# The Value of Water in GMD 5

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## Executive Summary

This report provides estimates of the economic value of irrigation water in GMD 5. These estimates provide an understanding of the overall value of irrigation to the district and also provide estimates of the impact of restrictions in water use.

*Total Value of Irrigation*

Chapters 1 and 2 provide estimates of the total value of irrigation. In other words, these chapters estimate the impact if irrigation had never been available in GMD 5. Chapter 1 estimates the impact on land values by using historical transaction data of irrigated and nonirrigated parcels to estimate the additional land value due to a parcel being irrigated. We find that irrigation increased agricultural land values in GMD 5 by $1.44 billion in 2015. For those parcels that are irrigated, the ability to irrigate provides a 73% premium to the land price on average. The magnitude of the premium varies substantially across the district.

Chapter 2 estimates the economic spillover of irrigation to the livestock and agribusiness sectors. We use regression analysis to compare outcomes in counties overlying the High Plains Aquifer to counties just outside the aquifer while controlling for differences in soils and climate. We estimate the average impact per 100 feet of saturated thickness across the aquifer and apply those estimates to the soils and climate of Kansas counties. We find that in Kansas, the long run impact of losing the aquifer would decrease total animal sales by 28.9%, cattle on feed by 63.2%, fertilizer expenditures by 20.0%, chemical expenditures by 15.2%, and farm operating expenditures by 20.2%. Table 1 shows statistics for the total economic activity in GMD 5. Applying the percentage impacts for Kansas to these statistics for GMD 5, we find that in the long run losing irrigation in GMD 5 would annually decrease animal sales by $236 million, cattle on feed sold for slaughter by 213,200 head, fertilizer expenditures by $22.6 million, chemical expenditures by $10.7 million, and total farm operating expenditures by $259.8 million. It is important to note that these represent the impact of losing irrigation in the *long run* because the estimates

**Table 1. Livestock and Agribusiness Statistics for GMD 5 from the 2012 Census of Agriculture**

| | GMD 5 Total |
|---|---|
| **Sales from Animals** | $817.2 million |
| **Cattle on Feed Sold** | 337,300 head |
| **Hogs Sold** | $96.2 million |
| **Milk Sales** | $2.4 million |
| **Fertilizer Expenditures** | $112.9 million |
| **Chemical Expenditures** | $70.5 million |
| **Farm Operating Expenditures** | $1,286.2 million |

compare outcomes in counties with irrigation from the aquifer and those that never had irrigation from the aquifer. We discuss the impact in the short run in the next section of the executive summary.

*Impact of Water Use Restrictions*

The impact of partial reductions in water use are not necessarily equal to the proportional impact on the total value of irrigation. In other words, a 15% reduction in water use would not necessarily reduce the value of irrigation by 15% of the total value. Economists refer to this as the difference between marginal and average value. Chapter 3 provides insights to the economic impact of restrictions to water use, and therefore estimates the marginal value of irrigation. Our analysis in chapter 3 is necessarily an *ex ante* analysis because significant restrictions on water use have not been previously imposed in GMD 5 and the economic impact in GMD 5 with predominantly sandy soils is likely to differ from other regions of Kansas with silt loam soils.

We calibrate a state-of-the-art crop simulation model (DSSAT) to experimental data from Southwest Kansas and apply the calibrated model to a Pratt loamy fine sand with historical weather data from St. John. The crop simulation model is used to predict yields under alternate soil moisture targets with 30 years of historical weather data. Selecting a larger soil moisture target means that the farmer triggers irrigation more frequently and thus applies more water on average. The simulated relationship between soil moisture target, water use, and yields are then incorporated into an economic model that determines the irrigation strategy that maximizes expected net returns over the 30 years of historical weather. Our economic model accounts for the fact that farmers can reduce water use by either applying water to the same irrigated acreage or by reducing irrigated acreage. We find that corn yields are highly responsive to the amount of water applied up to a certain point and then yields plateau with additional water applied. Therefore, economic impacts can be small if the restriction allows water use to continue above the point where the yield curve plateaus. But if the restriction is large enough that water use is below the plateau, then economic impacts will be much larger, and many farmers will likely find it optimal to reduce irrigated acres in response to the restriction. They may reduce irrigated acres by only irrigating a portion of their current center pivot, by not irrigating in some of the years of the allocation period, or by pooling together an allocation across multiple fields and converting a field to nonirrigated.

We estimate the impact of a 15% reduction in water use and a 30% reduction in water use using our model. One challenge is that our model predicts a larger optimal water use than the historical water use in the region, so the impact depends on whether we calculate the percent reduction from the model's optimal use or the observed historical use as the baseline. We calculate the economic impact using both baselines to create upper and lower bounds of the likely economic impact. We find that a 15% reduction in water use would decrease returns by $7.30/acre using the model's baseline water use or $27.80/acre using historical baseline water use. A 30% reduction in water use would decrease returns by $27.80/acre using the model's baseline water use or $40.33/acre using historical baseline water use.

Another way to reduce water use is to retire some fields from irrigation. If these retirements were mandated, then the present value of the economic impact on the farmer can be estimated as the difference between the land value of irrigated versus nonirrigated. The economic impact of water right retirements is provided by our regression model of land values. One important point is that the value of irrigation differs substantially across GMD 5. The blue points in figure 1 are predicted to have a greater premium in land value due to the ability to irrigate. Therefore, the economic impact of water right retirement will be larger in darker blue areas.

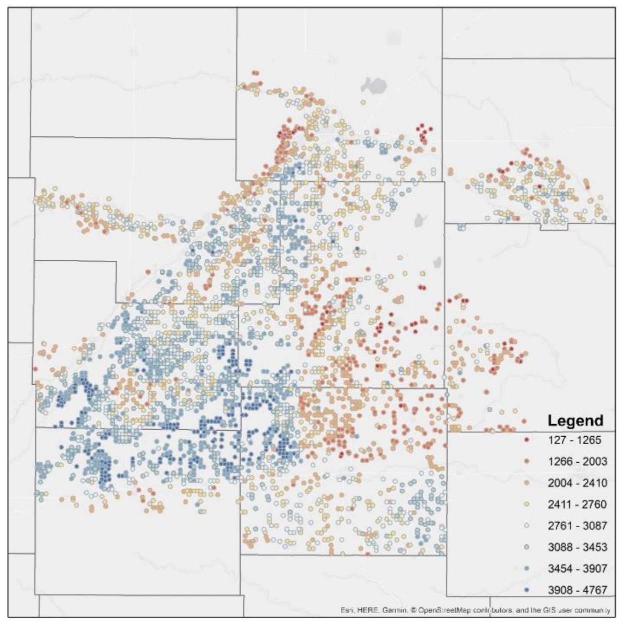


**Figure 1. Premium for irrigated versus nonirrigated land ($/acre) in 2015 for GMD 5**

Estimating the impact of water use restriction on the livestock and agribusiness sectors is more challenging. Restrictions to water use will likely cause reductions in crop input expenditures, but the impact of a 15% reduction in water use is likely to be smaller than 15% of the total impact of irrigation on input expenditures. A reduction in water use is also not likely to have a proportional impact on the livestock sector. Livestock producers have sunk costs of infrastructure in the district and may not move out of the district if the reduction in crop production is small. However, the cost of purchasing grain for feed will increase for livestock producers as the basis will strengthen due to loss of local production.

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# Chapter 1. The Impact of Irrigation on Agricultural Land Values in GMD 5

Nathan P. Hendricks and Mykel R. Taylor

## Highlights

- Irrigation increased agricultural land values in GMD 5 by $1.44 billion in 2015.
- Irrigated land received approximately a 73% premium relative to nonirrigated land in 2015.
- Irrigation has become more valuable since 1988 in both absolute and relative terms.
- The value of irrigation (i.e., the difference between irrigated and nonirrigated land values) varies significantly across GMD 5. Therefore, the economic impact of any potential restriction on water use depends on where the restriction is imposed.
- The value of irrigation is largest in areas with lower nonirrigated productivity.

## Data

We assembled data on agricultural land sales from the Property Valuation Division (PVD) of the Kansas Department of Revenue from 1988 to 2015. The PVD data record sales data for every agricultural land transaction in Kansas. We restrict our analysis to those sales that are considered arms-length transactions as these transactions should accurately reflect the market value of the land. We also restrict our analysis to parcels of land lying within the boundaries of GMD 5. Parcels with greater than 25% of the area in grass were excluded. We also only include parcels that either had no irrigated area or greater than 70% of the parcel was irrigated. We consider a parcel irrigated if greater than 70% was irrigated.

*Land Sale Variables*

The PVD data provide information on the total amount of the sale and an estimate of the dollar amount of improvements on the land (e.g., a house, buildings, etc.). PVD also provides information on the acres of the parcel that are dryland, irrigated, grass, and homestead. We calculate the price per acre of agricultural land as the total dollar amount of the sale minus the dollar amount of improvements divided by agricultural acres (i.e., dryland plus irrigated plus grass). For our regression analysis we convert the price per acre into a real price per acre (2015 dollars) using the consumer price index.

*Soil and Weather*

The PVD data also contains information on the area of the parcel with different types of soils. We merge information on the characteristics of each soil type using the Soil Survey Geographic Database (SSURGO) collected by the Natural Resources Conservation Service (NRCS). These are the same data which can be viewed using Web Soil Survey online (https://websoilsurvey.sc.egov.usda.gov). We are then able to calculate average soil characteristics for each parcel. SSURGO contains a large number of soil characteristics and often different soil characteristics are highly correlated with each other. In our work, we have focused on the NCCPI (National Commodity Crop Productivity Index) for nonirrigated corn and soybeans and the slope of the parcel. The NCCPI is a rating of the potential productivity of the land to produce nonirrigated corn and soybeans. NCCPI accounts for both the soils and climate characteristics. The NCCPI is an index that ranges from 0 to 1.

High-resolution weather data were obtained from PRISM Climate Group (*http://prism.oregonstate.edu/*). PRISM contain information on daily precipitation, minimum temperature and maximum temperature at a resolution of roughly 2.5 miles x 2.5 miles from 1981 to 2014. We merge the PRISM data to the parcel according to the parcel's section.

*Water Rights*

Unfortunately, the PVD data do not list the water right numbers associated with the sale. The PVD data do provide a GIS coordinate for the parcel and the acres of the parcel (PVD does not provide a precise boundary for the parcel). We create a square area surrounding the GIS coordinate for the parcel and find any water rights that are authorized to irrigate within this area and associate those water rights with the parcel. We use data in our regression analysis on the quantity authorized or irrigation (inches/acre) and the priority date of the water right.

*Hydrology*

We also identify characteristics of the aquifer underlying the parcel. Aquifer characteristics are spatially interpolated by Kansas Geological Survey to the section-level from monitoring well data. This provides data on the saturated thickness of the aquifer and the depth to water. We also collected data on the salinity level of the aquifer. There are portions of GMD 5 where the chloride levels in the aquifer are high and affect irrigation practices. We digitized the map of chloride levels at the base of aquifer shown in the figure 1 below from the Kansas Geological Survey and merged the chloride levels with the parcels that had land sales. We assume that chloride levels are minimal in areas outside the region in the map.

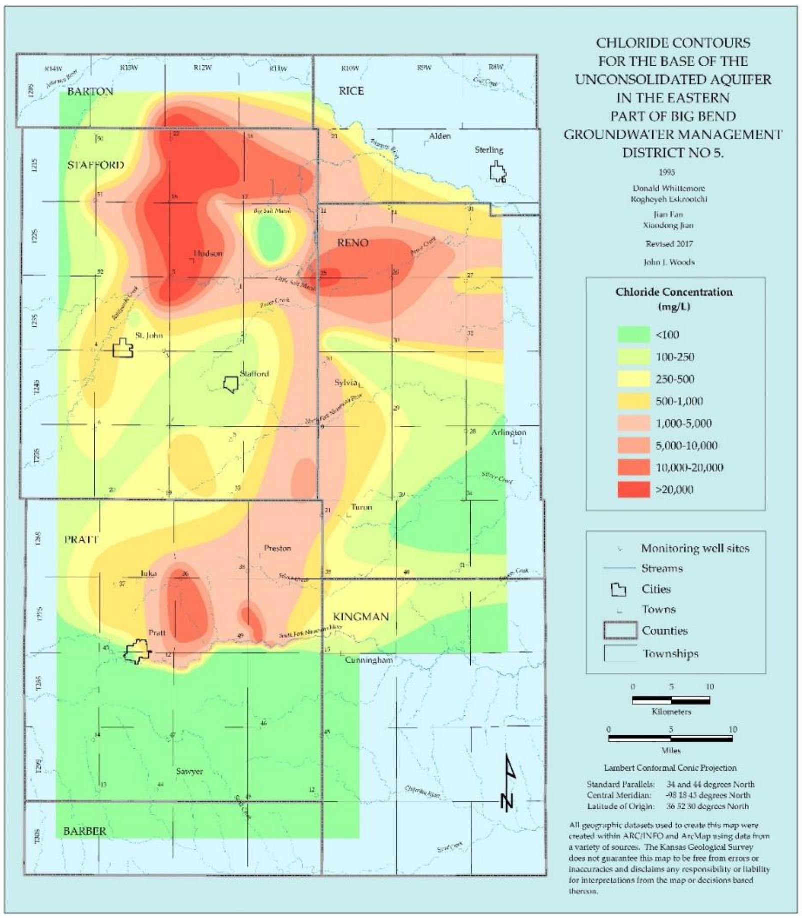



**Figure 1. Chloride concentrations (i.e., salinity) from the Kansas Geological Survey**

*Urban Influence*

Land values increase close to urban areas because of the potential to convert the land to residential or other non-agricultural uses. We use data on the commute time to a city with population 10,000 or greater. Commute times are calculated from the parcel using Google Maps.

## Regression Model

We developed a regression model to estimate the effect of different characteristics of the parcel on the price per acre of the parcel and to create a prediction of land values across all irrigated parcels in GMD 5. Our specification allows for the possibility that climate and soil factors affect irrigated values differently than nonirrigated values. Our specification also accounts for the fact that characteristics of the aquifer and water rights should only affect the price of irrigated parcels. Our regression specification is as follows

$$\ln(PricePerAcre_{it}) = \beta_0 + \beta_1 NCCPI_i + \beta_2 \ln(Slope_i) + \beta_3 CommuteTime_i$$
$$+\beta_4 Irr_i + Irr_i\{\beta_5 SatThick_i + \beta_6 PriorityYear_i + \beta_7 Authorized_i + \beta_8 NCCPI_i$$
$$+\beta_9 \ln(Slope_i) + \beta_{10} Saline_i\} + \beta_{11} Grass_i + \gamma_t + \varepsilon_{it}$$

Definitions of the variables are

- $\ln(PricePerAcre_{it})$: The natural logarithm of the real price per acre.
- $NCCPI_i$: National Commodity Crop Productivity Index for nonirrigated corn and soybeans, which includes both a precipitation and soil quality component to the index.
- $\ln(Slope_i)$: Natural logarithm of the average slope.
- $CommuteTime_i$: Time (in hours) to commute from the parcel to a city with population 10,000 or greater. Time is censored at 0.5 hours. Effectively that means that we assume being close to a city of 10,000 people increases the land value until you are 30 minutes away from the city and then time to travel to the city has no impact on land value.
- $Irr_i$: A variable equal to 1 if the parcel is greater than 70% irrigated and 0 otherwise.
- $SatThick_i$: The saturated thickness of the aquifer underlying the parcel.
- $PriorityYear_i$: The number of years after June 28, 1945 (the date prior appropriations was enacted in Kansas) for the priority date of the water right. Therefore, larger values of the variable $PriorityYear_i$ denote more junior water rights.
- $Authorized_i$: The amount authorized for irrigation by the water right measured in inches per authorized acre.
- $Saline_i$: A binary variable that indicates if the chloride concentration at the base of the aquifer is greater than 250 mg/L.
- $Grass_i$: The proportion of the parcel that is grass.

