model to determine how optimal irrigation management practices change in response to different values for output price, variable costs, and rainfall (or GW). In addition to analyzing the effects of variation in these economic variables, we also investigate the effects of policies to restrict the amounts of water used for irrigation. These policies are modeled through constraints on ET. The answer depends on TWA and BW's impact on yield, costs and prices on output, as well as the ET constraint when applied.

We develop response functions to analyze the impact water applied has on yield and ET. We use two functional forms that describe different farmers' behavior and are significant in describing the relation of water to crop yields. The LRP model reflects the behavior of producers who apply irrigation without considering changes in input and output costs, as long as both prices are in a reasonable range. The quadratic model reflects the behavior of producers who change their irrigation strategy based on expected input and output prices. We also model the expected amount of ET under different amounts of TWA to examine if ET could be easily reduced by cutting back on water application. Our results show that yield is heavily impacted by TWA, but ET is not. Attempting to slightly limit ET would result in a large decrease in irrigation use, which dramatically decreases yield and therefore profit.

We are also interested in analyzing the marginal value of irrigation or BW and therefore, we develop a separate yield response function explicitly identifying the marginal impact of BW and GW. Results indicate that the marginal value of a unit of BW is substantially higher than GW, suggesting that controlling (via soil moisture probe) when farmers apply BW is valuable. GW is applied outside of the producer's control and may occur when the soil is already wet, thereby contributing little to yield. Our results suggest that applying BW water strategically appears to have a higher impact on yield than random GW. While BW comes with environmental concerns and added producer's production costs larger than GW, it does provide a higher return on yield than GW. This result emphasizes why it is important to model the impact on producer's profit when considering policy limiting water use.

Previous research from Hoekstra et al. (2011) suggested that farmers from water scarce regions would benefit in focusing production on commodities that require little water and trade with countries that have abundant water supplies. Our research shows there is a flaw in this idea because water availability is only one factor farmers should consider in deciding what to produce. Decisions on production are usually based on potential profit to be earned and the factors that impact profit include water but also many other factors including arable land, cost of labor, and access to fuel resources (Zhang et al., 2014; Kumar and Singh, 2005).

Our constrained optimization model indicates that full irrigation is the profit-maximizing strategy in all scenarios that do not involve limiting ET, even when there is a mild to severe drought and high variable irrigation costs. Water is currently a small cost to producers and without government intervention, a large reduction in water from natural resources, or a large increase in costs surrounding irrigation (labor, electricity, ownership of center pivot, etc.), farmers should apply full irrigation to achieve the highest profit. At the same time, farmers and communities should be concerned with the environmental impact irrigation may have on future food production and the natural habitat.

To improve on our research, data must be gathered on deficit irrigation as well as excess irrigation. Our data does not include TWA or BW beyond full irrigation, thus we cannot evaluate how saturated soil affects yield. Our research would also benefit from more years and multiple sites across Nebraska and the United States. With additional variation and a larger volume of data, our response functions for yield and ET would be more reliable.

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Tables

Table 1: Response Functions Results

Variable	LRP Yield Response Function	Quadratic Yield Response Function	Quadratic ET Response Function	QRP Yield Response Function
Intercept	-349.580 ***	-249.580 ***	-5.775	16.379
	(-36.078)	(-93.785)	(-3.917)	(180.80)
TWA	20.019 ***	28.782 ***	1.637 ***	
	(-0.935)	(-7.195)	(-0.301)	
TWA^2		-0.377 ***	-0.021 ***	
		(-0.136)	(-0.006)	
BW				24.183***
				(1.639)
BW^2				-0.882***
				(0.182)
GW				1.740
				(15.33)
GW^2				0.129
				(0.314)
Repetition 1	-0.918	-2.212	-0.196	-0.121
	(-3.617)	(-7.191)	(-0.3)	(3.329)
Repetition 2	1.73	-1.314	-0.196	1.736
	(-3.663)	(-7.191)	(-0.3)	(3.365)
Low Plant Population	10.794 **	-26.829 ***	-1.464 ***	12.112
	(-5.039)	(-10.129)	(-0.423)	(5.045)
Knot Point	242.309 ***			247.08
	(-3.18)			(3.270)

Note: ***=p<0.01, **p<0.05, *=p<0.10. Number of Observations: 84. Standard errors in parentheses.

Table 2: LRP and Quadratic Yield Response Functions to TWA Results with Normal Conditions

Response Function	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)
LRP	242.3	$94.03	7.64	29.57
Quadratic	246.0	$61.72	12.52	34.45

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Average Precipitation During Growing Season (May 1- Sept 30): 17.205 inches (Irmak 2015a;2015b
Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 3: LRP and Quadratic Yield Response Functions to TWA Results with Different Irrigation

Response Function	Irrigation Cost	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
LRP	Average	242.3	$94.03	7.64	29.57	24.61
Quadratic	Average	246.0	$61.72	12.52	34.45	26.16
LRP	Low	242.3	$128.85	7.64	29.57	24.61
Quadratic	Low	249.9	$123.01	14.36	36.29	26.50
LRP	High	242.3	$59.20	7.64	29.57	24.61
Quadratic	High	239.6	$8.84	10.68	32.61	25.69

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Average Precipitation During Growing Season (May 1- Sept 30): 17.205 inches (Irmak 2015a;2015b
Irrigation Cost: Average $9.12; Low $4.56; High 13.68 (Irmak 2015a;2015b)

Table 4: LRP and Quadratic Yield Response Functions to TWA Results with Different Corn Prices

Response Function	Corn Price	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
LRP	Average	242.3	$94.03	7.64	29.57	24.61
Quadratic	Average	246.0	$61.72	12.52	34.45	26.16
LRP	Low	242.3	-$133.75	7.64	29.57	24.61
Quadratic	Low	241.1	-$167.62	11.04	32.27	25.80
LRP	High	242.3	$321.80	7.64	29.57	24.61
Quadratic	High	248.1	$294.07	13.34	35.27	25.33

Corn Price: Average $3.28; Low $2.34; High $4.22 (Walters and Johnson, 2014; USDA 2018)
Average Precipitation During Growing Season (May 1- Sept 30): 17.205 (Irmak 2015a; 2015b)
Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 5: LRP and Quadratic Yield Response Functions to TWA Results with Different Rainfall

