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Using Regression Analysis to Determine Land Cover Impacts on Groundwater Levels in the High Plains

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USING REGRESSION ANALYSIS TO DETERMINE LAND COVER IMPACTS ON GROUNDWATER LEVELS IN THE HIGH PLAINS

by

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Many parts of the High Plains region are facing declining aquifer levels, which threatens the long-term viability of irrigated agriculture. Furthermore, some areas of the High Plains region, like the Republican River Basin in Nebraska, need to keep groundwater levels high enough in the short-term to ensure that hydrologically connected rivers have enough streamflow to fulfill surface water obligations, such as Nebraska's interstate river compact with Colorado and Kansas. To better manage groundwater, it is important to understand the unintended effects of policies that may not be aimed at groundwater conservation, such as the USDA- Conservation Reserve Program (USDA-CRP). The CRP pays farmers to take cropland out of production and put it into conservation covers, mainly grassland. Environmental benefits include reduced soil erosion, improved surface water quality, and increased wildlife habitat. But, the changes in land cover due to CRP enrollment could also impact the infiltration of precipitation through the soil, thus changing groundwater recharge. The paper estimates the potential effect of CRP on groundwater levels using data from Ogallala Aquifer region of Kansas and the Republican River Basin portion of Nebraska. The analysis relates disaggregated aquifer level data with spatial land cover data, weather, soil, and groundwater extraction data. Grassland land cover is used as a proxy for grassland put in by CRP. Findings suggest that grassland leads to a lower yearly recharge rate than common crop land

covers in the Republican River Basin of Nebraska. Recharge in the Ogallala Aquifer region of Kansas seems too small to have a detectable impact though. These results imply that in addition to other environmental benefits, policymakers need to pay attention to the impact of CRP enrollment on regional aquifer conditions in regions where groundwater levels are a concern but can expect recharge to take place.

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CHAPTER 1

INTRODUCTION

Worldwide, population growth and climate change are putting stress on the available water resources needed for agricultural production, other economic activity, domestic consumption, and ecosystem services. Areas like the High Plains Aquifer (HPA) region of the United States are heavily dependent on groundwater for irrigated agriculture, and about 90 percent of all water used in the HPA region is from groundwater (Dennehy, 2000). The HPA covers parts of eight states (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming), with the greatest use in any single state in Nebraska. In 2012, Nebraska had more irrigated acres than any other state (8.3 million acres), and almost 92 percent of the irrigation water used in the state was from groundwater (estimated at 7.4 million acre-feet from groundwater).[1] Kansas, by comparison, had 2.85 million irrigated acres in 2012, with about 98% of irrigation coming from groundwater (estimated at 3.4 million acre-feet from groundwater). However, many parts of the HPA region are facing declining aquifer levels, putting the long-term economic viability of the region in peril. The region is estimated to have reduced recoverable groundwater by 273.2 million acre-feet since predevelopment (around 1950) to 2015 with 2013 to 2015 accounting for a decline of 10.7 million acre-feet (McGuire, 2017). In addition, groundwater levels in several areas are hydrologically connected to surface water flows. In areas like the Republican River Basin (RRB) of Nebraska, water managers are mandated with ensuring that hydrologically connected rivers have

[1] See the 2013 U.S. Department of Agriculture Farm and Ranch Irrigation Survey (USDA-FRIS) at https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/ for more information.

enough streamflow to fulfill Nebraska's surface water obligations for the Republican River interstate compact with Colorado and Kansas.

Therefore, there exists a strong interest in finding and using policies that will maintain or increase groundwater levels, or in redirecting policies that may be harmful to that objective. Assessing the impact of current government programs, such as the USDA Conservation Reserve Program (CRP), is an important step in that process. The CRP is a voluntary conservation program that pays farmers to take environmentally susceptible cropland out of production for 10 to 15 years to achieve environmental benefits. This involves putting the land into a new land cover, such as grassland, woodland, or wetlands. The CRP was established in the 1985 U.S. Farm Bill as a program to reduce soil erosion, and it has been shown to have erosion reduction, surface water quality, and wildlife habitat benefits (Ribaudo et al., 1990; Hansen, 2007). However, CRP can affect aquifer levels, as it pays farmers to shift land from crop production to conservation land covers, mainly grassland, which might alter infiltration of precipitation and subsequent groundwater recharge. CRP rental payments are based on non-irrigated rental rates, so irrigation reduction through enrollment of irrigated acres is not expected. Some land retirement programs, such as the Conservation Reserve Enhancement Program (CREP) as practiced in some HPA states, do target irrigated acres. While CRP is known to have several positive environmental benefits, such as reduced soil erosion; the connection between CRP and groundwater recharge is less known. The hydrology literature suggests that differences in groundwater recharge between grassland (expected CRP land cover) and cropland exist in the HPA, with grassland leading to a lower groundwater recharge rate (Dugan and Zelt, 2000). Any unintended effect of CRP is especially important because of recent changes in the amount of land enrolled in the program. Largely due to reductions in the CRP acreage cap, total enrolled acreage in CRP has declined from 36.8 million acres in 2007 to 23.9 million acres in 2016. CRP acreage in the HPA states decreased from 14.7 million acres in 2007 to 10.1 million acres in 2016.[2] This reduction in acreage could have measurable effects on aquifer levels if the land coming out of CRP is put into crop production.

The goal of this paper is to estimate the impact of the conversion of cropland to grassland, the predominant land cover associated with CRP, on aquifer levels. this paper's analysis uses USGS groundwater monitoring wells and other spatial data from the Republican River Basin in Nebraska and the Ogallala Aquifer in Kansas for the 2007 to 2015 period. These regions were chosen due to the ongoing groundwater quantity concerns and availability of data. This paper uses a spatial buffer to determine annual local land cover, weather, and groundwater extraction around each observation well. The change in depth to the aquifer measured from observation wells is related to the local data using a fixed effects model. Grassland is used as a proxy for CRP-induced land cover changes. The results suggest that grassland covers, and therefore CRP grassland, will lead to decreased recharge compared to the common crops in the Republican River Basin of Nebraska (corn and soy). No difference is detected between grassland and common crops (corn and winter wheat) in the portion of Kansas over the Ogallala Aquifer. The findings suggest a need to balance the known environmental benefits of CRP and associated programs like the USDA Conservation Reserve Enhancement Program (USDA-CREP) with expected regional impacts on groundwater and available funding. The results can inform policymakers and agency personnel to better target CRP enrollment, and to incorporate any positive or negative externalities on groundwater levels associated

[2]This information is available on the USDA-Farm Service Agency website at https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index

with changes in land cover.

This article make several contributions to the existing literature. The first contribution is to the economics literature by considering the impact of CRP land cover change on aquifer recharge. Previous economics work on CRP has examined the environmental and economic benefits (Ribaudo et al., 1989, 1990; Hansen et al., 1999; Hansen, 2007), methods of targeting enrollment to attain environmental goals or greater economic benefits (Ribaudo, 1989; Szentandrasi et al., 1995; Babcock et al., 1996; Feather et al., 1999; Wu et al., 2001; Feng et al., 2004), what happens to land exiting CRP (Skaggs et al., 1994; Johnson et al., 1997; Roberts and Lubowski, 2007; Secchi et al., 2011; Hellwinckel et al., 2016), and possible slippage issues (Wu, 2000; Wu et al., 2001; Roberts and Bucholtz, 2005; Wu, 2005; Roberts and Bucholz, 2006). This paper adds to the literature by considering the potential unintended impact of CRP on aquifer levels through land cover based recharge change. Ribaudo et al. (1989) and Ribaudo et al. (1990) do consider irrigation reduction impacts on aquifer levels through possible enrollment of marginal irrigated acres into CRP. The widespread enrollment of irrigated acres into CRP specifically is not expected, given that CRP payments are based on non-irrigated rental rates. Similar programs (e.g. CREP) that are targeted at irrigated acres might achieve notable irrigation reduction, at a higher cost than CRP. CRP land cover change, and any related recharge change, is a more widespread factor for aquifer impacts that needs to be considered. Fulfilling that need is where this paper stands out from the economics literature.

The paper makes an additional contribution through its method of estimating aquifer recharge, in contrast to methods generally used in hydrology. In contrast to the hydrology literature, this paper uses regression analysis to estimate expected regional impacts of land cover, weather, and groundwater extraction on groundwater level changes and uses the regression results to make inferences about recharge. Scanlon et al. (2002) provide a good overview of standard hydrological methods for estimating recharge. Table 1.1 provides a summary of methods relevant to previous research in the study area. This paper's method has several advantages. First, by using water level data, the method looks at actual groundwater changes. Additionally, looking at the saturated zone allows us to integrate factors of recharge over an area, which in turn allows for an understanding on how the local extent of land cover impacts recharge. Other methods that are based on the unsaturated zone provide a more focused point estimate, but cannot fully account for recharge conditions beyond that point. Another advantage of this paper's method is the ability to account for the impact of irrigation, as some hydrological methods are not reliable in irrigated areas. The main disadvantage of this paper's method is that there is uncertainty the lag between when precipitation occurs and when it reaches the water table. While using lagged values can reduce this concern, it does not eliminate it.

Groundwater Recharge

Groundwater recharge is expressed as a flux (to the water table), and in the hydrological setting, a flux measures the volume of water that passes through an area in a given amount of time. This can be simplified as $ft^3/ft^2/year = ft/year$. Estimates of future, or potential, recharge can be given by water fluxes at earlier stages, such as what water passes through the root zone of vegetation into the unsaturated zone. Water in the unsaturated zone can take some time to reach the saturated zone and might move elsewhere (e.g. lateral flows), and provide recharge at a different location. As such, potential recharge does not equal actual recharge.

