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The Effects of Economic Factors and Groundwater Policies on the Timing of Well Drilling

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THE EFFECTS OF ECONOMIC FACTORS AND GROUNDWATER POLICIES ON THE TIMING OF WELL DRILLING

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Understanding the factors that affect farmers' irrigation decisions is critical for a better groundwater management. This study addresses the question of how economic, agronomic, and policy variables affect the timing of irrigation adoption in Nebraska. The key contribution of this paper is to identify farmers' strategic responses to a particular type of policy intervention, a moratorium on well drilling. Our results estimate how farmers respond when a moratorium is announced but not enforced yet, and when neighboring areas implement a moratorium, which we refer as pre-regulation effect and policy spillover effect, respectively. Results show that farmers are more likely to drill a new irrigation well at least one year before the moratorium is implemented due to concerns about future constraints on water use, and the probability increases by 62%. We also find strong evidence that as any of the neighboring NRDs enforces a moratorium, the probability of drilling a new well in a given NRD increased by 77%. Unsurprisingly, the probability of drilling a well significantly decreased by 21% after the moratorium is implemented.

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1 Introduction

The US High Plains aquifer, one of the largest freshwater aquifer systems in the world, continues to decline, threatening the long-term viability of an irrigation-based economy. As the most intensively used aquifer in the United States, the High Plains aquifer provides 30% of the total withdrawals from all aquifers for irrigation (Sophocleous, 2010). More importantly, it also provides drinking water to 82% of the people within the boundaries according to both the 1990 census and 2000 census (Sophocleous, 2010). The aquifer system including the Ogallala and Equus Beds underlies parts of eight US states, and mostly underlies the three states: Nebraska has 65% of the aquifer's volume, Texas has 12% and Kansas has 10% (Peck, 2007). The increasing demand for groundwater resources when the aquifer is being extracted at rates in excess of recharge has gained major attention on groundwater use management. The problem that the regions are facing has prompted each state government to regulate groundwater use for sustainability. For example, the establishment of minimum desirable stream flows in Kansas and instream flow requirements in Texas aim at protecting stream flows and maintaining water levels. Such regulations have made some progresses, but piecemeal arrangements for managing the supplies and quality of water are inadequate to meet the water challenges of the future (Sophocleous, 2010). Thus, identifying and understanding the factors that affect farmers' irrigation decisions and examining the effectiveness of current policies are important for a better groundwater management.

Due to the nature of state-level autonomy in managing water allocations, each state employs different groundwater management policies that best serve their own needs for water resources. For instance, the local districts exercise almost sole authority to establish groundwater control in Nebraska and Texas (Stephenson, 1996). Nebraska is one of the most groundwater-rich states in the United States. Around 88% of residents rely on groundwater as their source of drinking water, and the majority of groundwater is used for irrigation (2017 Nebraska Groundwater Quality Monitoring Report). Thus, Nebraska has a long history of analyzing the local officials' rule-making behaviors and identifying a set of factors that contribute to the development of groundwater management system (Stephenson, 1996).

The paper addresses the question about how one type of groundwater policy (a well drilling moratorium) affects the timing of a farmer's decision to invest in a new irrigation well. Previous studies show that the early well drilling decisions made by farmers are mainly due to the development and diffusion of irrigation technologies (Aiken 1980; Stephenson, 1996; Sampson and Perry, 2018). With no regulations on groundwater use, this decision is also primarily determined by economic, agronomic, and climate factors. With restrictions such as well drilling moratoria, we would observe changes in farmers' irrigation adoption decisions. If a moratorium is perfectly enforced and passed with no warning, we would not expect to observe any strategic responses toward the policy intervention. However, policies are typically debated for a period before they are enacted, and policy heterogeneity across the state allow us to identify how farmers respond to the moratorium policy. Producers may choose to invest in an irrigation well if a moratorium is announced but not enforced yet since they expect that they will not be able to drill a well in the future. Producers may also respond to a moratorium in a neighboring region by drilling a new well, because they are concerned about an expansion of such regulation to their own region in the future. Thus, we expect an increasing number of well drilling before the policy implementation and also when any of the neighboring NRDs implements a moratorium.

The key contribution of this paper is to analyze farmers' strategic responses in terms of policy changes using survival analysis. The results show that farmers are 62% more likely to drill a new irrigation well at least one year before the moratorium is implemented as demonstrated by *pre-policy dummy* variable. We also find strong evidence that as neighboring NRDs enforce a moratorium, the probability of drilling a new well in a given NRD increased by 77%, as demonstrated by the *neighboring NRDs dummy* variable. The probability of drilling a well significantly decreased by 21% after the moratorium is implemented as demonstrated by *post-policy dummy* variable.

The paper is organized as follows: **Section 2** introduces the institutional background about Nebraska groundwater management system. **Section 3** reviews the previous literature on irrigation adoption decisions and the important factors to consider. **Section 4** discusses the statistical methodology used for empirical analysis, and sources on data for each type of explanatory variable are followed in **Section 5**. **Section 6** and **Section 7** presents the results and discussion, followed by conclusion.

2 Institutional Background in Nebraska

During the period of 1950-1975, the quantity of groundwater used annually for irrigation in the western states increased from 18 to 56 million acre feet, which accordingly led to significant groundwater mining in the High Plains regions from Texas to Nebraska (Aiken, 1980). Figure 1 shows distribution of well registrations between 1950 and 2017 in nine NRDs in Nebraska where most irrigation wells were drilled. The 1957 Well Registration Statute required that all irrigation wells be registered with the Department of Water Resource (DWR), which is illustrated by the large number of well registrations in 1957. Until 1975, the state of Nebraska almost exclusively relied on a “reasonable use doctrine”, which granted a nearly unlimited pumping privilege to all overlying landowners. With the agricultural technological development in the 1970s, such as the widespread use of center pivot irrigation technology, the common law principle was not effective at limiting groundwater use, thus led to significant reductions in groundwater levels in several regions in Nebraska (Stephenson, 1996).

The state of Nebraska developed a unique system of 23 Natural Resource Districts (NRDs) to manage its groundwater resources, with boundaries based on river basins. The introduction of NRDs in Nebraska started in 1969 and was officially established in 1972, with responsibilities including allocating water, augmenting surface water, requiring flow meters, instituting well drilling moratoria, requiring water use reports and restricting the expansion of irrigated acres (Nebraska Natural Resources Districts).

The Upper Republican NRD (URNRD), as one of the NRDs with the most severe water level declines, was designated as the first groundwater water control area in 1977 due to its uncontrolled groundwater use and inadequate water supply (Aiken, 1980). As shown in Figure 2, number of wells in the four NRDs along Republican River Basin during 1960-1980 show consistent trends. Besides the technological advances, farmers' well-drilling decision is also affected by social factors. For example, energy crisis due to the embargo on oil by the Organization of the Petroleum Exporting Countries (OPEC) in 1970s, which led to a reduction in number of new irrigation wells during the period (Powell and Landers, 1979). Moreover, increased production and productivity also led to overproduction, groundwater use and land use. Therefore, Nebraska' agricultural sector mainly depended on government farm programs, which further caused farm credit crisis due to the heavy buildup of indebtedness and record-high interest rates that drove many farmers out of business, as indicated by the decreasing number of irrigation wells in the 1980s (Johnson, 1986).

Besides social factors, URNRD was the first NRD that implemented a complete well drilling moratorium in 1997 to further manage the severe water level declines in the region. With the implementation of the moratorium, farmers could no longer drill a new irrigation well at their own advantage. New well registrations in the URNRD have declined and remained at a low level since mid 1990s, which provided insightful evidence for the effectiveness of a well drilling moratorium on limiting new irrigation wells and reducing water-level declining rate.

