THESIS

THE COST OF CONSUMPTION: AN ANALYSIS OF THE HETEROGENEOUS IMPACTS OF GROUNDWATER AVAILABILITY IN THE HIGH PLAINS AQUIFER

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ABSTRACT

THE COST OF CONSUMPTION: AN ANALYSIS OF THE HETEROGENEOUS IMPACTS OF GROUNDWATER AVAILABILITY IN THE HIGH PLAINS AQUIFER

Nearly 20-percent of the wheat, corn, cotton and cattle produced in the United States are made possible by the hydrologic resources of the High Plains Aquifer (HPA) (NRCS, 2017). Despite being a source of agricultural prosperity, this aquifer has long been subject to overdraft including reductions in saturated thickness exceeding 50m in the southern extents (Haacker et al., 2016). We follow Hornbeck et al. (2014, 2015) in comparing economic outcomes among counties inside the HPA to similar counties within 100km from the aquifer boundary, building on this research by also evaluating the impact of initial groundwater endowments as an exogenous measure of irrigation access. Utilizing a hedonic pricing model based on Ricardian theory of land valuation, we choose to examine irrigation intensity, land values, and population density using census data at the county scale to measure the marginal benefit of groundwater. These economic outcomes are examined across ranked groupings of initial saturated thickness for three distinct time periods: approximate pre-development of the aquifer (1925-1945), during the height of irrigation expansion (1950-1992), and during contemporary time periods of irrigation water shortages (1997-2012). Results indicate that previous studies which have regarded the HPA as a homogeneous unit overlook the true marginal contributions of groundwater. We find that the counties with the largest initial endowments of groundwater in the HPA have increased land values by as much as 42-percent during the height of irrigation expansion, and more importantly have maintained the longest lasting economic benefits compared to counties with lower initial saturated thickness and those outside the aquifer. Our results differ from previous studies (i.e., Feng et al., 2012) as we find no statistical relationship between access to groundwater (or aquifer depletion) and population density.

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INTRODUCTION

The High Plains Aquifer underlies 174,000 square miles in the mid-western United States, stretching north from the Texas Panhandle to the southernmost extent of South Dakota. Almost one-fifth of the wheat, corn, cotton and cattle produced in the United States are made possible by the hydrologic resources of the High Plains Aquifer (HPA) (NRCS 2017). The aquifer's largest formation is the Ogallala, which underlies some part of all eight states in the aquifer's range. References to the aquifer often interchangeably use the name Ogallala; however for the purposes of this study we will employ the more encompassing appellation of HPA.

The broad variation among initial groundwater endowments, groundwater consumption, and management practices in the High Plains region is epitomized when comparing the Texas Panhandle and western Nebraska. Texas has seen substantial decreases in water levels since the introduction of the center-pivot irrigation technology in the 1940s. From just 2001 to 2008, Texas' decline in saturated thickness comprised 32-percent of the cumulative depletion that had taken place during the entire 20th century. Conversely, aquifer recharge has actually occurred in Nebraska, with saturated thickness in some cases increasing by more than 50 feet. Groundwater pumping limits are also commonplace for Nebraska's Natural Resource Districts. The lion's share of the HPA has an annual recharge rate of less than one inch (Scanlon et al., 2012), meaning that despite being an unconfined aquifer, its slow rates of replenishment categorize the majority of the aquifer as economically non-renewable.

The magnitude of the HPA both in terms of capacity and regional dependence, have made it a subject of study for academics and government entities starting in the early twentieth century (Kromm et al., 1992). The High Plains Aquifer is one of the most comprehensively monitored ground water formations in the U.S. (Konikow 2013). There are currently over 68-thousand monitoring wells throughout the HPA administered by local, state and federal water managers (Steward, 2016). The vastness of data available for the HPA both temporally and spatially, makes it a fitting candidate to examine the implications of declining aquifer storage.

Management of groundwater can be costly to implement and politically unfavorable. However, accurately capturing the effect that groundwater levels have on land values, profitability and population can provide justification for policy makers and producer groups that seek to implement water conserving measures. Furthermore, understanding the impact that groundwater access has had on land values since the early 1940s can help water users and policy makers to make informed decisions about the future of groundwater management in the HPA region.

The institutional history of water management in the United States, especially in the arid West, has made direct market price analysis unfeasible as a method to understand the value of irrigation water. Consequently, revealed preference methods have been used in many economic studies over the last half century to extract the value of irrigation water through observed differences in agricultural land values. However, previous studies have omitted critical geographies of the HPA and/or excluded location specific aquifer traits which influence irrigation capacity and therefore productivity of the land.

Our study utilizes cross-sectional data to identify a causal relationship between aquifer characteristics and agricultural land values. Specifically, we use data from the US Census of Agriculture on average agricultural land value for 240 counties within and 128 counties that lie within 100 kilometers outside of the aquifer. These data are paired spatially with pre-development (i.e., 1935) estimates of saturated thickness, in addition to stationary climate characteristics such as average annual precipitation. This Ricardian method assumes that aquifer characteristics, some of which vary over time, are capitalized into land values and production practices, thus allowing us to capture the marginal value of groundwater as it may vary across the aquifer.

Our study aims to capture the impact across space and time of HPA irrigation water on select economic outcomes through exogenous measures of groundwater access. We follow Hornbeck et al. (2014) in comparing farmland values amongst counties inside the Ogallala to similar counties within 100km from the aquifer boundary, building on this research by also evaluating the impact of initial groundwater endowments within the aquifer's boundaries. We further expand on a subsequent article (Hornbeck et al. 2015) by using updated Census data to assess the connection between access to various parts of the HPA and broader economic outcomes. The present study examines how initial saturated thickness explains variation in irrigation intensity, crop choice, land values, and population density using census data at the county scale. These economic outcomes are examined across levels of saturated thickness in three distinct time periods: pre- approximate development of the aquifer (1925-1945), during the height of irrigation expansion (1950-1987), and during contemporary time periods of irrigation water shortages (1992-2012).

We use the term 'economic outcome' throughout this study to describe measures of land productivity which impact agricultural profit and are considered to be resultant of irrigation water availability. For example, we analyze irrigation intensity and crop choice because the per-acre yield for irrigated corn can be more than three times that of dryland. The lucrativeness of irrigated acreage is highly dependent on the price of energy, efficiency of the system, price of the commodity, and investment position of the irrigation technology. However, corn receiving full applications of irrigation water has the potential to net almost $400 per acre of additional profit as compared to dryland (Payero, 2017). Because corn has the potential to be highly profitable, yet the lucrativeness of the commodity is highly connected to irrigation resources, it's a prime candidate for economic analysis through the lens of water availability.

We hypothesize that higher initial endowments of groundwater will be associated with a greater percentage of irrigated acres within a county, support a greater fraction of water intensive crops, and therefore have higher agricultural land values over time. However, we expect that there will be no statistical difference between counties inside or outside the aquifer prior to the development of the HPA, as access to irrigation water should have been comparable between counties inside the aquifer and outside. Economic intuition does not clearly guide what an expectation may be for population dynamics in our study area. Anecdotally however, concerns have been expressed by agricultural stakeholders of the High Plains regarding the connection that exists between irrigation water supplies and the larger economy (Kansas Health Institute).

By treating the HPA as a heterogeneous resource, we propose to more accurately measure the impacts over time and space of irrigation water in the High Plains. We also include two additional census data and water storage measurements, adding another decade of insight onto these previous projects. Our study expands on the shallow body of economic literature related to natural resource endowments, agriculture, and population dynamics by exploring the connection between valuable production inputs (irrigation water) and population density over time.

Thesis Overview

This introductory section is followed by background on the High Plains including a physical description, history of irrigation, and historic events that have influenced population in our study area. A literature review then describes past work relevant to our research which provides insight into our methods and situates our contribution in the economic literature. After, we explain the theory motivating our study and outline our data sources and empirical model. The following section then includes the results of our empirical analysis and provides brief comment. We close this paper with a discussion of the study’s results and conclusion which includes directions for further research. Tables and figures are included at the end of the thesis.

BACKGROUND

Physical Description

The HPA underlies over 110 million acres, extending from the Rosebud Sioux Indian reservation in southern South Dakota to Odessa, in western Texas. Within the High Plains, both the aquifer itself and the growing conditions above it are highly variable (Figures 1-3). Predevelopment estimates of saturated thickness in the HPA range from 1,200 feet to almost zero (McGuire, 2017). Precipitation in the High Plains region is highly stratified: the eastern border sees upwards of double the rainfall of the western border, at roughly 33 inches each year. Similarly, hydraulic conductivity is variable across the HPA, ranging from nearly 0 to 200 feet per day (USGS, February 2014). Of the approximately 4,000 cubic kilometers of water originally stored in the HPA, 63-percent was deposited under Nebraska (Steward et al., 2016). Ironically, some of the greatest endowments of water in the HPA are only accessible in the sand hills of Nebraska, a highly unproductive agricultural area (Peterson et al., 2015).

