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RESEARCH ARTICLE

Economics of deficit irrigation utilizing soil moisture probes in the western corn belt

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Abstract

Effective irrigation management is critical for future food supplies and the prosperity of producers engaged in irrigation production. Through a deficit irrigation field experiment, we determine the financial impact on producers caused by changing irrigation costs, corn prices, extreme weather events, and restricting irrigation levels. Results suggest that the optimal economic strategy within our constrained optimization model is to fully irrigate, with the economic impact highly dependent on commodity prices, restriction level, and irrigation costs. The greatest economic losses caused by irrigation restrictions come from decreases in yield. Some simulations resulted in negative profits, indicating that a switch to alternative crops requiring less irrigation may be warranted.

Keywords: Evapotranspiration; linear response stochastic plateau response function; profit maximization; stochastic quadratic response function

JEL Codes: Q00; Q15; Q18

Introduction

According to the United Stated Department of Agriculture Economic Research Service (USDA-ERS 2018), 80% of the water consumed in the United States is used to irrigate agricultural crops. The amount of irrigation water applied and the number of irrigated acres in the United States have been stable in recent years, although the techniques used to irrigate have shifted from gravity systems to pressure sprinklers, notably in the form of center-pivot irrigation systems (Colaizzi et al. 2009). Center-pivot systems use irrigation water more efficiently than earlier irrigation methods, and these systems have allowed output to increase even though the amount of water applied has not grown significantly (USDA-ERS 2018). However, Spencer and Altman (2010) argue that current water use, particularly in the arid Western states, is not sustainable because of climate change and growing water demand. According to a report by the U.S. Geological Survey (2003), groundwater depletion is widespread across the United States leading to lower water tables, and increased pumping costs, land subsidence, reduced amounts of water in streams and rivers, and adverse effects on water quality. Because irrigation contributes to groundwater depletion, effective irrigation management is critical for future food supplies and sustainable farming systems.

Nebraska offers a good example of the water use issues presented above. In the eastern part of the state, rainfall is generally adequate for corn and soybean production. Moving west, average annual rainfall amounts decline to levels that require either substantial irrigation or drought-tolerant crops. Over the period 1980–2020, average annual rainfall was 31.8 inches in Omaha (Douglas County) but only 15.5 inches in Scottsbluff in western Nebraska (Scotts Bluff County) (NOAA 2022). Because of abundant groundwater resources in the Ogallala aquifer and surface irrigation from Platte River diversions, it is possible to grow crops such as corn and soybeans in this arid climate. Nebraska accounted for almost 15% of the total irrigated acres in the United States in 2017, more than any other state (NASS 2021). Although groundwater resources are abundant, interaction between surface and underground water can give rise to conflicts when drought conditions lead to extensive groundwater use for irrigation. In 2006, the U.S. Supreme Court ruled in favor of Kansas which had sued Nebraska over reduced stream flows in the Republican River, which runs through Colorado, Nebraska, and Kansas (Supreme Court of the United States 2014).

The efficient use of scarce water resources is critical for agriculture, particularly for the prosperity of producers in the arid parts of the United States. New technology plays an important role in improving water use efficiencies. Simultaneously, research must be updated using both technological and methodological advancements. The goal of this study is to determine the economic value of deficit irrigation management using both technological and methodological advancements. The technological improvement is incorporated using soil moisture probes in a deficit irrigation system. To understand deficit irrigation, one must understand the yield response to water and the economic impact of yield reductions (English 1990). We provide improvements in the methodology as follows. Regarding data, we employ a field-size study, instead of plots, where the irrigation decision is determined by the moisture level in the soil measured through a soil moisture probe. Regarding the understanding of the yield response to water, although we examine the commonly used quadratic function, we improve upon this specification by also examining an alternative response function. Specifically, our objectives are to identify the financial impact on producers of reducing water use by increasing irrigation costs, reducing irrigation amounts, the role of changes in corn prices, and extreme weather events on the profitability of irrigating corn.

It is important to study the economic impact of reducing irrigation (Hargreaves and Samani 1984; English 1990; English and Raja 1996; Amosson et al. 2009; Hoekstra et al. 2011; Gobin et al. 2017; Manning et al. 2018; Varzi et al. 2019; among others) to measure water-use efficiency and make policy recommendations to reduce the impact of agriculture on water supplies. In this light, one of our objectives is to identify the financial impact on producers of limiting water use through hypothetical reductions in evapotranspiration (ET) as a proxy for government water limiting policies and the relation to other important economic parameters like output prices and input prices. ET represents the water that exits the soil through evaporation and transpiration (Irmak 2015a). To achieve this objective, we include an ET response function as a constraint in the constrained optimization model to reflect the effects of potential water restrictions. The ET constraint allows us to estimate the impact of ET-restricting policies on farm profitability. This approach provides insights into the economic impacts of water restrictions, as the only way to reduce ET is through water restrictions.

We model the irrigation production system through the producer lens with a unique dataset collected between 2005 and 2010 from field plots with varying levels of irrigation (full irrigation, deficit irrigation, and rainfed), producing corn in central Nebraska. These data are used to estimate equations describing the yield response to irrigation and the relation between irrigation and evapotranspiration. These relations are then incorporated into constrained optimization models that calculate the profit-maximizing level of irrigation under differing weather and market conditions. To our knowledge, this is one of the first papers to use such a detailed irrigation experiment, including using a soil moisture probe to accurately measure irrigation needs, evaluating alternative response functions, to analyze farmer profitability under different price, weather, and policy scenarios.

Literature review

Deficit irrigation represents an important concept in managing water use through irrigation (Hargreaves and Samani 1984; Martin et al. 1989; English 1990). Research on deficit irrigation has spanned across a wide range of applications (Galindo et al. 2018; Expósito and Berbel 2020), has focused corn production (Payero et al. 2006; Klocke et al. 2011), and for recent work that focuses on corn production with an economic component, has continued to advance the deficit irrigation concept (Trout and Manning 2019). The original work by English (1990) relies on winter wheat data for 1 year across multiple farms, used a quadratic response function, and varied the results through two different wheat prices. Focusing on corn production, Payero et al. (2006) estimate a linear response function, while Klocke et al. (2011) estimate a quadratic response, with no emphasis on the reasoning for choosing these functional forms.