Response Function	Rainfall	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
LRP	Average	242.3	$94.03	7.64	29.57	24.61
Quadratic	Average	246.0	$61.72	12.52	34.45	26.16
LRP	Low	242.3	$76.20	13.37	29.57	24.61
Quadratic	Low	246.0	$9.44	18.25	34.45	26.16
LRP	High	242.3	$163.64	0.0	31.95	25.49
Quadratic	High	246.0	$153.15	2.49	34.45	26.16

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)

Precipitation Inches: Average 17.205; Low 11.471 (2005); High 27.23 (2008) (Irmak 2015a;2015b; High Plains Regional Climate Center, 2018)

Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 6: LRP and Quadratic Yield Response Functions to TWA Results with Droughts and Floods

Response Function	Year/ Rainfall (inches)	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
LRP	1940/7.56	242.30	$6.06	17.28	29.57	24.61
Quadratic	1940/7.56	246.03	-$26.24	22.16	34.45	26.16
LRP	1993/37.2	242.30	$163.64	0.0	41.92	26.61
Quadratic	1993/37.2	250.83	$234.70	0.0	41.92	26.61
LRP	2002/12.77	242.30	$53.58	12.07	29.57	24.61
Quadratic	2002/12.77	246.03	$21.28	16.95	34.45	26.16
LRP	2012/16.12	242.30	$84.13	8.72	29.57	24.61
Quadratic	2012/16.12	246.03	$51.83	13.60	34.45	26.16

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)

Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 7: LRP and Quadratic Yield Response Functions to TWA Results with Droughts/ Floods with the Price Change from the Exact Year

Response Function	Year/ Rainfall (inches)	Price Difference	Percent Change (Increase)	Profit (dollars)	Profit Change from Table 6 (dollars, Increase)	ET (inches)
LRP	1940/7.56	$0.53-$0.64	15%	$124.79	$118.73	24.61
Quadratic	1940/7.56	$0.53-$0.64	15%	$147.12	$173.36	26.16
LRP	1993/37.2	$2.00-$2.67	31%	$408.37	$244.73	26.61
Quadratic	1993/37.2	$2.00-$2.67	31%	$488.00	$253.30	26.61
LRP	2002/12.77	$1.85-$2.48	34%	$322.54	$268.96	24.61
Quadratic	2002/12.77	$1.85-$2.48	34%	$295.81	$274.53	26.16
LRP	2012/16.12	$5.80-$8.13	40%	$401.56	$317.43	24.61
Quadratic	2012/16.12	$5.80-$8.13	40%	$427.88	$376.05	26.16

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Rainfall: 7.56 (inches); 37.2 (inches); 12.77 (inches); 16.12 (inches) (High Plains Regional Climate Center, 2018)
Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 8: LRP and Quadratic Yield Response Function to TWA Results with Droughts/ Floods with the Price Change from the Exact Year

Year/ Rainfall (inches)	Yield / Yield Change (bu/acre)	Irrigation /Irrigation Change(inches)	TWA/TWA Change (inches)	Irrigation /Irrigation Change(inches)	ET/ ET Change (inches)
1940/7.56	247.3/1.25	22.64/0.48	34.96/0.48	22.64/0.48	26.26/0.10
1993/37.2	250.82/0	0/0	41.92/0	0/0	26.61/0
2002/12.77	248.3/2.26	17.88/0.93	35.38/0.93	17.88/0.93	26.35/0.18
2012/16.12	248.5/2.51	14.65/1.05	35.50/1.05	14.65/1.05	26.37/0.21

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 9: LRP and Quadratic Yield Response Functions to TWA Results with Scenarios with more than one Variable Change

Response Function	Irrigation and Output Cost/Rainfall	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
LRP	High/Drought	242.3	$155.03	17.3	29.57	24.61
Quadratic	High/Drought	244.2	$104.57	21.5	33.84	26.02
LRP	Low/Flood	242.3	-$64.12	0	41.92	26.61
Quadratic	Low/Flood	250.8	$6.45	0	41.92	26.61

Corn Price: Average $3.28; Low $2.34; High $4.22 (Walters and Johnson, 2014; USDA 2018)

Rainfall: 7.56 (inches) (Drought, D); 37.2 (inches) (Flood, F) (High Plains Regional Climate Center, 2018)

Irrigation Cost: Average $9.12; Low $4.56; High $13.56 (Irmak 2015a;2015b)

Table 10: LRP and Quadratic Yield Response Functions to TWA Results with Fixed Irrigation According to USDA (2013) and Nebraska Extension (2013)

Response Function	Rainfall (inches)	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
LRP	17.205	242.3	$54.20	12.0	33.93	26.05
Quadratic	17.205	244.5	$61.39	12.0	33.93	26.05
LRP	17.32	242.3	$89.76	8.1	30.14	24.84
Quadratic	17.32	226.4	$37.59	8.1	30.14	24.84

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)

Rainfall: 17.32 (inches) (Araphoe, NE)l 17.205 (inches) (Clay Center, NE) (High Plains Regional Climate Center, 2018)

Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 11: LRP and Quadratic Yield Response Functions to TWA Results with ET Restrictions from Optimal ET from Table 1

Response Function	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET Restriction	ET (inches)
LRP	190.2	$-53.26	5.03	26.96	5%	23.38
Quadratic	227.2	$39.07	8.24	30.17	5%	24.86
LRP	147.0	$-175.22	2.86	24.80	10%	22.15
Quadratic	206.8	$-1.81	5.35	27.28	10%	23.55

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)

Rainfall: 17.205 (inches) (High Plains Regional Climate Center, 2005-2010)

Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 12: QRP Yield Response Function to BW Results with Normal Conditions

Yield (bu/acre)	Profit (dollars)	BW (inches)	TWA (inches)	ET (inches)
247.1	$112.01	7.38	29.312	24.503

Corn Price: $3.28 (Walters and Johnson, 2014;
USDA 2018)
Average Precipitation During Growing Season (May 1- Sept 30): 17.205 inches (Irmak 2015a;2015b
Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 13: QRP Yield Response Function to BW Results with Different Irrigation Prices

Irrigation Cost	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
Average	247.1	$112.01	7.38	29.31	24.50
Low	247.1	$145.67	7.38	29.31	24.50
High	247.1	$78.35	7.38	29.31	24.50

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Average Precipitation During Growing Season (May 1- Sept 30): 17.2047 inches (Irmak 2015a;2015b)
Irrigation Cost: Average $9.12; Low $4.56; High 13.68 (Irmak 2015a;2015b)

