Impact of Climate Change on Groundwater Extraction for Corn Production in Kansas

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Selected Paper prepared for presentation at the 2018 Agricultural & Applied Economics Association Annual Meeting, Washington, D.C., August 5-August 7

Abstract

This paper exploits the variability in weather variables to explain irrigation water demand. This paper also examines the bias related to use of reference evapotranspiration to measure crop water demand instead of crop evapotranspiration. Using farm-level irrigation water use, we estimated the impacts of climate change on irrigation water demand. The coefficient of reference evapotranspiration is biased toward zero and underestimates the effect of warming on crop water demand. The result shows that irrigation water demand increases as temperature increases. We relax an assumption of cumulative effects from the weather by implementing time separability to understand the impact of warning and pattern of crop water demand. This assumption was tested empirically and the assumption of cumulative effects was rejected. The result shows a different pattern in water demand by corn for different stages of growth. Increases in temperature increase irrigation water demand at emergence and reproductive stage. Our findings show an approximate 3% net increase in irrigation water demand for every $1^{o}C$ increase in daily minimum and maximum temperature. The key result is that farmers are less responsive in increasing crop water requirement as climate changes.

Introduction

The exploitation and use of the Ogallala aquifer in Kansas over the last century has increased the amount of irrigated acreage by over 2.1 million acres between 1960 and 2005 (Rogers et al., 2008). The depletion of the water level in the Ogallala aquifer is due to the withdrawal surpassing the rate at which the aquifer is recharged (Steward et al., 2013). Different sources of irrigation are affected by climate variables, especially with surface and groundwater depending mainly on precipitation for recharge (Kumar and Seethapathi, 2002). Precipitation is the primary source of renewable water supply for the Ogallala aquifer and during seasons of above normal precipitation, the rate of recharge increases while irrigation demand is less. This is sometimes accompanied by lower temperature and solar radiation and higher humidity (Rosenberg et al., 1999). As fluctuation in climate conditions increases, uncertainty and production risk rises. Half of the irrigated acres in Kansas are used in producing irrigated corn, and this drops during drought and low corn price year (Rogers et al., 2008). A shift in timing of peak irrigation demand and increases in temperature lead to corn yield reductions (Woznicki et al., 2015). More than one-quarter of the corn produced in the USA was lost to the drought between 2010 and 2012 (Rippey, 2015).

Over-exploitation and climate change have not led to the reduction of irrigated acreage in Kansas over the years even with the emergence of water saving technology to conserve the aquifer. Crop price and risk preference of a farmer influence their management practice and decision to stay with irrigation schedule or not. When farmer's risk is assumed to be a neutral or down-side risk is ignored, the magnitude and direction of input responses may be wrongly predicted (Groom et al., 2008). For example, extreme weather events have driven the corn price up in the past (Barton and Clark, 2014) and for farmers to benefit from the expected high corn price, farmers may have to produce under constraining water supplies. Corn is a high water use crop producing 19.6 bu./acre of grain for each inch of water used above a threshold of 12.9 inches (Lamm et al., 1995). Crop use water through evapotranspiration and as the climate becomes warmer, crop water demand will increase. Gondim et al. (2012) projected that irrigation water demand will increase by 8-9% by the mid-21st century as evapotranspiration increases between 6.5-8% as result of a projected decrease in precipitation by 11-18%. Climate variability will drive crop water demand, putting stress on the alternative source for precipitation. With the continuous decline of the water level in the aquifer, farmer's response to climate change will depend on the quantity of water available from the aquifer, risk preference, and the price of the crop (Finger, 2012).

This paper exploits the variability in weather variables to explain irrigation water demand and how warming effects of temperature impacts water use (Mieno, 2014). This study also examines the bias related to use of reference evapotranspiration (reference ET) to measure crop water demand instead of crop evapotranspiration because reference evapotranspiration does not consider the crop's growth stages. Waller and Yitayew (2015) defined crop evapotranspiration as a function of both weather (reference ET) and the growth stage of the plant. As climate becomes warmer, more pressure will be exerted on the aquifer as the water level continues to decline and crop water requirement increases. This study also examines the sensitivity of irrigation water demand and schedule at different stages of growth in relation to change in weather variable. This study incorporates time separability by dis-aggregating the total water demand effects from warming at different stages. Ortiz-Bobea and Just (2012) and Tack et al. (2015) implemented time separability using crop yields and degree days at different sub-periods during the growing season to explain weather effects at different periods during production. For example, due to the length of winter wheat and extreme variation in temperature over the duration of production, aggregating warming effects without considering temperature effects during different stages of growth may underestimate warming impacts and yield sensitivity to temperature at different periods in time.

Our findings show that the coefficient on the reference evapotranspiration underestimates the effect of warming on crop water demand. Increase in temperature raises crop water demand as more pressure is exerted on different alternative sources of irrigation to meet the optimal water crop requirement. I relax an assumption in the literature (Schlenker and Roberts, 2009) that weather effect is additive by implementing time separability to understand the impact of warming and precipitation variability during different stages of growth. This assumption was tested empirically and the assumption was rejected. More water is needed by crop during the emergence and reproductive stages of growth while less water is needed by crop at the later stage of growth as the plant has developed enough extensive root to extract water from the soil. Our findings show an approximate 3% net increase in irrigation water demand for every 1^oC increase in daily minimum and maximum temperature. The key result is that farmers are less responsive in increasing crop water requirement as climate changes.

Climate Change and Water Use

Climate change has different impacts on irrigated agriculture. Climate change affects yield through water available to crop (Nelson et al., 2009; Schlenker and Roberts, 2009), recharge of irrigation sources (Rosenberg et al., 1999), agricultural enterprise[1] (Howden et al., 2007; Steward et al., 2013), and irrigation cost (Fischer et al., 2007). There is an extensive literature on the effects of climate change on crop yield (Kang et al., 2009; Schlenker and Roberts, 2009; Tack et al., 2015) because crop yield modeling is purely biophysical. This is different for crop water use as the decision to irrigate depends mainly on farmer's judgments on when and how much water to use (Mieno, 2014). When water need by crop exceeds the water available through effective precipitation, irrigation water is used to supplement precipitation. As precipitation variability changes from one year to another as the climate becomes warmer, the amount of supplementary water used will vary for different spots on the field and time.