For our analysis, we focus on the period between 1995 and 2017, since this period is after the technology-driven expansion in the 1960s and 1970s, and when groundwater regulations started to become common in the region. The study region includes the nine NRDs along Republican River Basin (RRB), Platte River Basin (PRB), and Blue River Basin (BRB), which are Lower Republican NRD, Middle Republican NRD, Upper Republican NRD, Tri-Basin NRD, Central Platte NRD, South Platte NRD, Twin Platte NRD, Little Blue NRD and Upper Big Blue NRD as highlighted in Figure 3. There are some fluctuations in the number of wells implemented each year in the nine NRDs, but the overall number of wells in the region is increasing between 1995 and 2017 as illustrated in Figure 4. Based on the observations for the regions and the variations in the timing of implementation of well drilling moratorium in each NRD, we are able to analyze how well drilling moratoria, by either a farmer's own NRD or a neighboring NRD, affect the decision to drill an irrigation well. Conducting analyses on a larger scale of observations provide critical insights on how to design an appropriate policy to maintain a sustainable water supply in the long run.

3 Literature review and theoretical framework

There is extensive literature that examine the factors determining farmers' irrigation technology decisions, such as when to start irrigating or when to invest in modern irrigation systems. These literature has iterated the important factors to consider in explaining farmers' adoption decisions in agricultural irrigation (Caswell and Zilberman, 1986; Lichtenberg, 1989; Negri and Brooks, 1990; Green et.al.,1996; Carey and Zilberman, 2002). Another branch of literature focuses on modeling a farmer's decision as a discrete choice, with adoption measured at a single point in time. In most cases, the literature uses field-level or farm-level data to empirically test the significance of each independent variables, and the most common method is logit or probit models (Lichtenberg, 1989; Westra and Olson, 1997; Knowler and Bradshaw, 2007; Sampson and Perry, 2018). An extension of this branch is to consider farmers' adoption decision as a dynamic process in which farmers learn about a technology or an agricultural practice and decide to adopt when the expected profit is positive. These results predict not only whether people adopt an irrigation technology, but also when a farmer chooses to adopt. A common method used in these papers is survival/duration analysis (Burton et. al., 2003; Alcon, 2011; Savage, 2011). However, most of the studies model the adoption process as a discrete decision that occurs at a point of time, thus commonly employ a probit/logit model, and literature on agricultural irrigation decisions that uses survival/duration analysis is limited.

Caswell and Zilberman (1986) provide fundamental explanations on the variables that determine farmers' irrigation decisions. Land quality and well depth are the two major factors in farmers' adoption decisions. More specifically, water-holding capacity is a more direct indicator of soil quality and is directly associated with the irrigation effectiveness of the chosen irrigation technology. Well depth affects farmers' decisions because it affects the cost of pumping groundwater. The variations in land quality and well depth are critical to understand adoption and diffusion patterns. Results show that modern technology tends to increase yield and save water in most cases, and is most likely to be utilized on low quality land with a high depth to groundwater.

Carey and Zilberman (2002) develop a stochastic dynamic model to examine farmers' technology adoption decisions under uncertainty. The study incorporates farm characteristics that affect efficiency gains associated with investment decisions, such as crop type, soil type, and land slope. The paper concludes that farmers will not invest in modern technologies unless the expected present value of investment exceeds the cost by a potentially large hurdle rate. In addition, the paper finds a counterintuitive result that the introduction of a water market, which would mitigate the uncertain about water supply, actually decreases technology adoption incentives for some farms. This result serves an important insight for farmers' irrigation decisions in which farmers require some certainty in water supply before adopting a new technology.

Negri and Brooks (1990) employ a discrete choice model to estimate the determinants of irrigation technology choice using a national cross section of farm-level data. The choice of a specific irrigation technology varies in terms of physical and economic attributes of the farm. The study confirms the importance of land quality and water cost in determining technology choice. As the price of water increases, the probability of adopting water-saving technology increases. Soil characteristics are included as dummy variables to classify spoil productivity and specific climate variables are generated as proxies for evaporation. In both technology choice models, soil characteristics and climate dominate farmers' selection probabilities.

Green et.al (1996) use a microparameter approach when explaining irrigation technology choices and point out that crop type plays an important role in technology choice, as high-value crops that require specialized capital affect the probability of specific irrigation technology. Moreover, water price is not the most important factor governing irrigation technology adoptions, and the results on water price variable are not robust in all cases, because the study areas focuses on arid and hot districts where irrigation water is already relatively high. Physical and agronomic characteristics are significant in determining farmers' adoption decisions, which is consistent with the results from other literature.

Knowler and Bradshaw (2007) review and synthesize 31 recent papers on farmers adoption of conservation agriculture to identify important independent variables to explain adoption. The paper summarizes four categories of factors that affect farmers' decisions: farm and farmers characteristics, biophysical, financial, and other economic factors. Though these factors are key determinants in each individual study, it is less likely to conclude that there universal variables to regularly explain the decision across analyses. The paper also highlights the most commonly used econometric approaches to analyze such decisions, which are OLS, probit or logit, random effects GLS.

Lichtenberg (1989) develops a framework that incorporates land quality into an empirical study to examines the interactions between land quality, crop choice, technological change and cropping patterns change. The paper empirically tests the framework using observations in western Nebraska during 1966-80 using a multinomial logit model. The study finds that land quality (measured using available water capacity and topography) has been one of the key determinants of cropping patterns and technology choice in the study region.

Westra and Olson (1997) use logit analysis to understand why farmers with similar soil type make different decisions about adopting a certain production practices (e.g., conservation tillage). The study uses data from two Minnesota counties, and includes factors such as climate, farmers and farm characteristics, geographic locations, and sources of information on conservation tillage practices. Results show that farmers' perceptions about such practices is a key determinant on whether to adopt it. Economic factors, farmers' ability and willingness factors, and farm sizes are the most critical factors in an adoption decision.

Sampson and Perry (2018) analyze spatial peer effects in acquisition of groundwater rights for agricultural irrigation using well-location from Kansas. The paper incorporates factors found to be significant in predicting technology adoption decisions, such as soil characteristics, market prices for corn and wheat, climate data for the period of 1950-2014.

The results demonstrate that an increase in the cumulative number of adopters in the closest geographic regions increases the probability of groundwater rights adoption with diminishing effect. Moreover, as the average distance to neighbors increases, the probability of groundwater rights acquisition decreases. In addition, commodity prices and climate variables also affect the decisions to acquire groundwater rights.

Burton et. al.(2003) employ duration analysis to model the adoption of organic horticultural technology in the United Kingdom using economic and non-economic determinants. This is one of the first studies to use duration analysis in an analysis of agricultural technology. The paper aims to identify the sign and magnitude of the effects of explanatory variables (i.e., farm and farmers characteristics, cropping patterns, economic factors, sources of information and attitudes to environmental issues) on the length of time farmers remain non-adopters. Results highlight the significant advantages of duration analysis over conventional approaches, such as probit or logit model.

Alcon (2011) employs duration analysis when studying farmers' adoption decisions of drip irrigation based on observations from southeastern Spain. The objective is to analyze the magnitude and sign of adoption determinants. The paper highlights the significance of using duration analysis and its great advantages over logit or probit model because it facilitates the study of both cross-section and time-dependent variables. Among other significant variables, water availability increases the adoption speed for drip irrigation, as more water allotment in a year provides reassurance of the profitability of technology investment. Moreover, farmers with access to groundwater are more likely to adopt modern technology than those without groundwater use. Both variables indicate that the farmers would require some certainty in water supply before investing in a modern technology.

Using data from the Republican River Basin (RRB) NRDs in Nebraska, Savage (2011) employs duration analysis to study how individual irrigation decisions are affected by physical heterogeneity and a spatial pumping externality. Results show that land quality, well yield, and depth to groundwater significantly affect farmers' investment decisions. One of the main contributions of this paper is the finding that relative profitability of irrigation is non-monotonic in land quality, in which the probability of adoption is greater on intermediate quality land relative to high quality land, but is less on low quality land relative to high quality land. The paper also demonstrates that when adequately controlling for endogeneity (something that previous studies failed to do), the relationship between farmers' irrigation behaviors and spatial externalities is found to be weak in this study region.