Irrigation Chronology

While surface water appropriations began widely in the late 19th century, groundwater irrigation was not a popular alternative for several more decades. However, early irrigation technology, such as centrifugal pumps powered by steam engines, which were capable of delivering thousands of gallons per minute were in use in Eaton, Colorado and Garden City, Kansas as early as 1896. In 1909, the first internal combustion powered pumps tapped into the HPA near Hereford, Texas; inspired by pumping which was already taking place in Portales, New Mexico. From 1919 to 1937, the acreage capable of being serviced by a single pump had doubled to 139 acres (Kromm, 1992).

Perhaps out of necessity, and supported by state laws, broad development of the HPA began in the Texas High Plains in the 1930s, following the temperature gradient north over time. Attributed to McGuire (2004), 1950 has been cited as a general predevelopment date for the entire aquifer, as it predates widespread use of high capacity pumps (Haacker et al., 2016). The center-pivot was patented by Frank Zybach in 1949, and despite high upfront costs, was far less labor intensive than earlier irrigation technologies. In 1950, Oklahoma had 50 high capacity irrigation wells (capacity greater than 100 gpm) accessing the HPA, but by 1970 that number had increased to 900 (Luckey et al., 1999). In the 1960s, furrow irrigation (the process of digging trenches between rows of crops and filling these small ditches with water to irrigate) was largely replaced with Zybach's center-pivot irrigation systems. Nebraska, currently the most irrigated state, had less than 3,000 center-pivots in 1973. By 1979, Nebraska's HPA supported 15,000 center-pivots (Kromm et al., 1992).

Since the arrival of irrigation by groundwater, agriculture in the High Plains has become highly dependent on the resources provided by the HPA. In 1949, 2.1 million acres of farmland were irrigated, increasing to 15.8 million acres in 2005 (McGuire, 2017). In the High Plains of Colorado, groundwater withdrawals are currently about two and a half times that of surface withdrawals, and 96-percent of the groundwater pumped is used for irrigation (USGS, November 2014).

Water Management in the HPA

The history of groundwater exploitation in the HPA has varied spatially, as much as temporally. Longstanding legal institutions have shaped both the opinions about groundwater conservation, and the policies which currently govern withdrawals (Peterson et al., 2003). Ground and surface water are predominantly managed under the Doctrine of Prior Appropriation in the High Plains, although the application of the doctrine varies by state. In Nebraska, groundwater is managed under a combination of the Reasonable Use Rule and Correlative Rights Doctrine, often limiting the volume of water which may be applied per acre owned. Oklahoma applies the Correlative Rights doctrine to ground and surface users, while neighboring Texas is governed by the Absolute Dominion or Rule of Capture and frequently does not legally limit the amount of groundwater withdrawals which can be made by a landowner. Still, all states in the High Plains have some element of seniority, or priority dates in their permitting system, indicating that those who have used water the longest have the most right to access it. There are approximately 50 management districts for water throughout the high plains, most focusing on groundwater resources within their district boundaries. The oldest such district is the High Plains Underground Water Conservation District, which was formed in 1951 and includes the metro area of Lubbock, Texas. Ironically, despite having local management tools for nearly seventy years, the High Plains District has seen some of the greatest percent depletions in the entire aquifer (Haacker et al., 2016). While the differences in groundwater management can vary greatly within a state, the underlying attitudes and rule making possibilities are best captured at the state level.

Population Dynamics

In the last century, cultural and socioeconomic events at the federal level have impacted economic outcomes for irrigators across state lines in the High Plains. The Dust Bowl refers to the phenomena of rolling dust storms, which caused the wide spread loss of life and severely damaged the agricultural economy in the High Plains from about 1930 to 1936. Extensive debt from industry-wide investments in agricultural machinery and a depressed larger economy exacerbated the effects of widespread drought. Agricultural plowing and tillage techniques ill-suited for the dryland farming of the High Plains provided a catalyst for the high winds to develop into storms capable of moving top soil states away and burying houses in soil drifts. At the same time, wheat prices sank as a result of oversupply, partially spurred by the events following World War I (Opie, 2000). Land values in counties with high erosion fell by 30-percent from 1930 to 1940. During this decade, total population in Oklahoma, Kansas, Nebraska, South Dakota, and North Dakota states fell by as much as eight percent, with population declines in moderate and highly eroded counties persisting through the 1950s. Dust Bowl "refugees", estimated in the hundreds of thousands, are popularly cited as migrating west to California (Lockeretz, 1978). Lasting effects from diminished land values coupled with reduced revenues from agriculture still impact the highly eroded counties in High Plains (Hornbeck, 2012). Despite multi-year droughts in the 1950s, '70s, and '90s, the severity of dust storms has been reduced accordingly as irrigation as grown. A concern of depleting the HPA will be the ability of the High Plains farmers to combat wind-fueled erosion if the supply of groundwater is exhausted (Opie, 2000).

Though the event likely had roots in the previous decade, the U.S. Farm Financial Crisis is typically associated with 1980s, and had large impacts on land values and rural populations. In the early to mid-1970s federal policies were implemented aimed at spurring agricultural exports, as high dollar values had created a trade imbalance. At the same time, many less industrialized countries experienced drought and crop failure, subsequently causing U.S. commodity prices to soar. Grain exports doubled from 1970 to 1973, and net farm income grew from $34 billion to $69 billion annually (in 1982 dollars). Land values in the High Plains escalating a total of 73-percent nationwide (Figure 4), which Ricardian theory would suggest was an effect of higher commodity prices (Currie, 1981). During a period of particularly high inflation on the dollar, purchasing increasingly valuable farmland was erroneously viewed as a hedge against inflation, particularly for agricultural producers. These investment strategies intensified already high demand for agricultural land. By the late seventies, worldwide markets had caught up with grain production, and surplus production domestically caused commodity prices to drop. Corn, soybean and wheat prices fell by over fifty-percent from 1980 to 1986. Inflation peaked in 1979 at 11.3-percent, causing the Federal Reserve to tighten the money supply. The federal interest rate climbed to 18.9-percent in 1981, having a particularly marring effect on the agricultural industry as many farms had been purchased through financing during the growth of the previous decade. In 1983, the real farm income (adjusted for inflation) was the lowest on record since the USDA began collecting income data in 1910, likely due to a combination of high interest payments, low grain prices, and drought (Barnett, 2000). Studies in the late eighties projected as much as a 32-percent decline in population of agriculturally dependent communities as a result of the Farm Crisis (Murdock et al., 1998). The Farm Financial Crisis (from years 1974 to 1982) represents one of the only stagnant periods of population density growth in areas of high, medium, and low initial saturated thickness, as well as those outside the HPA (Figure 5).

LITERATURE REVIEW

This review investigates literature related to economic outcomes associated with natural resource consumption and endowment. We begin by establishing the motivation and necessity for our empirical work, followed by relevant examples of the various modeling techniques applied to our outcomes of focus. This study relates to three branches of economic literature: hedonic studies, Ricardian models, and population dynamics. Hedonic techniques have been applied to real estate in many studies to extract the marginal willingness to pay for non-market attributes such as environmental quality. Similarly, Ricardian models relate land value to characteristics of productivity; relevant to our study as we examine irrigation as a mechanism of production. Lastly, we add to a shallow body of economic literature that looks at natural resource endowments as determinants for economic outcomes, specifically how groundwater endowments and use has influenced population dynamics across time.

On a local geographic scale, water (especially surface) can be modeled as a commodity which may have observable market transactions that establish a theoretic equilibrium price and output. On a larger scale, water (especially groundwater) is subject to the collective action problem; as such, the theoretical underpinnings for this study can be described by the dilemma of a common pool resource being over appropriated. Common pool resources (CPR) are characterized as being rival, or subtractable in nature, but are non-exclusionary (Ostrom, 1994). Groundwater resources fit in the CPR category based on the following criteria. First, when the rate of recharge is very slow, or in the case of confined systems, an irrigator is reducing the supply available for other users, in addition to themselves in the future. Second, the statutory history of groundwater regulation in the western United States makes groundwater use available to almost any type of user who puts the resource to beneficial use. Further, legal action taken to limit groundwater use in a single administrative unit (such as a state or management district) will have no immediate reactions from groundwater users of the same aquifer across boundary lines. As such, many examples exist in the arid western United States of groundwater stocks being irreversibly depleted; a tragedy of the commons. Olen et al. (2015) empirically demonstrate groundwater as a CPR or open access resource. Their model describing the impact of water scarcity and climate variation on irrigation decisions finds that pumping behavior is only changed in the face of very significant increases in depth-to-water. This parallels open access theory which states that resource consumption only stops when net benefits are less than zero (Field, 2015).