- $\gamma_t$: A set of binary variables to indicates each year and quarter that the sale occurred.

Note that all of the variables within brackets {} only affect the price when the parcel is irrigated (i.e., when $Irr_i = 1$). Therefore, variables in brackets affect irrigated parcels differently than they affect nonirrigated parcels.

## Average Land Values over Time

Figure 2 shows a simple average of irrigated and nonirrigated land sales over time in nominal values (i.e., the values are not adjusted for inflation). That is, figure 2 does not adjust land sales for the quality of land that sold. Figure 2 shows that the value of both nonirrigated and irrigated land has increased significantly in the GMD 5 region since the early 2000's. The increase was driven by both high commodity prices and low interest rates on farmland and production inputs. Over time, the added value of higher yields on irrigated land has driven a larger wedge between nonirrigated and irrigated land values. This divergence may temper somewhat if land values fall due to lower commodity prices and/or profitability.

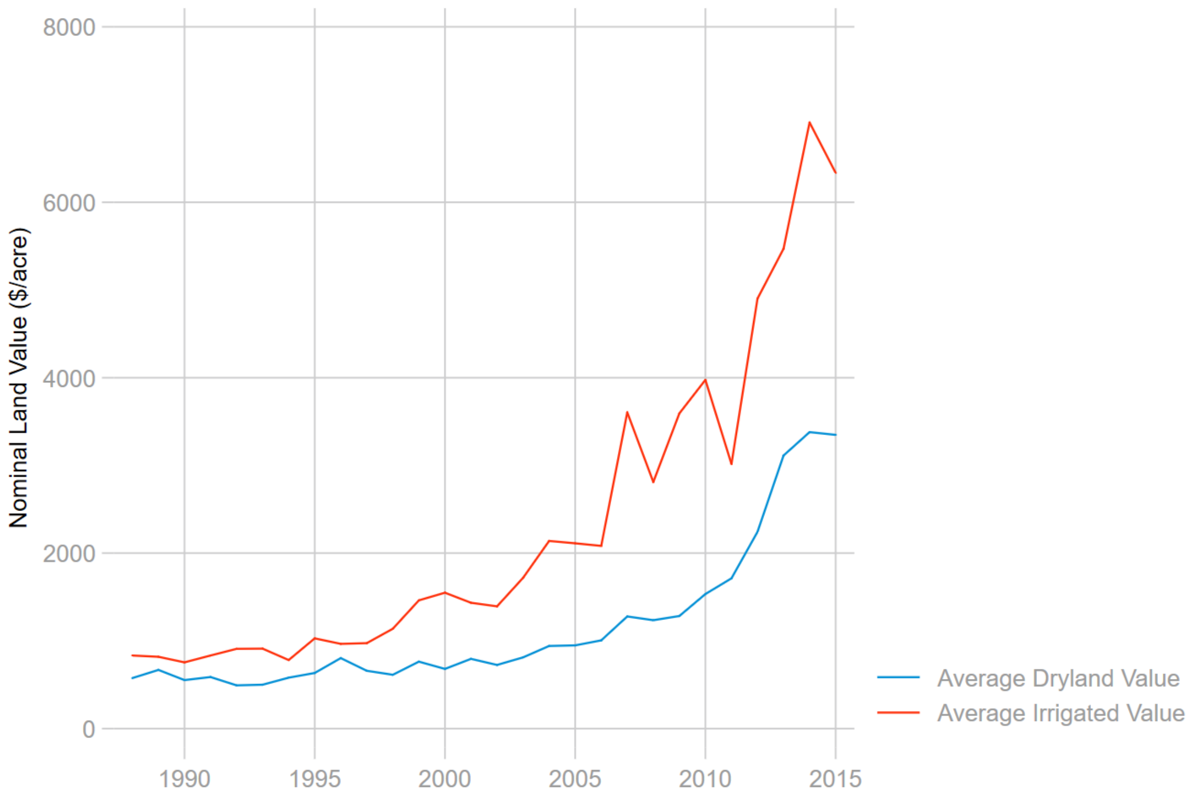



**Figure 2. Average dryland and irrigated land values (1988 to 2015)**

## Maps of Land and Hydrologic Characteristics in GMD 5

The figures on the following pages show maps of some key factors that affect land values in GMD 5. Figure 3 shows the NCCPI across the GMD. Larger values of NCCPI indicates a greater potential productivity of nonirrigated cropland. There is substantial variability in the productivity of the land across GMD 5 and the lower productivity areas are driven primarily by soils that are very sandy (figure 4). The soils that are sandy also tend to be more highly sloped (figure 5). Average annual precipitation varies across GMD 5, but not dramatically (figure 6). The eastern portions of the GMD receive about 29 inches of precipitation annually and the western portions receive about 25 inches annually.

Figure 7 shows the average saturated thickness of the aquifer between 2013 and 2015. There are two areas in the GMD with an especially large saturated thickness. The average saturated thickness is 100 feet and the saturated thickness is greater than 64 feet on 75% of the sections in the GMD. Sections on the western edge of the GMD tend to have the least saturated thickness. Figure 8 shows the depth to water across the GMD. The average depth to water is about 38 feet in GMD 5, which is generally quite shallow compared to regions in western Kansas overlying the Ogallala Aquifer. However, there are some areas near the southern border of GMD 5 that have a depth to water greater than 60 feet.