Table 1.1: Summary of Reviewed Hydrological Methods

Model	Summary	Used By
Water Table Fluctuation	Measures recharge from rises in the water table	Scanlon et al. (2005)
Chloride Mass Balance	Equates Chloride Mass leaving and exiting a system	Scanlon et al. (2005), McMahon et al. (2006), Nolan et al. (2007), Scanlon et al. (2012)
Tracer Front Displacement	Tracks movement of a tracer pulse through the soil	McMahon et al. (2003), McMahon et al. (2006), Scanlon et al. (2005)
Water Balance/Budget	Equates water entering and exiting a system	Dugan and Zelt (2000),Szilagyi et al. (2003), Szilagyi et al. (2005)
Darcy's Law	Calculates recharge from hydrologic conductivity and gradients	Nolan et al. (2007)

Hydrological Methods

The Water Table Fluctuation (WTF) method is the most comparable to this paper's method. WTF also uses changes in the groundwater level to infer about recharge using the equation $R = W * S$ where R is recharge, W is the water table increase, and S is the specific yield (the water content of soil). The major shortcoming of the WTF method is that it can only account for increases in the water table, and any concurrent losses to the water table (such as groundwater extraction) will lead to an underestimation of the water added to the aquifer through recharge. In contrast, this paper's method uses extraction as an explanatory variable in the regression analysis to incorporate both gains from precipitation and losses from extraction. The Chloride Mass Balance (CMB) method is a common tracer method that assumes a steady state exists in the movement of chloride through the soil. Chloride is naturally produced in the atmosphere and is deposited into the soil (either by precipitation or dry deposition) which does not produce chloride. Chloride can also be deposited by human means, such as by applying irrigation water or fertilizers with chloride in it. The Chloride Mass Balance method equates the chloride mass flux into a system with the chloride mass flux out of it. The chloride mass flux out of the system will be mixed with water, so dividing the mass of chloride entering the system (M) by the concentration of chloride in the water flux out of the system (C) provides an estimate of recharge (R); $R = M/C$. This equation is only valid when the mass of chloride moving through the system stays relatively constant (exists in a steady state). This can be checked by taking a soil core and plotting chloride levels by depth to make sure it reaches a steady state in the soil profile a few feet below the surface. The distinction between recharge from precipitation and irrigation return flows cannot be distinguished, and not accounting for all sources of chloride will result in an underestimation of recharge. The CMB can be applied using the chloride concentration in the saturated or unsaturated zone, but using data from the unsaturated zone cannot account for recharge at nearby locations that have different rates of recharge. The primary shortcomings of the CMB method are a reliance on the existence of a steady state, and the inability to distinguish different sources of recharge.

The Tracer Front Displacement (TFD) method also utilizes tracer chemicals but instead estimates recharge based off the movement of a specific large concentration (pulse) of the tracer through the soil. The main equation of TFD methods is $R = \delta D/\delta T$ where R is recharge, D is depth of the tracer pulse and T is time. This method can utilize chloride in cases where there was a large chloride build up in a rangeland cover root zone that was released when the land was switched to irrigated agriculture. The addition of agricultural chemicals can be used in a similar way. The Tritium pulses produced from nuclear testing (best seen from the 1953 start and the 1963 peak of testing) are also common choices. TFD requires a good knowledge of historical land use and can be unusable if the tracer chemical has not moved past the root zone. TFD uses data from the unsaturated zone that cannot take into account other rates of recharge.

A Water Balance/Budget method equates the water entering a system with the water leaving a system. An example model could have recharge as the left-over amount of precipitation not lost to estimated evapotranspiration or estimated run off. Models using this approach might only consider data from near the surface, so recharge estimates would not account for the impact of soil characteristics. Some variables, such as transportation, are also difficult to estimate, especially when interpolated over large areas.

Darcy's Law is an equation for the movement of fluids through porous mediums. In hydrology, it can calculate recharge when expressed as $R = -C * (dH/dz) = -C * ((dh/dz) + 1)$, where R is recharge, C is hydraulic conductivity ambient water content and H is the total head, h is the matric pressure head, and z is elevation. Hydraulic conductivity can be hard to properly estimate over large areas given its variability. The potential water loss from soil samples between their extraction and hydraulic conductivity measurement can also impact estimations.

Hydrological Papers

Several studies on recharge have examined parts of the HPA, and thus are of interest to us. Scanlon et al. (2012), Dugan and Zelt (2000), and Szilagyi et al. (2005) provide general yearly recharge maps for parts of the HPA without direct comparisons between cropland and grassland. McMahon et al. (2006) and Scanlon et al.

(2005) do compare recharge between cropland and grassland at select sites in the HPA. Nolan et al. (2007) provide an interesting comparison of regression analysis compared to other methods for measuring recharge.

Scanlon et al. (2012) interpolate estimates of recharge from 6600 wells across the HPA (excluding part of Texas) using the Chloride Mass Balance method. The map they create shows RRB yearly recharge estimates ranging from 0.08 to 2.95 inches, with the middle of the RBB mostly ranging from 0.98 to 1.97 inches and the northwest and southeast of the RRB ranging from 0.20 to 0.98 inches. The Kansas Ogallala yearly recharge estimates range from 0.08 to 0.98 inches with the larger areas of lower recharge in the center and southwest of the Kansas Ogallala region. They only account for chloride from precipitation and dry deposition, so estimations in irrigated areas may not be accurate. Furthermore, the data for the estimations come from the saturated zone, so soil cores were not checked to see if the required steady state or the CMB equation exists at the data locations.

Dugan and Zelt (2000) estimate yearly potential recharge through the root zone for irrigated and non-irrigated conditions across the HPA using a water budget model. Their non-irrigated RRB yearly recharge estimates range from 1 to 2 inches of potential recharge, and 0.25 to 2 inches for the Kansas Ogallala region. In both areas, recharge generally decreases going west. The irrigated conditions had yearly recharge estimates ranging from 1.5 to 3 inches for the RRB, with greater recharge in the western and eastern portions of the RRB, with the middle RRB having the lowest estimated recharge. The irrigated conditions for the Kansas Ogallala region are similar to the non-irrigated conditions.

Szilagyi et al. (2005) provide a recharge map of Nebraska with modified recharge estimates from Szilagyi et al. (2003). The model in Szilagyi et al. (2003) is a water budget that utilizes base flow from rivers to calculate base recharge and Szilagyi et al. (2005) makes modifications to calculate total recharge. The papers create maps for the whole state of Nebraska, but the base flow method used to estimate recharge is most relevant where there are river interactions with groundwater. Szilagyi et al. (2005) estimate yearly recharge in the RRB ranging mostly from 0.12 to 1.46 inches, but with a range of 1.46 to 2.37 inches along the eastern edge of the RRB.

McMahon et al. (2006) estimate recharge at nine sites across the HPA using data collected from soil cores to evaluate recharge comparisons between rangeland and irrigated cropland. Recharge was mainly estimated with tritium based tracer front displacement (TFD) models. However, CMB was used in two rangeland settings where the tracer displacement front models were unusable. The nine sites include three sites in Kansas included in McMahon et al. (2003). McMahon et al. (2006) add six sites split evenly between Nebraska and Texas. The sites in each state are further split between one rangeland site and two irrigation cropland sites. The six sites in Kansas and Nebraska are within this paper's study area. The measured water fluxes through the unsaturated aquifer at rangeland sites are 2.76 and 0.20 inches per year for Nebraska and Kansas, respectively, while the water fluxes at irrigated sites are 4.02 and 4.37 inches per year in Nebraska, and 2.13 and 1.54 inches per year in Kansas. However, McMahon et al. (2006) find agricultural chemicals in the water table which would not have reached the water table at the estimated recharge rates given the land use history. This could imply nearby preferred paths in the soil that provide greater recharge, leading to some concern about the validity of the results.

Scanlon et al. (2005) use about 20 soil cores split among three areas in the HPA portion of Texas and one area in Nevada (not in the HPA) to evaluate recharge differences between rangeland, dryland crops, and irrigated crops. They estimate recharge at the Nevada site and one Texas site using the CMB and TFD models. The TFD models track chloride and nitrate pulses at irrigation cropland sites recently converted from rangeland. Less direct methods were used to evaluate recharge expectations for the remaining soil cores. Apart from the soil cores, they also use the water table fluctuation (WTF) model for the non-irrigated regions of Texas. Results from the CMB and TFD models find that irrigated cropland in Nevada had recharge between 5.1 and 25.2 inches per year and the dryland fields at the Texas site had recharge between 0.35 and 1.26 inches per year. Overall findings suggest greater recharge in irrigated areas, lower recharge for dryland areas, and negligible recharge for rangeland areas. The greater recharge in irrigated areas compared to dryland is attributed to irrigation return flows. That said, the extraction of groundwater for irrigation also leads to a declining water tables, as return flows can never be greater than extraction in areas that are not hydrologically connected to surface water. Results for dryland areas generally find rising water tables.

Nolan et al. (2007) estimate recharge using soil core data from 120 USGS National Water Quality Assessment (NAWQA) soil cores across the eastern United States (including eastern Nebraska) using CMB (108 sites) and Darcy's Law (76 sites). The recharge estimates are then used as the dependent variables in non-linear regressions to find the most statistically significant factors of recharge. Grass and crop land cover shares are included in the initial set of over 100 explanatory variables, but are rejected for the final specification. Using data points from several regions might mask the intra-regional impacts of land cover compared to the selected inter-regional factors of recharge. A key difference in how Nolan et al. (2007) use regression, compared to this paper, is that they estimate recharge first, and put that estimation into a regression, whereas this paper uses regressions to assess factors that impact groundwater levels, and infer recharge from those results.

Additional studies in other parts of the world have also looked at the recharge impacts of grassland and cropland (O'Connor, 1985; Le Maitre et al., 1999; Leduc et al., 2001; Favreau et al., 2002; Leaney and Herczeg, 1995; Kendy et al., 2003; Pan et al., 2011). The previously mentioned literature shares similar conclusions of finding greater recharge for cropland compared to grassland. That said, the finding of increased recharge for cropland is not unanimous. Daniel (1999) did find greater recharge native grasses compared to winter wheat under different tillage methods for a shallow aquifer in Fort Reno, Oklahoma (in years with average or greater rainfall).