Hedonic Pricing Models

Traditionally, hedonic models assume a schedule of prices for the differentiated products, which can allow economists to extract the marginal willingness to pay for a particular characteristic. Our study differs in that we instead assume that willingness to pay for resource characteristics can be aggregated and measured on a county level. Palmquist (2003) points out that hedonic theory provides little guidance for the appropriate functional form for hedonic analysis; Faux et al. (1990) echo this sentiment, stating that utilizing the data to determine appropriate functional form of the model is recommended. Palmquist contends that simple models perform best in the face of uncertainty of specification or variable estimation, a valuable note as our work involves data not collected firsthand.

The hedonic method implies that the marginal benefit associated with changes in aquifer levels can be estimated as the change in economic outcomes given an incremental change in initial saturated thickness, all else constant. This relationship is explained by Palmquist (2003), who proposes that a duality exists between the price of the land and the landowner's bid function, so that a partial derivative equation may be used to solve for the landowner's marginal willingness to pay for changes in groundwater levels. Using the marginal difference in land value with respect to irrigation-determining aquifer characteristics, we propose that the social cost incurred to the agriculture industry (and by extension, society as a whole) is equal to the sum of the marginal value of these characteristics across all counties. We assume these irrigation determinants are independent of one another, because we are utilizing initial endowments of groundwater. By extension, the other economic outcomes we examine (irrigation intensity, population density, etc.) directly influence the value of land, and can therefore be analyzed using this same approach.

Torrel et al. (1990) use an Ordinary Least Squares (OLS) model to estimate the price differential between dryland and irrigated land throughout the Ogallala. The authors use land sales data from 1979 –1986 to infer the value of unitary and aggregated values of the aquifer. They include stationary and dynamic aquifer characteristics, and conclude that saturated thickness and aquifer recharge are important determinants of land value when including a large geography of sample data. The authors do not find depth to water to have a statistically significant impact on land prices. However, in a similar study design Swanepoel et al. (2015) include an interaction term between depth to water and acres irrigated, to capture the price influence of a particular well on irrigated lands, finding that a one-foot decrease in depth to water decreases sales price by $1.80/acre. These studies are both geographically and contextually applicable to our work, but a key difference is that we propose to include a richer sample size of farmland values over time, as well as provide valuable comparative measures by including non-Ogallala counties in our regression. A shortcoming of our data, however, is that because it is a county-wide average, it may not pick up these discreet differences in the relationship between well capacity and parcel value that exist, especially in very large counties.

Buck et al. (2014) use a hedonic model with tax-lot level fixed effects in order to control for omitted variable bias when using surface water availability as an explanatory variable of price per acre of agricultural land. The authors equate the partial derivative of the hedonic price with respect to water as the value of increasing a unit of water for each parcel in perpetuity. The authors attempt to control for ground water availability by estimating the price per acre in a specific hydrologic unit. The authors do not indicate which level of hydrologic unit code they use to summarize groundwater. This study finds that omitted variable bias from heterogeneity across individual parcels can significantly lower the estimated value of surface water deliveries. In fact, their estimates were four-times what has been previously estimated; in doing so, this study provides support for why repeat analysis of specific counties in the Ogallala would control for unseen, or difficult to control for, influences of land value. Supporting the conclusion about underestimation, Brozovic et al. (2010) and Faux et al. (1999) find that hedonic methods may be biased toward lower values if models do not account for land quality characteristics (such as soil type), which should influence the decision to irrigate in the first place.

While it’s known that groundwater provides a valuable input to agricultural production, relief from drought, and an alternative to surface water resources, the hedonic literature has not provided a consistent story about the value that groundwater adds to agricultural land (Foster et al., 2015; Manning et al., 2017). Mukherjee et al. (2014) notes the disparities that exist between conclusions from hedonic studies over the last three decades with regard to the value that groundwater adds to agricultural land. Using parcel-level sales data, Mukherjee suggests that groundwater’s value is a function of the quality, suggesting water quality as a missing component of past groundwater variables. Generally speaking, with the exception of the southernmost extents, water quality has not been a large concern for most of the HPA over the last 100 years (Gurdak et al., 2009). This may be changing as water levels decline and nitrate laden waters percolate, leaving room to incorporate water quality measures in future HPA studies. We offer instead that variability in original endowments of groundwater resources could be a source of bias in previous groundwater studies, and choose to incorporate a county-wide measure of spatial heterogeneity in original saturated thickness, weighted by percent share over the Ogallala. Similarly, Yoo et al. (2016), use spatial fixed effects to account for omitted variable bias, which yield consistent and unbiased estimators for a large sample size and cross sectional data. The authors use a hedonic price method to determine the negative impact of land subsidence, as an externality of aquifer depletion. An alternative perspective about the disamenities associated with groundwater overdraft, the study estimates that homes within subsidence areas near Phoenix, Arizona lose approximately 10-percent of their value. The authors account for the price influences of locational characteristics, including neighborhoods and proximities to highways and parks. The authors choose a semi-log model, citing that this form better allows for estimation of marginal prices in the situation of model misspecification.

Ricardian Approaches

The Ricardian theory of land value equates the economic rent of farmland land to a schedule of quality or fertility differences. Ricardian approaches are analogous to hedonic models which examine the effects of quality measures on sales price. The Ricardian approach has commonly been used to measure the impacts of climate variability on the agricultural industry. In an analysis using county-wide estimates, Mendelsohn et al. (2003) explore the climate change sensitivity of surface water users, and the relationship between surface water access, total withdrawals, and agricultural land prices. The authors note a potential pitfall of using a Ricardian approach to farmland value is that it aggregates farms across all crops. However, Mendelsohn suggests that controlling for soil and climate characteristics should also account for crop choice, as climate and soil are usually determinants of the types of plants that are the most fruitful in a region. The study didn't include groundwater in their final results, as their regression coefficient was not statistically significant; they conclude that this was likely due to the fact that they did not have data that uniquely identified the impact of groundwater. The authors found that surface water access increases the per-acre value of land, a conclusion which was further refined by Schlenker et al. (2005). In a similar study design, Schlenker et al. emphasize how misspecification of hedonic models, through omitted variables, can cause biased results for the value of irrigation water. Their study also examines climate change impacts on farmland value in U.S. counties, finding that dryland and irrigated acreage necessitate different regression equations. The authors choose to omit urban counties from their analysis because of the connection between urbanization and farmland values. In examining the Urban Influence Codes for the HPA, we do not expect urbanization to be a pervasive source of bias for our results (see Figure 6). Additionally, since a focus of our study is the switch from irrigation to dryland practices (as measured by the differences in irrigated acres in a county and the total cropland operated over time), we instead prefer a single model specification.

Also employing a Ricardian model to assess the impact of climate change on land values, Polsky (2004) focuses on the spatial and temporal variation in the HPA from 1969 to 1992. Using quarterly precipitation and temperature data, the study derives sensitivities of land values as a result of climatic events, like drought, to estimate the impact of an increase in rainfall throughout the High Plains. Polsky employs OLS, incorporating spatial lag and groupwise heteroscedastic terms in supplemental regressions to test the adaptability of irrigators to changes in climactic conditions. The spatial lag term is a weighted average of land values in bordering counties, accounting for discrete areas of high valued land which are independent of traditional productivity measures, such as the natural amenities of Boulder, Colorado. Polsky contends that incorporating a heteroscedastic error term measures the change in value of differing water management policies throughout the region, rejecting the null hypothesis that there are no spatial effects on land values in the HPA. The adaptability of agriculturalists is found to vary across time and space, and is likely dependent on the regional policies and outreach practices (what Polsky refers to as ‘communication processes’) throughout the HPA. Because our study accounts for both time, space and heterogeneity of water resources, we can be confident of our ability to control for some of the heteroskedastic concerns Polsky references with Ricardian models.