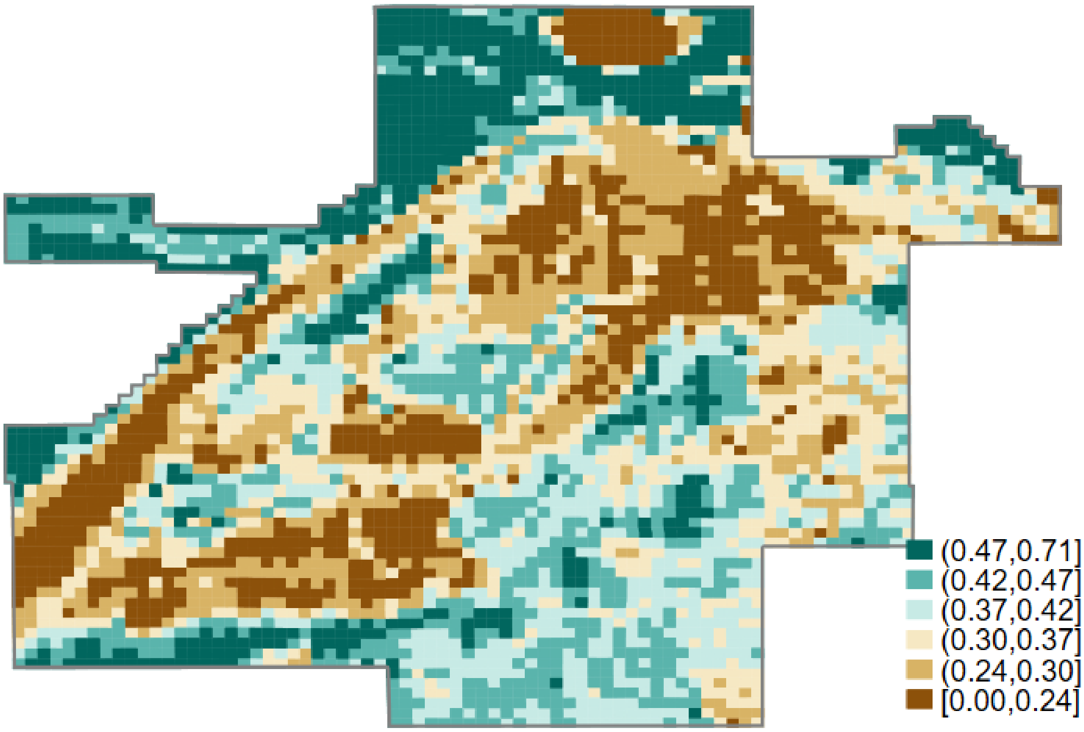



**Figure 3. National Commodity Crop Productivity Index (NCCPI)**

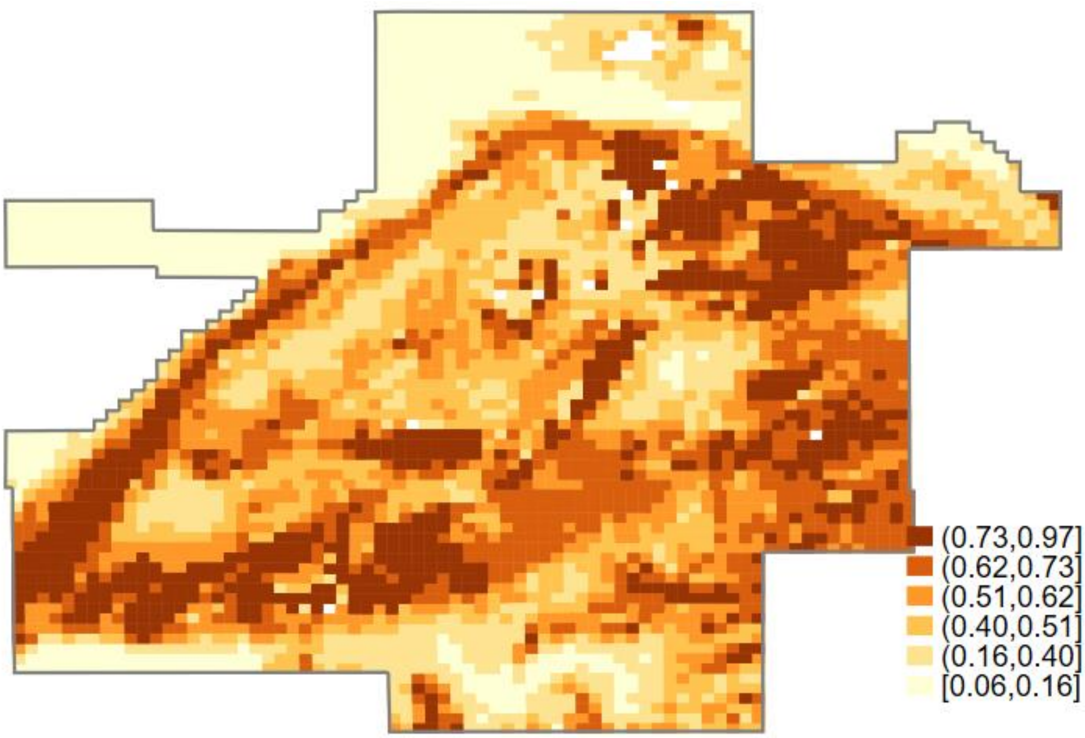



**Figure 4. Share of soil that is sand**

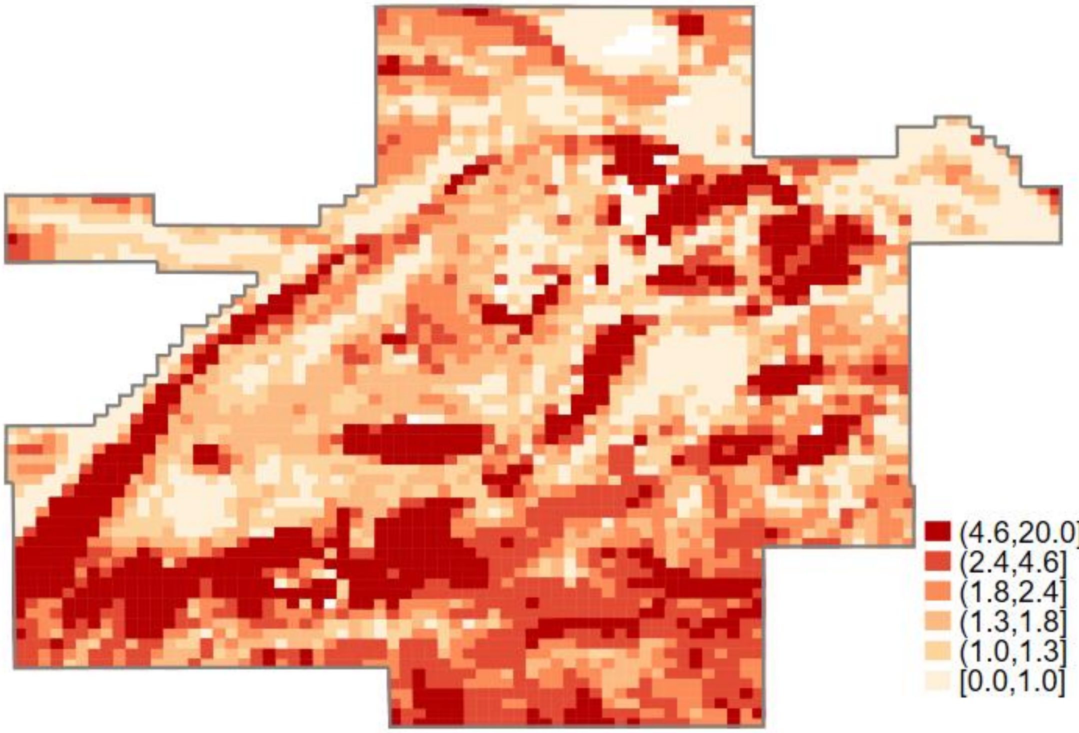



**Figure 5. Slope of the land**

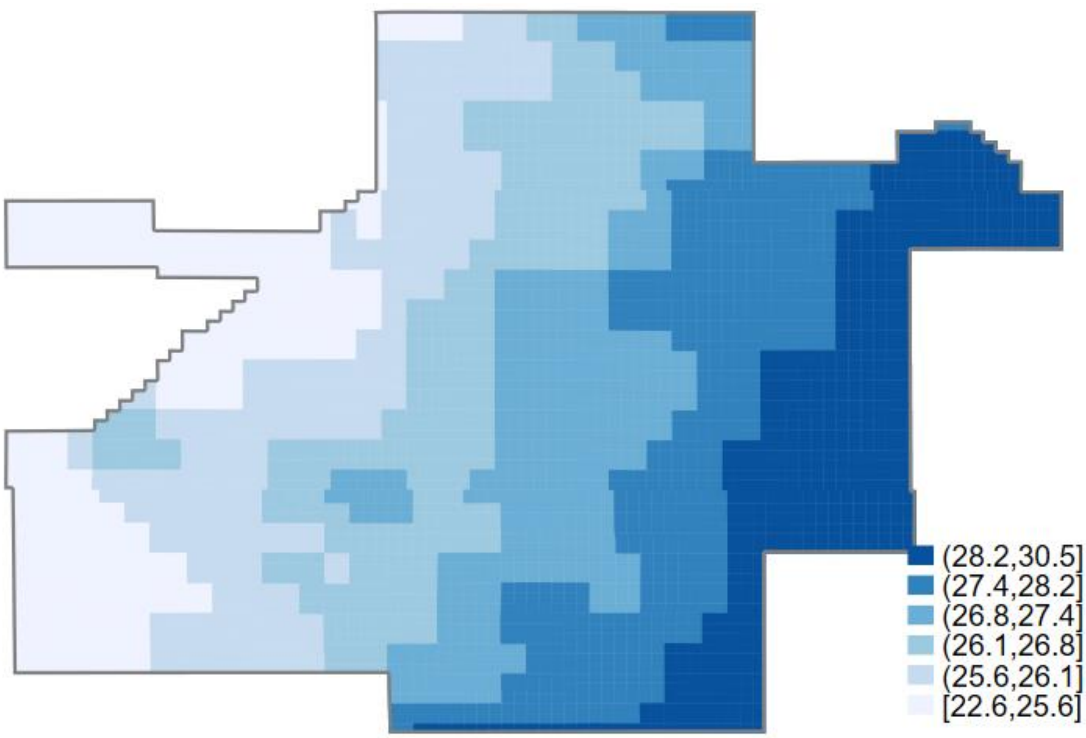



**Figure 6. Average annual precipitation**

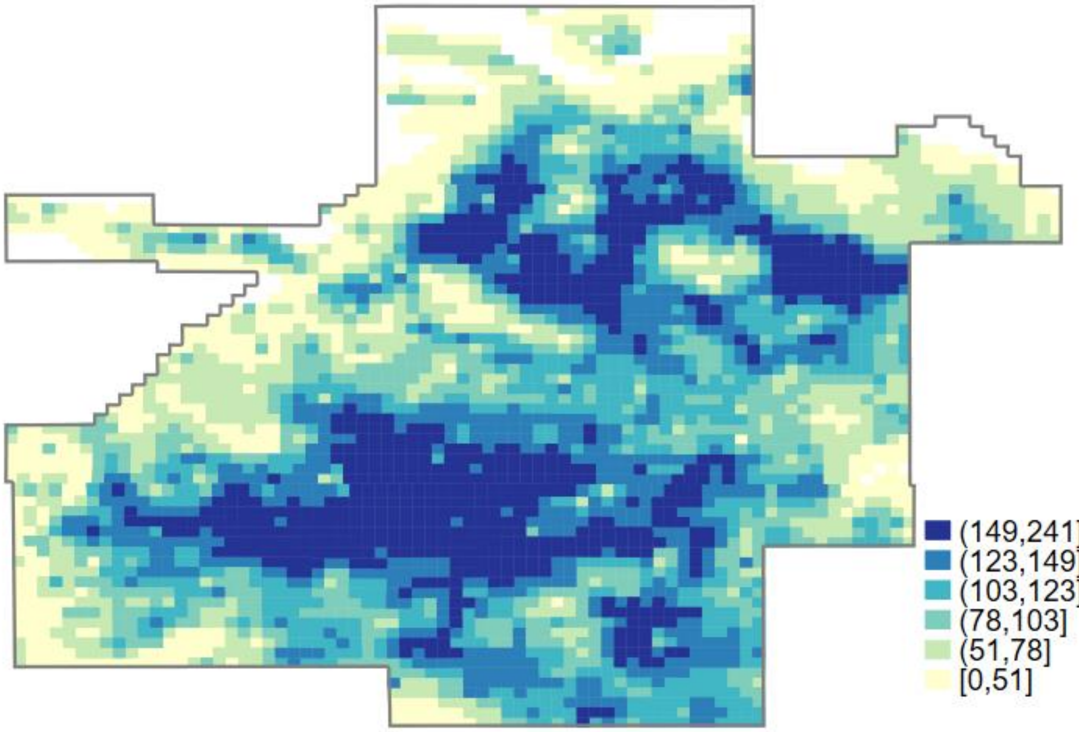



**Figure 7. Saturated thickness (2013-2015)**

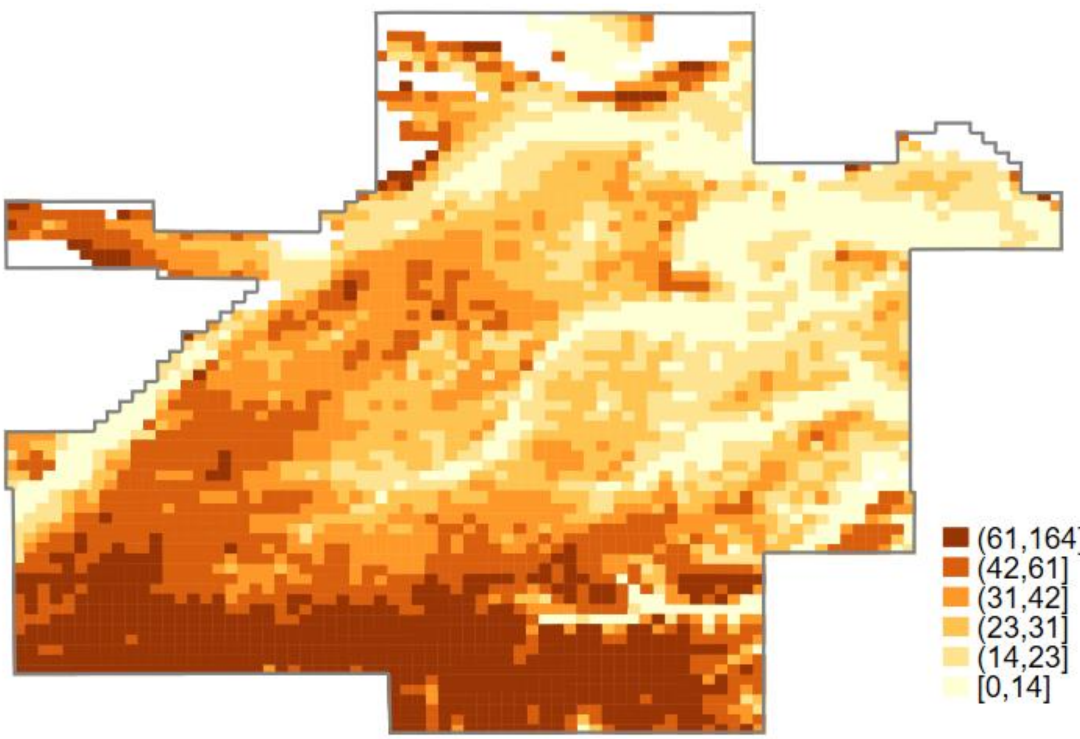



**Figure 8. Depth to water (2013-2015)**

## Interpretation of the Regression Results

In a statistical model, we include all the variables we believe impact the sales price of the land that we can also measure. Results of the statistical model are presented in appendix tables 1 and 2. Although we believe they will be important in explaining the variability in land values across nonirrigated and irrigated parcels, not all the variables included in the model were statistically significant in explaining the variability in price per acre. Just because a variable does not have a statistically significant impact on land values does not mean that we can conclude that it has no impact. Rather a statistically insignificant result means that we do not have enough data or do not have enough variability in the data to precisely determine if the variable has an impact on land values. There are 3,404 parcels that sold between 1988 and 2015 that we use in our regression analysis. The interpretation of all the variables included in the model are provided below.

*Variables that Impact Irrigated and Nonirrigated Values*

- NCCPI: An increase in the National Commodity Crop Productivity Index of a given parcel increases the value of nonirrigated parcels, reflecting the value added for both higher precipitation and higher quality soils. However, we find that a greater National Commodity Crop Productivity Index is associated with lower values on irrigated parcels. That is, irrigated parcels tend to have higher values in areas with a lower NCCPI. This result is likely driven by the sandy soils in areas of GMD 5. Sandy soils have low productive capabilities for nonirrigated production, but our regression results indicate that they are highly valued for irrigated production.
- ln(Slope): As the average slope of a parcel increases, the value of a nonirrigated parcel decreases. However, the slope of the land has essentially no impact on land values for irrigated parcels. This indicates irrigation is relatively more valuable (i.e., the difference between irrigated and nonirrigated value is greater) on more highly sloped land.
- Commute time: The impact of commute time to a city of 10,000 or more is negative. This means that being within 30 minutes of a city of 10,000 people increases the land value.
- Proportion Grass: Parcels that contain more grassland are worth less than cropland.

*Variables that only Impact Irrigated Values*

- Irrigated Premium: Irrigated parcels are worth more than nonirrigated parcels. According to the estimates provided by the model, irrigated land with average characteristics in the region was worth approximately 73% more than a nonirrigated parcel with the same characteristics in 2015. From 1988 to 1997, irrigated parcels were only worth about 40% more than nonirrigated parcels. Since 1998, the relative increase in value for irrigated versus nonirrigated parcels has ranged from about 60% to 100%.
- Saturated thickness: Greater saturated thickness of the aquifer underlying the parcel does not have a statistically significant impact on irrigated land values. This is likely because aquifer depletion is not a major concern in GMD 5 and well capacities tend not to be as limiting as in other areas of Kansas.
- Year of Water Right: More junior water rights decrease the value of an irrigated parcel, but the effect is not statistically significant. In other preliminary research conducted by Hendricks, we include all irrigated parcels overlying the High Plains Aquifer and find a statistically significant impact of the priority date on the irrigated land value.
- Authorized quantity: The amount authorized for irrigation by the water right does not have a statistically significant impact on irrigated land value. If most of the water rights are not constraining in most years, then we will find little impact on land values.
- Salinity: Irrigated land values are roughly 15% lower, holding all else constant, in areas where a chloride concentration at the base of the aquifer (i.e., saline water) is greater than 250 mg/L.

## Predictions of Irrigated Land Values across GMD 5

Using the parameters of the regression model, we can predict the value of all irrigated land in GMD 5. We obtain data on the location of all irrigated points of diversion in GMD 5 from the Kansas Department of Agriculture Water Rights Information System (WRIS) database. These data provide us with the location of every well in GMD 5 along with information about the corresponding water rights. We merge the same soil, climate, and hydrology data to the WRIS data as were used in the land value regression. We then use the regression model to predict the irrigated and nonirrigated values ($/acre) for every point of diversion. The regression model is specified so that it provides predicted values for the first quarter of 2015 and we assume each point of diversion is 30 or more minutes from a city so that the predicted values only reflect the agricultural value of the land. The WRIS data also provide information on the number of acres irrigated by each point of diversion so that we can aggregate the values to obtain a total value added by irrigation in GMD 5. Note that our regression model indicates the predicted value of an irrigated parcel, but usually only a portion of a parcel is actually irrigated (e.g., a center pivot sprinkler with nonirrigated corners). We aggregate the values across points of diversion assuming 81.5% of the parcel is irrigated—the average for parcels in the PVD land sales data.

There are 452,018 acres irrigated in GMD 5 and our model results indicate that irrigation added about $1.44 billion to the total value of land in 2015.

Figure 9 shows the predicted irrigated land value in $/acre across GMD 5 for 2015. Note that these are predicted values from the regression model and do not reflect the value from actual transactions. In other words, the values in figure 9 reflect what our model predicts the value of land had it sold in 2015. Our model is necessarily simplistic and cannot capture every potential characteristic of parcels that can affect land value, so our model is not a substitute for an appraisal. However, the model predictions are useful for getting a big picture understanding how irrigated land values vary spatially across GMD 5.

Figure 10 shows the value of irrigation in 2015. That is, figure 10 shows the difference between the predicted irrigated land value and the nonirrigated land value in $/acre. The value of irrigation varies significantly across GMD 5. In the eastern portions of the district—and a few other areas—irrigation adds less than $2,000/acre. But in the southwest portion of the district irrigation can add as much as $4,000/acre to the land value. Note that a restriction on water use will have a more negative impact in areas where irrigation is more valuable. Therefore, restrictions will have a more adverse economic impact in areas with darker blue dots in figure 10.