Table 14: QRP Yield Response Function to BW Results with Different Corn Prices

Corn Price	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
Average	247.1	$112.01	7.38	29.31	24.50
Low	247.1	-$120.25	7.38	29.31	24.50
High	247.1	$334.27	7.38	29.31	24.50

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Average Precipitation During Growing Season (May 1- Sept 30): 17.2047 inches (Irmak 2015a;2015b)
Irrigation Cost: Average $9.12; Low $4.56; High 13.68 (Irmak 2015a;2015b)

Table 15: QRP Yield Response Function to BW Results with Fixed Irrigation According to USDA (2013) and Nebraska Extension (2013)

Rainfall (inches)	Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET (inches)
17.205	247.1	$105.45	8.1	30.14	24.84
17.32	247.1	$69.88	12.0	33.93	26.05

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Rainfall: 17.32 (inches) (Araphoe, NE); 17.205 (inches) (Clay Center, NE) (High Plains Regional Climate Center, 2018)
Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Table 16: QRP Yield Response Function to BW Results with ET Restrictions from Optimal ET from Table 1

Yield (bu/acre)	Profit (dollars)	Irrigation (inches)	TWA (inches)	ET Restriction	ET (inches)
213.0	$51.66	4.84	26.77	5%	23.55
175.9	-$63.22	2.72	24.65	10%	22.05

Corn Price: $3.28 (Walters and Johnson, 2014; USDA 2018)
Rainfall: 17.205 (inches) (High Plains Regional Climate Center, 2005-2010)
Irrigation Cost: $9.12 (Irmak 2015a;2015b)