CHAPTER 2

BACKGROUND

The Conservation Reserve Program

The CRP is a voluntary conservation program run by the USDA-Farm Service Agency (USDA-FSA). The program involves enrolling previously active cropland into a conservation land cover, such as grasslands, forest, or wetlands. This is done to primarily to achieve reduced soil erosion, and improved surface water quality and wildlife habitat. Land is enrolled for a 10 to 15 year contract in which generates yearly rental payments based upon local non-irrigated farmland rental rates. The CRP may also provide cost share payments to achieve the contracted land use practices.

The CRP was first established in the 1985 U.S. Farm Bill, and has been reauthorized in every Farm Bill since then. The most recent version (the 2014 Farm Bill) reduced the national acreage cap from the 32 million acre cap in the 2008 Farm Bill to 24 million acres by 2017. This continued a trend of reduced acreage, since the 2008 Farm Bill had already reduced the cap from 39 million acres.

Actual enrollment in CRP has decreased from an all-time high of 36.8 million enrolled acres in 2007 to 23.9 million enrolled acres in 2016, but total payments have remained around 1.6 – 1.8 billion dollars a year. This means the average rental payment per an acre has been increasing. Nationwide average payments have increased from \$49.76 in 2007 to \$72.61 in 2016. In Kansas (from 2007 to 2016), enrolled acres decreased from 3.3 million to 2.1 million and average rental payments have only changed from \$39.26 to \$42.44. From 2007 to 2016, Nebraska's enrolled acres changed from 1.3 million to $0.8 million$ and rental rates changed from \$57.02

to \$79.82. The greater rental rates and rental rate increase appear to come from more eastern states, where greater rainfall likely influences a larger value of non-irrigated agriculture.

A landowner who wants to enroll a parcel into CRP needs to submit an offer, which is evaluated based on an Environmental Benefits Index (EBI). The six criteria that are used in the EBI to evaluate offers in the most recent sign-up period include wildlife habitat benefits, water quality benefits through reduced erosion, on-farm benefits of reduced erosion, enduring benefits, air quality benefits, and cost.[1] Impacts on water quantity are not one of the primary criteria. A submitted offer must outline the practices that a landowner will implement on the parcel and the per-acre payment rate the producer will accept. The maximum payment rates are based on average county-level non-irrigated rental rates. While there are obvious changes in water availability if land is shifted from irrigated crop production to grassland, it is unlikely that much of the CRP enrollment is from irrigated land since the maximum payment is based on the average value of non-irrigated land. If there are significant impacts of land cover on aquifer recharge, the EBI formula could be adjusted to incorporate water quantity impacts where relevant. This would involve higher scores if CRP has a positive effect on groundwater levels or lower scores if CRP has a negative impact on groundwater levels.

Another relevant policy is the USDA-Conservation Reserve Enhancement Program (CREP). While CRP is unlikely to lead to a significant change in irrigated acres since payments are based on non-irrigated rates, the same is not true for CREP. CREP environmental priorities are determined by individual states and involve a partnership between the USDA and the state. In Nebraska, CREP has aims to

[1] Details about the criteria considered for acceptance into CRP are available at https://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/

retire 100,000 acres from irrigated production in the Republican and Platte river basins. Kansas also has a CREP program to retire 28,950 irrigated acres around the Upper Arkansas River. Additional funding from the state allows CREP payments to be higher than standard CRP rates, making the program competitive with irrigated agricultural production. Any reduction in irrigated production will have a direct benefit on groundwater levels, but that benefit comes at a higher financial cost. Thus, an alternative to modifying the EBI criteria for CRP is to reallocate federal financial resources from CRP to CREP, although this reallocation will lead to fewer acres enrolled overall. Otherwise increased state funding would be needed.

The Study Region

Our analysis uses data from the area of the Ogallala Aquifer in Kansas, and the Republican River Basin (RRB) of Nebraska (mainly over the Ogallala), which are both part of the larger HPA region. We define the Ogallala portion of Kansas as land west of the 99.55 line of longitude. Economic activity in these areas are highly dependent on agricultural production. The HPA is a significant source of irrigation water for the overlying states (largely Nebraska, Kansas, and Texas). Groundwater levels in most of the HPA are declining due to groundwater extraction for irrigation. For the larger HPA the water level decline is an average of 189.6 inches from predevelopment (around 1950) to 2015 that account for about a 273.2 million-acre feet loss of recoverable stored water (McGuire, 2017). The average water level decline in Kansas (Nebraska) from predevelopment to 2015 is 314.4 (10.8) inches, with an associated loss of 69.3 (6.0) million-acre feet in recoverable water (McGuire, 2017). The two states differ both in their level of depletion, and in the potential for groundwater recharge to occur. More recently (2013 to 2015) Kansas has had a water level decline of 1.2 feet and recoverable water decline of 3.2 million-acre feet while Nebraska had near zero decline in water levels, but still lost about 0.3 million-acre feet in recoverable water (McGuire, 2017). More regionally in the two states, some parts of the Ogallala in Kansas have had declines greater than 1800 inches from predevelopment to 2015 and declines of up to 240 inches from 2013 to 2015 (McGuire, 2017). Some areas in the Republican River Basin in Nebraska have also seen water level declines of between 600 and 1200 inches since predevelopment, and up to 72 inch decline from 2013 to 2015 (McGuire, 2017).

Despite the lower decline of groundwater levels in Nebraska, both states make a strong use of groundwater. Data from the USDA-Farm and Ranch Irrigation Survey (FRIS) shows that in 2012 Nebraska had 7.7 million acres irrigated by an estimated 7.4 million acre-feet of groundwater applied, while Kansas had 2.8 million acres irrigated by 3.4 million acre-feet of groundwater applied. Nebraska has a greater overall use of groundwater, in part thanks to a greater extent of aquifers in Nebraska than Kansas, but Kansas has a greater application per an acre. The difference in decline of aquifer levels is most attributable to the much higher rates of recharge found in Nebraska than Kansas as seen in Scanlon et al. (2012) and Dugan and Zelt (2000).

The variable decline of groundwater caused by irrigation has led to a variety of groundwater regulations and local groundwater regulatory bodies aimed at balancing irrigation current needs with future ones. Kansas, for example, requires groundwater well permitting for all large-scale extraction (irrigation, municipal and industrial uses), and in times of shortage the law favors provision of water to those with older permits (first in time first right doctrine). Kansas also requires that all permitted wells be metered and with extraction reported each year. Additional restrictions or services may come from the Groundwater Management Districts (GMDs), Intensive Groundwater Use Control Areas (IGUCAs), Groundwater Conservation

Areas (GCAs) and Local Enhanced Management Areas (LEMAs). The different regulation frameworks across Kansas allow for more localized policy decisions based on local aquifer conditions and local management desires. The areas of Kansas over the Ogallala still face a long-term decline, in part due to low groundwater recharge rates, resulting in management goals to keep the aquifer economically viable for a 50-year horizon.

Nebraska overall has more stable or increasing groundwater levels, in part due to higher recharge rates, and thus has a goal of sustaining irrigated production indefinitely. That said, Nebraska still needs to limit groundwater use, especially due to the hydrological connectivity between rivers and aquifers. Extraction of groundwater from aquifers hydrologically connected to local rivers can lead to decreased streamflow. This has been an immediate concern in the Republican River Basin where Nebraska needs to provide enough streamflow to meet interstate compact requirements.

Nebraska's water rights system aims to give more equitable groundwater access but requires beneficial use of water on the overlying land (a mix of correlative rights doctrine and reasonable use doctrine). Nebraska's surface water rights however, uses first in time, first in right doctrine. Nebraska's groundwater allocations are managed through a network of Natural Resource Districts (NRD). Each NRD is governed by a locally elected board of directors with some state oversight. The local nature of NRD governance allows regulations to differ to meet local conditions and requirements. The four NRDs in the Republican River Basin (the Tri-Basin, Upper Republican, Middle Republican, and Lower Republican) have some of the strongest groundwater regulations in the state in order to meet the requirements of the Republican River Compact. These regulations include required irrigation metering, official meter inspections, and groundwater use limits.

CHAPTER 3

DATA

Data Sources

The dependent variable of the econometric estimation is the annual change in the depth to water table (DWT). The DWT data in the study area uses groundwater field measurements from the National Water Information System (NWIS) maintained by the United States Geological Service (USGS). NWIS contains data from wells maintained by the USGS as well as state and local agencies. The NWIS data provides measurements of DWT, the date of measurement, and the geographic coordinates of the measurement wells. Figure 3.1 shows the distribution of observations wells in the study area.

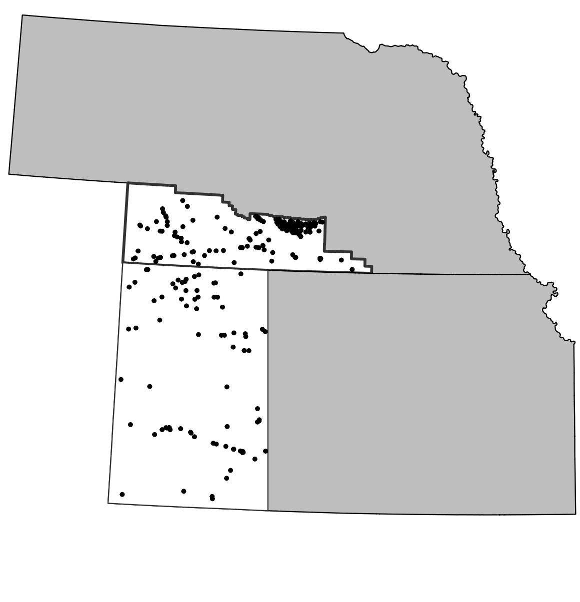

Figure 3.1: Study Area and Observations (Less Than 50ft DWT)

NWIS had available data for wells in the study area, however, we limit the wells to those with a DWT of 50 ft or less. This was to better ensure that the depth change data at these wells was related to the corresponded to the precipitation data. we discuss the reasoning of this approach later on. Check Appendix A for the tables and figures that include the deeper wells.