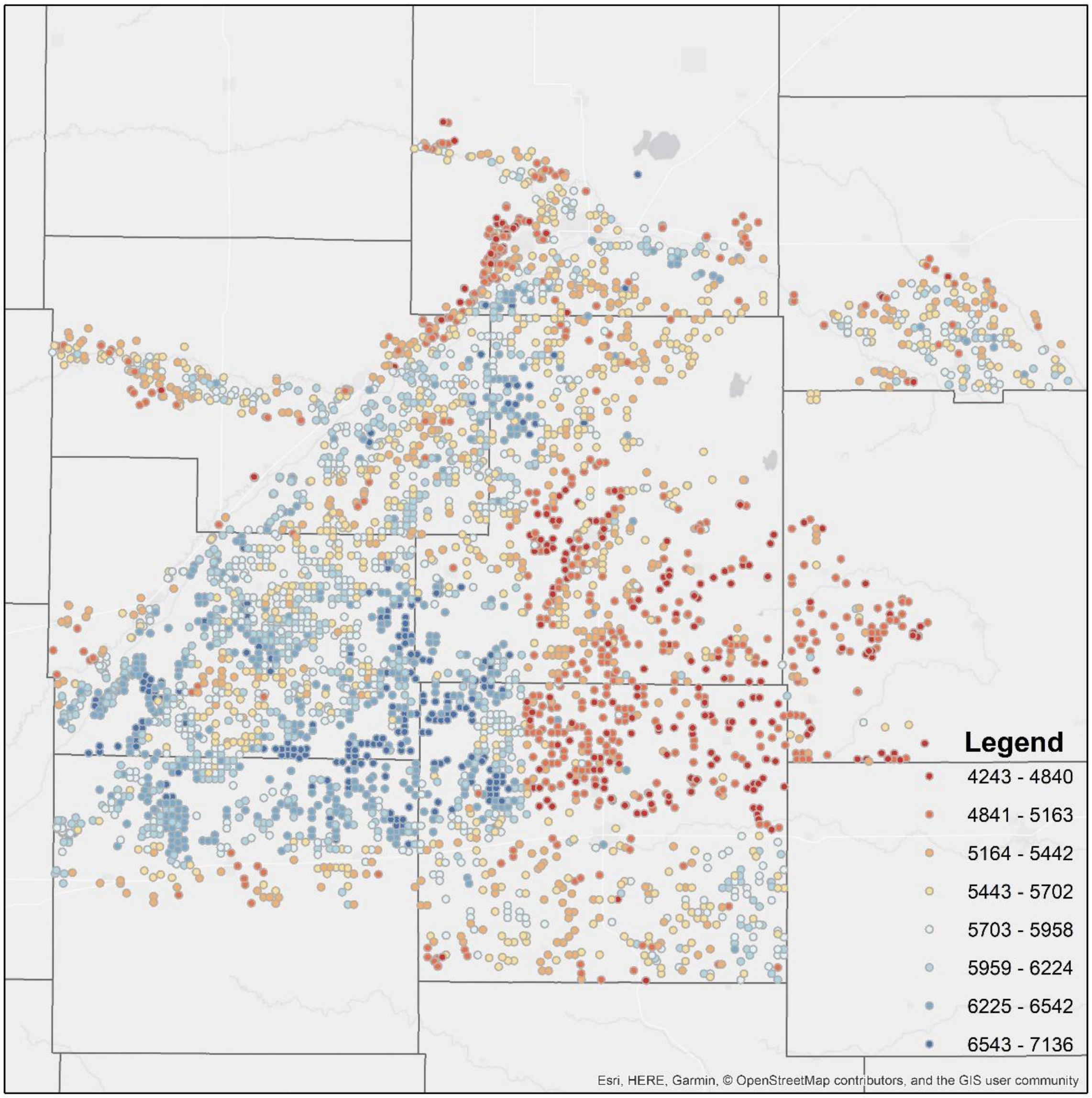



**Figure 9. Model predicted irrigated land value ($/acre) in 2015 for the entire GMD 5**

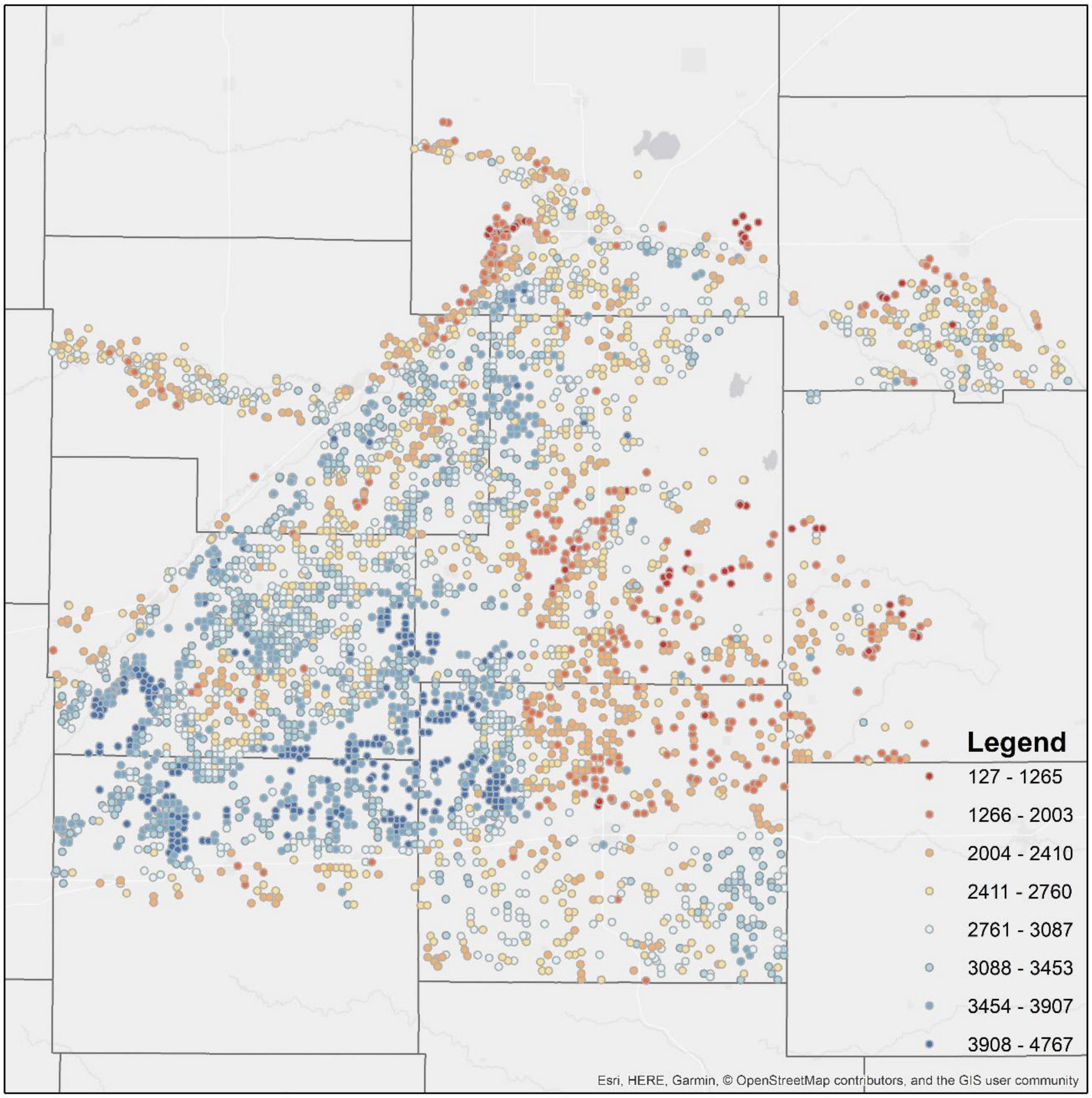



**Figure 10. Premium for irrigated versus nonirrigated land ($/acre) in 2015 for the entire GMD 5**

## Comparison to Statewide Land Values

The estimates from the statistical model indicate the value of irrigated land in GMD 5 for the year 2015. It is worth noting that some changes have occurred in the greater land market since then, which may also affect prices in GMD 5. Figure 11 shows the changes in land values for the state of Kansas over the period 2013 to 2017. For all the classes of land, 2015 was the peak year for land values, with a significant decrease in the two years following. The drop in land values in 2016 and 2017 is due primarily to a fall in profitability from the production of wheat, corn, soybeans, and grain sorghum. These crops were very profitable from 2008 to 2013, but profitability fell due to a decline in commodity prices and increases in production costs. The direction of land prices in the years to come will depend heavily on commodity prices and production levels in the state.

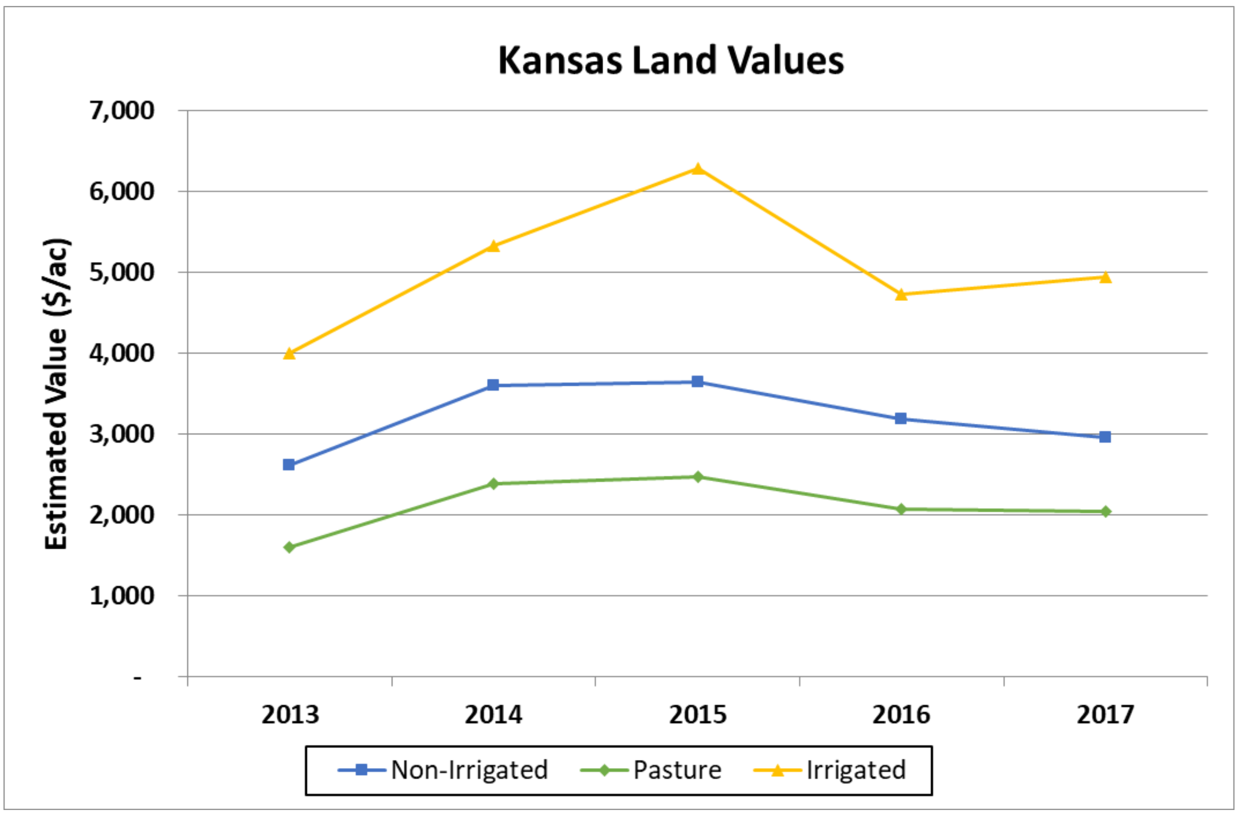



**Figure 11. Value of agricultural land in the state of Kansas (2013-2017).**

**Appendix Table 1: Results of Statistical Modeling of Land Values Part 1**

| Dependent variable: ln(Price per Acre) | Coefficient |
|---|---|
| **Main Effect of Variables** | |
| NCCPI | 0.182 |
| | (0.153) |
| ln(Slope) | -0.0777*** |
| | (0.000) |
| Commute time to 10k population | -0.271* |
| | (0.062) |
| Proportion Grass | -0.826*** |
| | (0.000) |
| Intercept | 6.979*** |
| | (0.000) |
| **Variables Interacted with Irrigation** | |
| Saturated Thickness | 0.000532 |
| | (0.316) |
| Year of Water Right | -0.00308 |
| | (0.214) |
| Authorized Inches per Acre | 0.00137 |
| | (0.831) |
| NCCPI | -0.794*** |
| | (0.005) |
| ln(slope) | 0.0778* |
| | (0.056) |
| Salinity | -0.152*** |
| | (0.007) |
| Number of Observations | 3,404 |

Note: *, **, and *** indicates statistical significance at the 0.1, 0.05, and 0.01 levels. P-values are listed below each coefficient in parentheses.

**Appendix Table 2: Results of Statistical Modeling of Land Values Part 2**

| Dependent variable: ln(Price per Acre) | Coefficient | | Coefficient |
|---|---|---|---|
| **Relative Difference in Price for Nonirrigated Compared to 1988** | | **Relative Difference in Price of Irrigated Compared to Nonirrigated** | |
| 1989 | -0.103 | 1988 | 0.359*** |
| | (0.403) | | (0.001) |
| 1990 | -0.139 | 1989 | 0.225 |
| | (0.216) | | (0.217) |
| 1991 | -0.196* | 1990 | 0.303** |
| | (0.054) | | (0.026) |
| 1992 | -0.430*** | 1991 | 0.428*** |
| | (0.000) | | (0.000) |
| 1993 | -0.369*** | 1992 | 0.669*** |
| | (0.000) | | (0.000) |
| 1994 | -0.316*** | 1993 | 0.680*** |
| | (0.001) | | (0.000) |
| 1995 | -0.239** | 1994 | 0.393*** |
| | (0.032) | | (0.003) |
| 1996 | -0.0992 | 1995 | 0.481*** |
| | (0.391) | | (0.000) |
| 1997 | -0.220** | 1996 | 0.185 |
| | (0.032) | | (0.268) |
| 1998 | -0.250** | 1997 | 0.440*** |
| | (0.012) | | (0.003) |
| 1999 | -0.137 | 1998 | 0.641*** |
| | (0.213) | | (0.000) |
| 2000 | -0.150 | 1999 | 0.589*** |
| | (0.107) | | (0.002) |
| 2001 | -0.166* | 2000 | 0.769*** |
| | (0.075) | | (0.000) |
| 2002 | -0.198** | 2001 | 0.580*** |
| | (0.037) | | (0.000) |
| 2003 | -0.0730 | 2002 | 0.614*** |
| | (0.458) | | (0.000) |
| 2004 | -0.0323 | 2003 | 0.704*** |
| | (0.741) | | (0.000) |
| 2005 | -0.0310 | 2004 | 0.942*** |
| | (0.739) | | (0.000) |
| 2006 | 0.0789 | 2005 | 0.841*** |
| | (0.437) | | (0.000) |
| 2007 | 0.192* | 2006 | 0.732*** |
| | (0.070) | | (0.000) |
| 2008 | 0.152 | 2007 | 0.981*** |
| | (0.173) | | (0.000) |

| | | | |
|---|---|---|---|
| 2009 | -0.0136 | 2008 | 0.777$^{***}$ |
| | (0.907) | | (0.000) |
| 2010 | 0.207$^{**}$ | 2009 | 1.073$^{***}$ |
| | (0.045) | | (0.000) |
| 2011 | 0.354$^{***}$ | 2010 | 0.954$^{***}$ |
| | (0.001) | | (0.000) |
| 2012 | 0.469$^{***}$ | 2011 | 0.631$^{***}$ |
| | (0.000) | | (0.000) |
| 2013 | 0.889$^{***}$ | 2012 | 0.783$^{***}$ |
| | (0.000) | | (0.000) |
| 2014 | 0.739$^{***}$ | 2013 | 0.596$^{***}$ |
| | (0.000) | | (0.000) |
| 2015 | 0.870$^{***}$ | 2014 | 0.893$^{***}$ |
| | (0.000) | | (0.000) |
| | | 2015 | 0.729$^{***}$ |
| | | | (0.000) |
| **Relative Difference in Price Compared to First Quarter** | | | |
| Second Quarter | 0.0929$^{***}$ | | |
| | (0.003) | | |
| Third Quarter | -0.00271 | | |
| | (0.937) | | |
| Fourth Quarter | 0.0640$^{*}$ | | |
| | (0.051) | | |

Note: *, **, and *** indicates statistical significance at the 0.1, 0.05, and 0.01 levels. P-values are listed below each coefficient in parentheses.

# Chapter 2. The Impact of Irrigation on the Livestock and Agribusiness Sectors

Nathan P. Hendricks

## Highlights

- I use modern statistical techniques to estimate the economic spillover impact of the High Plains Aquifer on the livestock and agribusiness sectors.
- The results indicate large and statistically significant spillover impacts of the aquifer on the livestock and agribusiness sectors.
- An additional 100 feet of saturated thickness increased animal sales in 2012 by 36.6% and cattle on feed sold for slaughter by 100.1%.
- An additional 100 feet of saturated thickness increased fertilizer expenditures in 2012 by 33.0%, chemical expenditures by 24.0%, and farm operating expenditures by 27.9%.
- Applying the model results to GMD 5, I find that losing irrigation from the aquifer would annually decrease animal sales by $236 million, cattle on feed sold for slaughter by 213,200 head, fertilizer expenditures by $22.6 million, chemical expenditures by $10.7 million, and total farm operating expenditures by $259.8 million.

## Methodology

The methodology I employ is very similar to the peer-reviewed paper by Hornbeck and Keskin (HK).[1] HK was recently published in a prestigious economics journal so the methodology has a high degree of credibility. The methodology uses regression to estimate the impact of the High Plains Aquifer on various outcomes while controlling for (i.e., holding constant) soil types, precipitation, temperature, suitability for corn and wheat nonirrigated production, longitude and latitude, and state-year specific effects. Intuitively, the regression technique compares outcomes of counties that overlie the High Plains Aquifer with similar counties that do not overlie the aquifer. More details

[1] Hornbeck R. and P. Keskin. 2015. "Does Agriculture Generate Local Economic Spillovers? Short-Run and Long-Run Evidence from the Ogallala Aquifer" *American Economic Journal: Economic Policy* 7(2): 192-213

on the regression specification are provided in the technical appendix at the end of this report.

There are two main differences between my analysis and HK. The first difference is that HK simply estimate the impact of a county overlying the aquifer. But the High Plains Aquifer is not homogenous. The saturated thickness varies significantly so that the aquifer can support more irrigation in some areas. The main independent variable in HK's regression is the proportion of the county overlying the aquifer. I account for the heterogeneity of the aquifer by multiplying the proportion of the county overlying the aquifer by the average saturated thickness of the aquifer.

The second difference is that HK estimate the spillover impact on *nonagricultural* activities. In my analysis, I estimate the spillover impact of the aquifer on the livestock sector, agricultural expenditures, and ethanol production. HK do not find any significant impacts of the High Plains Aquifer on nonagricultural (manufacturing, wholesale, retail, and services) development. I have replicated their results and find roughly similar results when I account for differences in saturated thickness. However, the more likely spillover impacts are on the livestock and agribusiness sectors, which represent a significant share of economic activity in rural areas. HK omit these sectors from their analysis.