More recent work by Manning et al. (2018) focus on corn and contains an economics component. The authors rely upon corn plot data from two different experiments (one focusing on deficit irrigation after growth stage V7 that had 4 years of yields, the second focusing on deficit irrigation depending upon the crop growth stage and contained 3 years). They estimate a Cobb–Douglas production function (chosen because of its flexibility) and incorporate the estimated parameters in a profit maximization framework. Manning et al. (2018) find that deficit irrigation could be profitable but only in the late vegetative stage and within certain values of water cost.

Regarding water response functions, previous literature has identified functions with diminishing returns (Musick and Dusek 1980; Sadler et al. 2002; Trout and DeJonge 2017). Musick and Dusek (1980) provide a discussion of the literature describing the relation between water and yield as quadratic or linear, settling for a linear fit for their analysis. Sadler et al. (2002) estimate a quadratic response of corn to irrigation. They find significant effects and a good fit for the quadratic response. Trout and DeJonge (2017) identify a quadratic relation between yield and irrigation water applied for corn after a 4-year experiment in the U.S. central plains, with the quadratic term being statistically significant.

While the yield response to water may display diminishing marginal returns or a linear relation, other factors may also be contributing to yield. To model the yield response to water in a more accurate way, these factors need to be controlled for. Advancements in econometrics allow for control of unobserved heterogeneity. Specifically, stochastic events, such as those coming from weather can be controlled by including a plateau year random effect (Boyer et al. 2013).

Tembo et al. (2008) develop a linear response stochastic plateau (LRSP) function. In the LRSP function, output will respond linearly to an additional unit of an input until it reaches the plateau, when additional inputs have no impact on output (Tembo et al. 2008). Several papers have analyzed how a LRSP yield response function responds to nitrogen (Tumusiime et al. 2011; Boyer et al. 2015; Boyer et al. 2013), but little recent research has been done on yield response to TWA using a LRSP yield response function. Grimm et al. (1987) hypothesize that a LRSP function would be a strong fit to represent a corn yield response to water as well as nitrogen application. Their results show that the LRSP functional form could not be rejected for both water and nitrogen inputs.

Our work most closely relates to Manning et al. (2018) and we improve upon this work in several important ways. First, our data comes from field level experiment that monitors the irrigation decision through soil moisture, using a soil moisture probe. Second, using advancements in response functions estimation strategies, we evaluate the potential for alternative response functions and control for unobserved heterogeneity. The alternative response function and ability to control for unobserved heterogeneity, while both simple and straightforward to implement, provides improvements in the estimation strategy. Third, we create an optimization model to simulate the economic impact on producers from restricting irrigation. The constrained optimization provides an effective way to find the best solution (profit maximization in our case) from changes in choice variables.

Agronomic experiment

To estimate the economic value of deficit irrigation management, we use harvested yield and measured ET from a corn production experiment conducted by Irmak (2015a, 2015b) at the University of Nebraska-Lincoln (UNL) South Central Agricultural Laboratory near Clay Center, Nebraska, between the years 2005 and 2010. In addition to yield and variable input and farm production costs, Irmak recorded the irrigation applied, rainfall, and weather and calculated actual ET using the formula in the soil water balance equation (1):

$$ET = P + I - RF + ISWC - DP, \tag{1}$$

where precipitation (P), irrigation water applied (I), surface runoff (RF), initial soil water content in the soil profile (ISWC), and deep percolation (DP) of water below the crop root zone data were collected at the field level. From the soil water balance equation (1), precipitation and irrigation contribute to ET. Both precipitation and irrigation can be lost to surface runoff and deep percolation.[1] As a result, the effect of irrigation on ET is unknown.

The experiment was conducted on a 40.77-acre field separated into 12 different plots of around 2.5 acres (one hectare) each, subjected to four different irrigation treatments: fully irrigated (FIT) and three deficit irrigation treatments (75% FIT, 60% FIT, and 50% FIT). The rainfed production practice represents the control group.[2] FIT is defined as irrigating the crop until soil water depletion is at 40–45 pecent of the total water-holding capacity of the soil. A soil moisture probe (model 4300 neutron attenuation soil moisture meter) was used to measure the soil water content. Soil water content was measured at different soil depths, once or twice per week during the time of the experiment. 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 of the experiments. The field was irrigated using a four-span 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.

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[1] From (Irmak 2015a, 2015b), deep percolation was calculated through a daily soil water balance approach using daily weather (air temperature, incoming shortwave irradiance, relative humidity, wind speed, and precipitation); irrigation dates and amounts; initial water soil water content; and crop specific and site-specific information (planting date, hybrid maturity date, soil parameters and maximum rooting depth).

[2] For 2005 yields were only available for 100% FIT and rainfed.

There were large differences in yields among years as growing conditions varied by year. The highest yield was observed in 2008 with 100% FIT. This year also corresponds to the highest yield for rainfed production. For each year, rainfed yields were the lowest while 100% FIT had the highest yield.[3] Through the years 2006–2008, the experiment controlled for two different planting populations for the rainfed control group.[4] For 2005 and 2009–2010, only one plant population was used in the experiment. For each irrigation treatment, there were a minimum of three replications, providing a total of 93 observations. Each year all plots were fertilized equally, and herbicide applications were the same on all plots although the type of fertilizer and herbicide changed year to year. Additional details can be found in Irmak (2015a, 2015b). Rainfall data collected outside the time frame of the experiment came from NOAA (2019). Corn prices for the period 2005–2010 were the observed average, high, and low harvest cash price (October 1st) for Hastings, NE during this period (Mark and Kabes 2007; Johnson and Walters 2014).

Deficit irrigation for each plot was based on how much irrigation FIT required that year as determined by the soil moisture probes. Under 75% FIT, irrigation was reduced by 25% relative to the amount used for FIT and similar adjustments were made for 60% (40% reduction) and 50% (50% reduction) FIT. 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 the desired level of soil water content.