While the USGS-NWIS data set includes DWT measurements from dates throughout the year, we only use values in off-season months. For Nebraska we use March and April Values, while in Kansas we use January values; these were the off-season months with the most observations in the respective states. We use off-season DWT measurements because we only observe groundwater extraction on an annual basis, and we want the DWT values to reflect conditions where aquifer levels have recovered from the dynamic impacts of intra-annual pumping for irrigation as much as possible. Figure 3.2 shows intra-annual depth changes using daily measurements. Observations in the off-season ensure that the impact of groundwater extraction and recharge is captured in changes in DWT. When multiple measurements are reported in a single year, we take the average of the monthly measurements.

Land cover data is from the National Agricultural Statistics Service (NASS) CropScape. It a spatial data layer of land cover types denoted in grids, such as corn, soy, and grassland. CropScape maps prior to 2010 use 56 meter grids, CropScape maps from 2010 on use 30 meter grids. Weather data is from the PRISM climate data group at the Oregon State University, which provides daily precipitation, minimum temperature, and maximum temperature with the spatial resolution of 4 by 4 (kilometer). Finally, annual groundwater extraction and related coordinate data is obtained from the Republican River Compact Administration (RRCA) for Nebraska and from the Water Information Management and Analysis System (WIMAS) for Kansas. Based upon the availability of groundwater extraction data, Nebraska

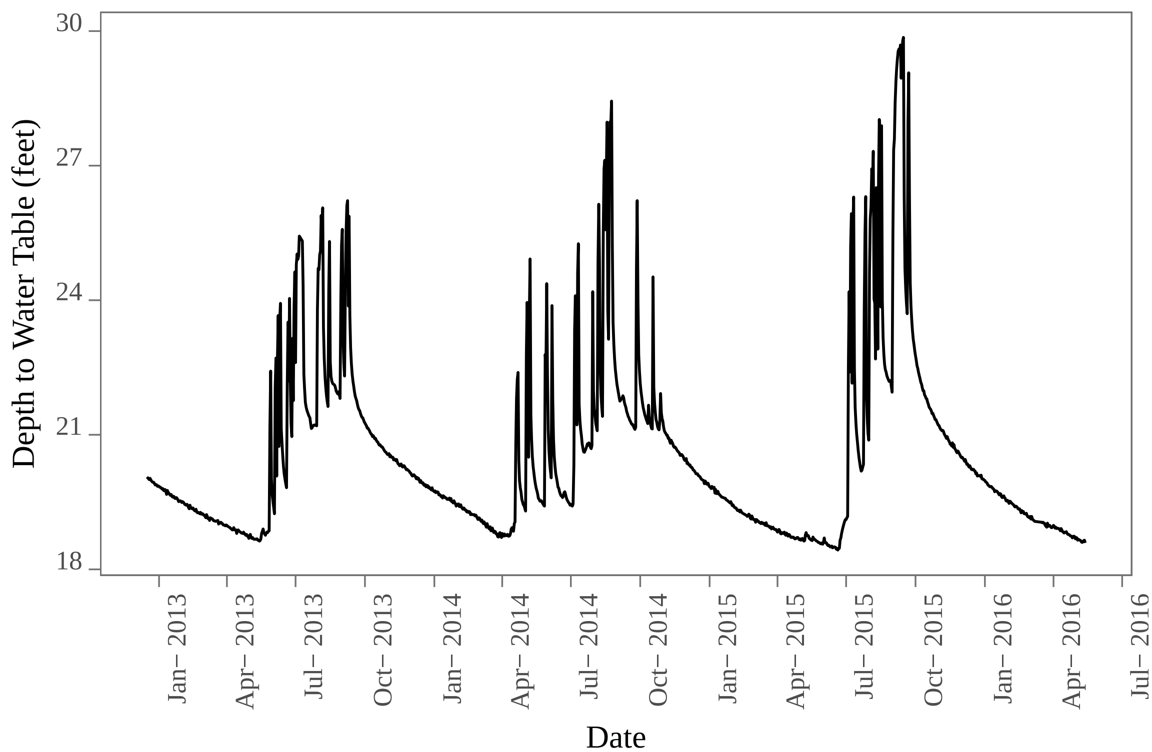

Figure 3.2: Example of intra-annual groundwater fluctuation

is covered from the years 2007 to 2015 and Kansas is cover from 2007 to 2014, excluding 2010. Notably, the Nebraska groundwater extraction data comes from inspected meters while the Kansas groundwater data is self-reported.

Data Processing

In order to find the local conditions of land cover, weather, and groundwater extraction around the observation wells, we draw two-mile radius buffers around each of the observation wells and then summarize information within the buffers. Because some data is limited to the geographic extent of the study region, observation wells that were closer than two miles to border of the RRB in Nebraska or the state line in Kansas were removed to avoid including cases of missing data. Figure 3.3 shows an example with a two-mile radius buffer used on a portion of the CropScape map. We also considered the use of multiple buffers at the same time, such as including both one-mile and two-mile buffers. This was dropped in favor of single buffer cases to avoid multicollinearity problems that could arise from the observed high correlation of land cover types between the two buffer areas.

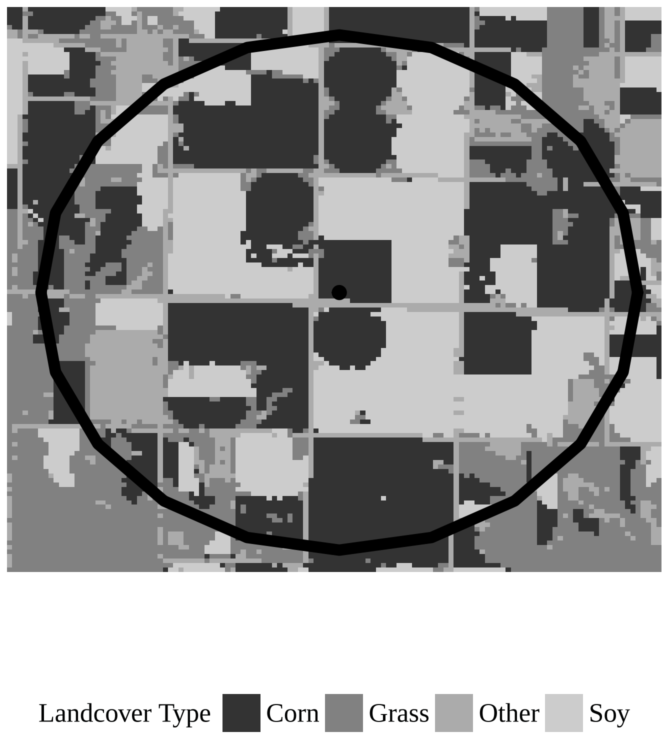

Figure 3.3: Example 2-mile radius buffer around a well on CropScape

To identify the share of each land cover type, we overlay the buffer onto the CropScape layer to calculate the number of grids for each land cover type and then calculate its share of the total grid cells. Similarly for the weather data, we overlay the buffer on the PRISM grids to identify which grids intersect or are contained in the buffer. Then we calculate the grid area-weighted weather variables for the time period in between the DWT measurements. For groundwater extraction, we identify all irrigation wells within the buffer and then add up their individual groundwater extractions and then divide that by the number of acres in the buffer (8042 acres) to get the average inches of groundwater extracted in the buffer. One inch per an acre amounts to about 670 acre-feet of water.

Summary Statistics

Summary statistics for the wells in Nebraska and Kansas are presented in tables 3.1 and 3.2, respectively. On average, depth to water table is a little higher in Kansas (333 inches) compared to Nebraska (304 inches). A striking difference between the two states are the rate of groundwater depletion. While the Nebraska wells experienced small a decline in DWT of 3.07 inches a year, Kansas experienced an average of 11.50 inches increase in DWT. This contrast is consistent with McGuire (2017) which saw an average zero decline for Nebraska overall from 2013-2015 and a 14.4 inch average decline for Kansas overall for the same time period. This contrast is also consistent with the annual recharge differences seen in Scanlon et al. (2012) for the study areas of Kansas (up to 1 inch) versus Nebraska (up to 3 inches).

Table 3.1: Summary Statistics of the Nebraska Data (less than 50ft DWT)

Statistic	N	Mean	St. Dev.	Min	Max
Depth To Groundwater (Inches)	920	304.407	148.033	15.480	600.000
Depth Change (Inches)	920	−3.068	16.243	−100.440	84.000
Groundwater Extraction (Inches/Acre)	920	2.906	2.009	0.000	11.363
Precipitation (Inches)	920	26.738	6.162	11.586	39.897
Average Daily Max Temp (Celsius)	920	17.547	1.405	14.816	21.967
Corn Share (%)	920	32.819	20.891	0.167	74.154
Soy Share (%)	920	13.677	12.546	0.000	48.276
Grass Share (%)	920	37.846	27.343	1.888	94.686
Other Share (%)	920	15.658	9.763	3.837	52.475

Table 3.2: Summary Statistics of the Kansas Data (less than 50ft DWT)

Statistic	N	Mean	St. Dev.	Min	Max
Depth To Groundwater (Inches)	380	333.191	137.307	58.560	598.560
Depth Change (Inches)	380	11.494	29.957	−116.760	111.600
Groundwater Extraction (Inches/Acre)	380	2.202	2.578	0.000	11.079
Precipitation (Inches)	380	20.091	5.663	9.165	33.068
Average Daily Max Temp (Celsius)	380	19.983	1.448	17.212	23.803
Corn Share (%)	380	9.748	7.980	0.008	34.562
Winter Wheat Share (%)	380	12.855	7.098	0.059	36.513
Grass Share (%)	380	51.227	15.885	18.938	95.332
Other Share (%)	380	26.171	10.272	3.180	73.985

Average annual precipitation is higher in Nebraska (26.74 inches) compared to Kansas (20.10 inches). However, the average groundwater extraction within the two-mile buffer of the chosen USGS observation wells is higher in Nebraska (2.91 inches/acre) than in Kansas (2.20 inches/acre). Increased precipitation would suggest a lower need for groundwater extraction, however greater precipitation and recharge in Nebraska might allow for more extraction to take place. There are notable differences in land cover types between Nebraska and Kansas. In Nebraska, corn (33%) and grass (41%) are the most dominant land cover types, followed by soybean (8%). All the other categories have very small individual shares and are lumped into a single category called “Other,” which include sorghum (0.64%), alfalfa (0.97%), development (2.68%), woods (0.19%), wetlands (1.20%) among other land cover types. Corn (17%) and grass (28%) are also important in Kansas. However, the share of soybean is negligibly small (0.75%) in the Kansas Study area unlike Nebraska, and winter wheat is more prominent (22%) instead. For Kansas, soy and the remaining land covers are group into ”Other”.