## Data

Data on livestock and agricultural expenditures are from the 1997, 2002, 2007, and 2012 Census of Agriculture. Sales from animals represent the total sales of animals, including products from animals, measured in dollars. Cattle on feed represents the number of head sold for slaughter. Sales of hogs are measured in number of head. Milk sales are measured in dollars. Fertilizer, chemical, and total operating expenses are also measured in dollars. Data on the operating production of ethanol plants—measured in millions of gallons per year—are obtained from the Nebraska Energy Office website, which obtains some of its data from the Renewable Fuels Association.[2]

The saturated thickness of the aquifer in 2009 is obtained from the US Geological Survey (USGS).[3] I calculate the average saturated thickness in each county over only the

[2] Data available at: http://www.neo.ne.gov/statshtml/122.htm

[3] McGuire, V.L., K.D. Lund, B.K. Densmore. 2012. "Saturated thickness and water in storage in the High Plains aquifer, 2009, and water-level changes and changes in water in storage in the High Plains aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009." U.S. Geological Survey Scientific Investigations Report 2012–5177. Available at: https://pubs.usgs.gov/sir/2012/5177/

parts of the county classified as irrigation according to the USGS dataset called Moderate Resolution Imaging Spectroradiometer (MODIS) Irrigated Agriculture Dataset for the United States (MIrAD-US).[4] The advantage of using MIrAD-US for aggregation is that some areas of the county without irrigation could have a smaller saturated thickness and I want to measure the saturated thickness in the portion of the county that actually has irrigation. I also obtain a boundary map for the High Plains Aquifer from USGS and calculate the proportion of each county overlying the aquifer. Then my key independent variable is the proportion of the county overlying the aquifer times the average saturated thickness measured in hundreds of feet. I winsorize this variable at the 95$^{th}$ percentile, meaning that all values greater than the 95$^{th}$ percentile (3.79 hundred feet) are set equal to the value of the 95$^{th}$ percentile. Winsorizing the data reduces the influence of extreme values because there are some counties where the average saturated thickness is more than 900 feet.

All of the other control variables used in the regressions are obtained directly from HK. HK posted the data used in their analysis alongside the online published version of their article.

## Census of Agriculture Statistics for GMD 5

Tables 1 and 2 report statistics from the 2012 Census of Agriculture on the livestock sector and agriculture expenditures in GMD 5. I provide data (when reported) for each county separately and the total for GMD 5. When I report the total for GMD 5, I account for the fact that only a portion of some counties lie within GMD 5. The approximate proportion of each county in GMD 5 is from a previous WaterPack report.

Table 1 reports livestock statistics in GMD 5. Sales from animals includes the sales of all livestock animals and the sale of livestock products such as milk. In 2012, there were roughly $817.2 million of sales from livestock. There were 337,300 head of cattle on feed sold for slaughter and 96,200 head of hogs sold.

Table 2 shows statistics on agricultural expenditures that generate economic activity for the agribusiness sector. Fertilizer expenditures in 2012 were $112.9 million and chemical expenditures were $70.5 million. Total farm operating expenses were $1.29 billion, where these expenses include crop and livestock production. Though not reported in one of the tables there is also an ethanol plant that operates in Rice county with a production in 2012 of 58.3 million gallons per year.

[4] Data available at: https://earlywarning.usgs.gov/USirrigation

**Table 1. Livestock Statistics for GMD 5 from the 2012 Census of Agriculture**

| County | Approximate Area in GMD 5 | Sales from Animals ($ Millions) | Cattle on Feed Sold (1,000 Head) | Hogs Sold (1,000 Head) | Milk Sales ($ Million) |
|---|---|---|---|---|---|
| **Barton** | 90% | 182.8 | 103.2 | - | - |
| **Edwards** | 100% | 24.8 | 1.9 | - | - |
| **Kiowa** | 50% | 16.6 | 0.8 | - | - |
| **Pawnee** | 100% | 270.2 | 203.6 | 0.006 | - |
| **Pratt** | 100% | 147.6 | - | - | - |
| **Reno** | 25% | 115.7 | - | - | 9.0 |
| **Rice** | 60% | 159.2 | 38.4 | 92.8 | 0.2 |
| **Stafford** | 100% | 77.4 | 15.5 | 40.4 | - |
| **GMD 5 Total** | | 817.2 | 337.3 | 96.2 | 2.4 |

Note: The total for GMD 5 accounts for the percent of each county within GMD 5 and is not the simple summation across counties. The Census does not report data for counties when it could reveal information of individual producers. For some counties, cattle on feed was not reported in 2012 but I report the 2007 data if available.

**Table 2. Agricultural Expenditures for GMD 5 from the 2012 Census of Agriculture**

| County | Approximate Area in GMD 5 | Fertilizer Expenditures ($ Millions) | Chemical Expenditures ($ Millions) | Farm Operating Expenditures ($ Millions) |
|---|---|---|---|---|
| **Barton** | 90% | 16.0 | 10.2 | 242.0 |
| **Edwards** | 100% | 16.7 | 11.3 | 101.2 |
| **Kiowa** | 50% | 9.7 | 7.6 | 70.0 |
| **Pawnee** | 100% | 14.8 | 16.0 | 346.2 |
| **Pratt** | 100% | 20.6 | 10.0 | 224.2 |
| **Reno** | 25% | 24.3 | 12.1 | 234.6 |
| **Rice** | 60% | 15.1 | 8.7 | 217.6 |
| **Stafford** | 100% | 26.4 | 11.9 | 172.7 |
| **GMD 5 Total** | | 112.9 | 70.5 | 1,286.2 |

Note: The total for GMD 5 accounts for the percent of each county within GMD 5 and is not the simple summation across counties. The Census does not report data for counties when it could reveal information of individual producers.

## Maps

In this section, I report maps that illustrate the difference in outcomes over the High Plains Aquifer and the surrounding counties. The maps provide a visualization of the impact of the aquifer on outcomes and illustrate the key data used in the statistical analysis. Each of the figures displays the counties included in the analysis and the boundary of the High Plains Aquifer.

Figure 1 shows the average saturated thickness of the aquifer in each county multiplied by the proportion of the county overlying the aquifer. This is the key independent variable included in the regression analysis. Saturated thickness is largest in Nebraska and the southern parts of Kansas and northern parts of Texas. The sand hills region in northern Nebraska has a substantial saturated thickness but has little irrigation because the soils are not suitable for crop production. Therefore, there is likely little impact of the aquifer on outcomes in this region. The statistical analysis accounts for the poor soils in the sand hills by controlling for soil types in the regression.

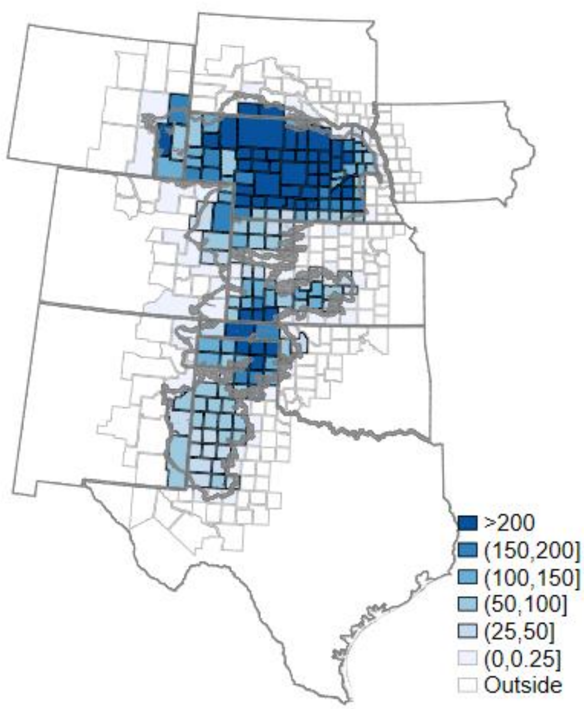



**Figure 1. Saturated Thickness of the Aquifer in 2009 Times the Share of the County Overlying the High Plains Aquifer**

Figure 2 shows maps of the livestock sector. Sales of animals and animal products are clearly larger within the aquifer boundary. One of the key drivers of this is that sales of cattle on feed are larger within the aquifer boundary. It is harder to discern an impact of the aquifer on sales of hogs. Most of the hogs are produced in Nebraska and Iowa and there is not a clear impact of the aquifer in this area. There are not enough data on milk production to reliably estimate a statistical model but it is interesting to see large milk production concentrated in the southern portions of the aquifer.

Figure 3 shows maps of expenditures. Again, it is appears that fertilizer, chemical, and total operating expenditures are larger in the counties overlying the aquifer. Expenditures are relatively low in the sand hills region of Nebraska, but again the aquifer is not utilized significantly for irrigation in this area due to the poor soils. Figure 4 shows a map of ethanol production. Ethanol production seems to be higher over the aquifer, especially in Kansas and Texas.

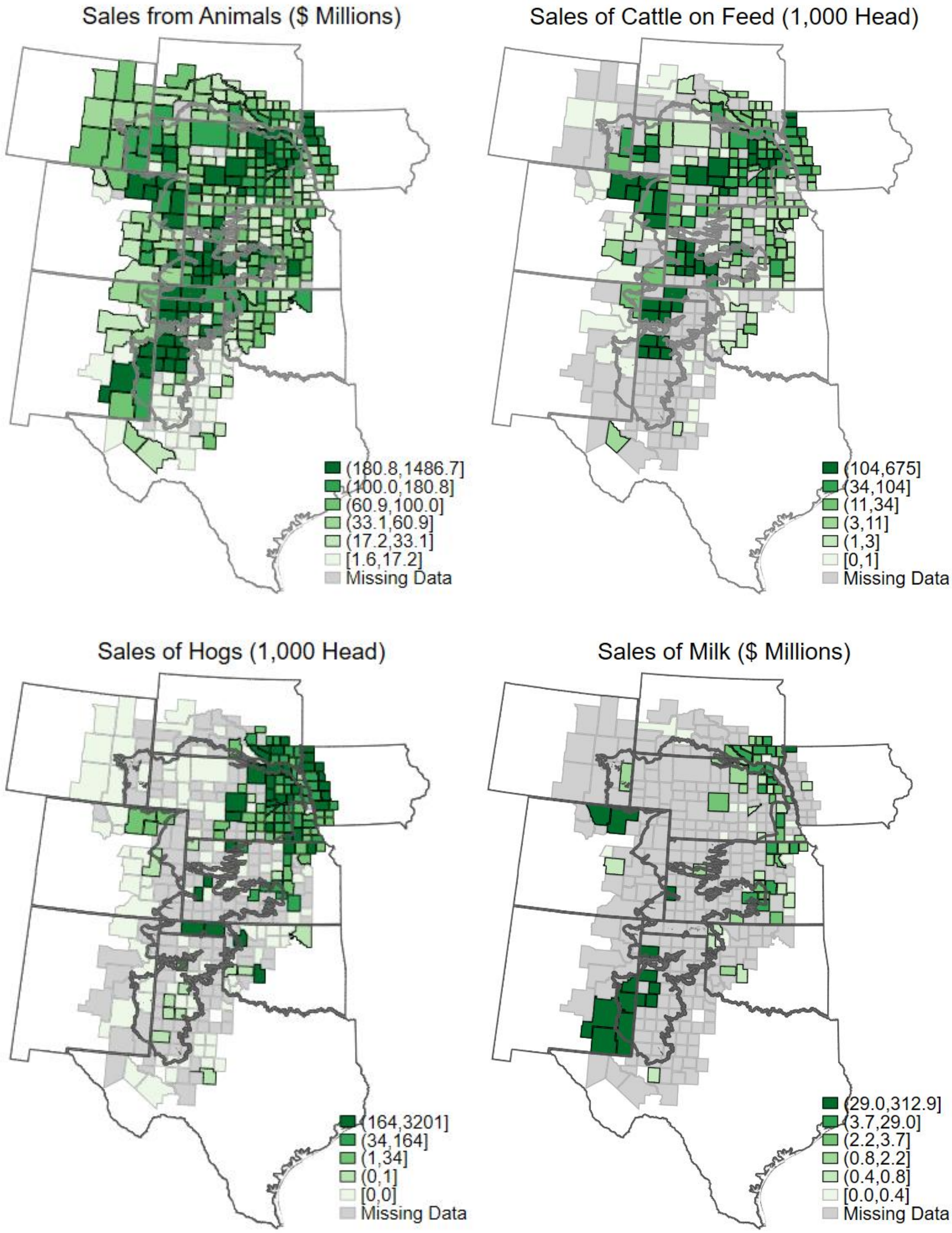
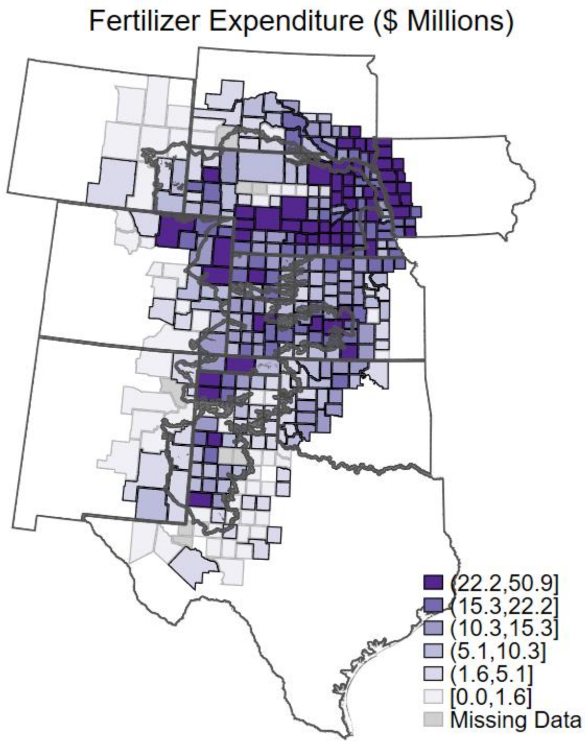
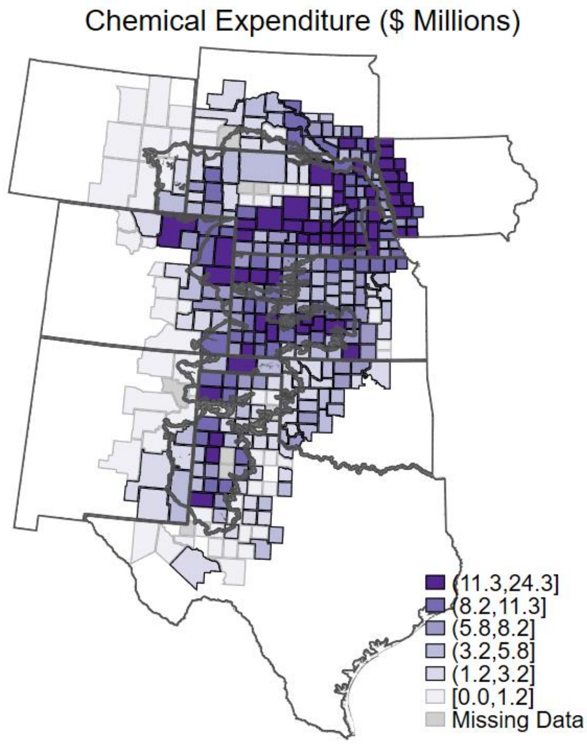