Methodology and data

Producers are most likely to employ irrigation strategies that maximize profits, and these strategies may not be the ones that use the least amount of water. For this study, an optimization model is used to calculate the profit-maximizing irrigation strategy based on the data from Irmak's field experiments (Irmak 2015a, 2015b). We consider a risk-neutral irrigated corn producer whose objective is to maximize expected profit from irrigated corn production as shown in the following objective function:

$$\max_{I} E(\pi_t) = \mathrm{p}\mathrm{E}(y_t) - c * I - FC_t$$

$$s.t. y_t = F(I) \tag{2}$$

where E represents the expectations operator; π_t represents the producer's net returns at time t; p represents output price; y_t represents yield; c represents irrigation costs; I represents the amount of water applied using irrigation; and FC_t represents fixed costs associated with agricultural production such as fertilizer, herbicide, equipment, taxes, insurance, and land rent. We include fixed costs to determine if outcomes result in negative profits. Expected profits are maximized when the marginal value product of irrigation is equal to the marginal factor cost of irrigation.

The objective function includes fixed costs of production consisting of the costs of owning and maintaining the irrigation equipment and other farm machinery and all input costs not affected by the level of irrigation. Variable costs are those that depend on the level of irrigation. Fixed and variable irrigation costs are obtained using the University of Nebraska crop budgets (UN Crop Budgets 2018). Costs were based on a recent year to give a more accurate representation. The annual fixed cost, consisting of fertilizer, herbicide, equipment, taxes, insurance, and land rent, is $631.10 per acre. The average variable

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[3] For a detailed description of the data and the production process see Irmak (2015a).

[4] The two plant populations for the rainfed control group are: 24,500 and 30,500 in 2006; 22,500 and 26,500 in 2007 and 2008.

irrigation cost is $9.12 per acre inch. Full irrigation (FIT) was achieved in the experiment when available soil water in the top 1.5 meter of soil was between 90% of the field capacity and a maximum allowable depletion set to approximately 40–45% of the total available water holding capacity (Irmak 2015a).

The amount of irrigation water applied not only constitutes a cost in the profit function but also leads to variations in revenue through its effects on yield. To account for the effect of irrigation on yield, yield–response functions are estimated, and the estimated parameters are included in the profit function. Because the irrigation applied to the crop depends on rainfall as measured by soil water content, we cannot distinguish between the contribution of rainfall and irrigation water. For this study, yield response equations are estimated for total water applied (TWA) defined as rainfall and initial soil water content plus irrigation water. In addition to the yield response functions, an equation representing the response of ET to TWA is also estimated. The ET response equation is included to reflect the impact of potential restrictions on water use. We include an ET response function as a constraint in the constrained optimization model, which reflects the effects of potential water restrictions. Including the ET constraint allows us to estimate the impact of such policies on farm profitability.

Irrigation response specification

The specification of the irrigation response function impacts the influence of the economic variables in the constrained maximization model. Our choice of functional form for the irrigation response function depends on the way we model producers' decision making, and it is limited by the scope of the experiment where our data comes from. While some studies assume that crop prices influence irrigation decisions (Mullen et al. 2009; Manning et al. 2018; among others), there is some evidence that producers decide how much to irrigate independent of crop price expectations (Sukcharoen et al. 2020). We proceed with two functional forms representing both types of producers.

The first functional form is a stochastic quadratic function. The stochastic quadratic functional form represents producers who would adjust irrigation values based on input and output prices. The quadratic functional form has been implemented in previous deficit irrigation studies (Martin et al. 1989; English 1990; English and Raja 1996; Trout and DeJonge 2017; and Trout et al. 2020).

The stochastic quadratic response equation for estimating yield (Y_{it}) for treatment i ($i =$ FIT, 75% FIT, 60% FIT, 50% FIT, and Rainfed) in year t ($t =$ 2005, …, 2010) is

$$Y_{it} = \gamma_0 + (\gamma_1 + \tau_t)TWA_{it} + (\gamma_2 + \delta_t)TWA_{it}^2 + \psi X + u_t + \varepsilon_{it}, \qquad (3)$$

where TWA_{it} is the total water applied; X is the vector of control variables (replication and plant population); $\gamma_0, \gamma_1, \gamma_2$ and ψ are estimated parameters; $\tau_t \sim \mathrm{N}(0, \sigma_u^2)$ represents the TWA random effect parameter; $\delta_t \sim \mathrm{N}(0, \sigma_u^2)$ represents the TWA^2 random effect parameter; $u_t \sim \mathrm{N}(0, \sigma_u^2)$ is the year random effect; and ε_{it} is the error term. Both τ_t and δ_t represent the stochastic components.

The second functional form is the LRSP function. This functional form has been used mostly on papers analyzing how a LRSP yield response function responds to nitrogen (Tumusiime et al. 2011; Boyer et al. 2013; Boyer et al. 2015). However, Grimm et al. (1987) found the LRSP function to be a strong fit to model the corn yield response to both water and nitrogen. The point at which the linear response hits the plateau is commonly referred to as the "knot point." Producers irrigating the same amount each year would appear to be following a LRSP functional form. Only under circumstances when marginal costs are higher than marginal benefits would the decision maker represented by the LRSP functional form cease irrigating. Examples of these circumstances would be when the decision maker experiences low output prices and/or high input prices. For all other price combinations, the decision maker irrigates at the knot point.

We estimate a LRSP equation for yield (Y_{it}) for treatment i ($i =$ FIT, 75% FIT, 60% FIT, 50% FIT, and Rainfed) in year t ($t = 2005, \ldots, 2010$):

$$Y_{it} = \min(\beta_0 + \beta_1 TWA_{it} + \eta X,\ \ Pl + v_t) + u_t + \varepsilon_{it}, \tag{4}$$

where TWA_{it} is the total water applied; X is the vector of control variables (replication and plant population); Pl is the expected plateau yield; $\beta_0,\ \beta_1$ and η are estimated parameters; $v_t \sim \mathrm{N}(0, \sigma_v^2)$ is the plateau year random effect which shifts the plateau; $u_t \sim \mathrm{N}(0, \sigma_u^2)$ is the year random effect; and $\varepsilon_{it} \sim \mathrm{N}(0,\sigma_\varepsilon^2)$ is the random error term (Tembo et al. 2008).