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[1] change in agricultural practices from high water use crop to low water use crop enterprise

Water use by crop is through evapotranspiration, which is the combination of evaporation and transpiration occurring simultaneously (Allen et al., 1998). Jensen et al. (1990) defined reference evapotranspiration as the rate at which readily available soil water is vaporized from specified vegetated surfaces. Reference evapotranspiration is often used to estimate actual evapotranspiration in water balance studies (Tao et al., 2015). As defined earlier by Waller and Yitayew (2015), crop evapotranspiration is defined as a function of both weather (reference ET) and the growth stage of the plant (crop coefficient). The ratio between reference ET and crop ET is the crop coefficient, which changes during the season with crop physiological changes (Figure 2). Corn water demand is low at the beginning before rising as more growth and development takes place. Average daily water demand reaches its peak in July and starts diminishing in August (Figure 1).

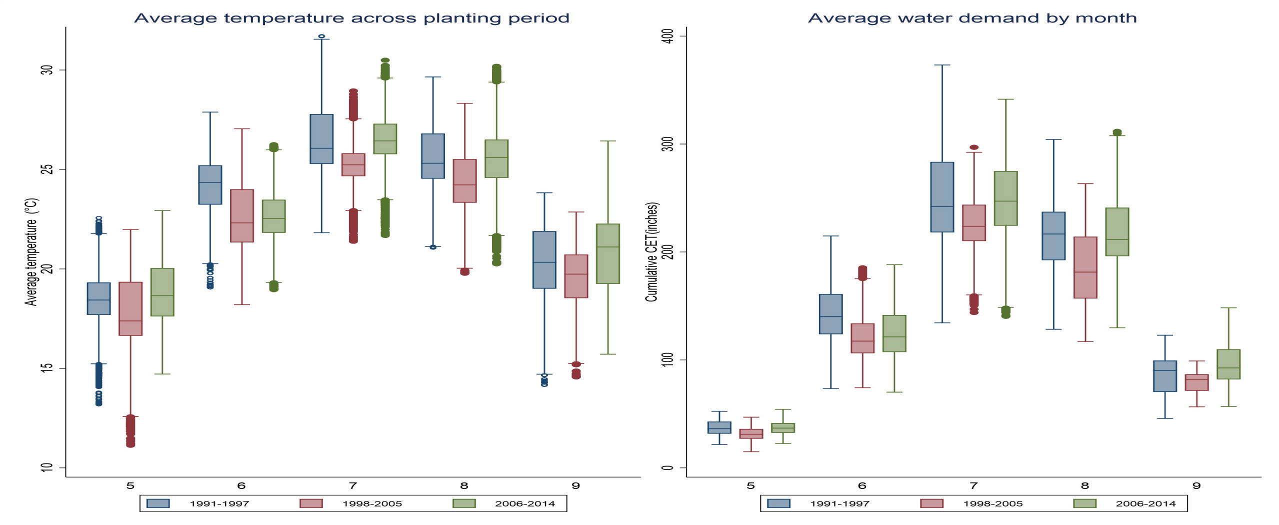

Figure 1: **Average temperature and crop water demand**

According to Allen et al. (2000), there are numerous methods to calculate evapotranspiration. Penman (Penman, 1948), FAO56 Penman-Monteith (Allen et al., 1998) and Modified Penman-Monteith (Doorenbos, 1977) are some of the reference equations used in calculating evapotranspiration. Reference evapotranspiration depends mainly on weather data and a referenced surface of hypothetical grass or alfalfa for computation (Allen et al., 1998; Walter et al., 2001) without considering the stages of growth of the crop (Figure 2). Different studies (Espadafor et al., 2011; Lu et al., 2005) have compared some of these reference equations. Lu et al. (2005) found that potential evapotranspiration values from different methods were significantly different from each other where greater differences were found among the temperature based potential evapotranspiration methods than radiation based potential evapotranspiration methods. Kite and Droogers (2000) compared evapotranspiration estimates from satellites, hydrological models and field data where the result shows that satellite methods and FAO-24 (Allen and Pruitt, 1991) methods have the greatest variability and while the FAO-56 models and the field methods show more consistency.