There is literature on farmers' preemptive behaviors in terms of policy implementations. List et.al.(2006) focus on exploring the extent to which the U.S. Endangered Species Act (ESA) has altered land development patterns, especially when most of the species listed on ESA are found in private land. Landowners can lose the development rights over the land if it is valuable to the listed species under ESA. Therefore, it is expected to observe a preemptive act from landowners to avoid such regulation, so that we expect a shift in the timing of development activities by the landowners. Based on observations from Arizona, empirical results show that there is a significant acceleration of development directly after several events deemed likely to raise fears among owners of habitat land.

Langpap et.al.(2017) review the recent literature regarding to the effectiveness of the Endangered Species Act (ESA). More than two-thirds of listed species under ESA inhabit only private land. Therefore, decisions on listing of species have caused conflicts between promoting species preservation and restricting economic activities, because it involves in more governmental control over grazing, irrigation, construction and energy development. As a result, such restrictions on land use provide farmers little incentive to maintain or improve habitat and may destroy it to preempt regulation. The paper uses survey and observational data to examine the effects of incentive programs and results suggest that perceived likelihood of ESA regulation did not have a significant impact on landowners' decision to participate in a conservation program. While perverse incentives are real, it is possible to mitigate such preemptive behaviors by proper designed incentive programs.

4 Survival Analysis

In this study, we use a survival analysis to examine farmers' well-drilling decisions. Survival analysis is the study of how long an individual survives in a certain state, and what factors affect the decision to leave that state. In our context, we assume that all producers are initially farming with a dryland system, and we analyze how long a producer survives as a dryland producer before choosing to invest in an irrigation well.

Formally, two key ways of specifying a survival distribution are the survival function and the hazard function (Moore, 2016). The simple survival function is demonstrated as follows:

$$S_i(t) = Pr(T_i = t_i | T_i \geq t_i, X_{it})$$

Which defines the probability that the random variable T exceeds t, where T_i is a discrete random variable representing the time that parcel *i* adopts irrigated production. X_{it} is the set of explanatory variables for parcel *i* at time *t*. The hazard function specifies the instantaneous failure rate at T=t, which is expressed as:

$$h_i(t) = \lim_{dt \to 0} \frac{pr(t \leq T_i < t + dt | T_i \geq t)}{dt} = \lim_{at \to 0} \frac{F(t+dt) - F(t)}{dt(1 - F(t))} = \frac{f_i(t)}{S_i(t)}$$

$h_i(t)$ defines the probability of a farmer remains in dryland production at T=t, conditional upon survival to time t, and decides to switch to irrigated farming in the next interval of time. $F_i(t)$ is the cumulative density function, and $f_i(t)$ is the continuous density function of the random variable t. These functions are defined as:

$$F_i(t) = \int_0^t f(s)ds = \Pr(T_i \leq t) = 1\text{-}S_i(t)$$

$$f_i(t) = -\frac{d}{dt}S_i(t) = \frac{d}{dt}F_i(t)$$

The relationship between these functions are defined. In addition, while other functional relationships between the proportional hazards and covariates are possible, the most widely used model is proportional hazard model, which decomposes the hazard into a baseline component and a component depends on individual covariates. There are many appropriate parametric specifications for the distribution of survival data to define the baseline survival function, such as exponential and Weibull distributions. However, parametric distributions require strong assumptions about form of the underlying survival distribution, thus Cox proportional hazards model is the most common regression modeling framework in practice, which allows for an unspecified baseline survival distribution (Moore, 2016). The Cox proportional hazards model demonstrates the relationship between covariates and the hazard of experiencing an event, and employs a partial likelihood approach to estimate the model parameters (Thomas and Reyes, 2014). The practical reason for the advantage of using the Cox proportional model is that it allows for time-dependent covariates in the case where such variables are expected to affect farmers' irrigation decisions.

Therefore, we use time-to-event data to model farmers' irrigation decisions based on the Cox proportional hazards model. The dataset includes initial starting year, ending year, event occurrence(i.e., the irrigation adoption decision), and also explanatory variables that include both time-fixed and time-varying variables. The Cox proportional hazards model requires a counting process style of dataset, which expands the dataset from one record-per-well to one record-per-interval between each event time for each individual observation. The model then compares the current covariate values of the subject who had the event and the current values of all others who were at risk at that time at each event time (Therneau et.al.,2018). The Cox proportional hazards model in terms of hazard functions is demonstrated as

$$h_1(t) = h_0(t)\exp(\beta X + \beta_Y^T Y)$$

where $h_0(t)$ is the baseline hazard function with all the covariates equal to 0, X and Y are vectors of time-fixed and time-varying covariates, respectively.

The effect of one unit increase in y given a common X is

$$\frac{h_1(t|Y=y+1,X)}{h_0(t|Y=y,X)} = \exp(\beta)$$

The primary interest of this study is to determine the factors that affect a farmer's decision to drill a new well (i.e., switch from dryland to irrigated farming), with a particular interest in the effect of policy variables. The dependent variable is the duration measured by the number of years farmers remain in dryland production. The data includes all the observations up to the year when an irrigation well is drilled, and the rest of the observations are dropped.

5 Data

Our data covers the southwestern and southcentral portions of Nebraska as displayed in Figure 3. Our unit of analysis is a quarter section of land, which is a 0.5 mile square.[1] A quarter section is the most typical size of a field, and is the standard size for a center pivot irrigation system. The quarter sections included in the study are those units that have not yet implemented an irrigation well by 1995, which is equivalent to 70% of the quarter sections in the nine NRDs. The full available spatial information on irrigation wells are from the

[1] Sections refer to the sections in the U.S. Public Land Survey System. Each section is one square mile.

Nebraska Department of Natural Resources. We filter out the wells that are not for irrigation use, leaving 69,415 irrigation wells in the nine NRDs. As described previously, the nine NRDs contain the majority of irrigation wells in Nebraska, and are the areas with the most activity in groundwater policy**.** The dependent variable is the duration until an irrigation well is drilled on the quarter section, thus the timing when a farmer adopts irrigation. Since we are particularly interested in well moratoria policies, we mainly focus on the period of 1995-2017. The starting time of 1995 is chosen because it is shortly before the first moratorium policy was enacted in the study area. The exit time is the year an irrigation well is implemented. In practice, some individuals may not adopt irrigation by the end of the observation period, which is 2017, then the procedure is to right-censor those observations in 2017. The maximum duration is thus 23 years.

In particular, survival analysis assumes that there is only one well in each quarter section, and it captures the probability of a well gets implemented in each quarter section in terms of the explanatory variables included. However, our well spatial data show that there are 45% of the quarter sections with multiple wells. In some cases, multiple wells are registered in the same year, while other cases have new wells added without an existing well deactivated. Thus, we only keep the first well for each quarter section, which is appropriate given our research interest in explaining when a farmer switched from dryland to irrigated production. For the period of 1995-2017, there are 5,010 irrigation wells included for our regression analysis. There are registration and completion year recorded for each well, and they are not always the same. In cases where the years differ, we use the earlier date, as this is an indicator of the irrigation adoption decision.

Previous research finds that soil characteristics are an important factor that determine farmers' irrigation decisions (Caswell and Zilberman, 1986; Negri and Brooks, 1990). Soil characteristics are likely to affect irrigation effectiveness and profitability. Spatial soil data are downloaded from USDA-SSURGO. Soil characteristics include sand and silt percent, slope, and available water capacity. The variables capture the main soil characteristics to measure the output productivity and irrigation efficiency. Monthly weather information is from PRISM climate data from Oregon State University. The grid cells analyzed are the standard PRISM 4km. Specifically, climate variables used in the study are monthly maximum temperature and total precipitation. These variables affect yields and associated profits with irrigated production (Negri and Brooks, 1990; Green et al, 1996; Sampson and Perry, 2018). Both SSURGO and PRISM data are spatial datasets, and are matched with the quarter sections of the nine NRDs.