Figure 3.4 presents the recent history of yearly groundwater depth changes, groundwater extraction, and precipitation in Nebraska. As seen in the summary statistics, the Nebraska wells exhibit a general decline in DWT. However, in 2012 and 2013 Nebraska had unusually severe droughts, higher groundwater extraction, and noticeable increases in DWT compared to other years.

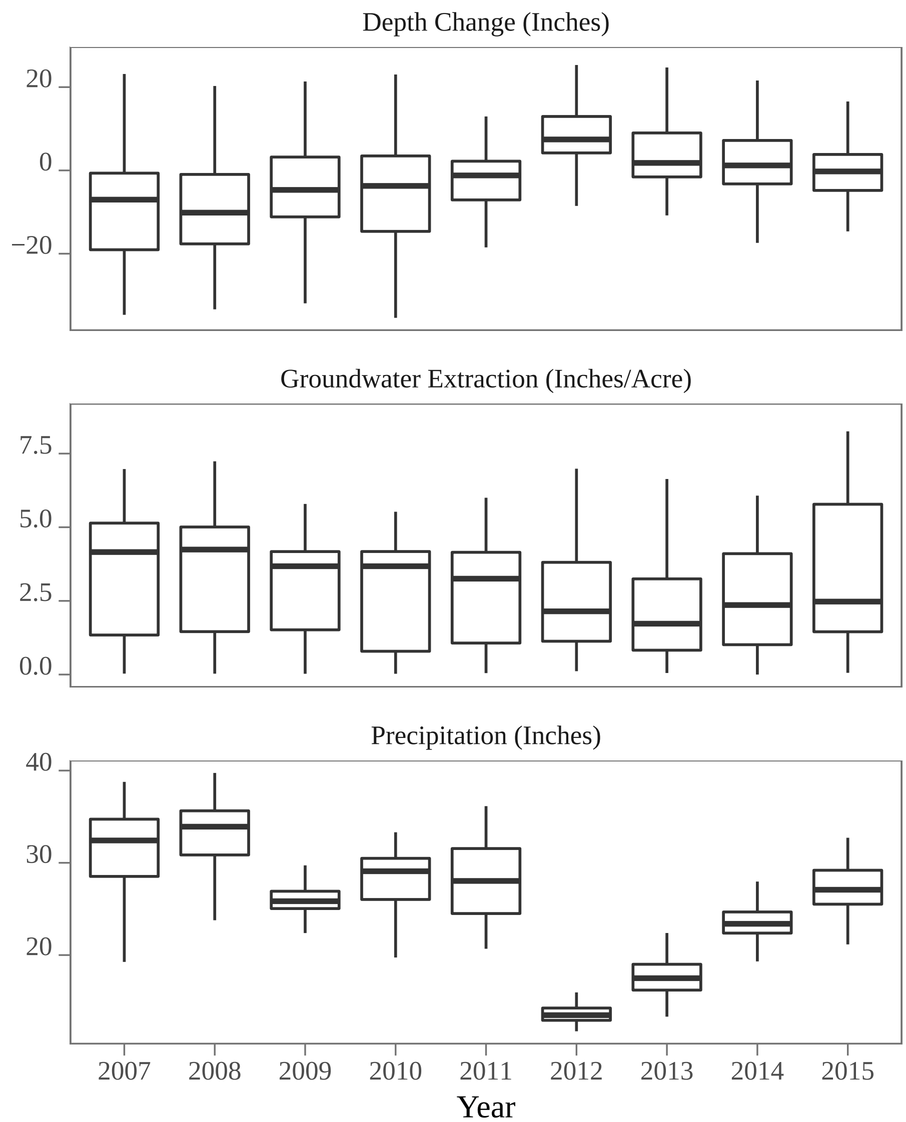

Figure 3.4: Distribution of Depth Change, Groundwater Extraction, and Precipitation by Year in Nebraska (Less Than 50ft DWT)

Figure 3.5 presents the recent history of yearly groundwater depth changes, groundwater extraction, and precipitation for Kansas. Unlike the Nebraska wells , the Kansas wells constantly had increases in the DWT with the largest median increase observed in 2012, in which Kansas also experienced a severe drought.

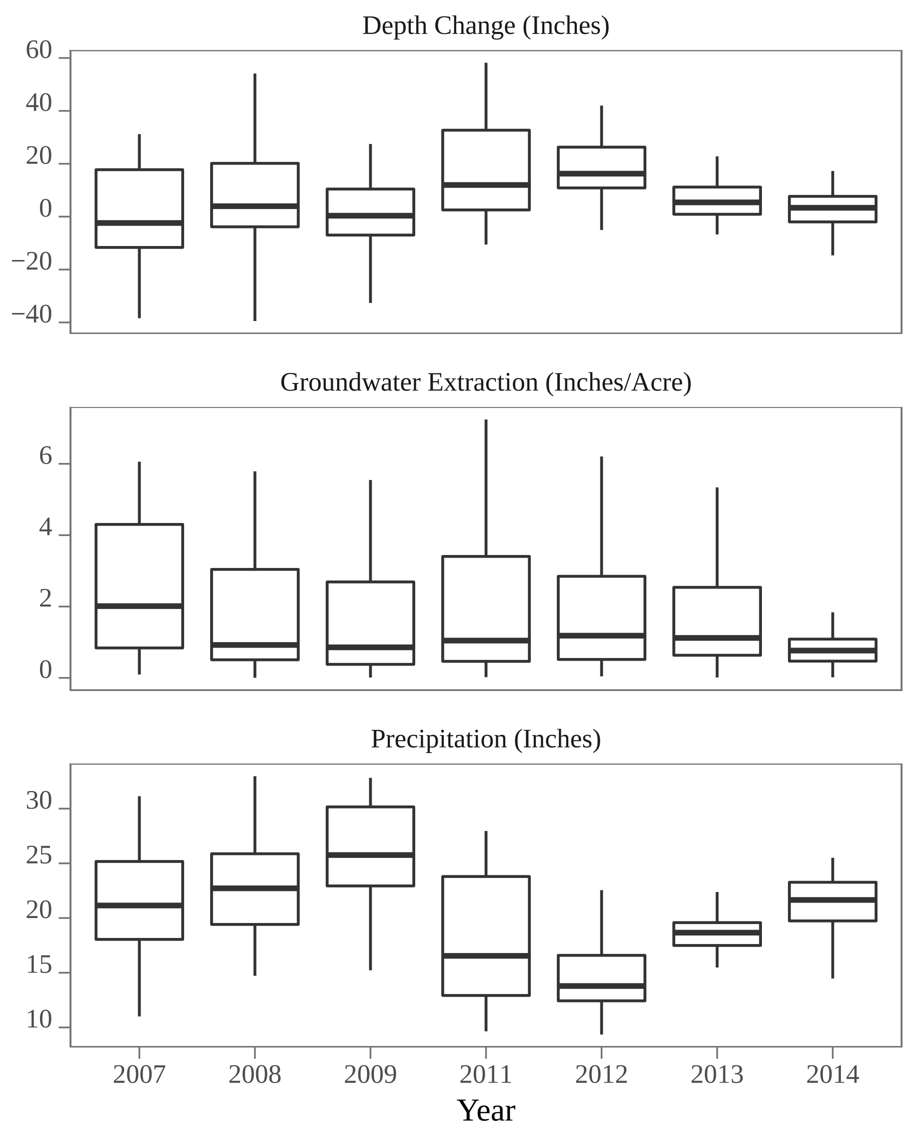

Figure 3.5: Distribution of Depth Change, Groundwater Extraction, and Precipitation by Year in Kansas (Less Than 50ft DWT)

CHAPTER 4

ECONOMETRIC METHOD

Here, we discuss the model specification and econometric methods used in this study. We first have a detailed discussion on how the impact of precipitation on groundwater level change is specified. We then present the full estimating equation.

Impact of Precipitation on Depth to Groundwater

We let i, j, t, and m indicate observation well, CropScape grid cell within the 2-mile radius of the well, year, and month, respectively. We let $P_{j,m,t}$ indicate the total precipitation that fell on grid j in month m of year t, and and $c_{j,t}$ denotes the crop type at grid cell j in year t, where $c = 1, \ldots, C$.[1] Further, we let $\Omega(c_{j,t})$ denote the growing months (the period within a year during which the land is covered with some vegetation), which varies based on the crop type at grid j ($c_{j,t}$). The growing seasons for crops are defined by USDA planting and harvesting dates[2]. The in-season is defined by the most active planting and harvesting dates for each crop and state, except for the last month of most active harvesting. The off-season is defined by the remaining months between the DWT measurement from current year to next year. Table 4.1 has the crop season definitions for the crops that we use in the study. Grass and the other remaining land covers are treated as always being in-season. For grass this is because we do not know its use (e.g. range or wild) or type (e.g. annual or perennial). For the other category it includes multiple crops with differing cropping seasons and other things like roads which have no cropping

[1] We use a single land cover for each grid cell.

[2] See the 2010 USDA Planting and Harvesting Dates at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1251 for more information.

season.