Previous work can provide comparative values for a final estimation of the social value lost as a result of depletion of the Ogallala aquifer. Hornbeck et al. (2014) explored farmland value inside the Ogallala and compared these to similar counties within 100km distance from the aquifer boundary. This provided an implied value of the aquifer, although the study didn’t use actual groundwater access (i.e. well locations) or measures aquifer productivity. In a subsequent article, Hornbeck et al. (2015) use census data of the Ogallala to decipher the connection between access to the aquifer and the influence on the broader economy. Their results indicate that agricultural land is the best real-estate measure of the Ogallala’s value, as other types of industry weren't impacted by its discovery or usage. We diverge from Hornbeck in that we incorporate spatial and temporal heterogeneity in aquifer storage, as well as include a decade of additional data to draw conclusions from.

Population Dynamics

Fishman et al. (2013) examine migration patterns of land owning males and their families related to groundwater depletion in Gujurat, India. India, being the largest consumers of groundwater in the world, is described as particularly vulnerable to changes in groundwater storage. The authors employed a randomized study of agriculturalists in the northern districts of the state of Gujurat, estimating the impacts of falling water tables via several econometric specifications including OLS, fixed effect of villages, and spatial trends. The survey finds that groundwater declines of 100 feet increases relocation to an urban area by 10-percent for each son of respondents. Further, the study estimated as much as 20-percent of migration was due to water scarcity. These results were more profound in wealthier families, and virtually only present in the younger generation of interviewees. Corresponding with increased depth to water, the authors conclude that the career decisions of younger generations have been impacted by groundwater changes, while the decisions of older family members have not. Similar to our study, the authors use an exogenous measure of water availability as a determinant of population dynamics. The presence of dark clay surrounding a well casing decreased well capacity and likelihood of well failure. The authors also found that this heterogeneously dispersed clay layer increases the likelihood of at least one migrant son by as much as 15-percent. An important difference in the results presented by Fishman et al. and our study is the timeframe and spatial extent of data, our results being based on nearly eight additional decades and an exponentially larger land area. Furthermore, the HPA supplies a much wealthier population of groundwater users who have access to some of the most advanced water saving technologies, including soil moisture monitoring, variable rate irrigation, and drought resistant seed varieties.

A study of more geographical significance is presented by Feng et al. (2012) who find that climate change increases migration away from rural areas for young to middle aged adults.

Using county level data for Midwest and eastern states, the study argues that decreased crop yield in the 'Corn Belt' region results in increased out-migration. The authors utilized Census Data and USDA's National Agricultural Statistical Service (NASS) to estimate a 2-Stage Least Squares equation, as well as multiple modeled climate change scenarios to test the robustness of these results. The effect of reduced yields for all crops was strongest for those under the age of 30, and was slightly more pronounced for females than males. The study projects a nearly four percent increase in 5-year rates of migration from the Corn Belt to more urban areas in the upper Midwest. While our study holds climate constant during the period of analysis, parallels between Feng's work can be drawn; as well capacity decreases, the ability of an irrigator to increase yields through timing and volume of irrigation water applied is likewise reduced, economic outcomes associated with these reduced well capacities is a focus of our study.

METHODOLOGY

Irrigation is an important factor in determining the productivity of agricultural land. In 2017, irrigated corn grain in Kansas yielded over 197 bushels per acre on average, while dryland corn produced only 107 bushels per acre (NASS, 2017). Census of Agriculture data further demonstrates the impact of irrigation water on agricultural profitability: in 1997, average gross farm sales per harvested hectare for Western states (including all states in the HPA region) were \$2,100 for irrigated land compared to \$300 for dryland (Gollehon, 2000). This relationship between groundwater, production, and profitability provides the theoretical foundation for our work. This study is based on an irrigator's profit maximization objective, in which we assume profit is a function of the decision to irrigate based on a specific set of inputs including crop choice, water availability, soil type, and climate characteristics. Similarly, the initial decision to invest in a specific tract of agricultural land is based on the expectation of future profits from owning and operating that parcel.

Theoretical Model

Our model is based on a Ricardian theory of rent, which describes the value of agricultural land as being tied to the marginal and average productivity of a tract of land less its input costs. Because there is a gradient of land suitability for agricultural production based on characteristics like soil fertility and climate, the land most suitable for the highest valued production will be put to that use. Assuming that the prices of inputs (such as labor) are fixed in any time period, the most productive lands accrue the most rents, and will therefore have the highest market value (Currie, 1981; Polsky 2004).

$$V_t = \int_t^{\infty} \{P_t * Q(X_t, S, C_t, Sw_t, Gw_t[ST_t, E]) - (RX_t + RE_t * DTW_t(ST_t, E)\} \, e^{-rt} \, dt \qquad (1)$$

Equation 1 describes a Ricardian model of land valuation, in which the price per acre of farmland (V) is equal to the discounted sum of expected future profits that can be generated on that parcel. The total revenue for the producer depends on P_t, the price of the crop, and Q, the production function for the crop. The production of any crop is a function of a vector of variable purchased inputs (X), soil classification (S), climate characteristics (C), and irrigation water. Irrigation water is assumed to be the sum of both surface water (Sw) and groundwater (Gw) that is applied. The subscript *t* denotes the time period of interest, and *r* is the discount rate which describes the time preference of accrued benefits from owning a parcel of land.

The benefit of groundwater in the production function is primarily focused on well capacity. Well capacity is assumed to be a function of both static and dynamic variables: the saturated thickness (ST) at time *t*, in addition to fixed aquifer traits (E) which also impact well capacity such as hydraulic conductivity (describing the fluidity of the aquifer in a given location) and specific yield (which indicates the volume of water per unit volume of aquifer that can be extracted through pumping). Beyond the ability to pump more quantity water, increased well capacity enables irrigators the precision to time irrigation water application during the most critical stages of plant development, impacting yield. For the purposes of this analysis, we assume that surface water supplies are renewable, unconnected, and variability in river flows from year to year contributes to an average experience for an irrigator in the long run.[1] The producer's costs are comprised of the amount of variable inputs purchased multiplied by their associated prices (RX_t) as well as pumping costs. Pumping costs are dependent on the current

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[1] The assumption of exclusivity between ground and surface water may not hold throughout the HPA, specifically in Nebraska's Upper Platte Basin where areas along the Platte River and tributaries have been designated as hydrologically connected to groundwater for the purposes of conjunctive management.

depth to water (DTW_t), and the price of energy, (RE_t). Depth to water is determined by exogenous geologic features (E) and the saturated thickness (ST_t) in time *t*. Because saturated thickness illustrates the water remaining in the aquifer, as it falls it captures the effect of increased depth to water in the HPA.

The profitability of agricultural land, both at the parcel and at the county level, varies with both revenue from production and the cost of production. As saturated thickness levels fall, increased energy is needed to move water to the ground surface for irrigation. In the southern extent of the Ogallala, aquifer storage has decreased as much as 48-percent from pre-irrigation levels (Haacker et al. 2015). Depending on the efficacy of the pumping system and price of electricity or fuel, groundwater extraction can pose a large expense to farmers using irrigation water in production. This is reflected in Equation 1, as the price of electricity and the effect of depth to water comprise a portion of the producer's total costs. Additionally, factors such as saturated thickness and hydraulic conductivity influence well capacity, which has a direct effect on productivity and therefore revenue. This relationship has been demonstrated empirically, as Brozovic and Islam (2010) found that well capacity had a positive influence on farm sales price per acre. While pumping behavior might not change until depth to water has increased substantially, diminished well capacity weakens the value of provided by groundwater; with less pumping capacity irrigators lose precision over the timing and volume of water application (Olen et al. 2016). We can draw two very important conclusions from Equation 1:

$$\frac{\partial(V_t)}{\partial(ST_t)} = P_t\left(\frac{\partial Q_t}{\partial ST_t}\right) - RE_t\left(\frac{\partial DTW_t}{\partial ST_t}\right) \tag{2}$$

The Ricardian model of land value (V) is impacted by saturated thickness through both the expectations of revenue and the expectations of costs. The partial derivative of quantity produced indicates that revenue ($P_t \times Q_t$) increases with saturated thickness, because improved well capacity equates to better timing of irrigation water application, positively affecting the biophysical processes of plant growth. Additionally, the first derivative of depth to water with respect to saturated thickness (ST) indicates that as saturated thickness changes, the depth to water increases, ultimately raising the cost to pump water to the surface. Saturated thickness is a determinant of both economic costs and crop yield, and therefore is expected to be a driving force in expectations of producer profit (Foster et al., 2015). Under a Ricardian model of productivity, the farms (or counties) with the largest endowments of water should likewise have the highest land values, based on the divergence mentioned earlier between the income from irrigated and dryland acreage. In many parts of the HPA, surface water resources are limited. As such, we hypothesize that pre-development stores of groundwater should be a determinant of long run economic outcomes.