**Figure 2. Maps of Livestock Production in 2012 and the High Plains Aquifer**



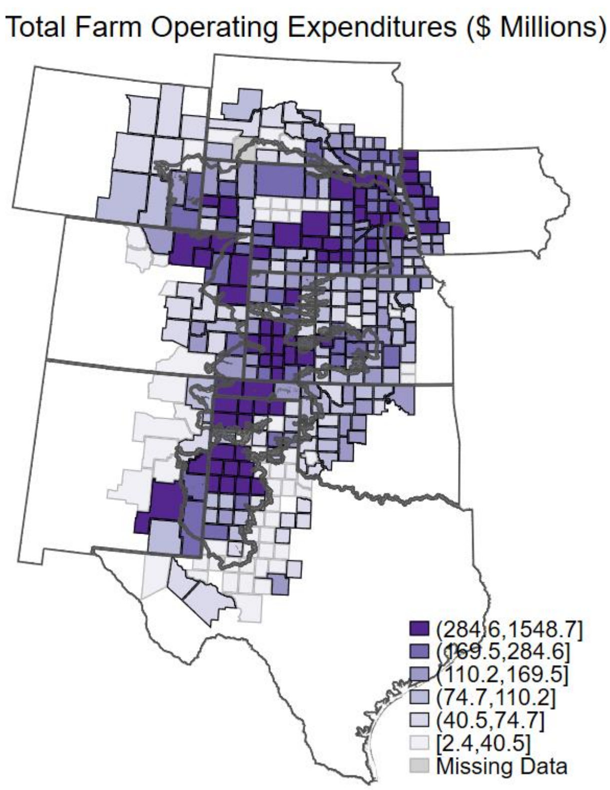




**Figure 3. Maps of Agricultural Expenditures in 2012 and the High Plains Aquifer**

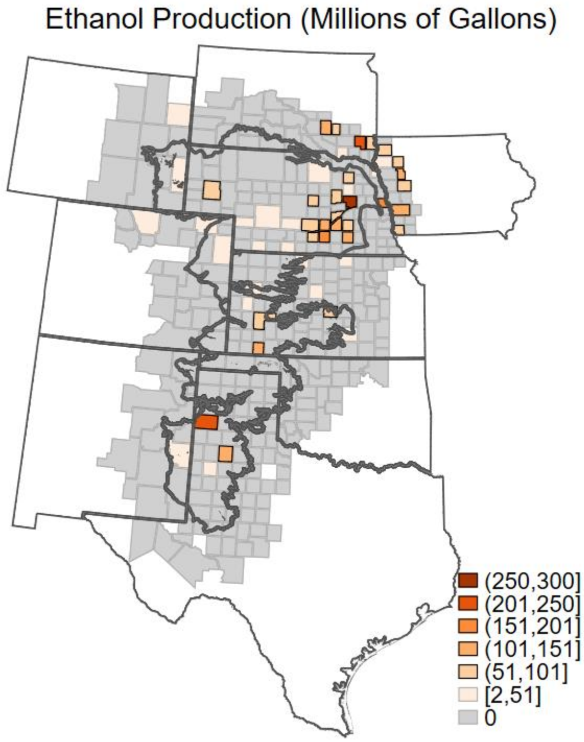



**Figure 4. Map of Ethanol Production in 2012 and the High Plains Aquifer**

# Results

*Regression Results – The Impact per 100 ft of Saturated Thickness*

First, I interpret the main coefficients from the regression output. Table 3 shows the impact of the aquifer on the livestock sector. Each column in table 3 represents a different regression and the rows show the impact of the aquifer in each year. Note that there are many more coefficients from the regression output than shown in the table, but for conciseness I only report the coefficients on the aquifer variables. The bottom row in the table reports the number of counties included in the analysis. There are fewer counties for some variables because the Census does not report data.

In 2012, an additional 100 ft of saturated thickness increased animal sales by 36.6%. This result is statistically significant at the 1% level indicating that it is extremely likely that there is an effect of the aquifer on animal sales. This increase in animal sales is in large part due to an increase in cattle on feed sold for slaughter. In 2012, an additional 100 ft of saturated thickness increased cattle on feed sold for slaughter by 100.1%. The impact of the aquifer on animal sales and cattle on feed appears to have increased since 1997.

There is a statistically significant impact of the aquifer on sales of hogs from 1997 to 2007 but no significant impact in 2012.

**Table 3. The Relative Impact on the Livestock Sector for each 100 Feet of Saturated Thickness**

| | Animal Sales | Cattle on Feed | Hogs |
|---|---|---|---|
| **1997** | 0.288*** | 0.752*** | 0.401* |
| | (0.000) | (0.000) | (0.059) |
| **2002** | 0.352*** | 0.816*** | 0.682*** |
| | (0.000) | (0.000) | (0.009) |
| **2007** | 0.337*** | 0.957*** | 0.629* |
| | (0.000) | (0.000) | (0.059) |
| **2012** | 0.366*** | 1.001*** | 0.409 |
| | (0.000) | (0.000) | (0.381) |
| **Counties** | 341 | 184 | 165 |

Note: *, **, and *** indicates statistical significance at the 0.1, 0.05, and 0.01 levels. P-values are listed below each coefficient in parentheses.

Table 4 shows the impact of the aquifer on agricultural expenditures. An additional 100 feet of saturated thickness increases fertilizer expenditures by 33.0%, chemical expenditures by 24.0%, and farm operating expenditures by 27.9%. These impacts have mostly remained stable since 1997.

**Table 4. The Relative Impact on Agricultural Expenditures for each 100 Feet of Saturated Thickness**

| | Fertilizer Expenditures | Chemical Expenditures | Farm Operating Expenditures |
|---|---|---|---|
| **1997** | 0.260*** | 0.217** | 0.254*** |
| | (0.003) | (0.013) | (0.001) |
| **2002** | 0.265*** | 0.262*** | 0.299*** |
| | (0.002) | (0.001) | (0.000) |
| **2007** | 0.320*** | 0.252*** | 0.276*** |
| | (0.000) | (0.003) | (0.000) |
| **2012** | 0.330*** | 0.240*** | 0.279*** |
| | (0.000) | (0.005) | (0.001) |
| **Counties** | 353 | 351 | 362 |

Note: *, **, and *** indicates statistical significance at the 0.1, 0.05, and 0.01 levels. P-values are listed below each coefficient in parentheses.

Table 5 shows the impact on ethanol production. In table 5 the result is in terms of millions of gallons of ethanol rather than a relative impact. I do not use a logarithmic specification for ethanol because most counties have zero ethanol production and it is important to account for zeros in the model. In 2007, the impact of the aquifer was statistically significant with an additional 100 feet of saturated thickness increasing ethanol production by 1.9 million gallons on average. The size of the impact increased in 2012, but the result is less precise and not significant at the 10% level.

**Table 5. The Impact on Ethanol Production for each 100 Feet of Saturated Thickness**

| | **Ethanol (Millions of Gallons per Year)** |
|---|---|
| **2007** | 1.909** |
| | (0.038) |
| **2012** | 2.646 |
| | (0.136) |
| **Counties** | 364 |

Note: *, **, and *** indicates statistical significance at the 0.1, 0.05, and 0.01 levels. P-values are listed below each coefficient in parentheses.

*Total Impacts across the Aquifer*

Tables 3-5 above show the impact of an additional 100 feet of saturated thickness on the outcomes and these impacts are exactly the coefficients estimated in the model. Next, I use the estimated regression models to predict the outcomes in each county with the 2009 saturated thickness and predict the outcomes under the counterfactual scenario where there is no aquifer. Then I calculate the relative change in outcomes between the scenarios for those counties that overlie the aquifer.

Table 6 shows the relative increase in outcomes due the availability of the aquifer. The first row shows the relative increase in outcomes totaled across all counties that overlie the aquifer. The second row shows the relative increase in counties that overlie the aquifer within Kansas. The availability of the aquifer increases total animal sales by 62.8% across the entire aquifer and by 40.7% in Kansas. Cattle on feed are 314.1% higher over the entire aquifer and 172.1% higher in Kansas. One reason the relative impact on livestock might be smaller in Kansas is that Kansas may be well suited to livestock production and would have a larger livestock sector than other areas in the absence of the aquifer. The results certainly indicate that the aquifer has a very substantial impact on the livestock sector. Farm operating expenditures are also much higher due to the aquifer, which have positive impacts on the local agribusinesses that sell inputs to farmers. Fertilizer, chemical, and farm operating expenditures are 52.1%, 32.5%, and 41.2% larger over the entire aquifer and 25.0%, 17.9%, and 25.3% larger in the counties overlying the aquifer in Kansas.

**Table 6. The Relative Change in Livestock and Agribusiness Sectors in 2012 Compared to Prediction Without Aquifer**

| | Animal Sales | Cattle on Feed | Fertilizer Expenditure | Chemical Expenditure | Farm Operating Expenditure |
|---|---|---|---|---|---|
| **High Plains Aquifer** | 0.628** | 3.141** | 0.521** | 0.325** | 0.412** |
| | [0.321, 0.977] | [1.003, 5.624] | [0.217, 0.772] | [0.010, 0.547] | [0.191, 654] |
| **Kansas** | 0.407** | 1.721** | 0.250** | 0.179** | 0.253** |
| | [0.194, 0.718] | [0.447, 4.021] | [0.101, 0.391] | [0.053, 0.312] | [0.111, 0.450] |

Note: ** indicates statistical significance at the 0.05 level. The numbers in brackets below the main estimate represent the 95% confidence interval.

Table 7 shows the relative *decrease* in outcomes if the aquifer were not available. These calculations are from the same model predictions as in table 6, but represent a different perspective of what would happen if the aquifer were not available. Losing the aquifer would decrease total animal sales by 38.6% across the entire aquifer and by 28.9% in Kansas. Cattle on feed would decrease by 75.8% over the entire aquifer and 63.2% in Kansas. Fertilizer, chemical, and farm operating expenditures would decrease by 34.3%, 24.6%, and 29.2% over the entire aquifer and 20.0%, 15.2%, and 20.2% in the counties overlying the aquifer in Kansas.

**Table 7. The Relative Change in Livestock and Agribusiness Sectors with No Aquifer Compared to 2012 Levels**

| | Animal Sales | Cattle on Feed | Fertilizer Expenditure | Chemical Expenditure | Farm Operating Expenditure |
|---|---|---|---|---|---|
| **High Plains Aquifer** | -0.386** | -0.758** | -0.343** | -0.246** | -0.292** |
| | [-0.494, -0.243] | [-0.849, 0.501] | [-0.436, -0.178] | [-0.353, -0.091] | [-0.395, -0.160] |
| **Kansas** | -0.289** | -0.632** | -0.200** | -0.152** | -0.202** |
| | [-0.418, -0.162] | [-0.801, -0.309] | [-0.281, -0.091] | [-0.234, -0.050] | [-0.310, -0.100] |

Note: ** indicates statistical significance at the 0.05 level. The numbers in brackets below the main estimate represent the 95% confidence interval.

Assuming that the relative impact in GMD 5 is similar to the impact in Kansas, I can calculate the change in outcomes in GMD 5 if the aquifer could not be used for irrigation. Total animal sales in GMD 5 are about $817.2 million dollars. Losing irrigation from the aquifer would reduce animal sales by 28.9% or $236 million. There are roughly 337,000 head of cattle on feed sold for slaughter in GMD 5.. Losing irrigation from the aquifer would decrease cattle on feed sold for slaughter by 213,200 head. Fertilizer expenditures would decrease by $22.6 million from the current $112.9 million. Chemical expenditures would decrease by $10.7 million from the current $70.5 million. Total farm operating expenditures would decrease by $259.8 million from the current $1.29 billion.

## Limitations and Caveats

The analysis in this chapter is a long run analysis. That is, I compare the outcomes in counties with irrigation to those that never had irrigation. Investors in the livestock sector in the 1960s to 1980s likely predicted substantial corn production in the aquifer region and invested in livestock infrastructure to capitalize on the local grain production. Now livestock producers have sunk costs in infrastructure in the region that create an incentive to stay within the region even if corn production decreases. Therefore, the short run impact of a reduction in water use may not lead to as large of a loss in the livestock sector as the long run impact if the aquifer had never existed.

The impact of a reduction in water use on chemical and fertilizer expenditures is likely to be similar in the short run and the long run, but the impact is not likely proportional to the total impact. That is, chemical and fertilizer expenditures could decrease slowly for small reductions in water use and then decrease more rapidly for larger reductions in water use.

One limitation of my study is that we assume the impact of 100 feet of saturated thickness has the same proportional impact on outcomes across the aquifer. This assumption is necessary because I cannot estimate an impact using only data from GMD 5 because there are too few counties to obtain a reliable statistical estimate.

## Technical Appendix

The results in this report on based on regressions of the following form:

$$\ln(y)_{it} = \beta_t ShareST_i + \boldsymbol{\theta}_t \boldsymbol{X}_i + \alpha_{st} + \varepsilon_{it},$$

where $\ln(y)_{it}$ is the logarithm of the respective outcome in county $i$ and year $t$, $ShareST_i$ is the share of the county overlying the aquifer times the average saturated thickness in the county, $\boldsymbol{X}_i$ is a set of other control variables, $\alpha_{st}$ is a set of state-year fixed effects (i.e., a binary variable for each state in each year), and $\varepsilon_{it}$ is the error term. When I estimate regressions for ethanol, the dependent variable is million gallons of production rather than the logarithm of production. I estimate a separate effect of the aquifer on outcomes in each year so $\beta_t$ differs by year. The controls included in $\boldsymbol{X}_i$ include the proportion of the county in different soil groups, the soil suitability for corn and wheat production, average precipitation and temperature, degree days between 10°C and 29°C, degree days above 29°C, longitude, and latitude. Standard errors are calculated by clustering at the county level. I estimate 95% confidence intervals in tables 6 and 7 using a bootstrap routine that is clustered at the county level.

# Chapter 3. Corn yield-water use relationships and the economic impact of restrictions on water use

Nathan P. Hendricks

Isaya Kisekka

Vaishali Sharda

## Highlights

- We calibrate a crop yield simulation model and apply it to the type of sandy soils common in GMD 5.
- The yield simulations are incorporated into an economic model that determines the irrigation strategy the maximizes expected net returns over 30 years of historical weather.
- The model is used to estimate the change in net returns due to different hypothetical allocations on water use.
- Results indicate that corn yields are highly responsive to the amount of water applied so it becomes optimal to reduce irrigated acreage in response to quotas of 11.5 inches or less.
- A 15% reduction in water use would decrease returns by $7.30/acre using the model's baseline water use or $27.80/acre using historical baseline water use.
- A 30% reduction in water use would decrease returns by $27.80/acre using the model's baseline water use or $40.33/acre using historical baseline water use.

## Corn yield-water use relationship

*Methods*

DSSAT (Decision Support System for Agrotechnology Transfer) CERES Maize crop model was calibrated using experimental data from western Kansas. The model was tested for its ability to predict corn yield response over a wide range of irrigation amounts. The model was then applied to study the yield response to various irrigation strategies using soil characteristics, weather and climate data, and other management practices typical of the region managed by WaterPack within GMD 5.

During the testing phase the model showed the expected reduction in yield with decrease in irrigation amount. Irrigation of more than 15 inches (400 mm) did not result in increase in yield under southwest Kansas soil and climatic conditions over a 17-year period from 2000 to 2016.

The model was used to simulate corn yields with Pratt Loamy Fine sandy soils common in GMD 5 and using historical weather data from St. John, KS. The weather data was obtained from High Plains Regional Climate Center (https://hprcc.unl.edu/) and SSURGO soils data (https://websoilsurvey.sc.egov.usda.gov/) were used to run the simulations. The management practices representative of the area used in the simulations are given in table 1. The seasonal analysis feature of DSSAT was used to simulate corn yields using 30 years of daily weather data from 1986 to 2015 and for a range of soil moisture targets and irrigation frequencies (see definitions in box below).

**Table 1. Typical operations for corn production**

| Period | Operation | Description | Amount | Characterization |
|---|---|---|---|---|
| March-April | Tillage | Minimum Tillage | | |
| 1st Week of May | Planting | Corn | 30,000 seeds/ac | Full season (2750-2800) GDD |
| Preplant | Nutrient | Urea | 300 lbs/ac | |
| Irr. Freq. (Varies) | Irrigation | Sprinkler | 1 in/pass | |
| October | Harvest | | | |

**Definitions**

**Soil moisture target**: The percentage of plant available water when irrigation is triggered. For example, a soil moisture target of 60% means that irrigation is triggered when 60% of total plant available water remains (i.e., 40% of the plant available water has been depleted).