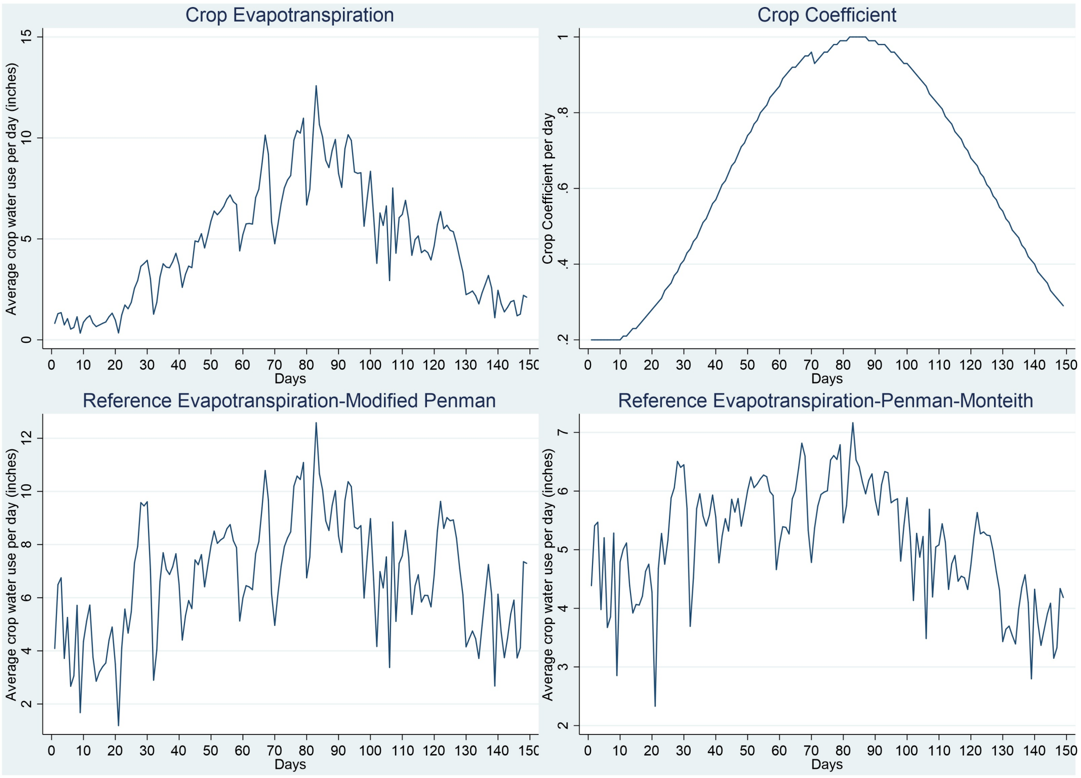

Figure 2: **Crop water demand and crop coefficient for the year 2002**

Climate affects evapotranspiration (Allen et al., 1998; Hess, 1998; Yu et al., 2002). The global average surface temperature has increased by about 0.6^{o}C over the 20th centuryHoughton et al. (2001). For example, the drought of 2011 in the Great Plains is a result of high temperature and low precipitation. This extreme conditions resulted in high crop water demand (Figure 3) and yield loss (Rippey, 2015). Espadafor et al. (2011) reported a statistically significant increase in reference evapotranspiration trend over the past 45 years in the Southern Spain due to increases in air temperature and solar radiation and decreases in relative humidity. Increasing temperature increases the rate of evapotranspiration while other factors such as increasing humidity may reduce the rate of transpiration (Snyder et al., 2011). Other factors that affect evapotranspiration (ET) are solar radiation reaching the soil surface, wind speed, and direction (Allen et al., 1998; Snyder et al., 2011).

Climate change effects on evapotranspiration across different locations have provided mixed results. Bandyopadhyay et al. (2009) studied the temporal trend of grass reference evapotranspiration in India to determine the existence and magnitude of any statistically significant trend over the time. They found a decreasing trend in grass reference evapotranspiration because of a significant increase in the relative humidity and a consistent significant decrease in the wind speed throughout the country. Irmak et al. (2012) found a similar result in Platte River Basin, Central Nebraska-USA where they observed a significant decline in estimated evapotranspiration which differs from Espadafor et al. (2011)'s result. Tang et al. (2011) did an attribution analysis to quantify the contribution of each input variable to reference evapotranspiration. The result is consistent with Irmak et al. (2012) and Bandyopadhyay et al. (2009) but Bandyopadhyay et al. (2009) found changes in air temperature to produce a large increase in the differential of reference evapotranspiration over time.

Water Demand Estimation

Majority of the existing economic studies focus mainly on the impacts of price elasticity of water (Hendricks and Peterson, 2012; Pfeiffer and Lin, 2013; Schoengold et al., 2006) based on variation in energy price or pumping cost with little to less attention at the influence of climate change (Mieno, 2014; Oehninger et al., 2016) on the crop water demand and how it affects crop choice and acreage allocation. Many of these previous studies of agricultural water demand equations depend on linear programming techniques (Scheierling et al., 2004), simulated data (Döll, 2002; Mieno, 2014) and self-reported irrigation data by farmers (Hendricks and Peterson, 2012; Oehninger et al., 2016; Pfeiffer and Lin, 2013).

Döll (2002) used a global irrigation model to compute how average irrigation water requirements may change under different climate conditions. The result shows that two-thirds of the global area equipped for irrigation in 1995 will possibly suffer from increased water requirements, and on up to half of the total area (depending on the measure of variability), the negative impact of climate change is more significant than that of climate variability. As water availability and requirements change due to climate change, water use by farmers will likely change as uncertainty and risk affect agriculture production (Moschini and Hennessy, 2001).

As stated by Mieno, 2014, LPJmL, EPIC, and pDSSAT are some of the existing models that incorporate mechanical irrigation practices, but may not effective in reflecting actual farmer's behavior due to lack of complete information about soil moisture condition. Apart from this shortfall, simulation to predict actual irrigation water use may be under or overestimated due to variability in precipitation received from one year to another (Guerra et al., 2005). Mieno (2014) used an econometric approach to explain a functional relationship between climatic conditions and irrigation water use, in which farmers' behavioral aspects are embedded implicitly. The study captured the daily nonlinear impacts of climate variability on water use by using Aquacrop (Steduto et al., 2009) to calculate corn evapotranspiration based on synthesized data. AquaCrop is a simulation-based model using real data for calibration. The result shows that hypothetical farmer programmed in AquaCrop is still more responsive to changes in climate than actual farmers.

Schoengold et al. (2006) estimated the price elasticity of irrigation water demand by decomposing the price elasticity into the direct effect of water management and indirect effect of water price on the choice of output and irrigation technology. The study used predicted values of land allocation and irrigation technology choice as instrumental variables to account for the endogeneity of technology and output choices in water demand equation. Although the study did not exploit the variability in weather variables, the study used annual and sectional average temperatures to account for the change in time and space. The result shows that the average temperature moves water use in the opposite directions. Increase in section temperature by 1^{o}C will decrease water demand by $20410^{3}m^{3}$. The direct elasticity is 0.415 which is higher than any of the estimates from contemporary econometric studies.