While we know that agriculturalists may not be exclusively profit maximizing in behavior, we can assume that increased profitability of land will be associated with higher utility. As such, our conclusions should hold if we were instead to base our model on the utility maximization of a farmer in the HPA. Hedonic models extract the willingness to pay for specific attributes of any marketed good based on observed sales of properties. Hedonic techniques have been commonly applied to real estate in order to elicit monetary values for features which are not traded on their own, such as environmental quality. Hedonic theory is based on a producer's utility maximization problem subject to a budget constraint:

$$U_j = U\{N, H_i(V_i), S_j\} \tag{3}$$

Where the utility of producer j is a function of a composite non-property good (N), a vector of property specific traits (H), and a vector of producer j's socio-economic characteristics

(S). The purchase price for property *i* is itself a function of the non-market characteristics that hedonic models seek to value. For agricultural producers, an important contribution to H is the expectations of profitability (V_i) from operating a specific tract of land. In this way, anticipated future profit (described above in Equation 1) contributes to the price of agricultural land. Depending on the individual's income and how each variable contributes to the utility function in Equation 3, producer *j* will have a specific willingness to pay for each attribute. By taking the first derivative of the equilibrium price of property *i* with respect to the variables of interest (such as saturated thickness), we can extract the marginal willingness to pay for productivity influencing attributes. As mentioned in previous sections, theory does not provide for a functional form of the hedonic equation, instead it has to be inferred from the data itself (Palmquist, 2003). An assumption of our study is the producers' uniform awareness of groundwater levels and education about the implications of over pumping, which in reality vary across location and time.

Empirical Model

The empirical modeling also considers how the distribution of groundwater impacts population. Neoclassical economic theory of migration is based on the assumption that migrants improve economic status by relocating from low-wage geographies to higher wage geographies (Eichenlaub, 2010). While there is not a robust set of literature to draw from, at least one study has found correlation between reduced agricultural yields and population outmigration in the corn producing region of the United States (Feng, 2012). Referencing the discrepancies in dryland and irrigated agriculture from the opening paragraph of this section, agriculturalists in the HPA should in theory be concerned with locating in an area with abundant, reliable irrigation resources. Therefore, we hypothesize that areas with lower endowments of groundwater should see declines in population relative to areas with higher groundwater endowments over the course of our study.

Our study area includes all counties within the Ogallala as well as those within 100km outside, which provides us with a natural experiment for identifying a causal relationship between initial aquifer levels and economic outcomes. The base empirical model was inspired by Hornbeck et al. (2014) and is described in Equation 4:

$$Y_{kit} = \alpha + \sum_{g=1}^{3} \beta_{gt} D_{gi} + \gamma_{st} S_{si} + \theta_{ct} LCC_{ci} + \beta_{rt} x_{ri} + \beta_{ft} x_{fi} + \beta_{nt} x_{ni} + \beta_{wt} x_{wi} + \varepsilon_{it} \quad (4)$$

We regress our economic outcomes of interest (k) in a single census year (t), for a particular county (i) on static determinants. We split initial endowments of HPA water (measured by pre-development saturated thickness) into high, medium, and low “groups” according to tertiles. We multiply these initial saturated thickness indicator variables by their percent share of the HPA (D_g). The result is separate beta parameters for dummy variables which are weighted by their land share of the HPA. Percent shares of the aquifer were determined by dividing the area overlying the HPA by the respective county’s entire land area. Counties 100km outside of the HPA are included in the dataset, and become the basis of comparison, captured in our alpha term.

The saturated thickness groups interacted with the percent share variable describe the average differences between counties having access to the aquifer, and also having access to stratified depositions of groundwater. The betas for each treatment group (β_g) describe the relative marginal effect of pre-development levels of saturated thickness in the HPA, for which we used modeled saturated thickness in 1935. Both the share and the group provide exogenous measures of water access, as they are not impacted by subsequent water usage, and should therefore be uncorrelated with our error term and dependent variables. Separate beta parameters are estimated for each saturated thickness group (g) in each census year (t). The coefficients on the percent share for each group can be interpreted as the impact of relative levels of initial saturated thickness on the economic outcome of interest (k) in a particular year, compared to counties outside the aquifer. The counties which are included in the three saturated thickness groups are therefore weighted by their location (or share) in the HPA. For instance, a county with 100m of initial saturated thickness which only overlies the HPA in 50-percent of its land area, would have a beta parameter which is reduced proportionately, by half. The inclusion of initial saturated thickness groups in the regression is the primary, yet significant, difference between this study and Hornbeck et al. (2014). As discussed in the Theory section, saturated thickness is a key determinant of the profitability of irrigated farmland; therefore the initial aquifer conditions should play a key role in identifying the marginal effect of water in the HPA, and how the impact of water access has changed over time. The statistical significance of, and relative differences in, coefficients of our tiered groups within the aquifer measure how initial saturated thickness influences economic outcomes, and indicates how the impact of these groups has changed over time.

The model also includes slope shifters for fixed effects of each state (γ_s) and county-wide averages of the non-irrigated land capability class (θ_c), in addition to four stationary climate-related variables: average precipitation (P_r), average annual temperature (T_f), latitude (Lat_n), and longitude (Lon_w), which have coefficients that are allowed to vary in each year of analysis. For each census survey, we separately regress the above model on the percentage of irrigated acres in a county, percentage of irrigated corn, percentage of irrigated wheat acreage, the natural log of the average value of land and buildings per acre, and the population per square mile. The nature of the aquifer allows for both inside/outside and high/medium/low saturated thickness comparisons to be made for otherwise similar counties across a large variety of climate types. The aquifer itself cuts across soil types and state boundaries, which provides for a natural experiment that teases out the marginal effects of these characteristics in a given census year.

An advantage in using cross-sectional modeling is the availability of data. Instead of having a longitudinal study with continuous data from the same individual farms in a county, we group and examine data by census year and assume that these average values are comparable for counties across time. The cross-sectional approach is preferred because we are interested in understanding the influence of stationary characteristics on variant economic outcomes. As with any survey, our data cannot be assumed to represent 100-percent of the individuals (farms, in our case) in the study area, and may include biases typical of self-reported information. However, because we are interested in identifying causality across a large geographic and temporal scale, county wide averages may offer a superior view of ‘macro-level’ dynamics instead of focusing on micro-variations in a given census year. County averages also offer a simplifying answer to repeat sales data, where farms may be divided over time and introduce uncertainties about appropriate comparisons.

As with other OLS models, we assume that our model is linear in its parameters and that multicollinearity does not harmfully impact our set of explanatory variables (location in the aquifer, initial saturated thickness, state-fixed effects, soil class, and climate characteristics). The underlying assumption of our empirical model is that the economic outcomes we selected as dependent variables can be explained by the initial availabilities of groundwater. Both the original depositions of irrigation water in the HPA, and location within (or outside of) the aquifer are exogenous to the economic events we’ve selected to analyze over time. While modeled estimations of saturated thickness throughout the aquifer was available in each census year (and this data partially informed our research questions) we did not include saturated thickness “current” to each regression because of the correlation which would exist between contemporary saturated thickness and our economic outcomes. Our theoretical model equates producers’ expectations of future profitability to land value, and by extension, the other economic outcomes in our study. Therefore we cannot select duplicative explanatory variables which are endogenous to conditions of a particular year, which may lead to biased coefficient estimates. In initial irrigation implementation we would expect all counties inside the aquifer to have an increased percentage of irrigated lands compared to counties outside the aquifer. In subsequent years, we would expect their irrigation experience to be shaped by the differentiated limitations of initial saturated thickness and provide sufficient expectations of future profitability for a particular tract of land. However, these producer expectations aren't based on variables inherent to the amount of irrigation supported by groundwater in a given year.

The significance of including the mean climate for a given county is that our theoretical model is based on long run expectations of profitability for an irrigator. We do not have data which captures a producer’s climate expectations and how those expectations may change. As such, the long-run climactic average become the next-best control method. The identification assumption of the beta-coefficient for HPA share of each saturated thickness group is based on the hypothesis that counties over the aquifer are comparable to counties outside the aquifer. The HPA may have a different impact in counties with poorer quality soils or harsher climates, which is why these elements are included as controls in the empirical model.

To supplement the previous analyses, we include difference-in-difference (DiD) calculations for several economic outcomes, aimed at further exploring the variation between saturated thickness groups. The right-hand side of the ‘differenced’ regression equations is identical to Equation 4. The outcome variable for these equations is the average value for an economic outcome in county *i* from 1925 to 2012, differenced from the average value between 1925 and 1969. We then difference the coefficients for High and Low counties to understand the changes over time in the relative effects between these two groups. For simplification, we assume that the covariance of these coefficients is zero. These time periods of analysis allow us to better understand the changes in the disparities of economic outcomes between high and low saturated thickness counties over time, and how these differ from counties outside the aquifer across distinct epochs of groundwater use.