ET is estimated as a function of TWA. We use a stochastic quadratic functional form, as this functional form represents the biological process by providing the best fit for the data. Because irrigation and ET are directly related, we use constraints on ET in the constrained 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 stochastic quadratic response function for estimating evapotranspiration (ET_{it}) for treatment i ($i =$ FIT, 75% FIT, …, Rainfed) in year t ($t = 2005, \ldots, 2010$) is

$$ET_{it} = \psi_0 + (\psi_1 + \tau_t) TWA_{it} + (\psi_2 + \delta_t) TWA_{it}^2 + \zeta X + u_t + \varepsilon_{it}, \tag{5}$$

where TWA_{it} is the total water applied; X is the vector of control variables (replication and plant population); $\psi_0, \psi_1,\ \psi_2$ *and* ζ are estimated parameters; $\tau_t \sim \mathrm{N}(0, \sigma_u^2)$ represents the TWA random effect parameter; $\delta_t \sim \mathrm{N}(0, \sigma_u^2)$ represents the TWA^2 random effect parameter; $u_t \sim \mathrm{N}(0, \sigma_u^2)$ is the year random effect; and ε_{it} is the error term.

Constrained optimization model

Yield–response functions are part of the profit function in the constrained optimization problem. The expected profit function based on the stochastic quadratic specification of the yield response to TWA (equation 3) is

$$\mathrm{Max}\ E[\pi] = P_c{*}E\big[\big(\gamma_0 + \gamma_1 TWA + \gamma_2 TWA^2\big)\big] - C{*}(TWA - Rain - ISWC) - FC,$$
$$\text{s.t.}\quad \big(\psi_0 + \psi_1 TWA + \psi_2 TWA^2\big) \le U \tag{6}$$

where E is the expectations operator; π is profit; P_c is the price of corn per bushel; $\gamma_0,\ \gamma_1$ and γ_2 are parameter estimates from the stochastic quadratic yield equation (3); C is the variable cost of irrigation applied per inch; *Rain* is the rainfall that occurred during the growing season; *ISWC* is the initial water content of the soil before the growing season begins; and *FC* is the fixed costs per acre associated with running a farm and an irrigation sprinkler system. The expected profit equation (6) is constrained by U, the maximum acceptable ET that will vary by potential government restrictions and $\psi_0,\ \psi_1$ and ψ_2 are parameter estimates from the stochastic quadratic ET equation (5).

The expected profit function based on the LRSP specification of the yield response to TWA (equation 4) is

$$Max\ E[\pi] = P_c * E\left[(1-\Phi)(\beta_0 + \beta_1 TWA) + \Phi\left(u_m - \frac{\sigma_v \phi}{\Phi}\right)\right] - \tag{7}$$
$$\mathrm{C{*}(TWA - Rain - ISCW) - FC},$$

$$\text{s.t.}\quad (\beta_0 + \beta_1 TWA) \le PL_{LRSP}$$

$$\left(\psi_0 + \psi_1 TWA + \psi_2 TWA^2\right) \le U$$

where β_0 and β_1 are parameter estimates from the LRSP yield equation (4); $\Phi = \Phi\left[\frac{(\beta_0+\beta_1 TWA)-Pl}{\sigma_v}\right]$and represents the cumulative normal distribution and $\phi = \phi\left[\frac{(\beta_0+\beta_1 TWA)-Pl}{\sigma_v}\right]$and represents the standard normal density. To solve our constrained optimization equation, the profit equation (7) is constrained by the yield equation in that yield cannot be more than the plateau yield, PL_{LRSP}. ET is constrained by U, the maximum acceptable ET that will vary with water-use restrictions set by government policy, potentially resulting in lower quantities of TWA.[5] P_c is multiplied by the LRSP yield response function to obtain total revenue. Fixed costs and the variable cost of applying irrigation are subtracted from revenue to calculate expected profit.

In addition to calculating expected profit under average farming conditions, 12 scenarios with variations in expected prices, rainfall, and allowable ET were analyzed. These variations changed the optimal amount of irrigation as well as expected ET, yield, and profit. We include scenarios from years in which Nebraska (Adams County) experienced severe weather conditions outside the range of the experimental data.

The stochastic quadratic and LRSP functional forms are estimated using maximum likelihood estimation (MLE) in StataSE 16. The constrained optimization model is solved using NLP in GAMS (General Algebraic Modeling System). In the constrained optimization model, we inspect the range of expected profit across three different characteristics: rainfall, irrigation costs, and corn prices. In addition, we include outcomes from within our dataset and out-of-sample outcomes. We include the out-of-sample outcomes because the study period did not include large variations in rainfall. For irrigation costs, we analyze seven levels: average ($9.12 per acre inch), high +50 ($13.68 per acre inch), high +30 ($11.86 per acre inch), high +10 ($10.03 per acre inch), low −10 ($8.21 per acre inch), low −30 ($6.38 per acre inch), low −50 ($4.56 per acre inch). High irrigation costs represent a 50%, 30%, and 10% increase in the average, while low irrigation costs represent a 50%, 30%, and 10% reduction, respectively. For variations in corn price, we rely on observed yearly average price outcomes during the time of the study. The average corn price was $3.19 per bushel, the highest corn price occurred in 2008 at $4.55 per bushel, and the lowest corn price occurred in 2005 at $1.59 per bushel (Mark and Kabes 2007; Johnson and Walters 2014).

Results

We begin by reporting estimation results for the yield and ET response functions. We then present the results of the constrained optimization model. Parameter estimates for the yield–response equations using both the stochastic quadratic and LRSP functional forms and the ET stochastic response function are reported in Table 1. Results from the different scenarios of the constrained optimization model are reported in Tables 2 and 3.

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[5] In practice, policy would focus on an irrigation restriction as policy limiting ET would be difficult and costly.