Hendricks and Peterson (2012) differs from Schoengold et al. (2006) by using fixed effect estimation instead of instrument variable to account for endogeneity and remove omitted variable bias when exploiting the variability in pumping cost over time to calculate the cost of reducing irrigation water use through water pricing, irrigation cessation, and intensity-reduction programs. The study estimate irrigation water demand using field level panel data from Kansas and district-level weather variables as a proxy for the farm level weather data. Reference evapotranspiration (alfalfa based) was used to capture crop water use. The crop water demand and water use move in the same direction. The estimated coefficient of crop water demand (evapotranspiration) is 0.07 which implies that water use will increases by 7% as crop water demand increase by 1 unit. However, little variability is left as the study used time fixed effect that absorbs most of the variability in precipitation and evapotranspiration across years. There is also attenuation bias due to measurement error with the use district-level data.

Pfeiffer and Lin (2013) built on Hendricks and Peterson (2012) to examine the effects of energy prices on groundwater extraction using an econometric model of a farmer's irrigation water pumping decision. The study used average yearly precipitation and evapotranspiration to account for the environmental effects in the water demand equation. Apart from the endogeneity issue, the coefficients of average precipitation and evapotranspiration were significant and inversely related to the water use. This result is different from Hendricks and Peterson (2012) as the coefficient of average evapotranspiration is -6.832 which implies that irrigation water use decreases by 6.832 acre-feet as evapotranspiration increases by 1 inch. The result also shows that irrigation water decreases as average yearly precipitation increases.

Oehninger et al. (2016) analyzed the effects of climate change on groundwater extraction for agriculture using an econometric model of a farmers irrigation water pumping decision that accounts for both the intensive margin (water use) and the extensive margins (crop acreage, whether to plant multiple crops and irrigation technology).The water use equation used average temperature and precipitation from past 3 years, a fraction of days with extreme temperature, precipitation, and humidity between January and April. The result shows that average temperature over the last 3 years increase water use while an increase in precipitation increases water use during the growing season.

In some of the empirical analyses, reference evapotranspiration is poorly estimated and used in climate change studies due to lack of necessary climate data or use of alternate based parameter like radiation and temperature (Irmak et al., 2012). For example, the structure of Oehninger et al. (2016)'s paper raised some question with the use of average evapotranspiration as one of the control variables for humidity and temperature. Evapotranspiration affects water use directly and temperature and humidity are parts of the components used in estimating evapotranspiration. Apart from using evapotranspiration as a control variable, the study used extreme temperature during offseason (January-April) to explain water use by corn during the growing season possibly between April-September. The intensive margin calculated is biased as climate effect through evapotranspiration is not included.

Our paper addressed some of the error related to the measure and use of reference evapotranspiration to capture crop water use by using reference evapotranspiration estimated by Modified Penman equation (Doorenbos, 1977) and crop coefficient (Kincaid and Heerman, 1974) to calculate crop evapotranspiration. According to Abtew and Melesse (2013), use of crop evapotranspiration is constrained by the availability of local crop coefficient. According to Lamm et al. (2007), Modified Penman equation method has been proven acceptable for Northwest Kansas. As reported by Lamm et al. (2007), a two-year comparison of this method to the ASCE standardized reference evapotranspiration equation which is based on FAO-56 (Allen et al., 1998) showed that the Modified-Penman values are approximately 1.5% to 2.8% lower. The Modified Penman method was considered to offer the best results with a minimum possible error in relation to a living grass reference crop (Allen et al., 1998). Schoengold et al. (2006) and Hendricks and Peterson (2012) provided an empirical structure for controlling endogeneity of land use either through fixed effect or instrument variable.

Data

Data about water use on each irrigated field, type of crop grown and irrigated area, and the delivery system will be obtained from the Water Information Management and Analysis System of the Kansas Department of Agriculture from 1991-2014. Daily weather information from PRISM[2] will be used to calculate the reference evapotranspiration based on grass using the Modified Penman equation (Doorenbos, 1977). The Modified Penman method was considered to offer the best results with a minimum possible error in relation to a living grass reference crop (Allen et al., 1998). Crop-specific coefficient based on Kincaid and Heerman (1974) is used to adjust crop water use at different stages of growth. Precipitation received during the growing season (May-September) will be used.

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[2] PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu

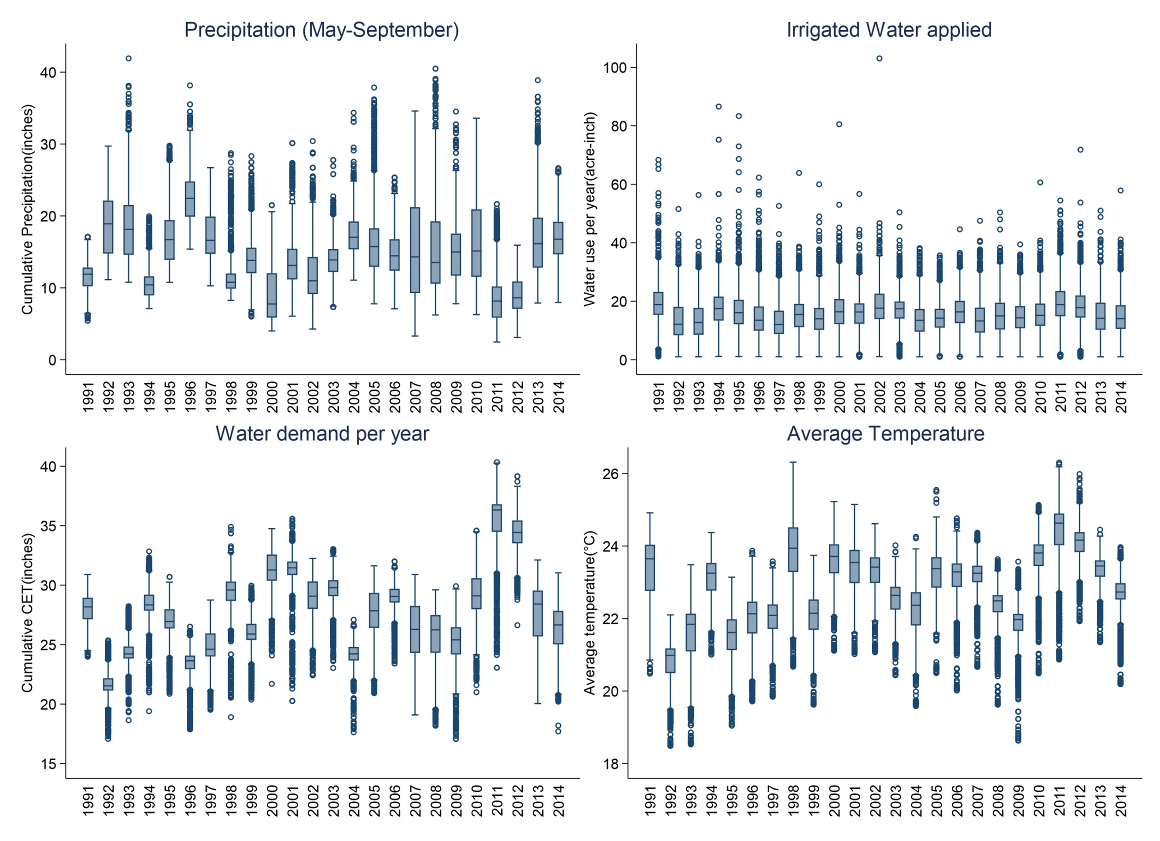

Figure 3: **Annual box-plots showing distribution and variability of water and weather variables over time**. The county and field measures were used to construct boxplots for each year. Each box is defined by the upper and lower quartile, with the median depicted as a horizontal line within the box. The endpoints for the whiskers are the upper and lower adjacent values, which are defined as the relevant quartile +/- three-halves of the interquartile range, and circles represent data points outside of the adjacent values.

Precipitation data at the district level are used as a proxy for the actual precipitation at each field. Estimate from precipitation may have attenuation bias due to measurement error. Information about root zone available water storage (rootznaws) is obtained from Web Soil Survey of the USDA Natural Resources Conservation Service. Figure 2 shows the distribution of precipitation (inches), average temperature(^oC), irrigation water demand (inches), and irrigation water applied (inches) by farmers for corn production across different counties in Kansas. Future corn prices are obtained from the CME Group. The summary statistics for different variables used in the analysis are presented in Table 1.

Table 1: Summary Statistics of all Variables

Variable	Obs	Mean	Std Dev.	Min	Max
Water related data					
Applied water per acre(inches)	103,763	15.521	6.509	1.000	103.059
Area Irrigated (acres)	103,763	127.215	64.049	1.000	3320.000
Soil related variable					
Root zone available water storage (inches)	103,763	9.525	2.039	1.539	13.189
Weather related data					
Precipitation (Inches)	103,763	14.538	5.276	2.461	41.921
Crop Evapotranspiration (Inches)	103,763	27.912	3.731	17.074	40.337
Reference Evapotranspiration (Inches)	103,763	40.388	5.162	25.367	57.155
Economic related variables					
Corn price	24	3.428	1.269	2.224	6.428

The weather variables are calculated between May and August of each year.

Econometric Model

This paper econometric specification differs from Mieno (2014) as a linear relationship between weather variables and irrigation water use are considered. Mieno (2014) used a nonparametric econometric approach to explain a functional relationship between climatic conditions and irrigation water use, in which farmers' behavioral aspects are embedded implicitly. This study differs from previous studies (Mieno and Brozović, 2016; Oehninger et al., 2016) that used temperature, degree days, and reference evapotranspiration(r.ET) instead of crop evapotranspiration (c.ET) to measure weather effects on water use. Warming impacts estimated with reference evapotranspiration will be biased toward zero even with fixed effect (Mieno and Brozović, 2016) as reference evapotranspiration does not account for crop water demand at different stages of growth. Crop evapotranspiration is defined by equation 1. K_{cd} is the corn crop coefficient at day d which is assumed constant over time and across Counties in Kansas.

$$c.ET_{it} = \sum_{d=1}^{149} (K_{cd} \times r.ET_{idt}) \tag{1}$$

Assume a water use model is defined as $W_{it} = \gamma_1 c.ET_{it} + \varepsilon_{it}$ with ε_{it} as the error term. If this model is estimated with reference evapotranspiration ($r.ET_{it}$) instead of crop evapotranspiration($c.ET_{it}$), assuming that the error related to omitted crop coefficient is additive, then;

$$c.ET_{it} = r.ET_{it} + \phi_{it} \tag{2}$$

the model becomes $W_{it} = \gamma_1 c.ET_{it} + \mu_{it}$. where $\mu_{it} = \varepsilon_{it} - \gamma_1 \phi_{it}$

$$\widehat{\gamma_1} = \frac{cov(\gamma_1 c.ET_{it} + \mu_{it}, c.ET_{it})}{var(c.ET_{it})} \tag{3}$$

$$\widehat{\gamma_1} = \gamma_1 \left(1 - \frac{cov(c.ET_{it}, \phi_{it})}{var(c.ET_{it})} \right) \tag{4}$$

$cov(c.ET_{it}, \varepsilon_{it}) = 0$, and $cov(c.ET_{it}, \mu_{it}) \neq 0$ as there is correlation between $c.ET_{it}$ and ϕ_{it}

$$\mathbf{E}(\widehat{\gamma_1}) = \gamma_1 \mathbf{E} \left(\frac{\sigma^2_{r.ET}}{\sigma^2_{r.ET} + \sigma^2_{\phi}} \right) \tag{5}$$

$$\widehat{\gamma_1} = \gamma_1 \lambda \tag{6}$$

where λ is the ratio of the variances which is $0 < \lambda < 1$. $\widehat{\gamma_1}$ will be biased toward zero. This shows that estimation with reference evapotranspiration is biased downward toward zero.