Data

The baseline data was provided by Hornbeck and Keskin (2014). The dataset is hosted on the American Economic Association website, and was accessed in March of 2017. The variables provided by the authors’ previous study come from a variety of sources, including the Inter-University Consortium for Political and Social Research (ICPSR), the National Agricultural Statistics Service’s Agricultural Census (NASS), the PRISM Climate Group of Oregon State University, and Dr. Wolfram Schlenker. The dataset, comprised of a mix of time variant and invariant information, begins in 1920 and extends through 2002 and includes 7,355 observations. Data is not complete for all variables for all 386 counties within the sample in every survey year; for instance the number of farms is only recorded for 349 counties, and irrigated lands are only reflective of 278 counties (Table 1). Because of this, regression analysis cannot be carried out for every census year for every economic variable of interest. Variables of primary interest for our study were those from the historical census data related to the value of agricultural land and buildings per acre and irrigated acres in a county. Data was appended for these variables in the years 2007 and 2012 from the U.S. Census of Agriculture using the publically available Quick

Stats tool. From the same source, data was acquired for acres of dryland, irrigated, and total acres harvested of corn and wheat for all years of the study. Acres of harvested crops were available for 273 counties growing corn and wheat in our study area. These irrigation, land value, and crop data comprised the dependent variables for each of our regression models.

Soil Data was summarized at the county level using the Natural Resource Conservation Service's Soil Data Viewer extension in ArcGIS. Soil suitability was measured by the Non-irrigated Land Capability Class (LCC, Equation 4), which is a scaled ranking (Class 1 to Class 8), that measures the soil's ability to produce crops and pasture plants without deteriorating over an extended period of time, with Class 1 being the most 'able' soil type. We chose the non-irrigated classification scheme because this provided a geographically more complete measure of the soil in the study area, and is independent of the current production method. The percent of the county in each soil classification was calculated using ArcGIS and related to census information using the county FIPS code. The average county in our sample has 11-percent land area containing Class 1 soil. The most common soils were Classes 2, 3 and 5, each averaging about 25-percent in a given county. Class 5 soils are primarily restricted for rangeland and pasture production. Including these controls in our model provides a more accurate picture of where irrigation water provides benefit to the HPA region.

Data which was not incorporated into our empirical work, but informed our research questions, included modeled estimations of the water table elevation and saturated thickness from 1935 to 2012; which were provided by, and using methods from, Haacker et al. (2015). However, the pre-development estimates (1935) of saturated thickness provided the hierarchical grouping which allows for identification of the marginal effect of the HPA on economic outcomes (Figure 7). Counties which were included in the "Low" grouping had less than 17.9m of saturated thickness at pre-development, “Medium” groups had between 17.9m and 42.3m in 1935, and the “High” counties were initially endowed with 42.3m to 266.0m of saturated thickness. Saturated thickness is averaged to a county wide measure, acknowledging the disparities which may exist inside a single county with regard to groundwater availability. Saturated thickness at pre-development in the HPA ranged from less than one meter to 266m (Figure 3), averaging 43.3 meters which is why the grouping scheme may appear skewed towards lower levels. Since pre-development, High counties have actually had the largest reduction in saturated thickness, at approximately 30 feet in increased depth to water (Figure 8). Because these estimates are endogenous to the model at any time period (i.e., does saturated thickness in time *t* explain irrigated acres, or do irrigated acres explain saturated thickness in time *t*), we did not use saturated thickness measures contemporary to any year in our modeling.

Percentage of irrigated acres was calculated as a percent of total county acres. While our study area averaged 6-percent throughout time, Hale County, Texas topped the survey data with 75-percent of its land area with irrigation in 1959. Across all years, wheat and corn (dryland and irrigated) have been the most prominent crops harvested, respectively averaging 59-thousand acres and 40-thousand acres harvested in a county (NASS, 2018). In our study data, only about 5-percent of wheat is irrigated on average.

County population estimates were also added for the two most recent Census years from the United States Census Bureau. The average county in our sample had 7,252 residents and a population density of 21 people per square mile, across all survey years. By far, the most densely populated county in our survey across all years is Douglas County, Nebraska, which includes Omaha. Texas, Kansas, and Nebraska account for 67-percent, or about 246 of the counties in our survey.

RESULTS

Using Equation 4, we estimate the relative impact of initial saturated thickness, state fixed effects, location information, and climate averages on the economic outcome of interest in a given county, in one of 20 census years. Separate equations are estimated for percent irrigated acres, percent of irrigated wheat, percent of irrigated corn, logged average value of land and buildings per acre, and population density, approximately every five years between 1920 and 2012. The results are provided in Table 2 and Tables 4-7. For each of these dependent variables, we assess the differences in counties with high, medium, and low levels of saturated thickness under baseline conditions, or pre-development of the aquifer before 1950. We then examine how usage of the aquifer after widespread implementation of irrigation technologies (approximately 1954 to 1969) influences economic outcomes in these counties. Finally, we analyze how these coefficients change over time and how they are impacting outcomes of interest in the current time period. The coefficient on the percent share of the HPA for each initial saturated thickness group captures the fixed effect of groundwater in a particular year on the economic outcome of interest using an exogenous measure of irrigation availability.

The significance of examining these time periods allows us to consider the influences that different rates of pumping and expectations of profits have had on land values and other economic outcomes. Pre-development describes a period of zero expectations associated with groundwater providing resources to increase profitability of agricultural lands. By contrast, we expect increased expectations of production and revenue to be associated with discovery and widespread usage. We hypothesize that awareness of aquifer limitations and subsequent declines in well capacity in contemporary time periods will provide another distinct time period of analysis for our chosen economic outcomes.

Percent Irrigated Acres

Pre-development of the HPA, through 1950, there is no difference in the intensity of irrigation amongst counties inside the aquifer and counties outside (Table 2). Specifically, none of the percent share coefficients are statistically different from zero in any of the years 1920, 1930, 1935, 1940. Also, there is not a statistical difference between any of the saturated thickness groups in these years, which supports our hypothesis of no difference between groups prior to aquifer development. Additionally, counties with the highest initial endowments of saturated thickness (greater than 42.3m at predevelopment), have the greatest impact on the percentage of irrigated acres in a county, and have for the longest time. Beginning in the 1950 Census, our results indicate that counties with initially “High” saturated thickness, had a two-percentage point increase in irrigated acres in a county compared to those outside the HPA. This relationship became stronger over time, peaking in 2007 with High counties generating an increase in average irrigated acres by roughly 20-percentage points over the average “Outside” county. Similar relationships are observed for “Medium” (17.9 m to 42.3m of initial saturated thickness) and “Low” (0 m to 17.9m initial saturated thickness) counties, but to a lesser degree, also peaking in recent time periods. In addition, from 1959 through 2012, we observe a statistical difference between each of the saturated thickness groups in how they impact the percentage of irrigated acres in a given county. These results support our hypothesis that counties with greater initial saturated thickness would irrigate more acres than counties with less initial saturated thickness.

It’s noteworthy that the difference in percentage of irrigated acres is greater between High and Low groups than it is between Low counties and those outside the HPA. Beginning in 1964, all counties over the HPA had a statistically significant, greater percentage of irrigated acreage than counties outside the aquifer, in decreasing order of initial saturated thickness (Figure 9). Low counties have had a statistically greater ratio of irrigated acres compared to counties outside the HPA for nearly five decades; however the impact of aquifer access is never larger than a four-percentage point increase in irrigated acres. State fixed effects indicate that Colorado and Nebraska have had a statistically significant, higher percentage of irrigated acres since 1978. As of 2012, Nebraska counties had 16-percentage point higher irrigated acres per county acre, than counties in New Mexico, which is the basis of comparison for state fixed effects.

To examine changes in the discrepancies amongst High and Low counties, we regress the difference of the average percentage of irrigated acres during the first half of our study from the average percentage irrigated over the entire dataset. We then difference these coefficients for High and Low counties, to better understand the difference-in-differences in irrigation intensity between High and Low counties over time. From this DiD regression result, we find that High counties have increased the irrigation gap over Low counties by almost six percent from 1974 to 2012. This indicates that High Counties have been able to sustain or increase irrigated acreage compared to those with Low initial endowments of groundwater, and those counties outside the aquifer.