Figures

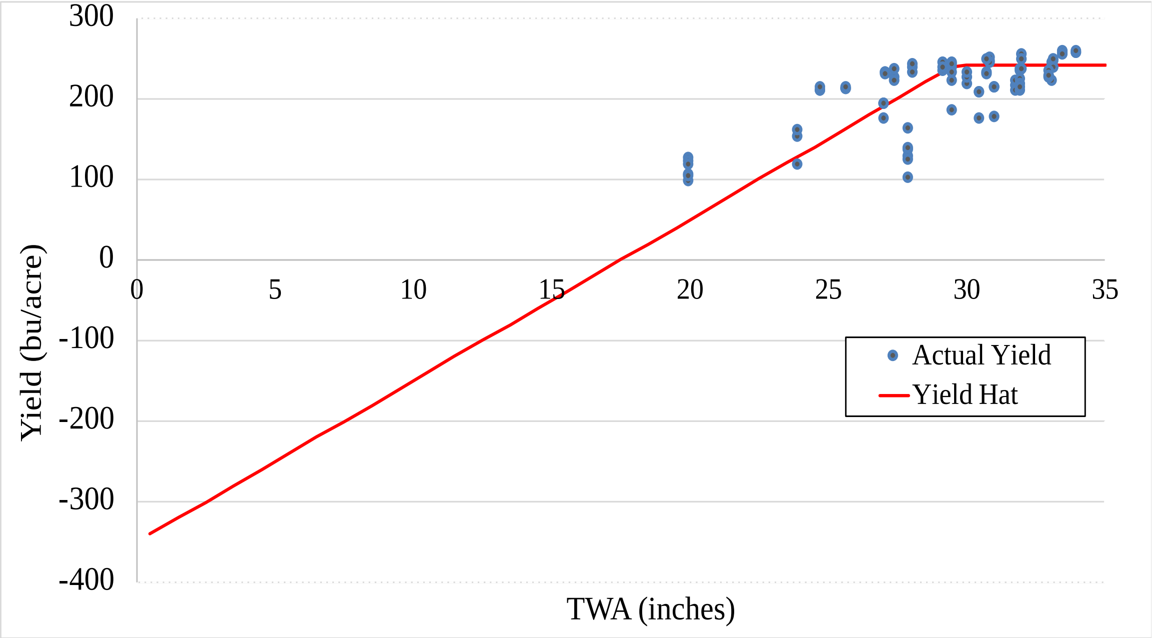

Figure 1: LRP Yield Response Function to TWA Compared to Actual Yield

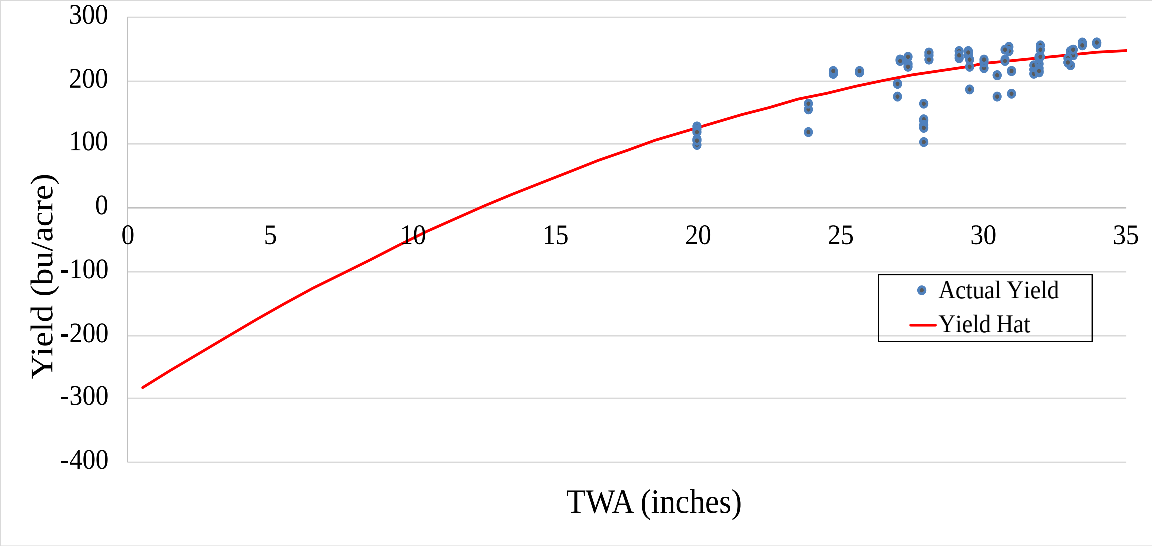

Figure 2: Quadratic Yield Response Function to TWA Compared to Actual Yield

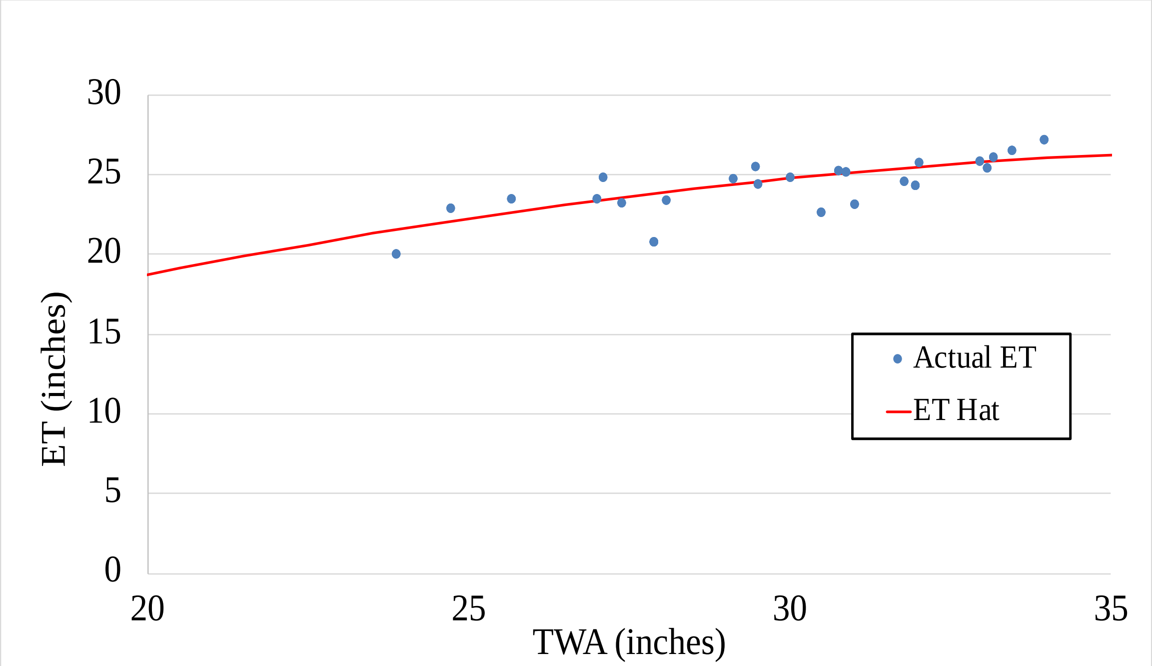

Figure 3: Quadratic ET Response Function to TWA Compared to Actual ET

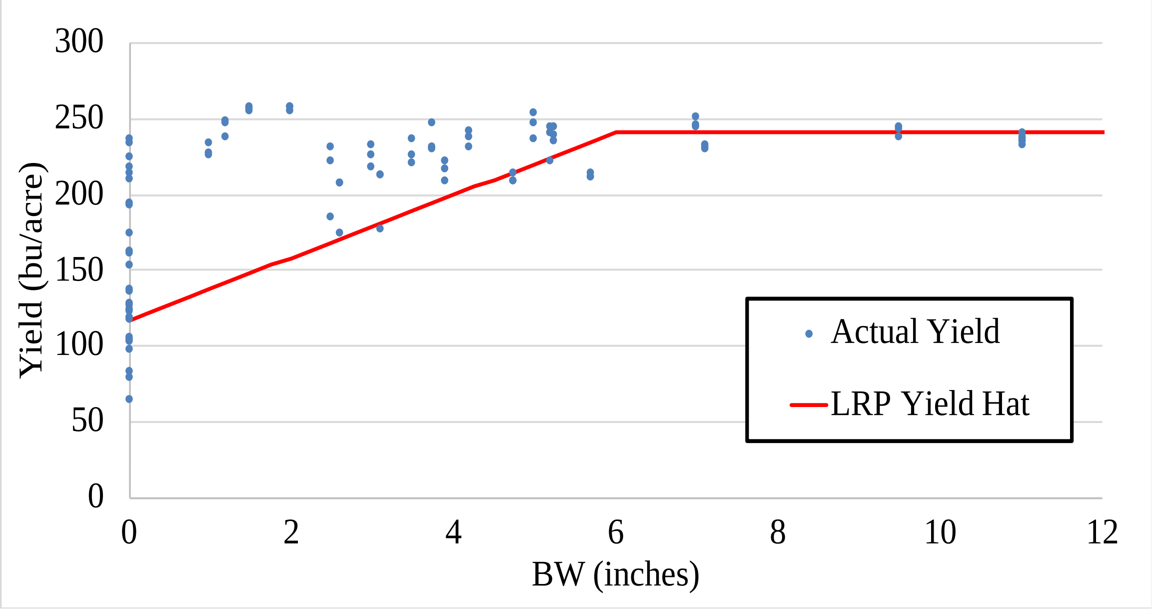

Figure 4: QRP Yield Response Function to BW Compared to Actual Yield[3]

---

[3] The intercept of figure 4 is the summation of the constant parameter α_0, the parameter estimate for GW, α_1, multiplied by the sum of average rainfall (17.205 inches) and ISWC (4.725 inches) , and the parameter estimate for GW^2, α_2, multiplied by the sum of average rainfall and ISWC squared

Appendix A: Data

Table A1: Fixed Costs of Production

Fixed Irrigation Ownership Costs-10 year life	**Installation Cost**
132 irrigated acre system with end gun	$48,000.00
Power and Water Connecting Equipment	$30,000.00
Ownership Cost	**Annual Cost**
Depreciation	$3,300.00
Interest	$4,893.00
Repair Well	$4,893.00
Pivot	$1,440.00
Insurance	$258.00
Total Ownership Cost Per Acre (Divide by 132)	**$87.05**
Operating Cost Per Acre	**Annual per Acre Cost**
Power: Fuel	$21.00
Total Operating Cost	$27.00
Total Estimated Annual Cost Per Acre	$114.05
Total Estimated Annual Cost Per Acre	**$114.05**
Variable Input Cost of Farm Production	**Annual Per Acre Cost**
Fertilizer	$52.21
Herbicide	$32.50
Seed	$105.72
Disk (used to till soil)	$10.91
Anydrous Application (fertilizer applicator)	$10.50
Planting	$12.80
Field Cultivation	$8.23
Herbicide Sprayer	$4.58
Combine for Corn	$26.38
Cart	$7.76
Real Estate Opportunity cost in Eastern Nebraska, No Irrigation	$173.70
Taxes	$57.90
Soil Moisture Probe (cost/40 acres)	$9.16
Truck (cost/10yr life/1000 acres)	$4.71
Total Field Operation Cost	**$517.06**
Total Fixed Cost Per Acre	**$631.11**