Since farmer's response to climate variability is assumed linear, irrigation water use "W_{it}" can be expressed as;

$$W_{it} = \alpha_i + \tau(t) + \beta Cprice_t + \sum_{s=1}^{3} \gamma_s c.ET_{ist} + \sum_{s=1}^{3} \lambda_{1s} Prec_{ist} + \sum_{s=1}^{3} \lambda_{2s} Prec^2_{ist} + \Gamma_{it} + \varepsilon_{it} \tag{7}$$

where W_{it} is the irrigation water applied to supplement precipitation, and it is expressed as a function of crop water demand. $c.ET_{it}$ and $Prec_{it}$ represent the crop evapotranspiration and precipitation respectively. $\tau(t)$ is the quadratic time trend, α_i is the county fixed effect to control for time-invariant heterogeneity and ε_{it} is the residual clustered at the point of diversion. Γ_{it} represents root zone available water storage (rootznaws) that serve as a control variable that may affect crop water use and groundwater extraction. $Cprice_t$ represents the corn price to capture farmer's response in relation to price to be paid for their produce. The corn growth period is divided into 3 different stages (Figure 5) based on details from Kranz et al. (2008) where crop water demand during different periods of corn growth was considered. The first stage is the period between the VE and V12 (emergence), while the second stage is the period between early tassel (R1) and full dent (R5.5) and the last stage is the maturity growth stage (R6) (Figure 4). Equation 8 is used to estimate the total water demand without time separability. This model will be used to compare crop water demand while using crop and reference evapotranspiration as a variable of interest.

$$W_{it} = \alpha_i + \tau(t) + \beta Cprice_t + \gamma cET_{it} + \lambda_1 Prec_{it} + \lambda_2 Prec^2_{it} + \Gamma_{it} + \varepsilon_{it} \tag{8}$$

The marginal impact of warming on irrigated water used will be simulated for each 1^oC increase in temperature up to 5^oC by increasing the observed daily maximum and minimum temperatures and then recalculating the appropriate weather variables for the whole growing season. Simulated impacts are obtained by multiplying estimated parameters by the projected mean climate change on the c.ET.

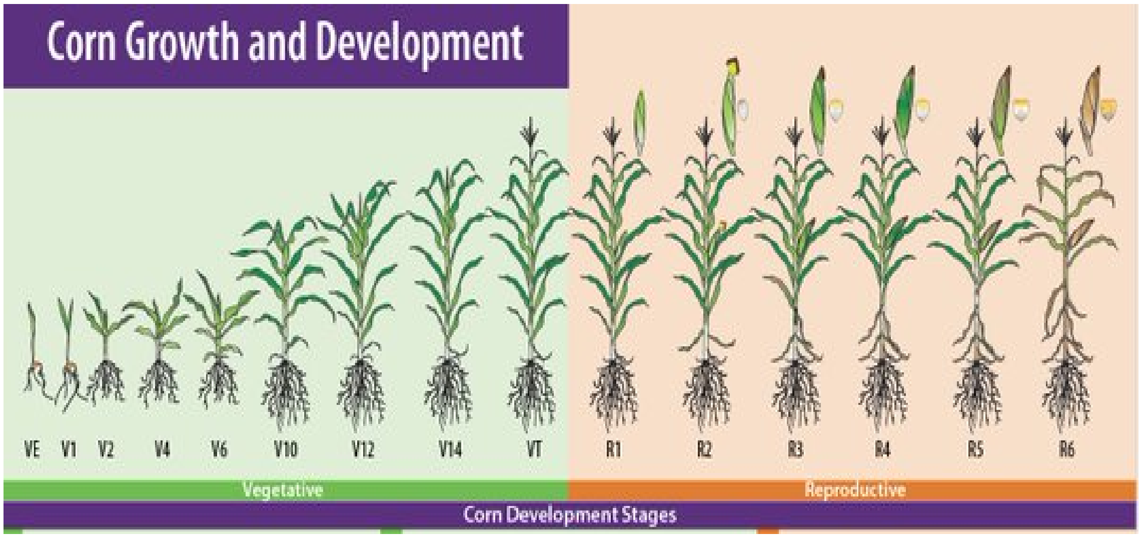

Figure 4: **Corn growth and development chart** adapted from by Ciampitti, I.A., R. Elmore, and J. Lauer.

Results and Discussion

The result from equation 7 is shown in Table 2. The effects of crop evapotranspiration differ for each of the stages as the F-statistic (688.93) against the null hypothesis that the warming impacts from the three stages are the same are rejected. One of the major points from the result is that crop water use is significant for all the stages and positive only for the first two stages. Crop water demand and precipitation during the third stage are the least responsive of all the 3 stages. This result is strengthened with Figure 6 when estimates from equation 7 and the simulated mean change in c.ET is used to show the impact of weather at different stages of growth. Figure 5 shows the importance of time separability in measuring weather effects on irrigation water use by showing the mechanism through which weather impacts crop water demand at different stages of growth (Figure 6). The estimated relationship changes somewhat, but in different directions after the first two stages. The projected impact shows that increase in temperature does not increase irrigation water use during the later stage of the growth (Figure 6). This is different for the first 2 stages of growth where water use demand increase as the temperature increases from 1^oC to 5^oC (Figure 6) but not at the rate the temperature increases.