The economic variables are from USDA National Agricultural Statistic Service. We first obtain state-level crop prices and county-level yields. Time-series data for energy costs are not available at the county or district level for the state of Nebraska. State-level costs only capture variation across time but not across each individual quarter section. Thus, due to data availability, we use crop price and yields to calculate the county-level revenue differential between dryland and irrigated production for corn, which measures the marginal yield benefit of switching from dryland and irrigated farming. Prices are all in constant 2017 U.S. dollars using the Consumer Price Index.

As for policy variables, the dates for the various moratorium are from each NRD's Rules and Regulations and Integrated Management Plan documents. The Rules and Regulations document is required of all NRDs, and describes operating procedures and rules. The Integrated Management Plan is required of some NRDs based on the history and concern over groundwater depletion and groundwater-surface water connectivity. Based on the policy information, we generate three dummy variables related to the policy well drilling moratoria. *Neighboring NRDs dummy* variable is created to capture the policy spillover effect that if farmers' decisions are affected by the policy implementation in their neighboring NRDs. For this dummy variable, we assign 1 if any adjacent NRD has implemented a well drilling moratorium, and 0 otherwise if the site NRD has not implemented a moratorium. The *pre-policy dummy* variable is to capture farmers' preemptive behavior to drill a new well if a moratorium is announced but not yet implemented. A '1' indicates one year prior to the actual implementation and a '0' indicates all other years. *Post-policy dummy* variable indicates whether an observation occurs after a moratorium is implemented. If the moratorium is effective and enforced, this will have a significant negative effect on well drilling. However, the Board of Director for each NRD has considerable autonomy to permit new wells, even when a moratorium exists. Thus, we do not expect that implementation is perfect. Table 1 presents descriptive statistics of the variables used in the econometric model.

6 Results

Recall that the dependent variable in survival analysis is the duration of time that farmers remain in dryland production until an irrigation well is drilled. The key variables of interest in this study are policy variables, which are *neighboring NRDs dummy*, *pre-policy dummy* and *post-policy dummy*. The variables are generated based on available information on the implementation years of well-drilling moratorium in the nine NRDs. Table 2 (1995-2017) reports the results of the survival model with NRD-fixed effect incorporated. The results show the relationship between each exogenous variable and the probability of well drilling for farmers within the nine NRDs. The coefficients demonstrate the proportional change in the hazard given a unit change in the exogenous variable. A positive coefficient implies a higher hazard associated with the variable, which tends to reduce time in dryland production, thus faster adoption. Column 3 in Table 2 shows the hazard ratio associated with each variable. A hazard ratio that is greater than 1 implies a positive effect on farmers' well-drilling decisions.

As illustrated in Figure 4, we observe an increasing number of well registrations at least a year before the policy implementation, and a decreasing trend for well drilling after the implementation. Results from Table 2 demonstrate expected sign of coefficients for the three policy variables, *neighboring NRDs dummy*, *pre-policy dummy* and *post-policy dummy*. Some of the NRDs still have significant well registrations after the well drilling moratorium was implemented, such as Central Platte, Little Blue, Tri-Basin and Upper Big Blue. These NRDs have partial moratoriums that only apply to some areas, but not to the full NRD. The coefficient of *pre-policy dummy* is positive and statistically significant, which means that *pre-policy dummy* increases the hazards and reduces survival duration thus leads to a faster well drilling decision, comparing to those without policy implementation. The hazard ratio for *pre-policy dummy* is $e^{0.365} = 1.6215$, as the hazard ratio represented in Table 2, it indicates that the probability of drilling a new well is 62% greater than those NRDs without potential policy interventions. Similarly, the positive coefficient of *neighboring NRDs dummy* and its hazard ratio show that if a moratorium is implemented in an adjacent NRD, the probability of farmers drilling a new well increases by 77% due to the expectation of such policy to expand to their own NRD in the future. On the contrary, the coefficient on *post-policy dummy* is negative and statistically significant. The relationship shows that after an implementation of well drilling moratorium, the probability of drilling a well decreases by 21%.

Soil characteristics are captured by *sand percentage*, *silt percentage*, *slope* and *available water capacity*. The coefficients on *sand percentage* and *silt percentage are* positive and statistically significant. The proportion of each soil component indicate the specific type of soil characteristics that determine irrigation efficiency, thus increases the probability for adopting irrigation. The coefficient on *sand percentage* indicates that a one-percent increase in *sand percentage* in soil component is associated with 3.6% higher chance of adopting irrigation. An additional increase in the organic matter increases the probability of drilling a new well due to a higher profit associated with irrigation production.

Some variables do not indicate expected relationship with farmers' irrigation adoption decisions based on results from Table 2. For example, the coefficient on *average maximum temperature* is negative and statistically significant, which means that one unit increase in temperature is associated with 33% lower probability of drilling a new well. Higher summer temperature increases the water evaporation rates and reduces water application efficiency, thus it is associated with higher hazard; therefore, the coefficient on this variable is unexpected. The insignificant explanatory variables are somewhat expected, because farmers' irrigation decisions in more recent period are dominant by the policy intervention on groundwater use, and depend less on soil characteristics, economic factors and climate variables. Recall that the locations included in the analysis are only those that have not already had well implementations by 1995. Thus, locations where the soil quality increases the net benefit of irrigation are likely to have already installed irrigation before 1995, so we do not observe significant impacts from the non-policy factors for this period.

7 Baseline effect of Non-Policy Factors between 1960 and 1995

In order to have a better understanding about the impacts that non-policy factors have on farmers' irrigation decisions, we also analyze the data on wells with corresponding explanatory variables for the early period of 1960-1995 for the nine NRDs in Nebraska. The first traceable irrigation well was implemented in 1919, however, due to the lack of available data on the earlier period and the fact that wells were required to be officially registered in

1957, we focus on the observations after 1960. Thus, we have a total number of 18,745 irrigation wells in the nine NRDs during 1960-1995, the distribution of well implementations per year is illustrated by Figure 6. The average well implementation per year is 520 between 1960 and 1995 which is twice of the number drilled during the period of 1995-2017. We expect that all of the explanatory variables, such as climate variables, soil characteristics, and economic factors would have greater impacts on farmers' irrigation decisions in the early period as they are the determinants for farmers' irrigation decisions, particularly when the policy variables are not relevant in early years. The same econometric model is employed that is the survival analysis. Results are reported in Table 3.

Results from Table 3 show the relationship between each exogenous variable and farmers' irrigation decisions based on the observations from 1960 to 1995. In general, the sign of coefficients on non-policy factors demonstrate consistent relationships from the results in Table 2 (1995-2017). Specifically, all the coefficients on the economic, agronomic and climate variables are statistically significant, and the magnitude for each variable is also greater.

Variables on soil characteristics are statistically significant on farmers irrigation decisions in early period during 1960-1995. *Sand percentage and silt percentage* in soil components illustrate that one-percent increase in the variables, the probability of farmers adopt irrigation increases by 2.8% and 2.9%, respectively. The coefficient on slope is negative and statistically significant, which reveals the importance of soil quality that one unit increase in soil slope would decrease the probability of drilling a new well by 0.4%. The coefficient on *available water capacity* is positive and statistically significant, which shows that higher land quality leads to a higher irrigation gain, so it increases the probability of drilling a new well by 2.6%.

In addition, the coefficient on *corn revenue differential* is positive and statistically significant as expected. Corn is the most water intensive crop commonly grown in the region, an increase in *corn revenue differential* between dryland and irrigated land leads to a 0.14% higher probability of drilling a well due to the higher profits associated with irrigated production.

However, the coefficient on *precipitation* is positive and statistically significant for the period of 1960-1995. The positive coefficient on *precipitation* means that as precipitation increases by one inch, it increases farmers' probability of drilling a new irrigation well by 4.7%. Comparing the climate trend and number of wells in Figure 6 and 7, during the period of 1970-1975, it shows that a negative relationship that as a decreasing precipitation trend is corresponding to an increase in number of wells. However, the significant decrease in well drilling after 1975 due to a more regulated groundwater pumping may cause the unexpected relationship between precipitation and farmers' well drilling decisions for the early period.