Table A2: Variable Irrigation Costs

Year	Cost per Irrigation Inch Applied
2005	$8.85
2006	$8.84
2007	$8.95
2008	$9.05
2009	$9.36
2010	$9.65
Average Irrigation Cost Across All Years	**$9.12**

Table A3: Corn and Input Prices and Rainfall under Scope of Experiment

Corn Price	$ per bushel
High	$4.22
Average	$3.28
Low	$42.34
Irrigation Price	**$ per inch**
High	$13.68
Average	$9.12
Low	$4.56
Rainfall	**During growing season (inches)**
High	27.23
Average	18.43
Low	4.56

Table A4: Extreme Rainfall Conditions in Clay Center, Nebraska and Changes in Corn Prices

Extreme Weather Year	Rainfall During Growing Season (inches)	Price of corn low-high
1993	37.2	$2.01-$2.65 (31% increase)
1940	7.56	$0.48-$0.56 (15% increase)
2002	12.77	$2.01-$2.65 (31% increase)
2012	16.12	$0.48-$0.56 (15% increase)

Appendix B: GAMS Code

Program 1: GAMS Program for the LRP Yield to TWA Constrained Optimization

```
$title LRP
Scalars

$ontext
The following are the parameter estimates for the LRP response function. See table 1.
The rainfall can be changed to any number and is currently set to average.
$offtext

b0 'constant for y '              /-349.58/
b1 'TWA for y '                   /20.019/
rn 'rainfall'                     /17.205/
iw 'initial water stock'          /4.72441/
fc 'fixed costs annual per acre ' /631.1/

$ontext
The following is the parameter estimates for the LRP response function. See table 1.
$offtext

b00 'constant for ET'             /-5.774709/
b11 'TWA for ET'                  /1.63669 /
b22 'TWA for ET^2'                /-0.0205972 /

$ontext
The following is a list of all possible output and input costs we used (average, low, and
high) To change one, put cp*** or ic*** in the objective function.
$offtext

cplow/2.34/
*average corn price
cpavg/3.28/
*high corn price
cphigh/4.22/
*low irrigation variable cost price per acre inch of irrigation applied
iclow/4.56/
*avg irrigation variable cost price per acre inch of irrigation applied
icavg/9.12/
*high irrigation variable cost price per acre inch of irrigation applied
ichigh/13.68/

$ontext
Variables are solved for in the objective function, z.
$offtext
Variables
```

```
        z, TWA, ET, y, i;

Equations

        obj        Objective function which is maximize profit
        TWAmin     TWA must be greater than rainfall
        ETmax      ET limitation (if one is implemented)
        eta        Solving for ET
        plateau    Knot point constraint
        yield
        irr        irrigation applied;


$ontext
cpavg and icavg can be changed to any corn price. The corn price is multiplied by the
yield and the irrigation cost is multiplied by the irrigation. The entire profit function is
subtracted by fixed costs. Equation eta calculates the output of ET with the TWA
equation z solves for. Equation irr computes for the TWA that is irrigation, and equation
yield computes yield.
$offtext

obj..   z =e= (cpavg*(b0+(b1*TWA))-((icavg*(TWA-rn-iw))+fc)) ;
eta..   ET =e= ((b00+(TWA*b11))+(b22*Power(TWA,2)));
yield.. y =e= (b0+(b1*TWA)) ;
irr..   i =e= (TWA-rn-iw) ;

$ontext
If TWAmin is above the knot point, 29.566 inches, profit must be computed by hand. ET,
TWA, and irrigation will be computed by GAMS. At 29.566 inches of TWA, Yield is at
the maximum of 242.31 bushels/acre. To solve for revenue, multiply 242.31 by the corn
price. To solve for profit, subtract only fixed costs since no irrigation is needed to
increase yield so there is no irrigation cost.
$offtext

TWAmin..   TWA=g=rn+iw;
plateau..  (b0+(b1*TWA))=l=242.31;
ETmax..    (b00+(b11*TWA))=l=5000;

$ontext
If TWAmin is above the knot point, 29.566 inches, profit must be computed by hand. ET
will be computed by GAMS. Yield is at the maximum, 242.31 bushels/acre and to solve
for revenue, multiply by the corn price. Subtract fixed costs from revenue which is your
profit since there is adding irrigation will not increase yield.
$offtext
```

```
Model LRP /all/;

Solve LRP maximize z using nlp;
option decimals=3;
display TWA.l, z.l;
```

Program B2: GAMS Program for the Quadratic Yield to TWA Constrained Optimization

```
$title quadratic
Scalars

$ontext
The following is the parameter estimates for the quadratic yield response function. See
table 1. The rainfall can be changed to any number and is currently set to average.
$offtext


b0 'constant for y'                  /-297.5803/
b1 'TWA for y'                       /28.78152/
b2 'twa squared'                     /-0.3774028/
rn 'average rainfall'                /17.205/
iw 'initial water stock'             /4.72441/
fc 'fixed costs annual per acre'     /631.1/

$ontext
The following is the parameter estimates for the quadratic ET response function. See
table 1.
$offtext

b00 'constant for ET'                /-5.774709/
b11 'TWA for ET'                     /1.63669 /
b22 'TWA for ET^2'                   /-0.0205972 /

$ontext
The following is a list of all possible output and input costs we used (average, low, and
high) To change one, put cp*** or ic*** in the objective function.
$offtext

*low corn price
cplow/2.34/
*avg corn price
cpavg/3.28/
*high corn price
cphigh/4.22/
*low irrigation variable cost price per acre inch of irrigation applied
iclow/4.56/
```

```
*average irrigation variable cost price per acre inch of irrigation applied
icavg/9.12/
*high irrigation variable cost price per acre inch of irrigation applied
ichigh/13.68/

$ontext
Variables are solved for in the objective function, z.
$offtext

Variables

        TWA, z, ET, y, i;

equations
        objfn  'profit'
        TWAmin 'TWA constraint'
        eta   'gives ET value'
        ETmax 'ET constraint'
        irr   'gives irrigation value'
        yield  ;

$ontext
cpavg and icavg can be changed to any corn price or to the ones above. The corn price is
multiplied by the yield and the irrigation cost is multiplied by the irrigation. The entire
profit function is subtracted by fixed costs. Equation eta calculates the output of ET with
the TWA equation z solves for. Equation irr computes for the TWA that is irrigation, and
equation yield computes yield.
$offtext

objfn.. z =e=(cpavg*(b0+(b1*TWA)+(b2*Power(TWA,2))))-((icavg*(TWA-rn-iw))+fc) ;
eta..   ET =e= ((b00+(TWA*b11))+(b22*Power(TWA,2)));
irr..   i=e= (TWA-rn-iw) ;
yield.. y =e= (b0+(b1*TWA)+(b2*Power(TWA,2)))  ;

$ontext
The following is the constraints. TWAmin is the minimum TWA that is applied which is
the rainfall plus initial water stock. ETmax is an optional constraint, which can be set to
any number. At 5,000, ET is not constrained.
$offtext

TWAmin..   TWA=g=rn+iw;
ETmax..    (b00+(b11*TWA))=l=5000;

model quadratic /all/;
solve quadratic using nlp maximizing z;
option decimals=3;
```

```
display TWA.l, z.l;
```