According to Barnabás et al. (2008), plant reproduction greatly depends on an adequate supply of photosynthetic products where water shortage during this period results in the inhibition of the photosynthesis process, and reduction in the nutrient supply to the generative organs. The authors also stated that water stress during flower induction and inflorescence development leads to a delay in flowering (anthesis), or even to complete inhibition. As more supplementary water is needed in the first two stages as temperature increases, less to no water is needed in the later stage. There is a net increase of 1.7% in irrigation water demand for every 1^oC increase in daily minimum and maximum temperature during the first stage (VE-V12) compared to a net increase of 2 % in stage 2 (R1-Full

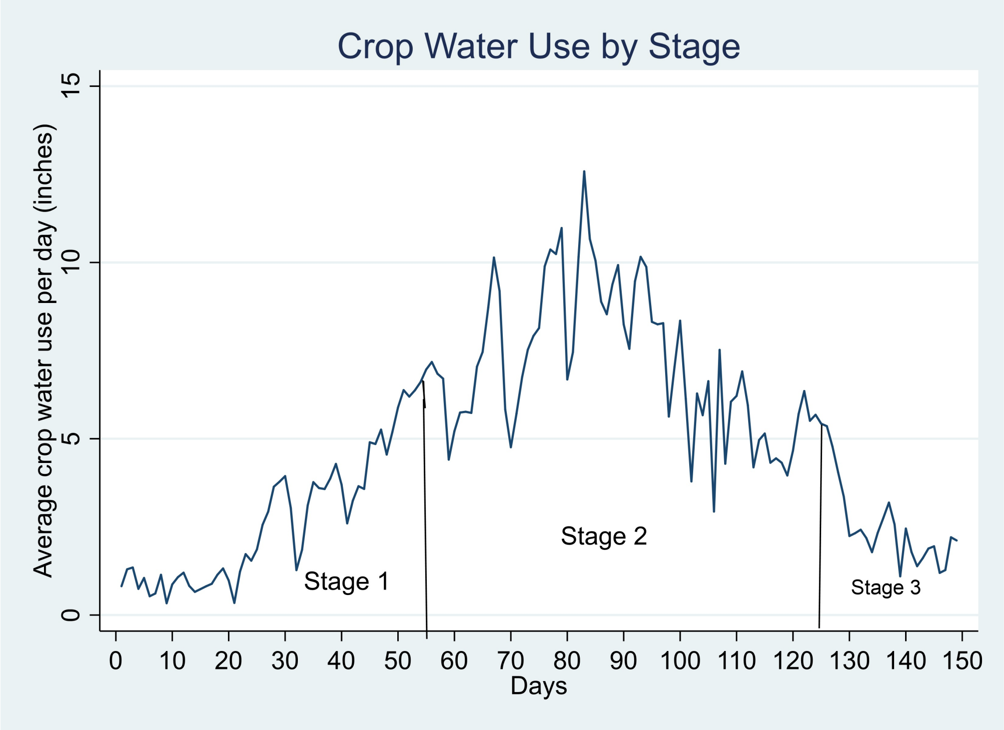

Figure 5: **Graph shows crop water use by stages**. Stage 1 is between day 1 and day 55, stage 2 is between day 56 and day 125 and stage 3 is 125 days above. Corn growth stages are divided based on details from to Kranz et al. (2008). Crop water demand was calculated under each stage

dent) as more water is needed by corn during the reproductive stage (stage 2). Net water demand during the third stage is reduced by 1% for every 1^oC increase in temperature as the plant can withdraw water from the soil without affecting the grain. Crop water demand drops as the crop reaches the final stage of growth (Kranz et al., 2008). At this stage, corn has developed an extensive root and water nearly needs goes to zero (Mieno, 2014).

Parameter estimates from different specifications without time separability (equation 8) are reported in Table 3. The result shows the difference between water demand estimation using crop evapotranspiration (c.ET) and reference evapotranspiration (r.ET). Our estimate on crop evapotranspiration is 0.302 which is higher than estimates from previous studies using reference evapotranspiration (Hendricks and Peterson, 2012; Pfeiffer and Lin, 2013). Using the c.ET model, a 1-inch increase in crop water demand will increase irrigation water use by 0.3 inches. The result is also supported by Figure 7 that shows how temperature increase by 1^oC results in a 3% increase in irrigation water applied. Climate change projection using reference evapotranspiration will underestimate the warming effects of temperature as shown in Figure 7. The key result is that a 1 inch increase in crop ET does not result in a 1 inch increase in water use. This shows that farmers are less responsive to increasing irrigation water when there is a weather shock or not responding as irrigation schedule would predict.

Table 2: Water Demand Estimation Result-Time separability Model

Estimates	Crop ET Model
Precipitation (Stage 1)	-0.196***
	(0.023)
Precipitation squared (Stage 1)	-0.003
	(0.001)
Precipitation (Stage 2)	-.224**
	(0.025)
Precipitation squared (Stage 2)	-0.003
	(0.012)
Precipitation (Stage 3)	-0.256*
	(0.033)
Precipitation squared (Stage 3)	-0.022*
	(0.005)
c.ET (Stage 1)	0.827***
	(0.039)
c.ET (Stage 2)	0.274***
	(0.009)
c.ET (Stage 3)	-1.072***
	(0.039)
Root zone available water	-0.397***
	(0.022)
Corn Price	-0.25***
	(0.025)
Observations	103,763
R-squared	0.3349
County Fixed effect	Yes
Trend	Yes
Quadratic Trend	Yes

Note: The dependent variable is the total water applied measured in acre-inches. Figures in the parenthesis are standard errors clustered by the point of diversion. *, ** and *** indicate significance at 10, 5, and 1 percent levels.

Using the estimated parameters from equation 8 and the simulated projected mean change in the c.ET, the result shows an approximate 3% net increase in irrigation water demand for every 1^oC increase in daily minimum and maximum temperature. Gondim et al. (2012) projected an increase in irrigation water needs due to increase in temperature and reduced precipitation. As temperature increases, more irrigation water is needed to meet crop water demand. The result also shows that 1-inch increase in precipitation will reduce irrigation water demand by 0.15 inches. Offsetting the warming effects from the interaction between precipitation and temperature will depend on the timing and the