8 Conclusion

Governmental interventions on groundwater use are considered as an important aspect of achieving a more sustainable groundwater management. This paper focuses on analyzing the impacts of a specific groundwater policy well drilling moratoria have on the timing of farmers' decisions on well drilling based on observations in the nine NRDs using survival analysis. In the context of agricultural irrigation adoption studies, we consider the factors that affect such decision involve economic, agronomic, climate, technology development and political variables, and farmers' irrigation decisions depends on more than a single observation of these variables at the time of adoption, but the accumulation of observations over the prior periods. Therefore, the strength of survival analysis over conventional bivariate method is that it captures the dynamic elements of the adoption process.

We find strong evidence for farmers' strategic responses toward a well drilling moratorium. Farmers' well drilling behaviors after the policy implementation are significantly reduced but not perfectly eliminated due to the fact that some of the NRDs only partially implemented well drilling moratoria in some counties; however, as farmers find out a moratorium is about to be implemented in their NRD in the future, farmers start to respond to such policy intervention by drilling more irrigation wells at least a year before the actual implementation as demonstrated by the *pre-policy dummy* variable and also by Figure 5. In addition, policy spillover effect as demonstrated by the *neighboring NRDs dummy* based on the results from Table 2 (1995-2017) shows that farmers are more likely to drill a new irrigation well if any of their neighboring NRDs implements either a partial or a full moratorium.

We also identify significant impacts from corn revenue differential between dryland and irrigated land production and soil characteristics, which reclaim the importance of these variables in determining farmers' irrigation decisions. In addition, results from Table 3 (1960-1995) illuminate the greater impacts from each exogenous variable, such as economic and agronomic factors. While the findings are not unexpected, and some of the variables do not demonstrate expected relationships, it reiterated the importance of considering included variables when analyzing farmers' irrigation decisions.

There are some policy implications based on the results. Well drilling moratoria tends to reduce well implementations by each NRD, and the different timing of policy implementations in each NRD demonstrates the sole authorization each NRD has for appropriate local groundwater resource management. However, both policy spillover effect and farmers' preemptive behaviors lead to a significantly increased probability of drilling a new well by 77% and 62%, respectively, make the moratorium less effective than we expect, comparing to a 21% reduction in the probability of drilling a well after the moratorium is implemented. Thus, understanding farmers' strategic responses in terms of a policy change is important for a better policy design.

Some limitations of this study include the lack of more complete variables selections due to data availability. For example, data on energy costs that are associated with irrigation in Nebraska such as natural gas and diesel are only available at state-level, which restricts the inclusion of such variable that are important to farmers' irrigation decisions. Thus, choosing different variables, such as depth to water levels to capture costs associated with irrigation results in a better estimation of factors that determine farmers' decisions. In addition, investigating variables that measure farmers and farm characteristics over time are also worth exploring their effects on farmers' irrigation decisions.

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10 Tables & Figures

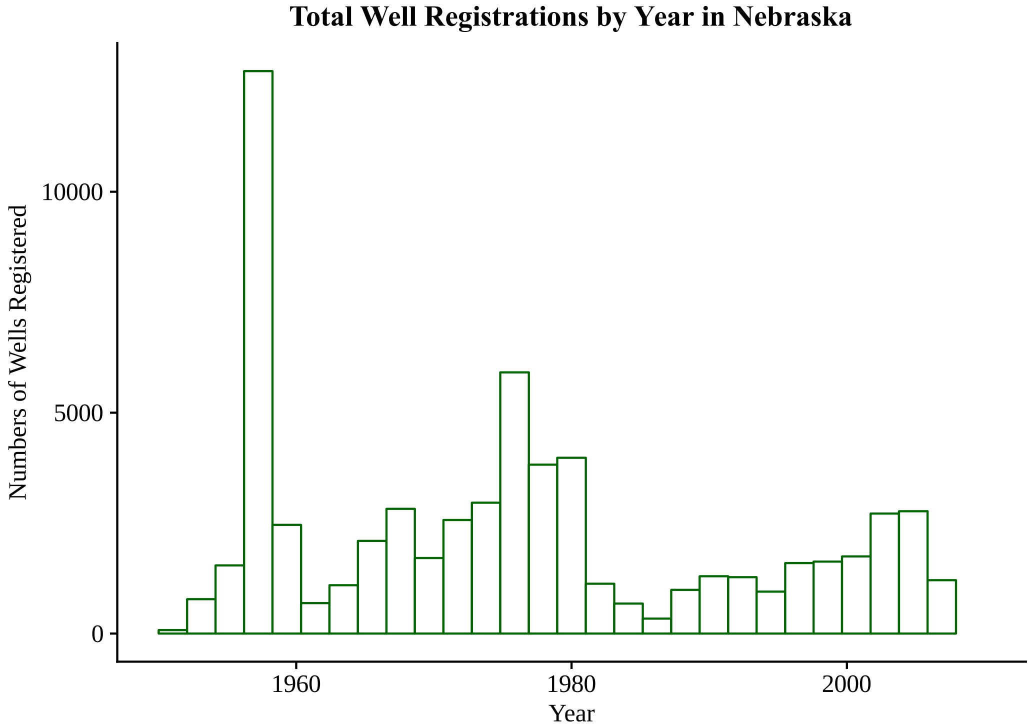


Figure 1 Well Registrations by Year in Nebraska (1950-2017)