**Irrigation frequency**: The number of days that must elapse before the next irrigation can occur. This is to account for the fact that a center pivot cannot irrigate every day because the pivot needs time to travel back to the same spot.

The well capacity determines the irrigation frequency that is feasible. We assume that the farmer applies 25 mm (0.98 inches) in each irrigation application. Assuming that the farmer irrigates a center pivot with 125 acres, a well capacity of 590 gallons per minute

(GPM) is required to irrigate with a frequency of 4 days. To irrigate every 2 days would require a well capacity of 1,179 GPM. We assume that farmers have a well capacity of roughly 600 GPM so we only consider frequencies of 4 days or larger in our economic model.

*Graphs of Irrigation and Yield Relationship*

Figure 1 illustrates how different soil moisture targets and irrigation frequency are related to the amount of irrigation water applied. For each combination, we calculate the average irrigation water applied across the 30 years of historical weather. When the soil moisture target is larger, then irrigation is triggered more often, and the farmer applies more water. When the frequency of irrigation is smaller the farmer applies more water also.

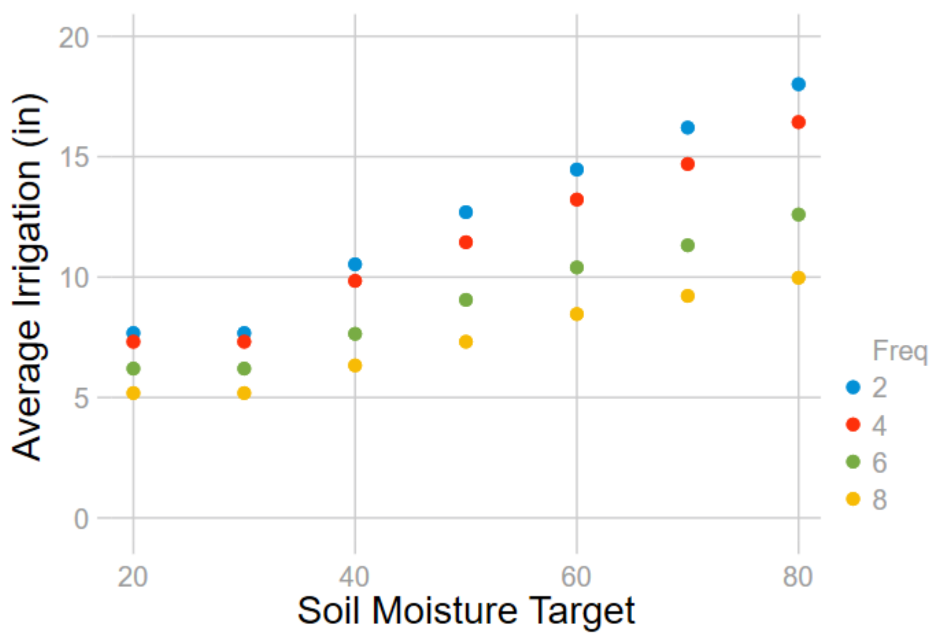



**Figure 1. Average Irrigation Water Applied for Different Irrigation Strategies**

Figure 2 illustrates the average yield for each irrigation strategy. The strategies that apply more water result in greater yields, though there are diminishing increases in yields. Increasing the soil moisture target above 60% has little effect on yields when the frequency is 2 days but has a larger impact when the frequency is 4 days.

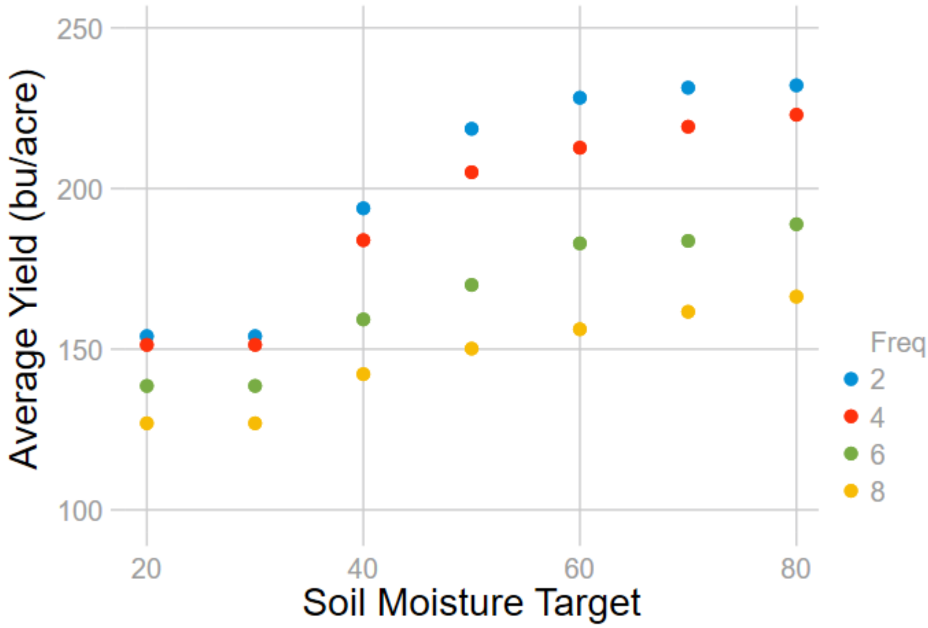



**Figure 2. Average Corn Yield for Different Irrigation Strategies**

Figure 3 shows the relationship between average water applied and average yield. These are the same data as in figures 1 and 2, but instead showing the relationship between irrigation and yield. Increasing irrigation has almost a linear impact on corn yield up to about 13 inches of applied water, where each additional inch of water applied increases corn yield by about 10.4 bu/acre. After this point, applying additional water has a diminishing impact on corn yield.

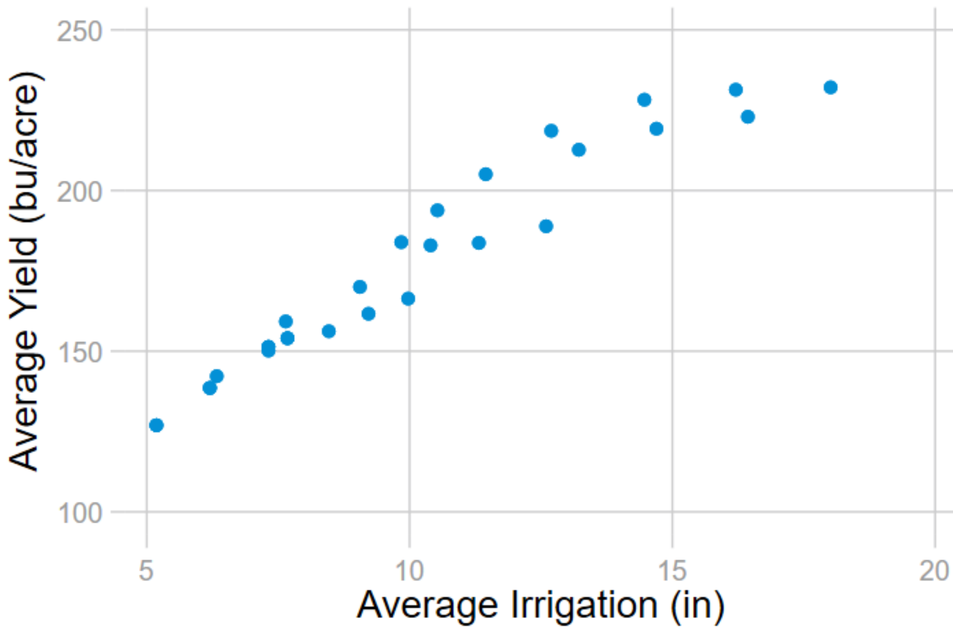



**Figure 3. Relationship between Average Irrigation and Average Yield**

## Economic Model of Water Use

*Methods*

Traditional economic models of optimal irrigation employ a single relationship between irrigation and yield (such as in figure 3) to estimate the profit maximizing amount of water to apply under average conditions. The problem with this approach is that farmers don't make decisions based on average conditions. Instead, we assume that the farmer chooses an irrigation strategy (i.e., soil moisture target and share of field irrigated) that maximizes his expected net return across different weather conditions. By choosing an optimal soil moisture target, the farmer naturally applies more water in dry years. Our estimates indicate that choosing an irrigation frequency has small as possible given the well capacity (i.e., 4 days for a well capacity of 600 GPM) is always optimal so the farmer only chooses the soil moisture target and share of field to irrigate.

The crop simulation model estimates corn yield for different soil moisture targets. However, the increments of soil moisture targets considered are fairly wide with only every 10 percentage points modeled. To resolve this limitation, we fit flexible nonlinear functions—natural cubic splines—for the relationships between the soil moisture target and irrigation water applied and the soil moisture target and corn yield. Different functions are estimated for each year. Figures 4 and 5 illustrate these functions for each year of weather data with an irrigation frequency of 4 days. The nonlinear functions fit the simulated data very well. Therefore, we use these nonlinear functions to predict irrigation water applied and crop yield for all soil moisture targets between 20% and 80% in increments of 1%.

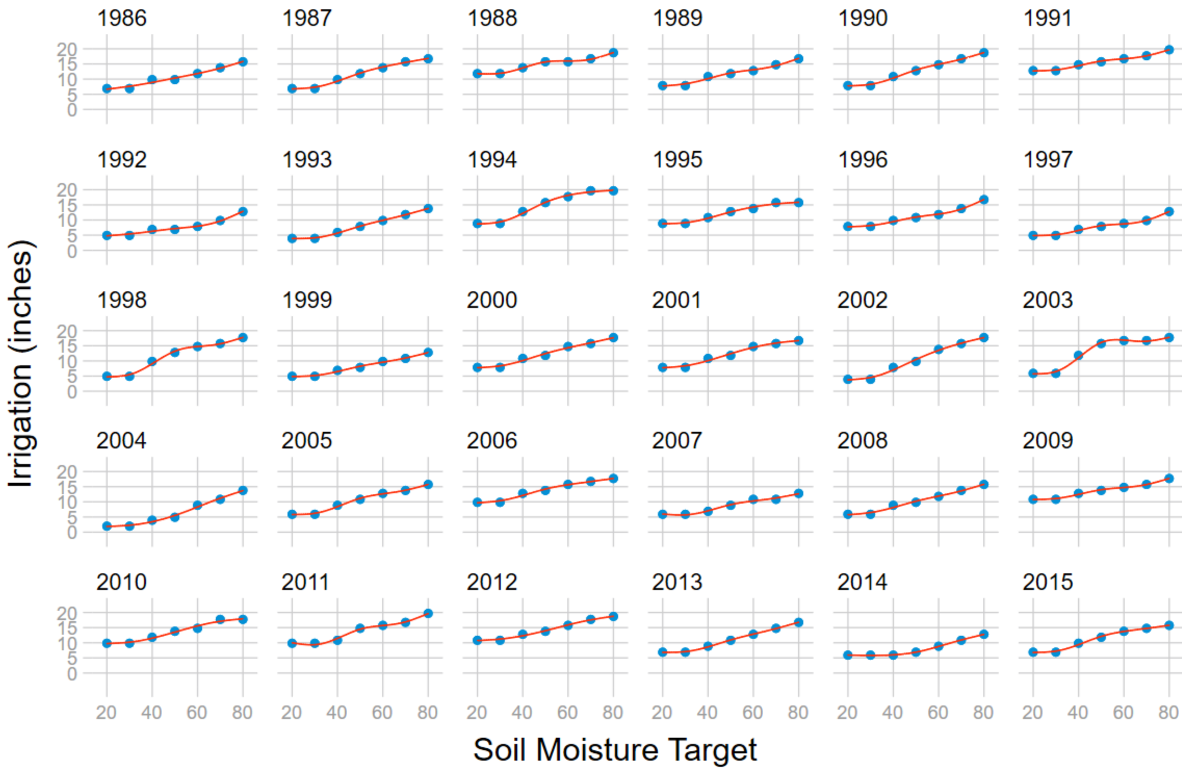



**Figure 4. Fitted Nonlinear Function of Soil Moisture Target and Irrigation Water Applied by Year for Irrigation Frequency of 4 Days**

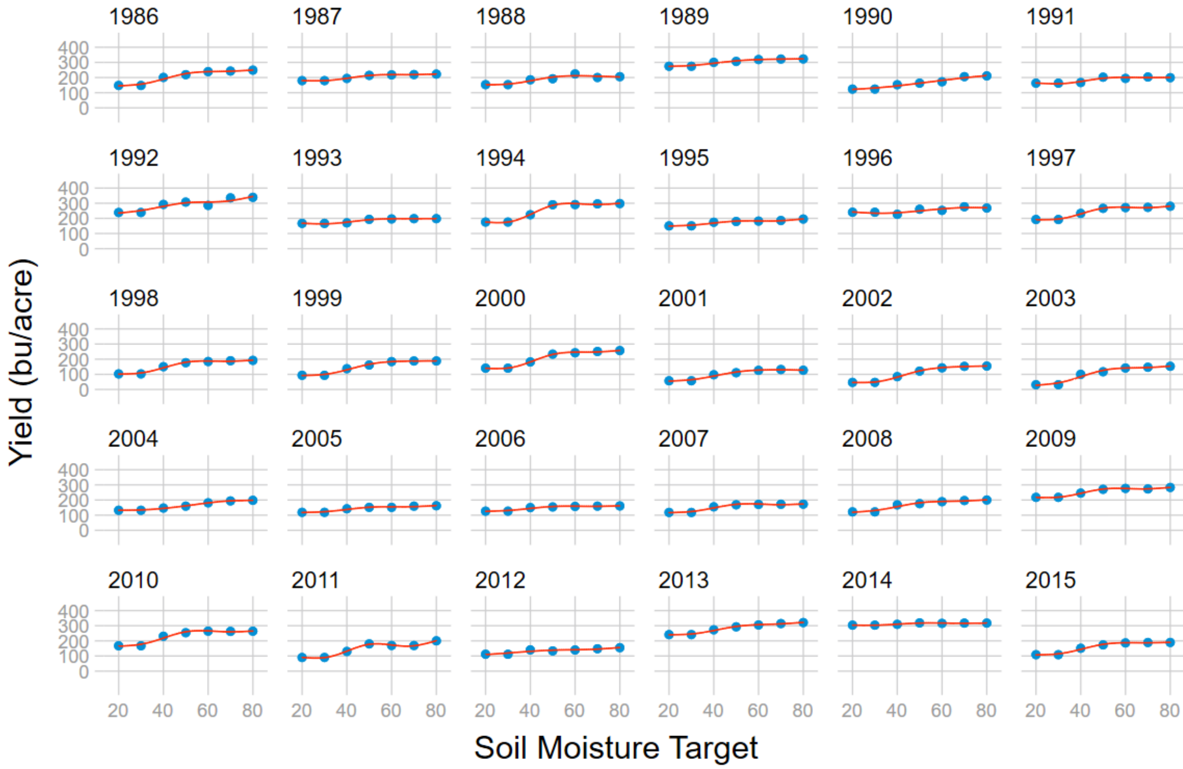



**Figure 5. Fitted Nonlinear Function of Soil Moisture Target and Corn Yield by Year for Irrigation Frequency of 4 Days**

We assume that the farmer irrigates 125 acres of corn using a center pivot system. We allow for the possibility that the farmer can reduce irrigated acreage as one way to optimally adapt to a restriction. The farmer can choose to irrigate 100%, 75%, 50%, 25%, or 0% of the center pivot. We consider increments of 25% because it is difficult to reduce irrigated acreage by a small amount with a center pivot, but a farmer could irrigate ¾ or ½ of the circle. If the farmer reduces irrigated acreage, then we assume that net returns on the portion of land not irrigated decrease by the difference between irrigated and nonirrigated cash rental rates.