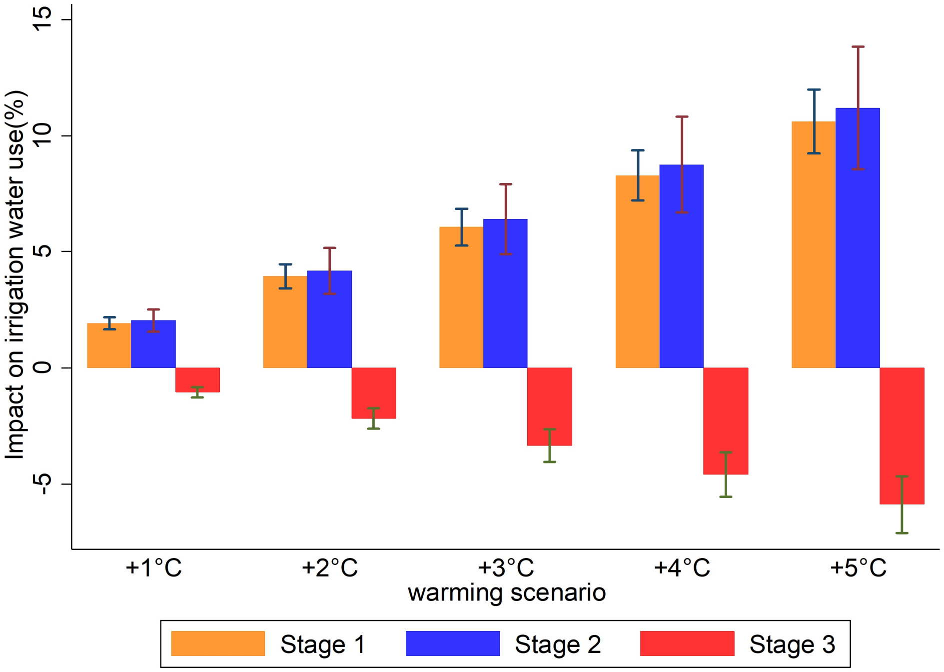

Figure 6: **Graph shows the predicted impact of warming on irrigation water use as the daily minimum and maximum temperatures are increased by 1^oC up to 5^oC.** Corn growth stages are based on days from Kranz et al. (2008). Crop water demand was calculated for each stage to model the effect of warming. The bars show the warming impact on water use for each of the scenario. Bars show 95% confidence intervals using standard error clustered by the point of diversion.

amount of precipitation received as crop water demand reduces as precipitation increases.

Table 3: Water Demand Estimation Results

Estimates	Crop ET Model	Reference ET Model
Precipitation	-0.151***	-0.179***
	(0.017)	(0.017)
Precipitation squared	-0.001**	-0.001**
	(0.000)	(0.000)
c.ET	0.302***	
	(0.000)	
r.ET		0.189***
		(0.006)
Root zone available water	-0.395***	-0.395***
	(0.024)	(0.022)
Corn Price	0.081***	0.158***
	(0.023)	(0.002)
Observations	103,763	103,763
R-squared	0.3341	0.3231
County Fixed effect	Yes	Yes
Trend	Yes	Yes
Quadratic Trend	Yes	Yes

Note: The dependent variable is the total water applied measured in acre-inches. Figures in the parenthesis are standard errors clustered by the point of diversion. *, ** and *** indicate significance at 10, 5, and 1 percent levels.

Conclusion

In this paper, we exploit the variability in weather variables to explain irrigation water demand and also examines the bias related to use of reference evapotranspiration to measure crop water demand instead of crop evapotranspiration. Inaccurate measurement of these warming effects will underestimate the climate change impacts projections on groundwater extraction. More water is needed by crop during the emergence and reproductive stages of growth while less water is needed by crop at the later stage of growth as the plant has developed enough extensive root to extract water from the soil. Our findings show an approximate 3% net increase in irrigation water demand for every $1^{o}C$ increase in daily minimum and maximum temperature. The key result is that farmers are less responsive in increasing crop water requirement as climate changes. The study also shows the importance of time separability in measuring weather impacts as a response during different stages of growth are different.

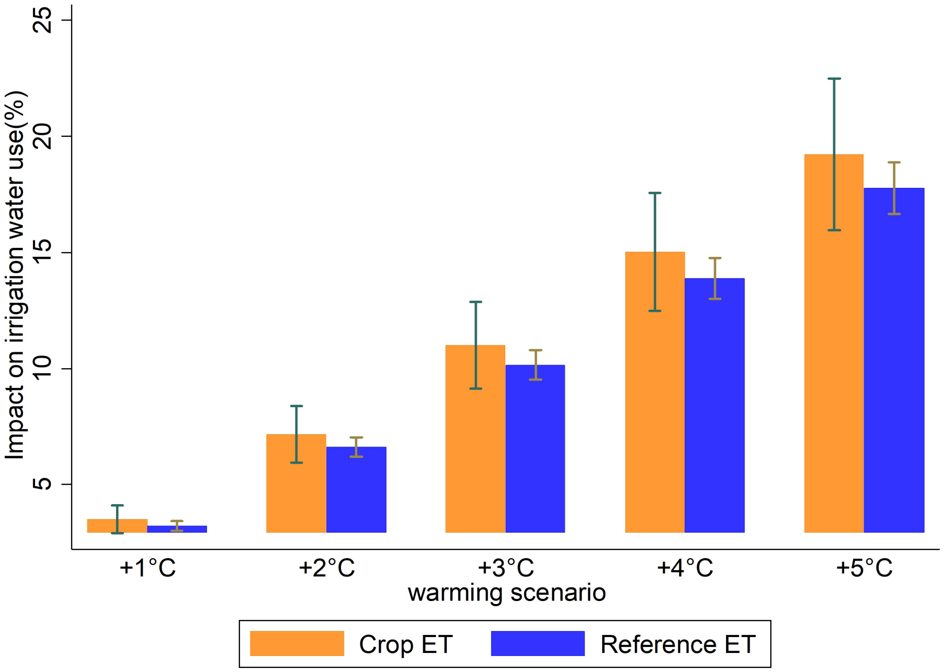

Figure 7: **Graph shows the predicted of warming on corn water use demand as the daily minimum and maximum temperatures are increased by 1^oC up to 5^oC.** Crop water demand was calculated under each scenario for each method to model the effect of warming on irrigation water demand. The bars show the warming impact on water use for each of the scenario. Bars show 95% confidence intervals using standard error clustered by the point of diversion.

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