Percent Irrigated Acres Harvested (Wheat and Corn)

In examining the percentage of irrigated wheat and corn acreage, we attempt to answer how producers respond when less irrigation water is available. We hypothesize that High counties will tend to plant relatively more acres of water intense crops, and that all HPA counties will support more irrigated agriculture than Outside counties. Corn and wheat are the most prevalently grown commodities in the HPA across all years in the study. Corn is relatively more water intensive than wheat, and therefore allows for consideration of how the distribution of saturated thickness influences water use and crop choice. From 1920 to 1945, Medium counties averaged as much as 22-percentage points fewer acres of irrigated wheat compared to counties outside the aquifer (Table 4). This result is somewhat surprising, as we would expect there to be no difference prior to the development of the HPA after controlling for climate and soil characteristics. Low counties demonstrated a reduced percentage of irrigated wheat acreage compared to Outside counties in all time periods except the most recent (Figure 10).

In 1974, there appears to be a change in the concentration of irrigated wheat in High saturated thickness counties. Aligning with the narrative of wheat expansion leading into the Farm Crisis of the 1980s, in 1978 High counties harvested an average of 10-percentage points more irrigated wheat acres than counties without access to the aquifer. This trend peaked in 2007, with an additional 19-percentage points irrigated wheat acres harvested in High counties (Table 4, Columns 1-3). Medium counties exhibited a similar trend beginning in 1974, but to a lesser degree, ceasing the trend of irrigating wheat less intensely than counties outside the aquifer. From 1974 to 2012, there is a statistical difference between initial saturated thickness groups on irrigated wheat acreage (Figure 10). Medium counties peaked in irrigation intensity in 2007, which was also the only year that the intermediate group exhibited a statistically significant and positive coefficient. Since widespread use of center-pivot technology, High saturated thickness counties consistently irrigated wheat more intensely than those outside the HPA.

We consider how irrigation choices may differ between wheat and corn in terms of percent acres irrigated across endowments of groundwater as compared to counties outside the aquifer. We hypothesize corn, being a comparatively more water intense crop, will be positively related to larger initial endowments of groundwater. Unfortunately, observations are not available for irrigated corn prior to 1950. During the early use of center pivot technology, there is neither an observed difference in irrigated corn practices between counties in the HPA nor between those inside and outside the aquifer (Figure 11). Beginning in 1964, there is a statistically significant increase in the amount of irrigated corn supported by the High counties. By 1969, all counties in the HPA had increased irrigated corn acreage compared to outside; with High counties having the largest margin of additional irrigated corn, an additional 18-percentage points compared to counties outside. However, between 1959 and 1992, there isn't a statistical difference in the irrigation intensity of corn amongst the levels of initial saturated thickness. Over the last two decades in our study, High counties are statistically different from Low and Medium counties, and supported an additional irrigation margin of 53-percentage points over Outside counties in 2007 (Table 5). When prices rose to \$6.67 per bushel in 2012, High counties were able to capitalize on additional yields provided by groundwater, irrigating corn 35-percent more as compared to those outside the aquifer. The results support our hypothesis that counties with more initial saturated thickness can support a greater fraction of irrigation for crops with high water demand. It's worth noting that the results show a greater divergence among saturated thickness groups for intensity of irrigated wheat when compared to irrigated corn. Additionally, we expected to see positive beta coefficients for all irrigated crops, indicating that the HPA would support more irrigated acres of these prevalent commodities than counties outside the aquifer. However, in census years 1992, 1997, 2007 and 2012, the difference in irrigation intensity amongst High and Low counties was greater than the difference between Low counties and those outside the HPA. This result supports the prediction that initial saturated thickness is a determinant of irrigation, a driver of agricultural income.

The interpretation that wheat has been irrigated less frequently among Low counties, and about equally among Medium counties, when compared to those outside the HPA is that the producers may be choosing to irrigate corn instead of wheat when faced with water shortages. All HPA counties have a higher intensive margin for irrigated corn when compared to Outside counties. However, observe that High counties have consistently irrigated both corn and wheat more intensely than the other saturated thickness groups, and also more so than counties outside the aquifer. The rationalization of this result is that only producers in the High Counties do not have to choose between irrigating corn or wheat due to physical water shortages. While preliminary reviews of the coefficients for HPA shares among saturated thickness groups does not follow our initial hypotheses of an increased percentage of irrigated acreage for all commodities, the nature of water as a scarce resource and theory of irrigators as profit maximizing aligns with the results that we observe in irrigated commodities and among saturated thickness groups.

Further supporting this narrative of Low counties choosing to irrigate corn over wheat, our DiD outcomes indicate the change in percentage of irrigated wheat in Low counties after 1969 was almost zero (Table 3). On the other hand, Low counties increased the intensity of irrigated corn by nearly 10-percent in the second half of the study. By contrast, High counties increased the spread in percentage of both irrigated corn and wheat during the second half of the survey. After 1969, the difference in irrigation intensity between High and Low counties for both corn and wheat grew by roughly 10- and 9-percent, respectively.

Average Value of Land and Buildings per Acre

The previous three regression series described the differences in intensity of irrigated acreage broadly and for specific, widely-grown commodities. Ultimately, the economic benefit of expanding the intensive margin for irrigation within a county should be capitalized into land values. Moreover, the differences in saturated thickness which are captured by land values reveal the marginal economic benefit of preserving groundwater. In initial time periods (1920-1950), there isn't a statistical difference in land values for the counties inside the Ogallala versus outside; which is consistent with our hypothesis based on Ricardian theory, as there wasn't wide spread usage of the aquifer at this time (Table 6).

Beginning in 1950, there is a land premium for all counties inside the HPA, the greatest of which is the Low saturated thickness group. This could be interpreted as the early usage and associated drawdown observed in the Southern High Plains from about 1935 to 1955 (Haacker et al., 2016; Steward et al., 2016). In 1964, land value premiums peaked for all time periods across all levels of initial saturated thickness, including a 46-percent increase in land values in Low counties versus those outside the HPA (Table 8). This may correspond with widespread implementation of high capacity pumps, and reflect expectations of future profitability of all counties in the HPA. In 1978, the benefit of irrigation water access decreased across the board; possibly explained by a couple of factors. First, farmland values rose nationwide during the bubble of the Farm Financial Crisis of the 1980s. Second, this coincides with the tail end of the highest rates of increased extraction and associated drawdown of the aquifer, growth which was not sustainable (Steward et al., 2016). Land values may have adjusted again during this drawdown to account for expectations of future profitability. In the eighties, the statistical significance of Medium and Low saturated thickness groups dropped off, while High counties still had a beneficial effect of 16-percent higher land values until the 1997 census (Figure 12).

Before 2002, the coefficient values follow our hypothesis; land values increased rapidly after development for all groups (about 1950), then as aquifer levels declined, the counties with the highest initial levels of saturated thickness appear to retain higher agricultural land values as compared to those counties outside the aquifer. Notably, the coefficients for each of the saturated thickness groups did not prove to be statistically different from one another in this entire regression series despite the fact that the coefficients differed by as much as 10-percent (Table 8). However, in the second era of our survey (post-1969) Low counties appear to have lost a percentage of the value per acre, whereas High counties actually continued to become more valuable, an increased difference of around 4-percent (Table 3, Figure 12). The last three survey years likely impact this result, as coefficients for saturated thickness groups converge and drop from statistical significance (Figure 12). The intercept term increases substantially in the most recent time periods (Table 6), indicating that factors beyond what are included in the model are impacting farmland value.

Rain also plays a statistically significant role, increasing land values by about 2-percent for each additional centimeter of precipitation, in all census years except the most recent (Table 6). Temperature plays an increasingly large part in the value of agricultural land, with an increase in average annual temperature by one degree Celsius negatively impacting land values by as much as 24-percent in 2012. These climactic coefficients indicate that changes in climate can be very costly. However, exploring the cost of climate variation any further is beyond the scope of this thesis, and has been widely studied (Mendelsohn et al. 2003; Schlenker et al., 2005; Frisvold et al., 2016; etc).

Population Density

Contrary to past studies, which equate economic opportunities to population migration, our results consistently indicate the lowest population density in counties with the largest groundwater endowments and therefore assumed most profitable farmland (Table 7). Alternatively, the largest change in population density during our study was in counties with low saturated thickness, increasing from about 18 people per square mile to about 39 people per square mile, on average (Figure 5). However, in none of the census years are any of the coefficients for HPA counties statistically different from those outside the aquifer, nor are the coefficients for each group different from one another (Figure 13). Meaning, that despite model results indicating land premiums for irrigation water access, there is no observable trend in population growth or decline as a result of falling groundwater levels in the HPA. This result is an unexpected divergence from the somewhat shallow body of literature related to natural resources and population dynamics. This outcome is a positive note for stakeholders in the High Plains, as statistical evidence that reductions in water resources do not exclusively equate to community collapse, even for agriculturally based economies.