Program B3: GAMS Program for the QRP Yield to BW Constrained Optimization

```
$title QRP
$ontext
This is the GAMS program for the QRP constrained optimization model noting the
marginal change of irrigation.
$offtext


$ontext
The following is the parameter estimates for the quadratic plateau yield response
function. See table 1.
$offtext

Scalars

b0 'constant for y'              /16.37973/
b1 'BW'                         /24.18273/
b2 'BW squared'                  /-0.88224/
b3 'GW'                          /1.740048/
b4 'GW squared'                  /0.1291369/
iwrn 'average rainfall plus ISWC'  /21.93/
fc 'fixed costs annual per acre'       /631.1/

$ontext
The following is the parameter estimates for the quadratic ET response function. See
table 1.
$offtext
b00 'constant for ET'               /-5.774709/
b11 'TWA for ET'                    /1.63669 /
b22 'TWA for ET^2'                  /-0.0205972 /
$ontext
The following is a list of all possible output and input costs we used (average, low, and
high) To change one, put cp*** or ic*** in the objective function.
$offtext
*low corn price
cplow/2.34/
*avg corn price
cpavg/3.28/
*high corn price
cphigh/4.22/
*low irrigation variable cost price per acre inch of irrigation applied
iclow/4.56/
*average irrigation variable cost price per acre inch of irrigation applied
icavg/9.12/
```

```
*high irrigation variable cost price per acre inch of irrigation applied
ichigh/13.68/
$ontext
Variables are solved for in the objective function, z.
$offtext
variables

        BW, z, ET, y, i, twa, c ;

equations
        objfn  'profit'
        yield
        eta
        twa
        plateau
        constant
        ETmax
       ;

$ontext
cpavg and icavg can be changed to any corn price or to the ones above. The corn price is
multiplied by the yield and the irrigation cost is multiplied by the irrigation, BW. The
entire profit function is subtracted by fixed costs. Equation eta calculates the output of ET
with the TWA equation z solves for. TWA equation solves for the value of TWA which
is BW+iwrn.
$offtext

objfn.. z
=e=(cpavg*(b0+(b1*BW)+(b2*Power(BW,2))+(b3*iwrn)+(b4*Power(iwrn,2))))-
((icavg*BW)+fc) ;
yield.. y =e= (b0+(b1*BW)+(b2*Power(BW,2))+(b3*iwrn)+(b4*Power(iwrn,2)))  ;
eta..   ET =e= ((b00+((BW+iwrn)*b11))+(b22*Power((BW+iwrn),2)));
twa..   twa =e= (BW+iwrn)      ;


$ontext
The following are the constraints. Plateau is the yield constraint so yield may not go past
247.0829 bu/acre. ETmax is an optional constraint, which can be set to any number. At
5,000, ET is not constrained.
$offtext

plateau..  (b0+(b1*BW)+(b2*Power(BW,2))+(b3*iwrn)+(b4*Power(iwrn,2)))=l=247.082
9 ;
ETmax..  ((b00+((BW+iwrn)*b11))+(b22*Power((BW+iwrn),2)))=l=5000;
model QRP /all/;
solve QRP using nlp maximizing z;
```

```
option decimals=3 ;
display BW.l, z.l;
```