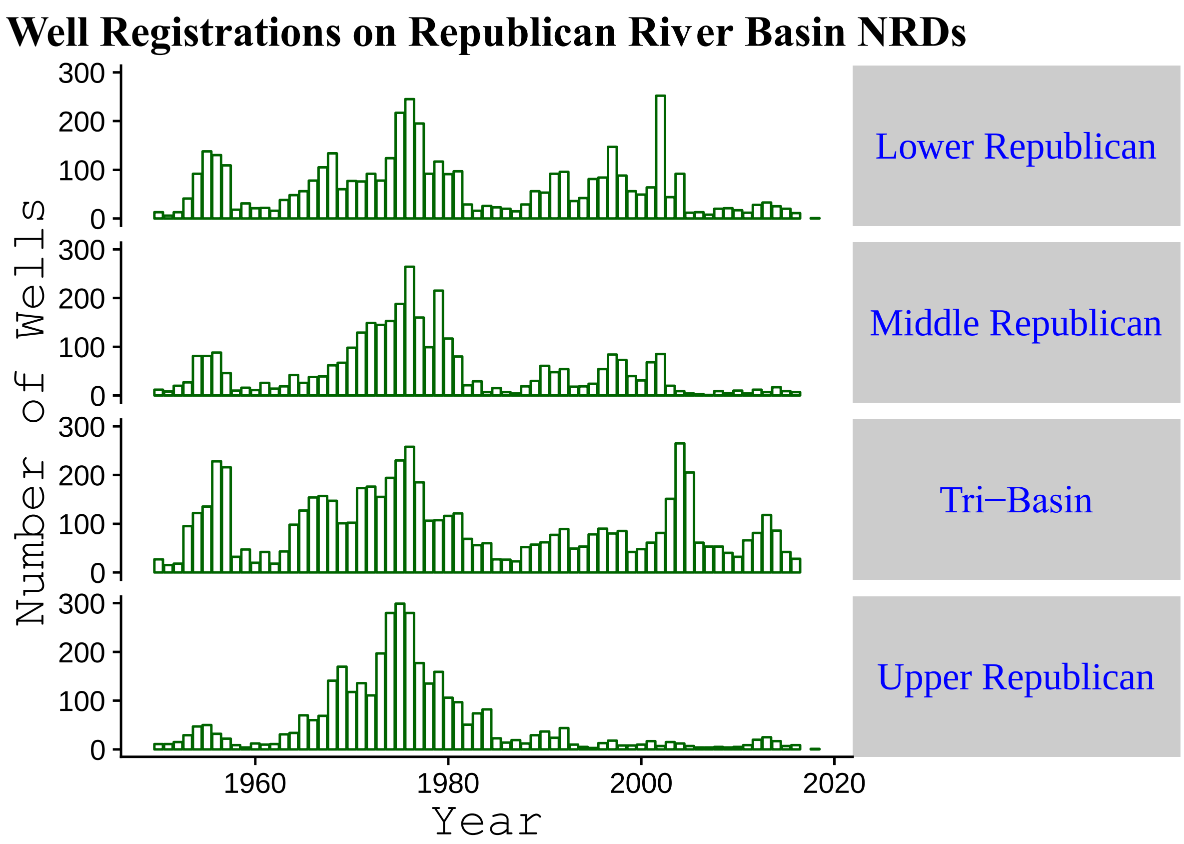


Figure 2 Well Registrations in Republican River Basin NRDs

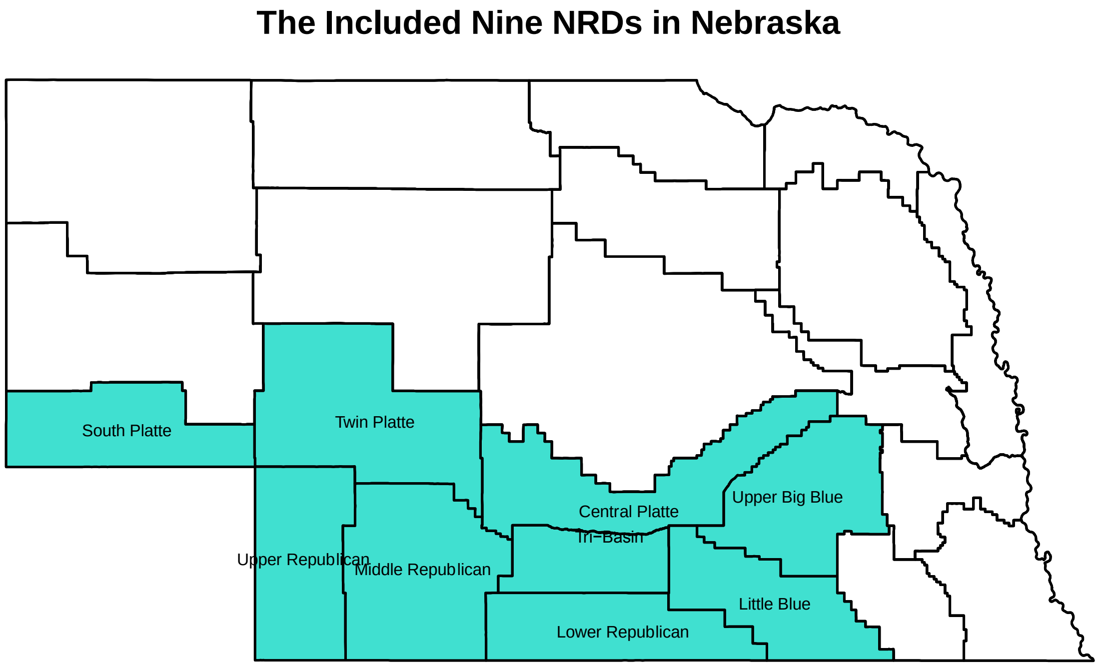
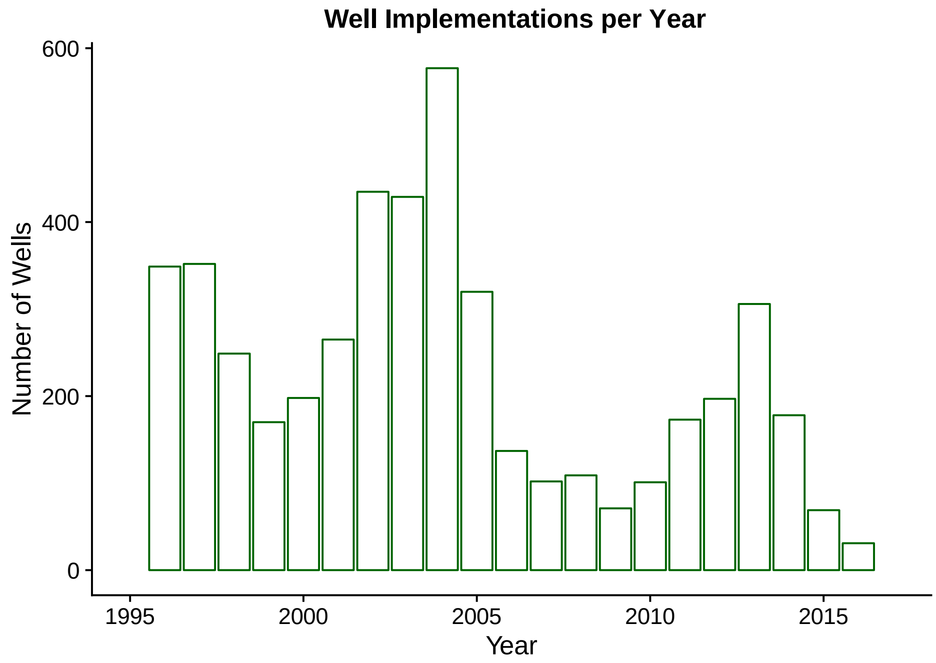