Table 1. Corn yield and ET response functions results

Variable	Stochastic Quadratic Yield Response Function	LRSP Yield Response Function	Stochastic Quadratic ET Response Function
Intercept	−980.26*** (130.70)	−295.90*** (29.50)	−19.43*** (3.01)
TWA	78.81*** (9.83)	20.08*** (0.93)	2.56*** (0.21)
TWA^2	−1.26*** (0.21)		−0.03*** (0.005)
Replication 1	0.38 (2.74)	−0.92 (3.62)	0.001 (0.05)
Replication 2	1.28 (2.74)	1.72 (3.66)	0.001 (0.05)
Low plant population	13.03*** (4.74)	10.96** (5.04)	0.025 (0.01)
Intercept random effect	14035.36 (9427.22)	2064.21 (1202.64)	13.08 (8.07)
Plateau random effect		23.04 (33.93)	
Knot Point		242.31*** (3.18)	
TWA random effect	0.001 (0.001)		0.001 (0.001)
TWA^2 random effect	0.02 (0.01)		0.001 (0.001)
Variance of error term	115.00 (18.97)	134.54 (21.17)	0.05 (0.01)
Log-likelihood	−385.73	−376.54	−28.87

Note: ***=$p < 0.01$, **$p < 0.05$. Number of observations: 93. Standard errors in parentheses. LRSP represents the linear response stochastic plateau. ET represents evapotranspiration. TWA represents total water applied.

Yield and ET response functions results

Focusing first on the stochastic quadratic yield response function, both estimated coefficients on TWA were significant with the estimated coefficient on TWA being positive and the estimated coefficient on TWA^2 being negative. The estimated signs on the stochastic quadratic response indicate diminishing marginal productivity between TWA and yield. For the LRSP yield response function, we found a significant and positive estimated coefficient on TWA.[6] These results indicate that yield is dependent upon TWA, which is consistent with Irmak (2015a, 2015b), who found a positive association between yield and irrigation. The estimated knot point, where the linear response meets the plateau, was 242.31 bushels per acre. In both the stochastic quadratic and LRSP response functions, the estimated coefficient on the intercept is negative. This result indicates that a minimum amount of water is necessary to achieve a reproductive state. That is, a minimum amount of water is needed before the plant can start to develop (reach a reproductive state). For the stochastic quadratic about 17 inches of water is necessary to result in a positive yield, while for LRSP, the value is about 15 inches (see Figures 1 and 2). For the ET equation, we also found significant and diminishing marginal productivity through the positive TWA parameter estimate and negative TWA^2 parameter estimate. The estimated coefficient

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[6] Results are considered significant at 5%.

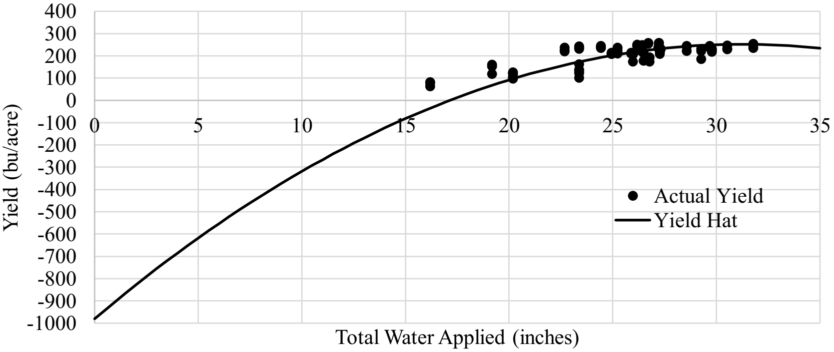

Figure 1. Stochastic quadratic yield response function to TWA and actual yield.

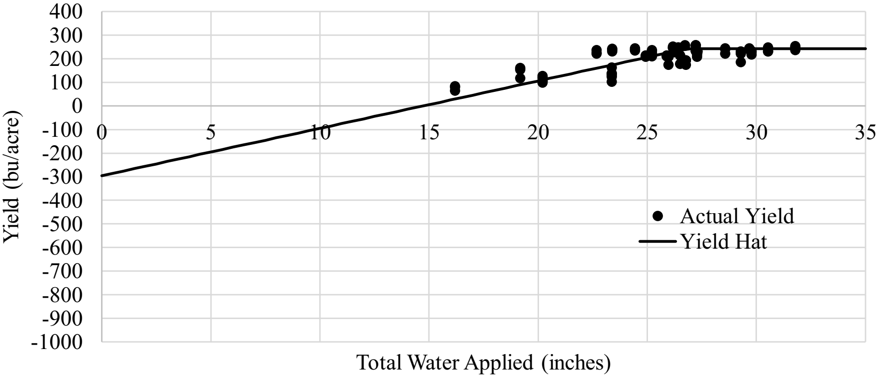

Figure 2. LRSP yield response function to TWA and actual yield.

on the intercept is negative, indicating that a minimum amount of water must be present for measurable ET to occur.

We found low plant population to be significant in both yield response functions with a positive estimated coefficient in both the stochastic quadratic yield response model and the LRSP yield–response model. Control variables for replications 1 and 2 were not significant in any of the three estimated models, as expected since the conditions for all three replications were the same.

In addition to discussing the parameter estimates, we provide a graphical representation of each of the estimated response functions and compare them with the observed data. The stochastic quadratic response function and observed data with TWA on the x-axis and yield on the y-axis are presented in Figure 1, in which we observe the curvature of the stochastic quadratic response function. The LRSP response function is presented in Figure 2, where we see a positive relation between TWA and yield, up to the knot point. The stochastic quadratic response function crosses zero yield, achieving a reproductive state with about 17 inches, slightly more TWA than the 15 inches with the LRSP response function. The ET stochastic quadratic response function is presented in Figure 3, where we

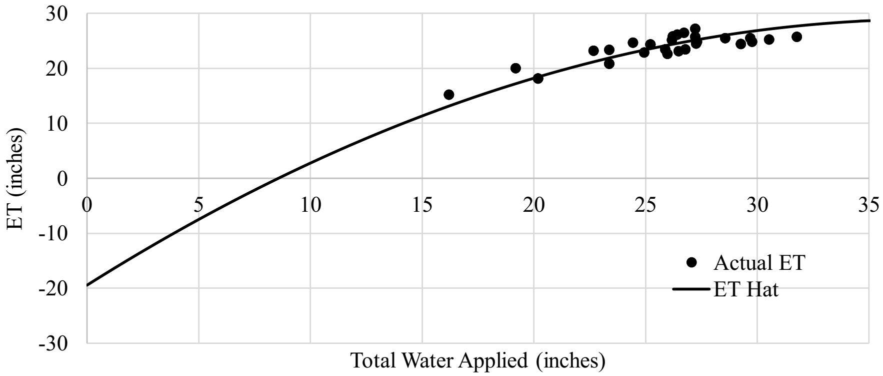

Figure 3. Stochastic quadratic ET response function to TWA and actual ET.

observe a relatively flat response function, due to a narrow range of ET across a wide range of TWA.