Table 4.1: The Definition of the In-season for Major Crops

State	Crop	Meaurement Period	In-Season
Nebraska	Corn	Mar(t)-Feb(t+1)	May-Oct (t)
	Soy	Mar(t)-Feb(t+1)	May-Sep (t)
Kansas	Corn	Jan(t)-Dec(t)	Apr-Sep (t)
	Winter Wheat	Jan(t)-Dec(t)	Jan-Jun (t) and Oct-Dec (t)

Note: t and $t+1$ in parentheses indicate the same year and next year, respectively. For example, for DWT observed between 2012 and 2013, t and $t+1$ mean 2012 and 2013, respectively. This is so the DWT Change reflects the 2012 growing season

For each well, we have a fixed number of total grid cells within its two-mile buffer, denoted by J. The impact of precipitation that falls on grid cell j on the DWT of well i between year t and $t+1$ (denoted as $DWT^p_{i,j,t}$) can be written as follows:

$$\Delta DWT^p_{i,j,t} = \sum_{m \in \Omega(c_{j,t})} \beta_c \cdot P_{j,m,t} + \sum_{m \notin \Omega(c_{j,t})} \alpha \cdot P_{j,m,t} \tag{4.1}$$

The parameter β_c is the marginal impact of precipitation on the aquifer level for precipitation that occurs when the vegetation of crop c is present (in-season), while α is the marginal impact of precipitation that occurred during the vegetation of the crop is not present (off-season). Since the parameters measure the impact of precipitation from a single grid cell on the depth to water at observation well i, we expect that the values of β_c and α are extremely small, and significantly less than one.

The total depth change at well i in year t is the sum of depth change contributions from all the grids surrounding the well:

$$\Delta DWT^p_{i,t} = \sum_{j}^{J} \Delta DWT^p_{i,j,t} \tag{4.2}$$

Now, we let N^c_t denote the number of grids where crop c is grown within the 2-mile radius of well i. Then,

$$\Delta DWT^p_{i,t} = \sum_{c=1}^{C} N^c_t \cdot \Big(\sum_{m \in \Omega(c_{j,t})} \beta_c \cdot P_{j,m,t} + \sum_{m \notin \Omega(c_{j,t})} \alpha \cdot P_{j,m,t} \Big) \tag{4.3}$$

Collecting terms by coefficients ($\beta_1, \ldots, \beta_C$ and α),

$$\Delta DWT^p_{i,t} = \sum_{c=1}^{C} \beta_c \big(N^c_t \sum_{m \in \Omega(C_{j,t})} P_{j,m,t} \big) + \alpha \big(\sum_{c=1}^{C} \big[N^c_t \sum_{m \notin \Omega(c_{j,t})} P_{j,m,t} \big] \big) \tag{4.4}$$

Finally, by dividing and multiplying the right hand side for each land cover type by the number of total grids (J),

$$\Delta DWT^p_{i,t} = \sum_{c=1}^{C} J\beta_c \big(S^c_t \sum_{m \in \Omega(C_{j,t})} P_{j,m,t} \big) + J\alpha \big(\sum_{c=1}^{C} \big[S^c_t \sum_{m \notin \Omega(c_{j,t})} P_{j,m,t} \big] \big) \tag{4.5}$$

where $S^c_t = (N^c_t / J)$ is the share of land cover type c in the 2-mile radius buffer. By including $S^c_t \sum_{m \in \Omega(C_{j,t})} P_{j,m,t}$ ($c = 1, \ldots, C$) as a covariate, we can recover the coefficient $J\beta_c$, which measures the impact of precipitation during their respective growing seasons if all the grids are of land cover type c. Similarly, by including $\sum_{c=1}^{C} \big[S^c_t \sum_{m \notin \Omega(c_{j,t})} P_{j,m,t} \big]$, we can recover $J\alpha$, which measures the impact of precipitation happened during off-season irrespective of what the crop type was when all the grids have no surface vegetation. Note that these coefficient can be greater than 1 because soil mass also contributes to the height of aquifer. For example, if specific yield of the aquifer (the proportion of water content in the soil) is 0.2 and 30% of precipitation reaches the aquifer, the coefficient estimate would be 1.5 (0.3/0.2).

Denoting $J\beta_c$ and $J\alpha$ by γ_c and λ, respectively,

$$\Delta DWT^p_{i,t} = \sum_{c=1}^{C} \gamma_c \big(S^c_t \sum_{m \in \Omega(C_{j,t})} P_{j,m,t}\big) + \lambda \big(\sum_{c=1}^{C} \big[S^c_t \sum_{m \notin \Omega(c_{j,t})} P_{j,m,t}\big]\big) \tag{4.6}$$

Under this specification, for example, if corn covers the 10% of the area withing the two-mile buffer of well i, then the change in DWT due to precipitation on grids with corn (and no vegetation after its harvesting) is

$$\Delta DWT^p_{i,t} = 0.1 \times \Big[\gamma_{Corn} \big(\sum_{m=5}^{10} P_{i,m,t}\big) + \lambda \big(\sum_{m=11}^{12} P_{i,m,t} + \sum_{m=1}^{2} P_{i,m,t+1}\big)\Big] \tag{4.7}$$

Estimating Equation

Using the notations established above, the estimating equation is,

$$\begin{aligned} \Delta DWT_{i,t} =& \beta_0 + \sum_{c=1}^{C} \gamma_c \big[S^c_t \sum_{m \in \Omega(C_{j,t})} P_{j,m,t}\big] + \lambda \sum_{c=1}^{C} \big[S^c_t \sum_{m \notin \Omega(c_{j,t})} P_{j,m,t}\big] \\ & + \beta_T T_{i,t} + \beta_E E_{i,t} + \alpha_i + \phi_t + \varepsilon_{i,t} \end{aligned} \tag{4.8}$$

where i denotes the USGS observation well and t the year. The dependent variable is changes in depth to the water table ($\Delta DWT_{i,t}$). This means that variables that increase aquifer levels will have a negative coefficient for decreasing the depth to groundwater while variables that decrease aquifer levels will have a positive coefficient. The variables of interest are the amount of precipitation that fell on various land cover season types as discussed above. Other independent variables include maximum temperature ($T_{i,t}$), groundwater extraction ($E_{i,t}$), individual well fixed effect (α_i), year fixed effect (ϕ_t). Finally, the error term is represented by $\varepsilon_{i,t}$. Individual fixed effects help control for the impacts of reasonably constant variables at each site, such as unobserved soil characteristics that may impact the movement of water through the unsaturated zone to water table. Using fixed effects in this manner represents a trade-off, as this study gains control for deeper soil characteristics for which there is limited data but then cannot observe surface level soil data. Standard errors are clustered by PLSS (Public Land Survey System) township to account for heteroskedasticity, autocorrelation, and spatial correlation of the error term.[3]

Consideration on the Recharge Speed and Potential Bias

For this study, we estimate the regressions using observations with starting a DWT of 50ft or less. Within a given time period, water in the unsaturated zone will only move so far. Given limited expectations of water movement, we restrict the DWT variable to wells that are more likely to receive the precipitation within the year it fell. Additional data and results with deeper wells can be found in the appendix. Even after focusing on observations that have a beginning depth of less than 50

[3] We confirmed that if We cluster by individual well, which ignores spatial correlation of the error term, standard error are substantially underestimated.

feet, we cannot know the age of the precipitation percolating to the water table with certainty. If one erroneously includes precipitation in the explanatory variable that has not yet reached the aquifer, or omits precipitation that did reach the aquifer in the measure of DWT, it could lead to bias the estimation of the true potential of groundwater recharge from precipitation.[4] This has implications for the variable of interest: the difference in recharge between major crop types and grassland. Now, it seems quite reasonable to assume that the speed at which the water travels down the soil are the same irrespective of the surface land cover types once the water goes past the root zone on average. In other words, deep soil properties are likely to be independent of the surface land cover types. Thus, this paper's estimates are likely to suffer from attenuation bias.[5] However, it is important to note that estimated differential is likely to keep the sign of the impact intact.

[4]We did test the importance of lagged precipitation by including lagged and current precipitation in the estimation. The lagged precipitation was not significant.

[5]Note that for attenuation bias due to the misspecification of the explanatory variable it does not matter if the misspecification increases or decreases the value of the explanatory variable.

CHAPTER 5

RESULTS

Table 5.1: The Impact of Landcover Types on Groundwater Depth Change for Wells Shallower than 50 feet

	Dependent variable:	
	Change in depth to water table	
	Nebraska	Kansas
Groundwater Extraction	2.792**	10.866**
	(1.135)	(5.419)
Precipitation on Corn	−2.677***	2.538
	(0.703)	(3.177)
Precipitation on Soybean	−2.717**	
	(1.102)	
Precipitation on Winter Wheat		1.039
		(1.844)
Off-season Precipitation	−3.084***	−6.958
	(1.007)	(4.792)
Precipitation on Grass	1.110	−1.368
	(0.728)	(1.013)
Precipitation on Others	−1.305	−1.859**
	(1.047)	(0.935)
Maximum Temperature	8.196	−0.405
	(5.475)	(5.820)
Year fixed effects included?	Yes	Yes
Observations	920	380
Adjusted R^2	0.363	0.656
Note:	*p<0.1; **p<0.05; ***p<0.01	

As shown in table 5.1, the regression results for Nebraska suggests that precipitation corn and soybean have almost the same degree of impact on groundwater recharge. As explained in the econometric method section, the coefficient on the precipitation variables measures the marginal impact of precipitation (in inches) on DWT (in inches). This means that an inch of precipitation that fell on corn or soybean during their growing seasons would contribute to decrease DWT by about 2.7 in if their shares on land cover type within the two-mile buffer is 1. Combining this information with specific yield one can obtain a rough estimate of recharge. On average, specific yield is around 15.1% in Nebraska (McGuire et al., 2012). Assuming the 15.1% specific yield, we get around $2.7 \times 0.151 = 0.41$ in of recharge per an inch of precipitation, which is to say estimated recharge is around 40% of precipitation if it only falls on cropland. Precipitation that happened during the non-growing season of corn and soybean has a coefficient comparable to those of soybean and corn in magnitude. This is rather unexpected because we anticipated that precipitation during the non-growing season would contribute more to groundwater recharge. This may be partially because of cover crops during the off-season. Unfortunately, we have no information with respect to the existence of cover crop vegetation. Precipitation on grass does not have a statistically significant impact on groundwater recharge, suggesting little or no recharge from precipitation on grass. This result differs from the findings of McMahon et al. (2006) which had estimates of 2.76 in for recharge under rangeland compared to 4.02 and 4.37 inches per year inches for crops for sites in the RRB. However, it may be because the estimates might suffer from a positive bias if all the precipitation that went past the root zone may not reach the aquifer in time, and such portion of water is not reflected in the value of the dependent variable. Therefore, we cannot rule out the possibility that precipitation on grassland actually contributes to groundwater recharge in the longer run. Similarly, if that is the case, the true recharge potential of precipitation on corn and soybean may be greater in magnitude than our estimates.