Appendix C: Irrigation and Rainfall Figures

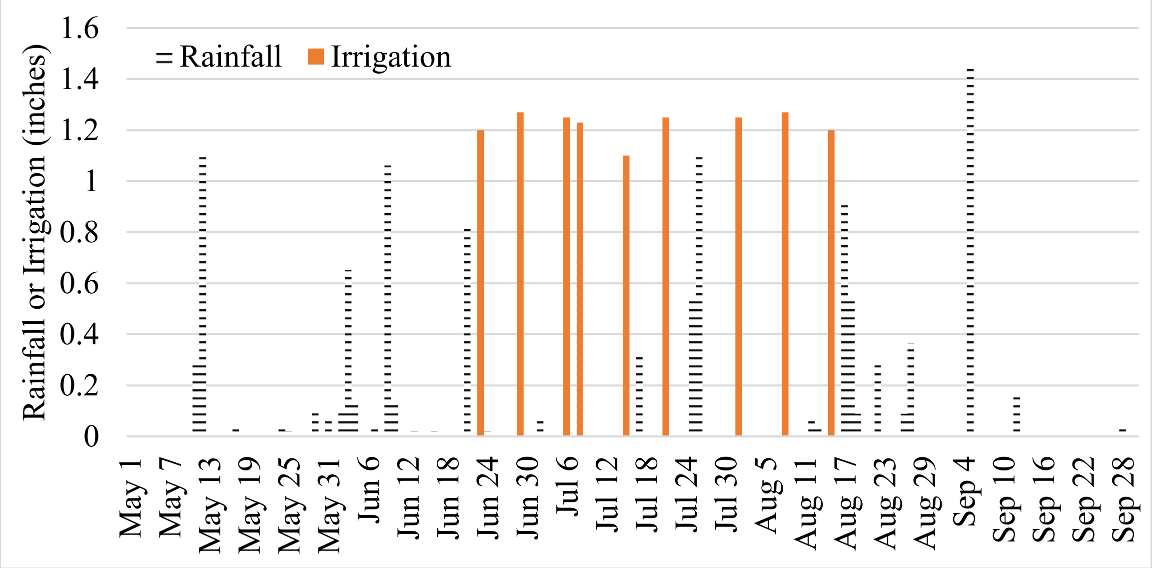

Figure C1: Days and Amount of Rainfall and Irrigation for 2005

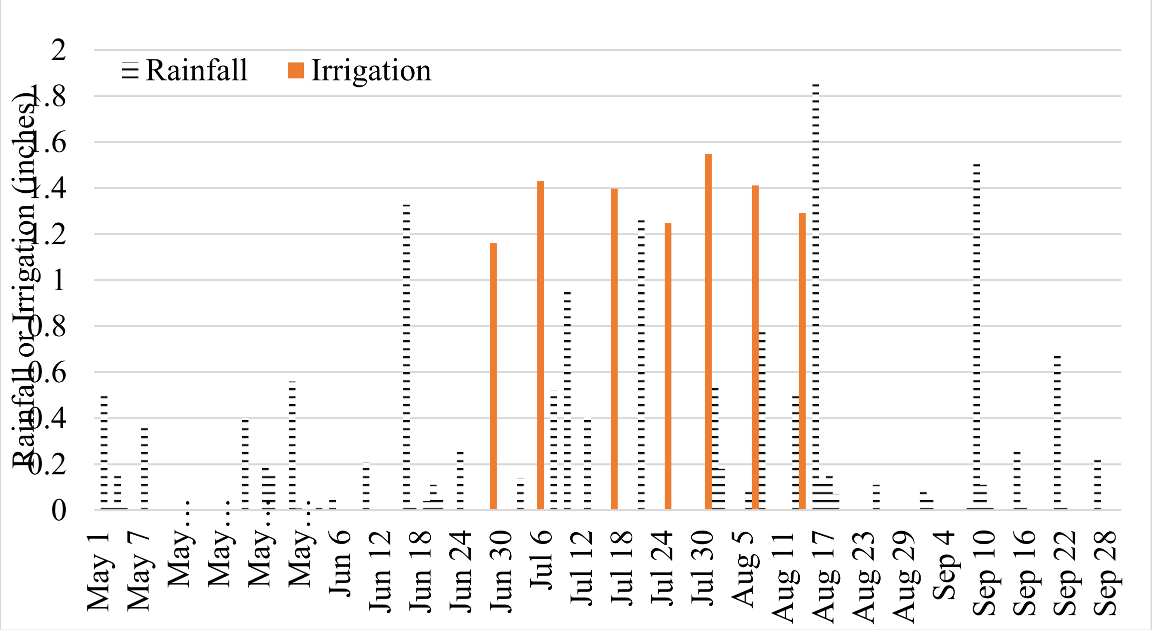

Figure C2: Days and Amount of Rainfall and Irrigation for 2006

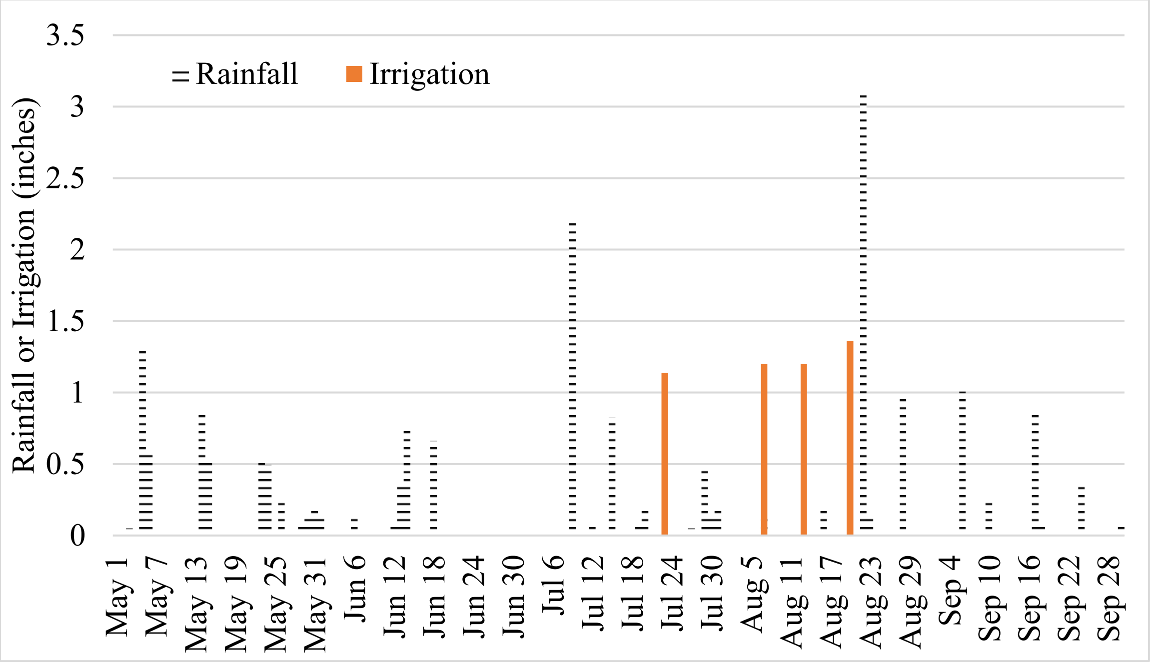

Figure C3: Days and Amount of Rainfall and Irrigation for 2007