Constrained optimization results

We use a constrained optimization model to examine the financial impact on producers from different weather and market conditions and restrict ET (by changing U). We first report results from changing rainfall, irrigation cost, or corn prices, followed by a discussion of the financial impact of restricting ET. The variation in rainfall considered is based on observed rainfall during the growing season (May 1–Sept 30): average 17.1 inches (in-sample); high 32.27 inches (out-of-sample, 1915); low 7.87 inches (out-of-sample, 1940) (Irmak 2015a, 2015b; NOAA 2019). Irrigation costs are average \$9.12 per acre inch (in-sample); high +50 \$13.68 per acre inch (50% higher than the average); high +30 \$11.86 per acre inch (30% higher than the average); high +10 \$10.03 per acre inch (10% higher than the average); low −10 \$8.21 per acre inch (10% lower than the average); low −30 \$6.38 per acre inch (30% lower than the average); low −50 \$4.56 per acre inch (50% lower than the average) (Irmak 2015a, 2015b). Corn prices are average \$3.19 per bushel (in-sample); high \$4.55 per bushel (in-sample, 2008); low \$1.59 per bushel (in-sample, 2005) (Mark and Kabes 2007; Johnson and Walters 2014). In addition to no constraint on ET, we consider four different levels of ET: 1%, 2%, 5%, and 10% reductions from the profit-maximizing level. This approach allows us to identify and compare the impact on profit of changes in rainfall, irrigation cost, or corn prices to the impact from constraining ET. For each rainfall, irrigation cost, and corn price scenario, we identify the amount of irrigation in TWA.

The results for the stochastic quadratic LRSP and functions under average rainfall, irrigation cost, and corn prices are presented in Table 2, first row. The profit-maximizing solution for the stochastic quadratic function resulted in an expected profit of \$92.05 per acre, expected yield of 250.46 bushels per acre, 8.31 inches of irrigation, and 30.47 inches of ET. The profit-maximizing solution for the LRSP yield response function with average rainfall, average irrigation cost, and average corn price, resulted in an expected profit of \$95.20 per acre, expected yield of 241.91 bushels per acre, 4.98 inches of irrigation, and 27.63 inches of ET. The expected yield incorporates the stochastic nature of the plateau and is slightly lower than the knot point, which is logical as additional

Table 2. Constrained optimization results

Rainfall	Irrigation Cost	Corn Price	Profit (dollars per acre)		Yield (bu per acre)		Irrigation (inches)		ET (inches)	
			Stochastic Quadratic	LRSP	Stochastic Quadratic	LRSP	Stochastic Quadratic	LRSP	Stochastic Quadratic	LRSP
Average	Average	Average	$92.05	$95.20	250.46	241.91	8.31	4.98	30.47	27.63
Average	High +50	Average	$55.43	$72.50	248.43	241.91	7.48	4.98	30.04	27.63
Average	High +30	Average	$69.77	$81.58	249.34	241.91	7.97	4.98	30.22	27.63
Average	High +10	Average	$84.52	$90.66	250.12	241.91	8.20	4.98	30.39	27.63
Average	Low −10	Average	$99.68	$99.74	250.77	241.91	8.43	4.98	30.56	27.63
Average	Low −30	Average	$115.26	$108.82	251.29	241.91	8.66	4.98	30.73	27.63
Average	Low −50	Average	$131.26	$117.90	251.68	241.91	8.88	4.98	30.89	27.63
Average	Average	High	$433.34	$424.19	251.29	241.91	8.65	4.98	30.73	27.63
Average	Average	Low	−$306.08	−$291.86	245.56	241.91	7.17	4.98	29.58	27.63
Scenarios using out-of-sample rainfall data										
High	Average	Average	$41.49	$141.87	210.84	242.31	0.00	0.00	34.22	34.22
High	Average	High	$328.23	$471.41	210.84	242.31	0.00	0.00	34.22	34.22
High	Average	Low	−$295.86	−$245.83	210.84	242.31	0.00	0.00	34.22	34.22
Low	Average	Average	$7.87	$11.02	250.46	241.91	17.54	14.21	30.47	27.63
Low	Average	High	$349.16	$340.02	251.29	241.91	17.88	14.21	30.73	27.63
Low	Average	Low	−$390.26	−$376.04	245.56	241.91	16.40	14.21	29.58	27.63

Notes: The initial soil water content is 4.725 inches. LRSP represents the linear response stochastic plateau. ET represents evapotranspiration.
Rainfall during growing season (May 1–Sept 30): average 17.1 inches (in-sample); high 32.27 inches (1915); low 7.87 inches (1940) (Irmak 2015a, 2015b; NOAA 2019).
Irrigation cost: average $9.12 per acre inch; high +50 $13.68 per acre inch (50% higher); high +30 $11.86 per acre inch (30% higher); high +10 $10.03 per acre inch (10% higher); low −10 $8.21 per acre inch (10% lower); low −30 $6.38 per acre inch (30% lower); low −50 $4.56 per acre inch (50% lower) (Irmak 2015a, 2015b).
Corn Price: average $3.19 per bushel; high $4.55 per bushel (2008); low $1.59 per bushel (2005) (Mark and Kabes 2007; Johnson and Walters 2014).

irrigation past the knot point, does not increase the yield, resulting in lower profit. To the left side of the knot point, each additional amount of irrigation improves profit, given average rainfall, irrigation cost, and corn prices. If the producer irrigates according to a LRSP response function, they would either irrigate at the knot point or not at all. The LRSP model provided a slightly higher expected profit over the stochastic quadratic with less irrigation and a slightly lower yield. A result is possibly due to the curvature in the quadratic model.