Now, let us conduct some thought experiments to put the coefficient numbers in context to illustrate practical significance of the conversion of corn or soybean to grassland. Here, we assume the impact of precipitation on grass is zero as its coefficient is not statistically different from zero. For a year with 15 (5) inches of precipitation during the growing (non-growing) season, a conversion of corn by 10% (10% of the total land within the 2-mile radius buffer is about 800 acres) to grassland would result in $0.1 \times (15 \times 2.677 + 5 \times 3.084) = 5.56$ in deeper aquifer.

In contrast to Nebraska, none of the precipitation variables are statistically significant except precipitation on the "other" category in Kansas. This result, however, is not entirely surprising given very small recharges expected in the region (Scanlon et al., 2012; Dugan and Zelt, 2000). Comparing to McMahon et al. (2006) suggests that there still should be some recharge under cropland. They estimated 1.54 to 2.13 inches per year under crops and 0.20 inches per year under rangeland in Kansas. Again, our estimates may underestimate the recharge potential of precipitation in the long run. Nonetheless, the insignificance of precipitation variables is in a stark contrast to the significance observed in the Nebraska results.

Finally, groundwater extraction is significant in the expected direction for both regions. The number however is much smaller in Nebraska than in Kansas. This difference could reflect greater irrigation return flows in Nebraska. The Kansas extraction coefficient might also be overestimated if the self-reported Kansas data has consistent errors below the true value. For Nebraska, reducing the average groundwater extracted by an inch across 8042 acres (670 acre-feet) reduced the DWT by around half of the 10% (804 acres) corn conversion scenario. If expectations for positive bias hold true, the 1 inch extraction reduction would have less than half the impact.

Discussions and Policy Implications

The findings suggest that grassland, a major CRP land cover, induces smaller amounts of recharge from precipitation compared to corn, and soy, which are the major land cover types in Nebraska's Republican River Basin. In Kansas' Ogallala Aquifer region however, there seems to be no land cover impact on recharge from precipitation, which is consistent with reports of the regions' overall poor recharge (Scanlon et al., 2012; Dugan and Zelt, 2000). This means that policy makers should be aware of and take into account the impact of land cover conversion from cropland to grassland on groundwater recharge in deciding where to place CRP acres, especially in regions where groundwater recharge is significant. However, such consideration is less warranted in areas where groundwater recharge is minimal in the first place, like Kansas.

Decision makers for CRP (or similar programs) that are concerned about net benefit of the CRP acres may find it prudent to reduce targeting (e.g. lower EBI scores) in areas with strong but insufficient recharge, such as near Rivers in Nebraska. The need in this area is to keep groundwater levels higher to improve streamflow in the hydrologically connected rivers. Additional CRP acres are expected to harm recharge to aquifers and therefore harm streamflow and can incur environmental and non-environmental costs. An example of a environmental cost could be Nebraska's Platte River, where streamflow is needed to help provide proper habitat for the Sand-hill cranes that migrate though the area. Non-environmental cost could be Nebraska spending funds on programs to improve streamflow to meet their Republican River compact streamflow retirements. Being mindful of these costs, and redirecting acres elsewhere can improve net benefits.

In areas where CRP may reduce needed recharge, another option is to direct funding towards CREP, or a similar irrigation reduction scheme to gain irrigation off-sets. Using CREP like programs could be beneficial in gaining both grassland environmental benefits and groundwater levels. Using a CREP like program in this manner requires a good understanding of the trade-offs between irrigation reduction and land cover change on groundwater levels. For the previously laid out scenario in Nebraska, a 1340 acre-feet reduction in extraction would be needed to off-set a 804 acre corn conversion to grassland. Policy makers and managers that are more concerned about groundwater levels may wish to encourage a shift from irrigated cropland to non-irrigated cropland instead to grassland.

Given the large amounts of land leaving CRP, aquifers that expect grassland to reduce recharge might receive a windfall to aquifer levels if the land exiting CRP is moved into non-irrigated production. However, these benefits are tempered by the loss of other environmental benefits that result from CRP exit. An additional concern would be a higher mobilization of pollutants to the water table that comes with the higher mobilization of water (Scanlon et al., 2007). As such, areas that are concerned about such pollutants may need to be targeted for more CRP acres.

CHAPTER 6

CONCLUSIONS

Using depth to groundwater table data maintained by USDA available for a large portion of the Ogallala aquifer along with other spatial data sets, I estimated the impact of land cover conversion on groundwater recharge. The findings suggest that grassland reduces groundwater recharge compared to cropland in the Republican River Basin of Nebraska within the span of a year. The Regression did not detect a difference between grassland and cropland for the Kansas portion of the Ogallala Aquifer in the same time frame.

Programs like the Conservation Reserve Program might wish to consider the regionally expected impact of land cover change on recharge when choosing which acres to enroll. Areas that require more groundwater recharge in the short term may be less desirable for CRP acres. Irrigation reduction programs aimed solely at improving groundwater levels might also work better by encouraging non-irrigated production instead of grassland. CREP (as seen in Nebraska and Kansas) or similar programs can be useful if groundwater levels and grassland environmental benefits are both a concern.

A different implication of increased recharge for cropland compared to grassland not fully explored here is the increased mobilization of pollutants into the water table with greater recharge (Scanlon et al., 2007). The increased recharge of cropland and the possible use of fertilizers and pesticides on cropland could lead to greater groundwater quality issues. Areas with greater groundwater quality concerns rather than quantity concerns could benefit more from CRP acres.

The conclusions of this study are for the immediate impact of land cover changes.

Land cover changes might also have long term impacts that are not yet accounted for, but require additional years of data for this paper's method to be utilized with longer lags. Another important limitation is that the CropScape map used for land covers only considers grassland and other land covers in general. Certain varieties of grasses or crops could have different recharge impacts. The previous limitation also extends to not knowing the land use practices from CropScape. This study also does not account for any variable impacts of hydrologically connected groundwater.

Future work should aim to address the previous limitations where possible. Additional extensions of this work could include looking at the groundwater quality impacts of land cover changes,and looking at the most optimal methods for spatially relating groundwater level changes with local conditions.

Ultimately, this study provides a useful first step in considering the trade-offs in environmental programs like CRP that focus on a subset of all possible environmental benefits, and other environmental impacts. It also highlights the need to consider and account for the unintended impacts of policies.

CHAPTER A

ADDITIONAL DATA

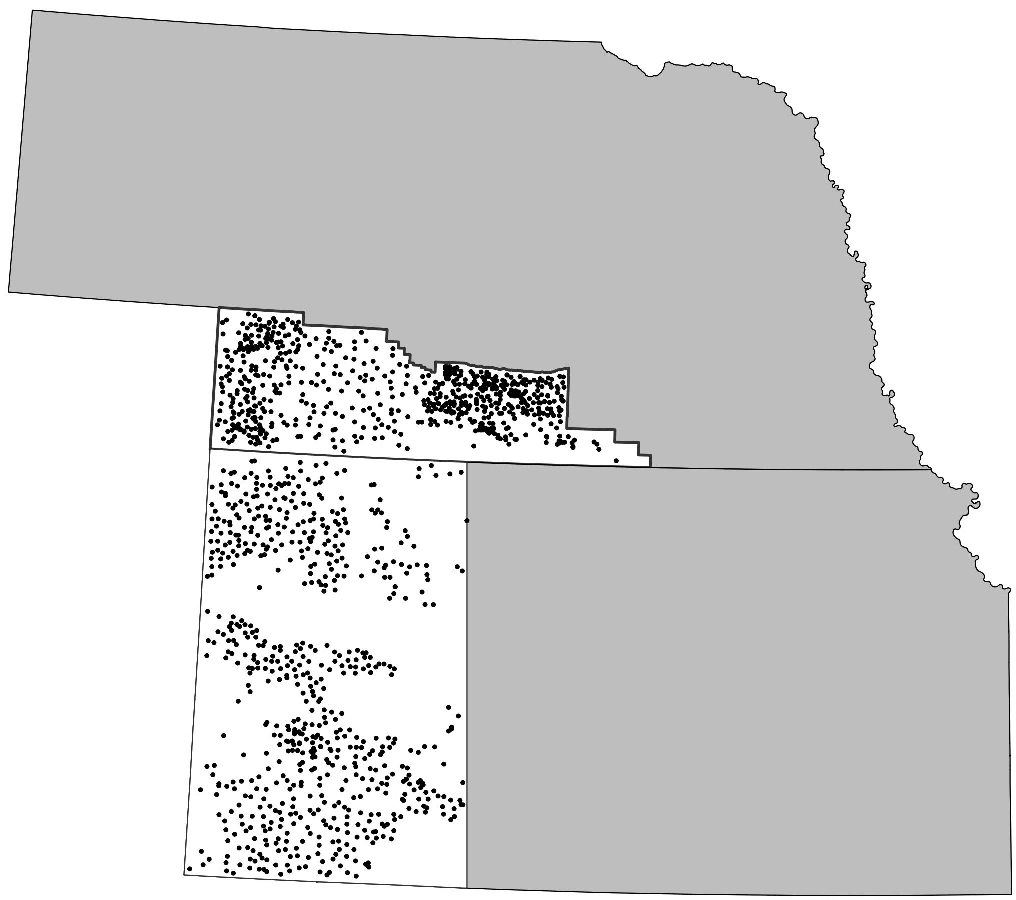

Figure A.1: Study Area and Observations (All DWT)