We use the predicted yield and irrigation water applied to estimate the net returns for every possible soil moisture target. Then we calculate the average net returns across the 30 years of weather for each irrigation strategy. The optimal irrigation strategy is the one that gives the greatest average net returns. The optimal irrigation strategy with a hypothetical water restriction is the strategy with the highest average net returns that applies less irrigation water than the allocated amount (i.e., the quota).

The economic impact of the restriction is the difference between the average net returns of the optimal strategy with the allocated quantity and the strategy with no allocation. Note that the estimated net return is not the key result of interest since it will be specific to the price and cost of production scenario. Instead, the key results of interest are the optimal irrigation strategy and the *change* in net returns due to an allocation.

*Parameter Assumptions in the Economic Model*

We obtain price and cost data—except for the energy cost of applying water—from the 2018 Kansas Farm Management Guide Cost-Return Budget (i.e., KSU budget) for irrigated corn in South Central Kansas (available at: https://www.agmanager.info/farm-management-guides-0). Our economic model only considers costs that change with the amount of irrigation water applied. That is, our economic model accounts for the fact that decreasing water use decreases revenue due to lower yield but a farmer can also decrease production expenses when applying less water. Since we only account for costs that depend on water applied, our estimate of the overall net return at a given amount of water applied is not accurate, but our estimate of the *change* in net returns from using less water is accurate.

**Table 2. Assumptions about Expenses that Change with Water Applied**

| Expense Category | Minimum | Reduction in Expense per inch of Reduction in Water Applied | Maximum |
|---|---|---|---|
| Seed ($/acre) | $57.75 | $3.82 | $122.06 |
| Fertilizer ($/acre) | $41.13 | $2.47 | $84.05 |
| Field Operations ($/acre) | $115.78 | $3.07 | $182.18 |
| Irrigation System Repair and Maintenance ($/acre) | $2.64 | $0.33 | $5.28 |

Table 2 lists our assumptions about expenses that change with the amount of water applied. The KSU budget lists expenses for low yield (8 inches of water; 180 bu/acre), average yield (12 inches of water; 210 bu/acre), and high yield (16 inches of water; 240 bu/acre) scenarios. The maximum expense listed in table 2 is equal to the irrigated expense in the high yield scenario of the KSU budget. The reduction in expense per inch or reduction of water applied is the difference between the expense in the high yield and low yield scenarios divided by 8 inches of water reduced. We also ensure that expenses cannot be less than the expense for nonirrigated corn. The minimum expense in table 2 is the respective cost for nonirrigated corn from the KSU budgets. The exception is the cost of irrigation system repair and maintenance. We assume that these expenses do not decrease beyond the expenses in the low yield scenario in the irrigated KSU budget.

Table 3 lists assumptions about other parameters used in the model. We assume the price of corn is $3.61/bushel as listed in the KSU budget. The difference between irrigated and nonirrigated cash rental rates in the south central district was $82/acre in 2017 according to district-level data from National Agricultural Statistics Services (NASS), USDA.

**Table 3. Assumptions about other Parameters**

| Parameter | Value |
|---|---|
| Price of Corn ($/bushel) | $3.61 |
| Difference between Irrigated and Nonirrigated Cash Rent ($/acre) | $82 |
| Energy Cost to Apply Water ($/acre-inch) | $0.74 |

Table 3 also notes that we assume the energy cost to apply irrigation water is $0.74/acre-inch ($8.92/acre-foot). The energy cost for applying irrigation water is calculated using the same formulas in the KSU Irrigation Energy Cost spreadsheet (available at: https://www.agmanager.info/decision-tools). We assume natural gas as the energy source with a price of $3.95/Mcf. The price of natural gas is the average industrial price in Kansas from June to August of 2017 obtained from the U.S. Energy Information Administration (EIA). The pressure of the irrigation system is assumed to be 20 psi. The efficiency of the pumping unit is assumed to be 82% of NPPPC (Nebraska Pumping Plant Performance Criteria). This efficiency assumption is based on recent tests of pumping units in Nebraska that found an efficiency of 82% for diesel and 84% for propane units.[5] We assume the depth to water is 38 feet. This is the average depth to water in 2013-2015 of all irrigation wells in GMD 5 according the Kansas Geological Survey interpolated section-level database.

[5] Study is available at: https://www.researchgate.net/publication/242492142_Updating_the_Nebraska_Pumping_Plant_Performance_Criteria

## Results

Our model indicates that the strategy that maximizes expected net returns is a soil moisture target of 80% and irrigating the entire field. This results in an irrigation application of 16.5 inches on average and corn yield of 224 bu/acre. The predicted irrigation water applied and corn yield are reasonable for the region. Figure 6 shows a histogram of average water applied to corn on fine sandy loam soils in Pawnee County. Data on water use are from the official water use records. Average water applied is 12.9 inches but most wells have average water use between 11 and 16 inches. Our optimal water use seems a little high for the region but if we assume a well capacity of 1,100 GPM the optimal water use is 14.3 inches with a yield of 230 bu/acre. There is lots of heterogeneity in the region and it is difficult to replicate observed behavior exactly. Recent average irrigated corn yields reported by USDA for counties in GMD 5 are between 190 and 210 bu/acre. We conclude that the model is useful for predicting the impacts of restrictions on water use because it approximates observed irrigation behavior reasonably well.

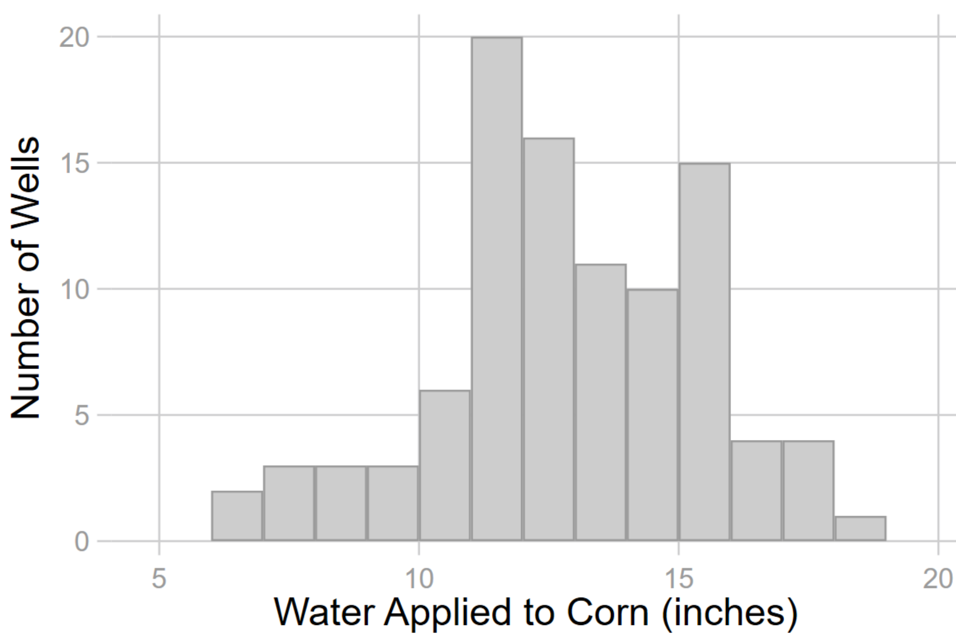



**Figure 6. Histogram of Average Water Applied to Corn on Fine Sandy Loam in Pawnee County**

The strategy that maximizes expected net returns does not minimize risk that the producer faces. For example, a strategy that applies only 13.4 inches of water has an average net return $8/acre less than the profit maximizing strategy. However, in the worst year, net returns are $16/acre larger than the profit maximizing strategy. The strategy that applies less water gives higher net returns in the worst year because the farmer had smaller irrigation costs but similar yields. Therefore, it is important to recognize that producers may rationally apply different amounts of water depending on their preferences to reduce their risk exposure.

Next, we simulate the impact of quota allocations on farm net returns. We assume that the allocation is imposed as a multi-year allocation so that average water use must be less than or equal to the allocated quantity. If the allocation is imposed such that water use in every year must be less than the quota, then the loss in net returns would be larger than our estimates.

Figure 7 shows the impact of different quotas and the change in net returns compared to the profit maximizing strategy. Table 4 gives the same information as figure 7 and lists the optimal irrigation strategy for each allocated quantity. The profit maximizing average water applied is 16.5 inches, so quotas larger than this amount result in no loss in net returns.

Figure 7 has the shape we expect where there are diminishing returns to additional water use above 12.5 inches. In other words, net returns are similar for water use above 12.5 inches so a quota between 12.5 and 16.5 inches does not have a large impact on net returns. For these relatively large quotas, farmers respond by decreasing the amount of water applied to corn but still irrigating the entire field.

However, corn yields are highly responsive to water applied (see figure 3) and begin decreasing rapidly due to further decreases in water use once the quota reaches 11.5 inches or less. At a quota of 11.5 inches it becomes optimal for the farmer to only irrigate 75% of the field at the rate that maximizes irrigated profitability and lose $82/acre on the portion converted to nonirrigated. The quota of 11.5 inches results in a loss in net returns of $27.8/acre on average across the 125 original acres. This same process continues of reducing intensity of water use and then reducing irrigated acreage as the quota becomes smaller. The decrease in irrigated acreage in increments of 25 percentage points is what leads to the stair step change in returns. When the quota reaches 3 inches, it is no longer profitable to irrigate and famers lose $82/acre annually—the difference between irrigated and nonirrigated rental rates.

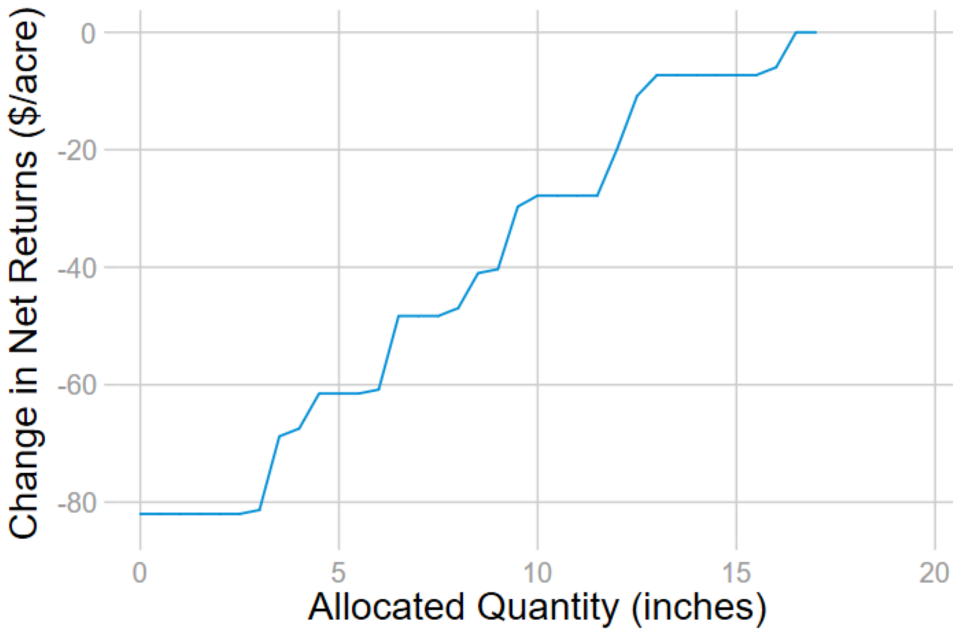



**Figure 7. The Impact of Quota Allocations on Net Returns**

We estimate the impact of a 15% reduction in water use and a 30% reduction in water use with our model. One challenge is that our model predicts a slightly larger optimal water use than the historical water use in the region, so the impact depends on whether we calculate the percent reduction from the model's optimal use or the observed historical use as the baseline. Average optimal water use in the model is 16.5 inches and average historical use on corn in Pawnee county with similar soils is 12.9 inches. A 15% reduction in water use implies an allocated quantity of roughly 14 inches or 11 inches depending on modeled or historical baseline use. A 30% reduction in water use implies an allocated quantity of roughly 11.5 inches or 9 inches. The results in table 4 indicate that a 15% reduction in water use would decrease returns by $7.30/acre using the model's baseline water use or $27.80/acre using historical baseline water use. A 30% reduction in water use would decrease returns by $27.80/acre using the model's baseline water use or $40.33/acre using historical baseline water use.

**Table 4. Optimal Irrigation Strategies and Change in Net Returns for Different Quota Allocations**

| Allocated Quantity (in) | Soil Moisture Target | Percent of Field Irrigated | Change in Net Returns ($/acre) |
|---|---|---|---|
| 16 | 77 | 100 | -$5.96 |
| 15.5 | 58 | 100 | -$7.30 |
| 15 | 58 | 100 | -$7.30 |
| 14.5 | 58 | 100 | -$7.30 |
| 14 | 58 | 100 | -$7.30 |
| 13.5 | 58 | 100 | -$7.30 |
| 13 | 58 | 100 | -$7.30 |
| 12.5 | 54 | 100 | -$10.84 |
| 12 | 51 | 100 | -$19.83 |
| 11.5 | 58 | 75 | -$27.80 |
| 11 | 58 | 75 | -$27.80 |
| 10.5 | 58 | 75 | -$27.80 |
| 10 | 58 | 75 | -$27.80 |
| 9.5 | 55 | 75 | -$29.68 |
| 9 | 51 | 75 | -$40.33 |
| 8.5 | 80 | 50 | -$41.00 |
| 8 | 77 | 50 | -$46.96 |
| 7.5 | 58 | 50 | -$48.30 |
| 7 | 58 | 50 | -$48.30 |
| 6.5 | 58 | 50 | -$48.30 |
| 6 | 51 | 50 | -$60.83 |
| 5.5 | 80 | 25 | -$61.50 |
| 5 | 80 | 25 | -$61.50 |
| 4.5 | 80 | 25 | -$61.50 |
| 4 | 77 | 25 | -$67.46 |
| 3.5 | 58 | 25 | -$68.80 |
| 3 | 51 | 25 | -$81.33 |
| 2.5 | 80 | 0 | -$82.00 |

## Limitations and Caveats

Our modeling framework has several limitations, which we acknowledge here. First, the accuracy of our model depends on the accuracy of the crop simulation model. While we apply a state-of-the-art crop simulation model, it may not perfectly represent the corn yield response in GMD 5. Second, our economic model assumes the farmer has perfect information about the relationship between crop yield and water use because the farmer maximizes profit based on the simulation output. In reality, farmers have uncertainty about this relationship which likely leads them to apply more water to avoid the risk of large yield losses because they don't know exactly what quantity of water will begin to trigger these large yield losses.

Third, we do not account for the management cost of implementing precise irrigation schedules assumed by the crop simulation models. For example, we assume that irrigation is triggered at certain soil moisture targets, but we do not account for the cost to the farmer of monitoring the soil moisture to determine when to irrigate. These costs could include soil moisture probes or labor to monitor soil moisture. Some farmers may find it less expensive to irrigate more frequently rather than incur the cost of monitoring soil moisture. Fourth, our model applies to a single type of soil with weather from the St. John weather station and does not represent the varying conditions across GMD 5.

Despite these limitations, our model provides a useful prediction of the impact of quota allocations. Much of the area in GMD 5 has sandy soils and the impact of quota allocations is likely to be different than in other areas of the state with silt loam soils. Our model leverages a state-of-the-art crop simulation model to provide predictions of the impacts in these conditions.