In the next six rows, we identify the profit-maximizing level under different irrigation costs (rows 2 and 3 in Table 2). We analyze the effects of increasing and decreasing the irrigation cost by 50%, 30%, and 10%. For the stochastic quadratic response function under differing irrigation costs, the profit-maximizing strategy affected the amount of irrigation. As expected, higher irrigation costs resulted in lower amounts of irrigation, while lower irrigation costs resulted in higher amounts. Going from high +50% to low −50% irrigation costs, expected yield increased from 248.43 bu/acre to 251.68 bu/acre and expected profit increased from \$55.43 to \$131.26 per acre. Going now to the smaller difference of high +10% to low −10% irrigation costs, expected yield increased from 250.12 bu/acre to 250.77 bu/acre and expected profit increased from \$84.52 to \$99.68 per acre. Increases (decreases) in irrigation costs under the stochastic quadratic model result in decreased (increased) irrigation; however, this amount is less than 1.5 acre inch of change from the optimal with average irrigation costs.

The profit-maximizing strategy for the LRSP response function with different irrigation costs is to irrigate to the knot point, or full irrigation, with expected profit ranging from \$72.50 to \$117.90 per acre, respectively. We then simulate the irrigation cost that would make the producer deviate from that strategy and not irrigate. Holding all other variables at the average value, we find that irrigation costs would have to increase to \$64.50 per acre inch for the producer to cease irrigation altogether. A result indicating that irrigation costs would have to increase 607% from the average cost for this scenario to occur. This result is similar to Manning et al. (2018), whose results indicate that irrigation costs would have to increase 400% to 800% before deficit irrigation becomes optimal. Given this high irrigation cost, profit is -\$177 per acre with a yield of 142.35 bu/acre. This outcome suggests that only substantial changes in irrigation costs would cause the producer following a LRSP response function to deviate from the optimal strategy of irrigating to just before the knot point. Under a LRSP response function, only large changes in prices will cause a change in the amount of irrigation, and the change would be to cease irrigating altogether. Said another way, producers following an LRSP function adjust irrigation values based primarily on inter-season rainfall and beginning of the crop year soil water content.

We simulated the most profitable irrigation management strategies under different corn prices, reported in rows 8 and 9 (Table 2). The average price of corn was \$3.19 per bushel during the period 2005–2010. We calculate farm expected profits at high (\$4.55 per bushel in 2008) and low (\$1.59 per bushel in 2005) corn prices during this period (Mark and Kabes 2007; Johnson and Walters 2014). The profit-maximizing strategy for the stochastic quadratic response function is, as expected, to irrigate more (8.65 inches) with higher corn price and less (7.17 inches) with lower corn price. The change in the optimal irrigation level had a small effect on expected yield (251.29 bu/acre with high corn price and 245.56 bu/acre with low corn price) but a large effect on expected profit (\$433.34 per acre with high corn price compared to -\$306.08 per acre with low corn price).

The profit-maximizing strategy for the LRSP response function is to irrigate to the knot point regardless of the output price in our price scenarios. Profits range from \$424.19 per acre at the high corn price to −\$291.86 per acre at the low corn price. We observe a larger expected profit effect from changes in output prices than input costs,

Table 3. Constrained optimization results – Evapotranspiration constraint

	Profit (dollars per acre)		Yield (bu per acre)		Irrigation (inches)		ET (inches)	
ET Restriction	Stochastic Quadratic	LRSP	Stochastic Quadratic	LRSP	Stochastic Quadratic	LRSP	Stochastic Quadratic	LRSP
1%	$91.41	$80.24	249.12	237.06	7.92	4.69	30.17	27.36
2%	$89.52	$65.07	247.40	230.91	7.52	4.41	29.86	27.08
5%	$77.74	$19.96	240.58	214.34	6.43	3.59	28.95	26.25
10%	$41.13	-$50.64	224.33	188.54	4.76	2.30	27.42	24.87

Notes: The initial soil water content is 4.725 inches. LRSP represents the linear response stochastic plateau. ET represents evapotranspiration.
Rainfall during Growing Season (May 1- Sept 30): Average 17.1 inches (Irmak 2015a, 2015b).
Irrigation Cost: Average $9.12 per acre inch (Irmak 2015a, 2015b).
Corn Price: Average $3.19 per bushel (Mark and Kabes 2007; Johnson and Walters 2014).

as there are more bushels to sell than inches to irrigate. These results show that changes in corn prices impact irrigation amounts more than changes in irrigation costs, given the current irrigation cost levels.

We are interested in producers' irrigation management strategies when faced with extreme weather. Adams County, Nebraska, where our study took place, experienced very high rainfall in 1913 (32.27 inches during the growing season) and a severe drought in 1940 (7.87 inches during the growing season) (NOAA 2019). Rainfall associated with these extreme events was used in the constrained optimization model for both stochastic quadratic and LRSP response functions. The results are reported in the bottom six rows of Table 2 (scenarios using out-of-sample rainfall data). With rainfall during the 1913 growing season of 32.27 inches, the extra TWA resulted in no irrigation for both response functions, therefore no variable irrigation costs were incurred. For both response functions, expected profits depend on corn prices. For the stochastic quadratic response function, expected profit decreased to $41.49 per acre with average corn price; increased to $328.23 per acre with high corn prices; and decreased to −$295.86 per acre with low corn prices, compared to $92.05 per acre with average study rainfall, average irrigation costs, and average corn prices. For the LRSP response function with very high rainfall, TWA was past the knot point, therefore no irrigation was applied, and no variable irrigation costs were incurred. With no irrigation costs, expected profits increased to $141.87 per acre compared to $95.20 per acre with average study rainfall, average irrigation costs, and average corn prices. With high corn price, expected profits increased to $471.41 per acre, while expected profits fell to -$245.83 per acre with low corn price compared with the original result of $95.20.

The very high rainfall and consequently no irrigation scenario emphasizes the implications of the choice of the functional form of the yield response model. With the stochastic quadratic functional form, there is a diminishing marginal productivity of TWA, but with the LRSP functional form the amount of water applied past the knot point does not change the expected yield. Once there is more TWA than the maximum yield given by the estimated stochastic quadratic function, expected yield starts to decrease. In the very high rainfall scenario, expected yields decreased to 210.84 bu/acre from 250.46 with average conditions.