Figure 3 The nine studied NRDs in Nebraska



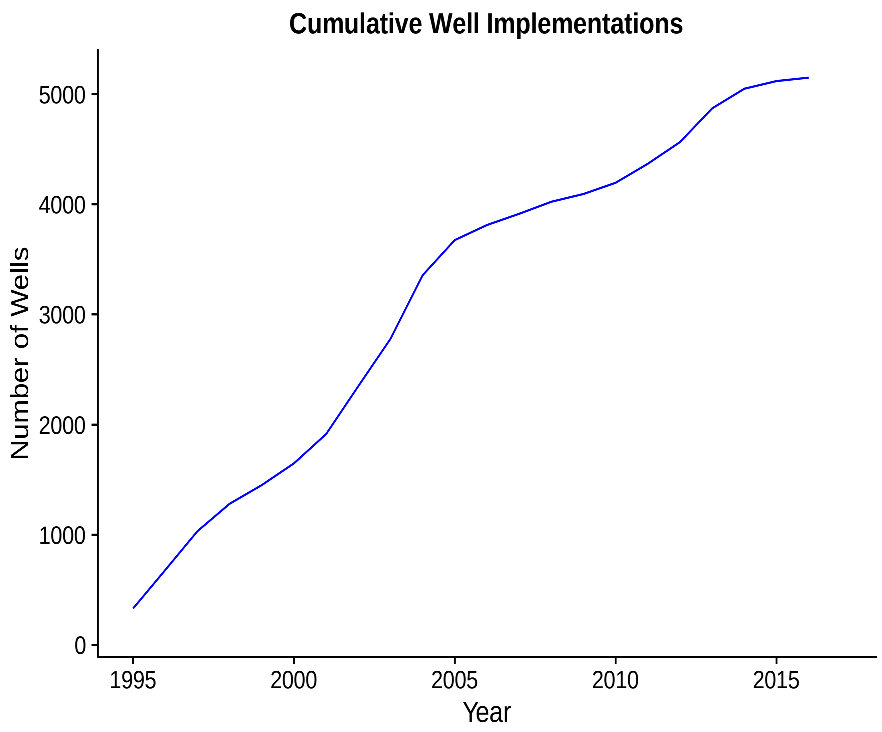
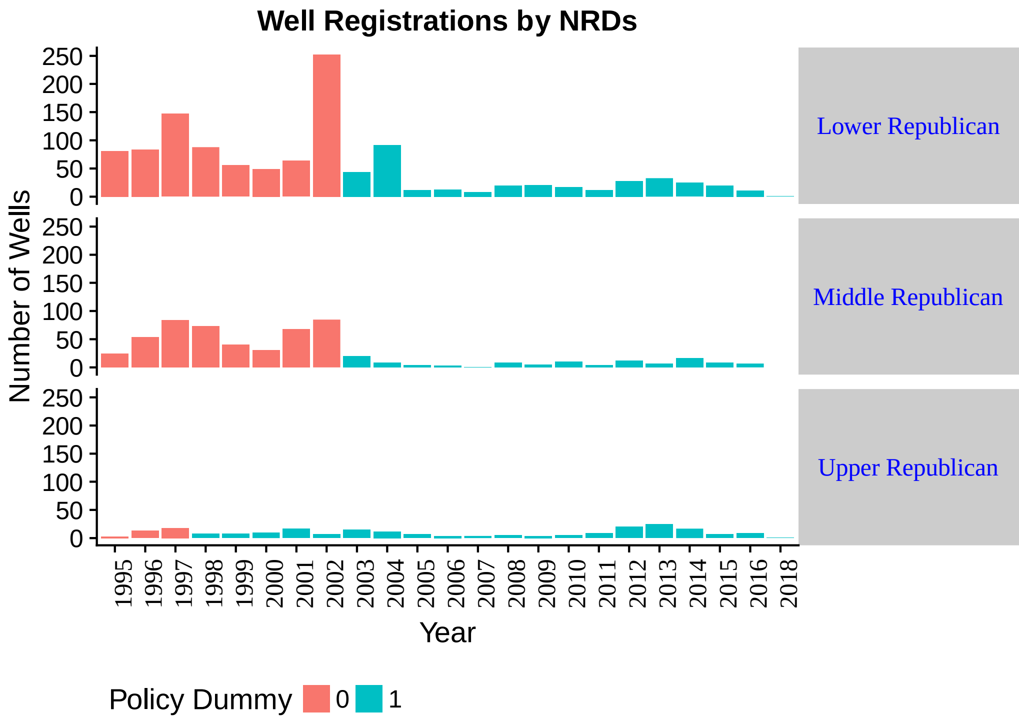
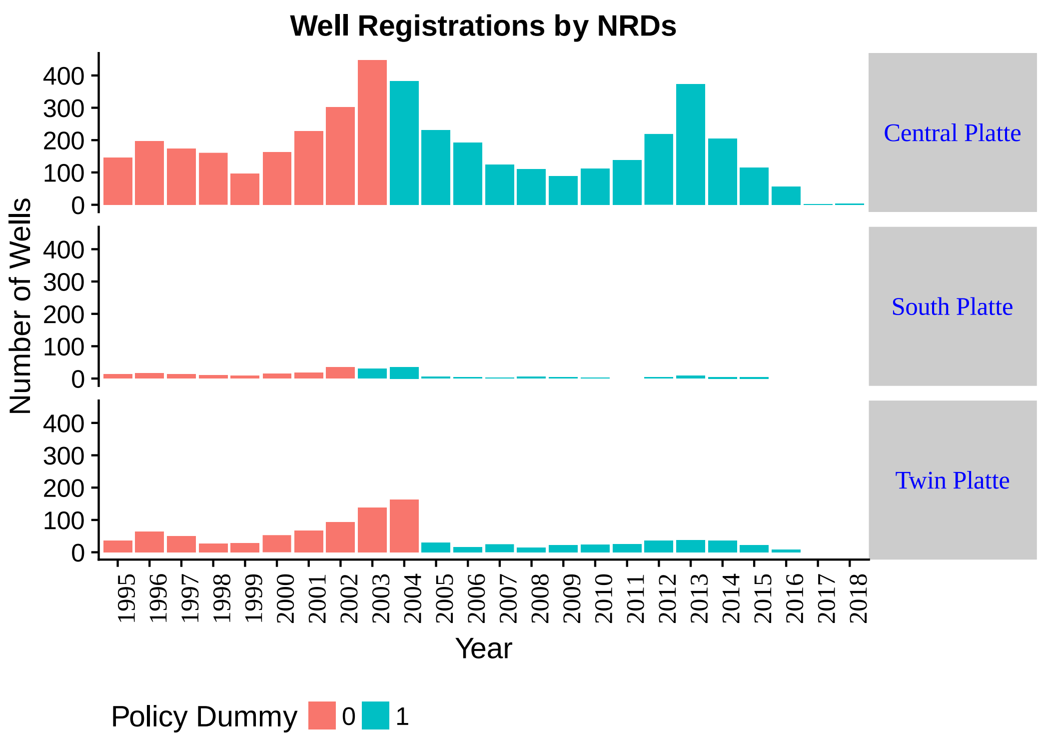


Figure 4 Well registrations by Year in Nebraska (top) and cumulative implementations over time (bottom) in the nine NRDs (1995-2017)



Well Registrations by NRDs
Number of Wells
0
50
100
150
200
250
Lower Republican
Middle Republican
Upper Republican
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2018
Year
Policy Dummy
0
1


Well Registrations by NRDs
Number of Wells
400
300
200
100
0
Central Platte
South Platte
Twin Platte
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year
Policy Dummy
0
1

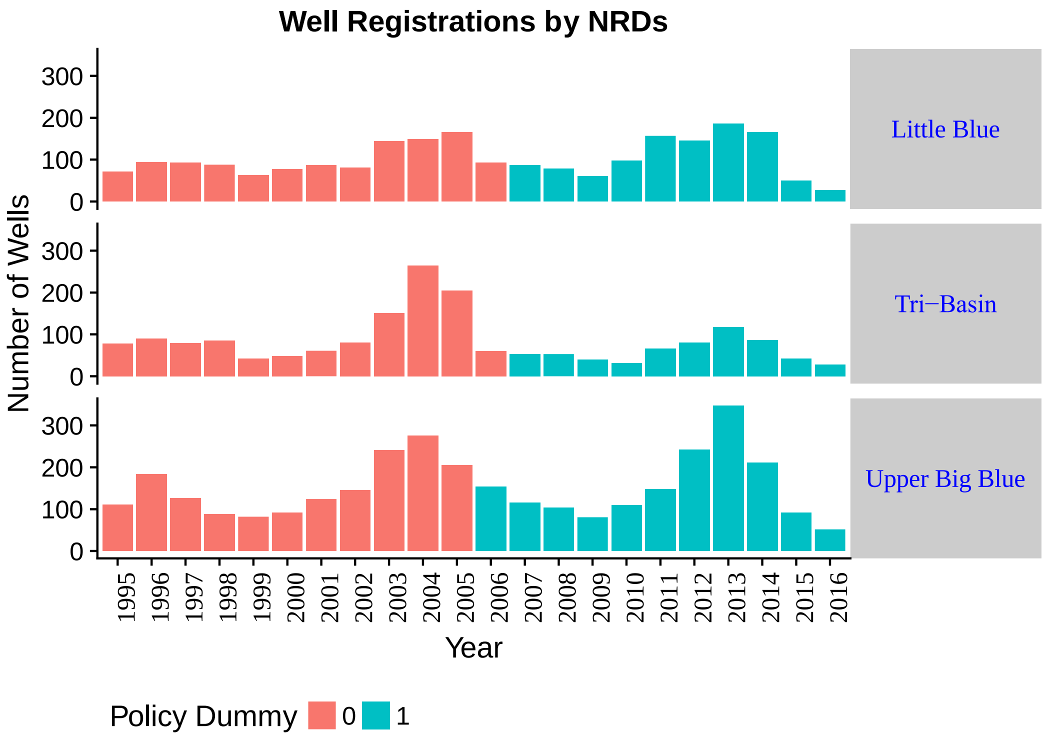


Figure 5 Well Registrations and policy implementation by NRDs (1995-2017)