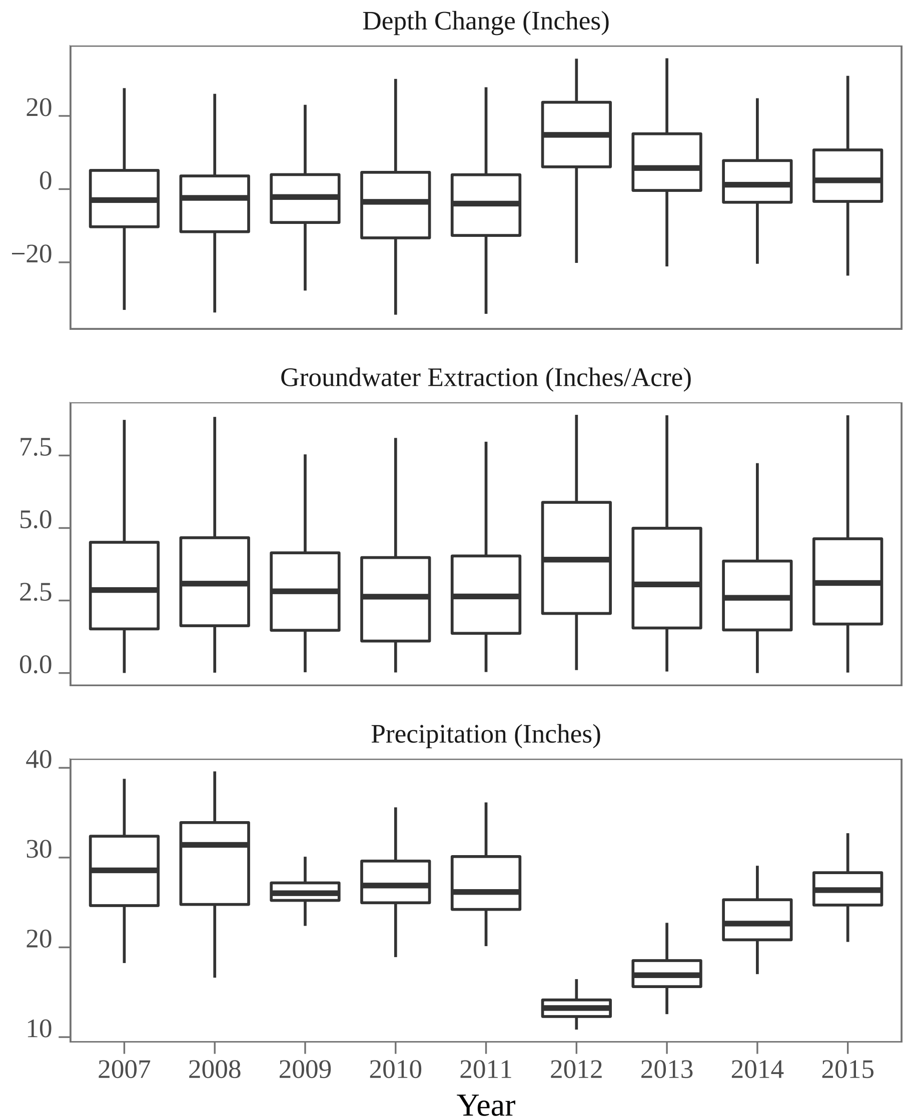

Figure A.2: Distribution of Depth Change, Groundwater Extraction, and Precipitation by Year in Nebraska (All DWT)

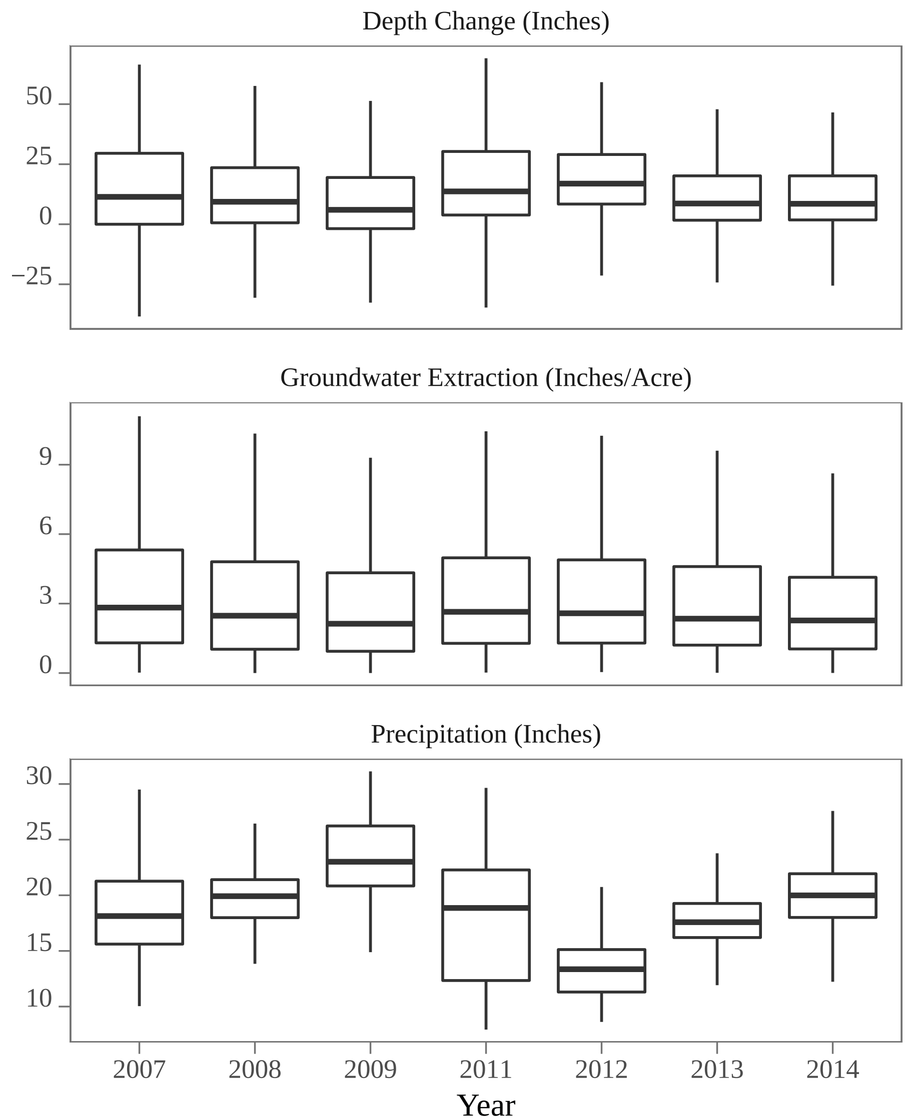

Figure A.3: Distribution of Depth Change, Groundwater Extraction, and Precipitation by Year in Kansas (All DWT)

Table A.1: Summary Statistics of the Nebraska Data (All DWT)

Statistic	N	Mean	St. Dev.	Min	Max
Depth To Groundwater (Inches)	4,638	1,334.529	773.203	15.480	3,666.600
Depth Change (Inches)	4,638	0.671	19.251	−118.800	117.720
Groundwater Extraction (Inches/Acre)	4,638	3.150	2.177	0.000	15.717
Precipitation (Inches)	4,638	24.958	6.002	10.121	40.193
Average Daily Max Temp (Celsius)	4,638	17.841	1.307	14.711	21.967
Corn Share (%)	4,638	33.024	17.804	0.000	83.406
Soy Share (%)	4,638	8.791	11.167	0.000	49.395
Grass Share (%)	4,638	41.140	24.083	1.111	97.108
Other Share (%)	4,638	17.045	11.445	1.463	80.092

Table A.2: Summary Statistics of the Kansas Data (All DWT)

Statistic	N	Mean	St. Dev.	Min	Max
Depth To Groundwater (Inches)	3,719	1,837.923	905.238	58.560	4,916.520
Depth Change (Inches)	3,719	17.044	29.492	−117.000	120.000
Groundwater Extraction (Inches/Acre)	3,719	3.591	3.449	0.000	18.787
Precipitation (Inches)	3,719	18.847	4.824	7.851	35.190
Average Daily Max Temp (Celsius)	3,719	20.088	1.386	17.136	23.807
Corn Share (%)	3,719	17.026	13.089	0.000	71.887
Winter Wheat Share (%)	3,719	22.641	10.285	0.059	57.230
Grass Share (%)	3,719	28.677	19.234	0.653	95.332
Other Share (%)	3,719	31.656	10.932	3.180	84.669

CHAPTER B

ADDITIONAL RESULTS

Table B.1: The Impacts of Landcover Types on Groundwater Recharge (50-100 ft DWT)

	Dependent variable:	
	Change in depth to water table	
	Nebraska	Kansas
Groundwater Extraction	3.099*	9.862**
	(1.703)	(3.859)
Precipitation on Corn	−2.949***	−1.961
	(0.453)	(1.643)
Precipitation on Soybean	−3.126***	
	(1.093)	
Precipitation on Winter Wheat		−0.807
		(2.294)
Off-season Precipitation	−0.103	0.277
	(1.192)	(2.629)
Precipitation on Grass	0.029	−1.167
	(0.407)	(1.040)
Precipitation on Others	−3.715***	1.228
	(0.948)	(1.180)
Maximum Temperature	−3.508	−2.215
	(3.234)	(5.565)
Year and Well Fixed Effects Included?	Yes	Yes
Observations	1,219	490
Adjusted R^2	0.408	0.469
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table B.2: The Impacts of Landcover Types on Groundwater Recharge (All DWT)

	Dependent variable:	
	Change in depth to water table	
	Nebraska	Kansas
Groundwater Extraction	3.456^{***}	5.132^{***}
	(0.804)	(1.000)
Precipitation on Corn	-2.076^{***}	-0.663
	(0.388)	(0.487)
Precipitation on Soybean	-1.865^{***}	
	(0.651)	
Precipitation on Winter Wheat		-1.146^{*}
		(0.611)
Off-season Precipitation	-2.474^{***}	0.306
	(0.705)	(0.904)
Precipitation on Grass	0.255	-0.992^{**}
	(0.291)	(0.414)
Precipitation on Others	-1.882^{***}	-0.298
	(0.529)	(0.325)
Maximum Temperature	3.119	-0.594
	(2.419)	(2.485)
Year and Well Fixed Effects Included?	Yes	Yes
Observations	4,638	3,719
Adjusted R^2	0.242	0.390
Note:	*p<0.1; **p<0.05; ***p<0.01	

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