When we simulate the drought of 1940, the profit-maximizing strategy is to increase irrigation to reach the same level of TWA found under average rainfall conditions. With the stochastic quadratic response function, producers irrigate to reach the same level of TWA found with average rainfall conditions, even though irrigation costs increase because of increased irrigation. Profits decline due to the additional irrigation costs and are again highly sensitive to corn prices. With the LRSP response function, producers irrigate to the knot point, which decreased expected profit compared to average rainfall due to a substantial increase in irrigation and, therefore, irrigation costs. As in the other scenarios, expected profit is highly sensitive to corn prices.

Results from the ET restrictions on expected profit are reported in Table 3. Restricting ET is the same as restricting the level of irrigation, as irrigation is the only component of TWA that can be influenced by decision-makers. Given the importance of ET in water-use efficiency studies, it is important to understand the economic impact on producers of restricting ET. The government could restrict producer irrigation use, which would be reflected in lower levels of ET. We restrict ET by 1%, 2%, 5%, or 10% from the optimal amount of ET under no restrictions, resulting in decreases in irrigation of 5% to 54% depending on the restriction and model (Table 3). The four restrictions cause reductions in expected profit, expected yield and irrigation for both the stochastic quadratic and LRSP response functions, with larger reductions observed for the LRSP response function. Specifically for the stochastic quadratic response function, expected profits decrease by 1%, 3%, 16%, or 55% corresponding to the ET restrictions (1%, 2%, 5%, or 10%, respectively). Expected profits decrease even more for the LRSP response function, by 14%, 31%, 28%, or 54% (negative expected profit) corresponding to the ET restrictions (1%, 2%, 5%, or 10% respectively). The ET restrictions result in irrigation levels below the know point. These results suggest that 1) deficit irrigation may not be economically optimal and 2) policy limiting the amount of irrigation toward the upper end of the range assumed in this study (e.g., a reduction in irrigation of 20–60%), will have large to dramatic effects on producer profitability.

We can rank the expected profit impacts from ET restrictions, changes in irrigation costs, and changes in corn prices. For producers, the worst financial event is low corn prices, followed by large reductions in ET (10% or more for stochastic quadratic, and 2% or more for LRSP), high irrigation costs, and lower reductions in ET (5% or less for stochastic quadratic, and 1% or less for LRSP). Said another way, constraining ET by 10% or more is financially worse than increasing irrigation costs by 50% but not as bad as the low corn prices observed during the time of the study. The effect of input prices on ET also depends upon the type of producer. A producer whose irrigation depends upon input prices, i.e., our stochastic quadratic specification, will have varying amounts of ET. Producers following an LRSP function will always have the same amount of ET (unless rainfall is much higher than TWA at the knot point) since they irrigate to the knot point and, under normally observed prices, will only respond to restrictions on ET. Consequently, smaller restrictions on ET have a higher impact on profit under the LRSP response function. All the ET levels identified under different scenarios in Table 2 are higher than those found with ET restrictions in Table 3. The exception is ET under low corn prices for the stochastic quadratic response function, which is lower than restricting ET by 1% and 2%, highlighting the impact of low corn prices not only on profitability but also on input use choice.

Conclusions

We identify the financial impact on producers of restricting water use by increasing irrigation costs, reducing ET, changing corn prices, and considering extreme weather events using data from a deficit irrigation experiment utilizing a soil moisture probe. We model the yield response to water using two functional forms: stochastic quadratic and linear response stochastic plateau (LRSP). The diminishing marginal value of TWA in the stochastic quadratic model reflects the behavior of profit-maximizing producers who change their irrigation strategy based on expected input and output prices. The LRSP model reflects the behavior of producers who apply irrigation to the expected profit maximizing level (knot point) and only deviate when the marginal value of the input is less than the marginal cost. We also model the response of ET to different levels of TWA to examine profitability if the irrigation level is restricted, for example, through a policy restriction.

Our results show that yield, and consequently profit, is heavily impacted by TWA, similar to findings in Musick and Dusek (1980), Hargreaves and Samani (1984), and Trout and DeJonge (2017), among others. Reducing irrigation causes a decrease in expected yield, resulting in decreased expected profits that switch from being positive to negative with large decreases in irrigation. Producers following a stochastic quadratic response function adjust irrigation use to prices. With a stochastic quadratic response function, low corn price reduces irrigation use more than high irrigation costs and ET restrictions. Producers following a LRSP response function and facing normal costs and prices would only change irrigation behavior through a constraint in irrigation, a result indicating policies that slightly increase irrigation costs will not impact water use. Some simulations resulted in negative profits, indicating a potential for a switch to alternative crops that require less water use. Crop insurance could provide indemnity payments, possibly making profits positive.

Our constrained optimization model indicates that full irrigation is the profit-maximizing strategy in all scenarios, even when there is a severe drought and high variable irrigation costs. Water is currently a small cost to producers and without government intervention, a large reduction in water available from natural resources, or a large increase in costs surrounding irrigation (labor, electricity, ownership of center pivot, etc.), producers would apply full irrigation to achieve the highest profit. Only substantial changes in irrigation costs would cause the producer to deviate from the optimal strategy of full irrigation. However, producers may experience large profit losses if deficit irrigation is implemented. If reducing irrigation is considered optimal for society, compensation for producers will need to be considered.

Previous research from Hoekstra et al. (2011) suggested that producers 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 producers consider in deciding what and how to produce. Decisions on production are based on potential profit and the factors that impact profit include water but also input prices, arable land, cost of labor, and access to fuel resources (Kumar and Singh 2005; Zhang and Wang 2014).

One limitation of this experiment is that there are no observations reflecting situations of very high rainfall and excess irrigation is not considered. From different experiments, it has been observed that excess water will decrease yield (Irmak and Rathje 2008; among others). However, we cannot observe the actual amount of water that would start to decrease yield in our data. Using the stochastic quadratic and LRSP functional forms allows us to measure the impact of very high rainfall if the excess leads to lower expected yields (stochastic quadratic) or if there is no impact on expected yield (LRSP). Another limitation of this study is that it lacks a multi-crop component, which was not part of the original experiment. Future work on deficit irrigation should also consider changing fertility when changing irrigation usage.

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