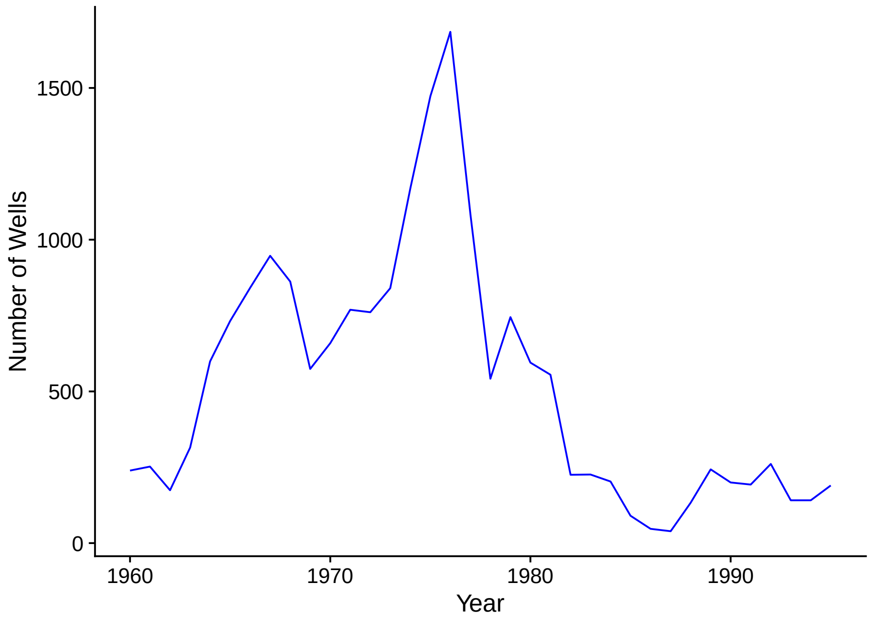


Figure 6 Well Implementation Per Year during 1960-1995

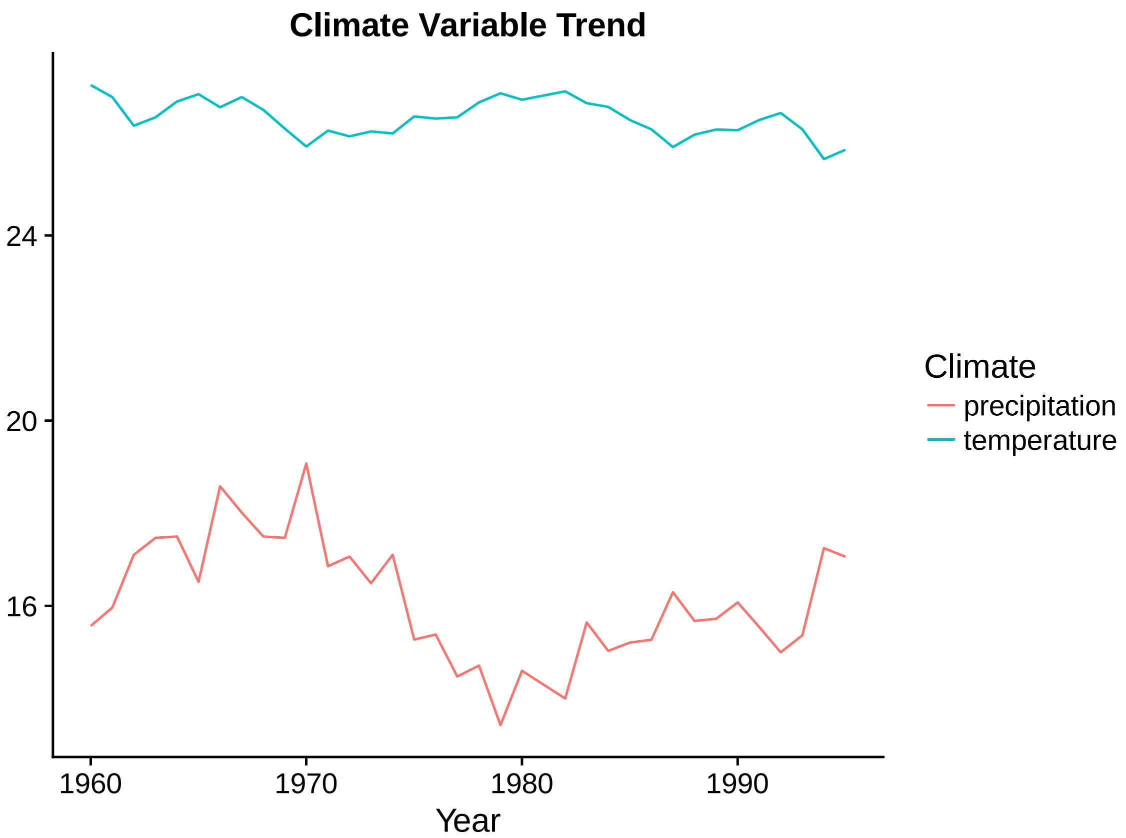


Figure 7 Climate Trend during the period of 1960-1995

Table 1 Summary Statistics

Variable (units)	Definition	N	Mean	St. D	Min	Max
Total Wells (1950-2017)	Number of wells in each NRD	33,493	3,618	2,229	727	8,261
Total Wells (1995-2017)	Number of wells in each NRD	5,010	572	371	95	1,246
Sand Percentage	Percentage of sand in soil components	70,525	39.7	31.3	5.0	96.0
Clay Percentage	Percentage of clay in soil components	70,525	18.8	9.5	2.0	39.9
Silt Percentage	Percentage of silt in soil components	70,525	41.5	22.9	0.6	73.0
Average Water Capacity (%)	Amount of water a soil can store	70,525	20.5	6.9	4.8	34.5
Slope (%)	Soil Slope	70,525	7.0	6.2	0.0	44.0
Policy Implementation Year	Implementation year of Well-Drilling Moratorium in NRDs	9	2003	2.8	1997	2006
Precipitation_t (mm)	Monthly total precipitation during growing seasons	98,164	17.3	3.2	8.9	29.7
Average Maximum Temperature_t(C)	Monthly maximum temperature during growing seasons	98,164	26.1	0.8	23.2	29.7
Corn Revenue Differential_t ($/bu)	Corn revenue differential between dryland and irrigated land	873	314.1	120.9	103.1	741.1

Note: Observations on exogenous variables are shown for the period of 1995-2017 and are recorded as five-year moving average values. $_t$ = time dependent variable.

Table 2 Regression Results for 1995-2017

Regression Results		
	Coefficient	*Hazard Ratio*
Precipitation	-0.016 (0.010)	1.0041
Average maximum temperature	-0.476^{***} (0.041)	0.6727
Corn revenue differential	0.0005 (0.0004)	1.0014
Sand percentage	0.028^{***} (0.004)	1.0362
Silt percentage	0.035^{***} (0.006)	1.0467
Slope	-0.002 (0.003)	1.0036
Available water capacity	0.014^{*} (0.008)	1.0302
Neighboring NRDs dummy	0.437^{***} (0.067)	1.7656
Pre-policy dummy	0.365^{***} (0.061)	1.6215
Post-policy dummy	-0.443^{***} (0.106)	0.7896
Observations	1,281,034	
R^2	0.004	
Max. Possible R^2	0.079	
Log Likelihood	-50,019.700	
Wald Test	$4{,}663.010^{***}$ (df = 18)	
LR Test	$5{,}734.792^{***}$ (df = 18)	
Score (Logrank) Test	$7{,}492.773^{***}$ (df = 18)	
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$	

Table 3 Regression Results for 1960-1995

Regression Results		
	Coefficient	*Hazard ratio*
Precipitation	0.045*** (0.007)	1.0465
Average maximum temperature	-0.073*** (0.022)	0.9292
Corn revenue differential	0.001*** (0.0002)	1.0014
Sand percentage	0.027*** (0.002)	1.0278
Silt percentage	0.029*** (0.003)	1.0290
Slope	-0.004* (0.001)	0.9964
Available water capacity	0.026*** (0.004)	1.0261
Observations	2,264,598	
R^2	0.006	
Max. Possible R^2	0.160	
Log Likelihood	-191,556.900	
Wald Test	11,898.360*** (df = 15)	
LR Test	12,934.720*** (df = 15)	
Score (Logrank) Test	15,910.830*** (df = 15)	
Note:	*p<0.1; **p<0.05; ***p<0.01	