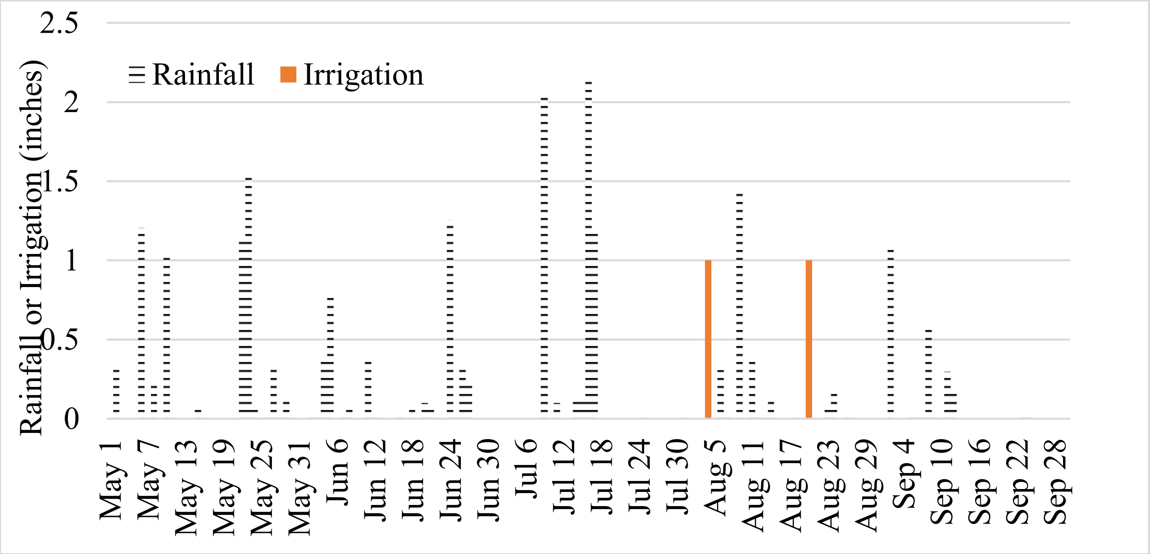

Figure C4: Days and Amount of Rainfall and Irrigation for 2008

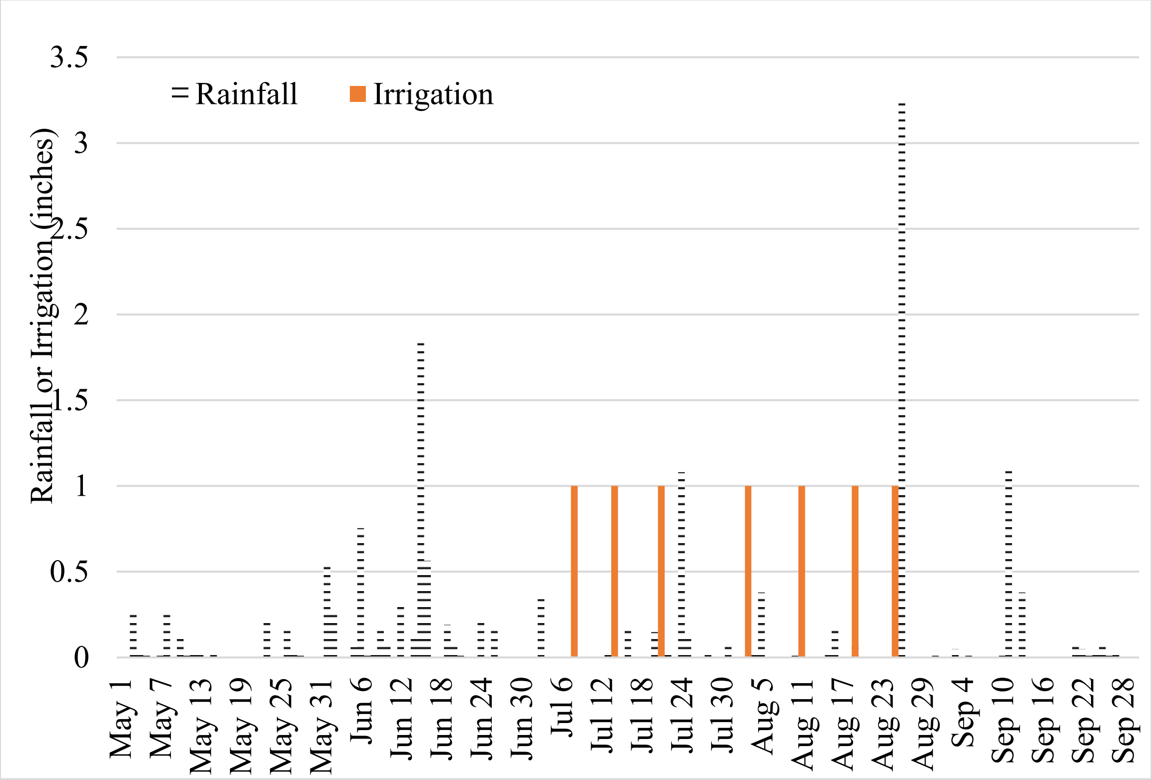

Figure C5: Days and Amount of Rainfall and Irrigation for 2009

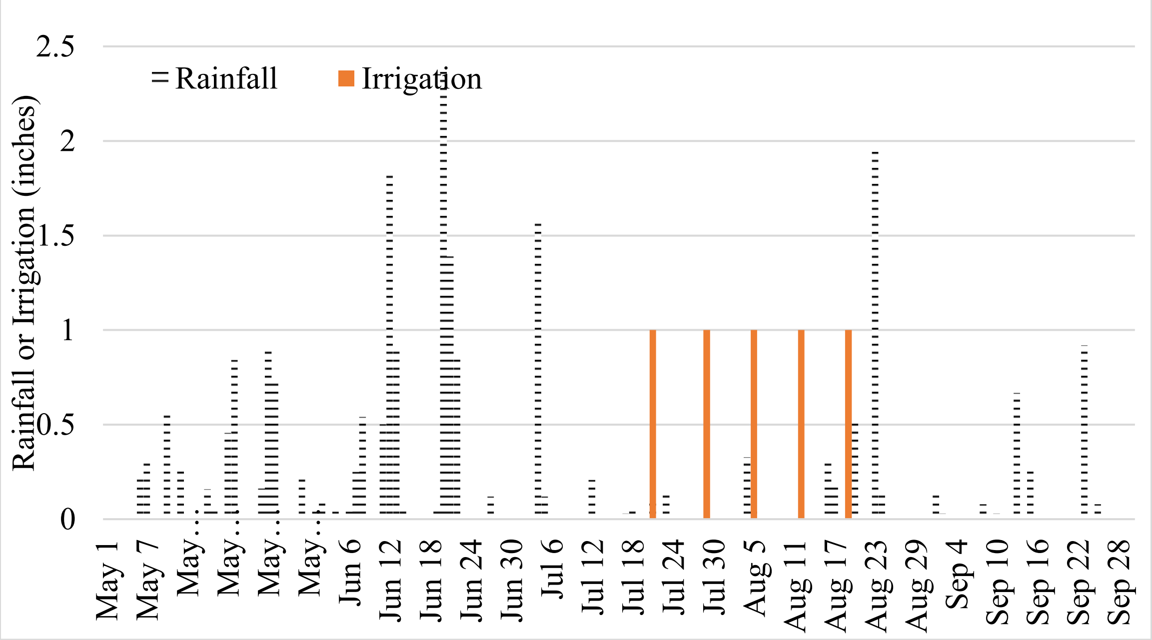

Figure C6: Days and Amount of Rainfall and Irrigation for 2010