DISCUSSION & CONCLUSION

Access to the HPA has provided American agriculture with substantial resources, and has contributed to the United States in becoming an agricultural production powerhouse during the 20th century. Both the discovery of the aquifer and subsequent declines in water storage offer an ideal setting to examine economic outcomes associated with natural resource endowments and their management. Exogenous measures of water access provided by the heterogeneity of the HPA allows for identification of the contribution that irrigation water supplies have on irrigation intensity, land values, and population density. The variant nature of the aquifer also allows for consideration of the possibilities that may exist if overdraft continues and reduces groundwater resources.

Before the widespread usage of the HPA, there wasn't a large difference in economic outcomes between counties inside and outside of the aquifer (Tables 2-7). Shortly after the invention of center-pivots, and continuing into following the decades coinciding with widespread installation, there is a distinct difference in the irrigated acreage supported by counties with high, medium and low levels of initial saturated thickness. As discussed in previous sections, the income generated by irrigated acreage is substantially larger than dryland production. In 1997, irrigated crops in the western United States comprised 27-percent of the farmland, yet generated 72-percent of the total value of sales (Gollehon, 2000). The data supports our hypothesis that producers in counties with higher initial endowments of groundwater would choose to plant more irrigated crops than those in Low counties or outside the aquifer (Tables 2-4). However, contrary to our expectation that water "thirsty" crops (as measured by corn) would have reduced irrigation on the intensive margin as groundwater levels decline, High counties harvested more irrigated corn per acre of corn grown in recent periods than ever before (Table 4). Similar results are demonstrated by wheat, but to a lesser degree (Table 2).

An important distinction between our results from previous studies (Hornbeck et al., 2014; Torrell et al., 1990) is that the varied initial endowments of groundwater translate to diverse impacts on tested economic outcomes. Previous studies which have regarded the HPA as a homogeneous unit overlook the true marginal contributions of groundwater to agricultural production. We find that the largest initial endowments of groundwater in the High Plains have increased land values by as much as 42-percent during the height of irrigation expansion, and more importantly have had the longest lasting economic benefit compared to counties with lower initial saturated thickness and those outside the aquifer. Moreover, the differences in economic outcomes between counties with High and Low initial saturated thickness have actually increased over time, as High counties have increased their comparative lead in irrigated acreage, commodities, and land values (Table 3). Similarly to Hornbeck et al. (2014), we find that land premiums over the HPA have decreased over time along with water in storage. However, the decrease in statistical significance of land premiums was in order of declining initial saturated thickness. This result is underscored by the fact that High counties have actually seen the largest declines in saturated thickness in the HPA. Ultimately, as groundwater levels decline, irrigated acreage and land values in High counties may begin to look more like Low counties (Figure 12). Most recent data suggests that factors independent of irrigation water are having a larger influence on agricultural land value, as farmland outside of the aquifer appears to generally be increasing in value at a faster rate than farmland over the HPA.

The last three census years offer a trend for land values which differs from the previous five decades. Further research may examine results of the 2017 Ag. Census, and consider what characteristics of land values apart from the productivity measures included in this thesis are influencing land values. Shortcomings of our approach include the completeness of records for all variables in all years, particularly for irrigated crops, and the scale of data. In reality, differences in soil and water availability impact agriculturalists within a few miles, not exclusively across county lines. Subsequent studies may also include indicators for groundwater withdrawal restrictions in local management areas, as policies can be incorporated at the county level across time.

Our results differ from previous studies (i.e., Feng et al., 2012) as we find no statistical relationship between access to groundwater (at any level) and population density. Our empirical model contradicts our original hypothesis that producers would choose to locate, or relocate, according to water resource access. Doomsday scenarios have been described in books and news outlets, reasoning that dwindling water resources as a result of poor management, agricultural to municipal transfers, or drought equate to disintegration of agricultural communities (Engelbert et al., 1984). However, using numerical evidence which cuts across a wide variety of depositions of water resources, time periods, and communities, we find no connection between water access and population decline. This conclusion may reflect the resiliency of rural economies which adaptively diversify long before a ‘well has run dry’. Further, counties in our study with the lowest saturated thickness exhibited the highest population density and the lowest land values in all years (Figures 4-5). While this data does not suggest that depleted aquifers equate to disbandment of rural communities, it does advocate for groundwater conservation as a method for preserving economic value of agricultural land.

Table 1. Summary statistics for study data

Variable	Obs	Avg. Obs / Year	Mean	Std. Dev.	Min	Max
Avg. Value Land & Buildings per Acre (2002 Dollars)	7,355	368	722.97	681.17	21.54	7,639.00
Acres of Farmland	7,296	365	640,083.10	481,590.20	73,300.00	4,023,040.00
Acres of Irrigated Farmland	5,561	278	33,057.42	56,913.66	0.00	467,482.00
Percent Irrigated Acres	5,350	268	6%	10%	0%	75%
Acres of Corn Harvested	5,452	273	40,540.60	56,108.93	0.00	351,860.00
Acres of Wheat Harvested	5,452	273	59,421.68	76,469.20	0.00	506,600.00
Acres of Irrigated Corn Harvested	5,452	273	12,029.14	30,938.17	0.00	228,500.00
Acres of Irrigated Wheat Harvested	5,452	273	2,757.97	9,394.40	0.00	102,100.00
Acres Non-Irrigated Corn Harvested	5,452	273	9,416.46	24,929.19	0.00	211,280.00
Acres Non-Irrigated Wheat Harvested	5,452	273	30,765.28	58,496.34	0.00	505,600.00
Corn - Percent Irrigated	3,938	197	0.3399074	0.4062334	0	1
Wheat - Percent Irrigated	4,116	206	0.0817469	0.1899383	0	1
Population	5,147	257	17,875.50	41,034.50	67.00	645,641.00
Population per Square Mile	4,951	248	21	72.17	0.08	1,595.52
Average Annual Precipitation (cm)	7,355	368	47.96	12.39	23.84	78.90
Average Annual Temperature (°C)	7,355	368	11.76	3.11	2.03	18.20
County Acres	7,075	354	751,398.90	633,536.80	152,320.00	5,059,200.00
Percent Share of HPA	7,355	368	45%	45%	0%	100%
Percent Share * High Group	7,355	368	18%	38%	0%	100%
Percent Share * Medium Group	7,355	368	15%	33%	0%	100%
Percent Share * Low Group	7,355	368	12%	29%	0%	100%
Saturated Thickness in 1935 (m)	4,620	368	43.30	46.16	0.26	266.02
Depth to Water in 1935 (m)	7,355	368	18.44	18.50	0.00	88.08
Urban Influence Code (2003)	7,355	368	8.16	3.14	1.00	12.00
Colorado - State Fixed Effects	7,355	368	0.07	0.25	0.00	1.00
Nebraska - State Fixed Effects	7,355	368	0.25	0.43	0.00	1.00
Kansas - State Fixed Effects	7,355	368	0.22	0.41	0.00	1.00
Oklahoma - State Fixed Effects	7,355	368	0.07	0.26	0.00	1.00
Texas - State Fixed Effects	7,355	368	0.20	0.40	0.00	1.00
Iowa - State Fixed Effects	7,355	368	0.04	0.20	0.00	1.00
New Mexico - State Fixed Effects	7,355	368	0.03	0.17	0.00	1.00
Wyoming - State Fixed Effects	7,355	368	0.03	0.17	0.00	1.00
South Dakota - State Fixed Effects	7,355	368	0.09	0.28	0.00	1.00
Longitude (County Center)	7,355	368	(351,969.70)	229,823.90	(901,310.30)	89,045.22
Latitude (County Center)	7,355	368	147,940.50	384,563.40	(742,415.40)	809,459.90
Non-Irrigated Soil Land Capability Class 1	7,355	368	3.5%	11.3%	0.0%	87.8%
Non-Irrigated Soil Land Capability Class 2	7,355	368	26.4%	28.5%	0.0%	99.9%
Non-Irrigated Soil Land Capability Class 3	7,355	368	25.3%	28.5%	0.0%	100.0%
Non-Irrigated Soil Land Capability Class 4	7,355	368	10.1%	17.1%	0.0%	96.7%
Non-Irrigated Soil Land Capability Class 5	7,355	368	24.4%	26.7%	0.0%	100.0%
Non-Irrigated Soil Land Capability Class 6	7,355	368	0.4%	1.6%	0.0%	12.2%
Non-Irrigated Soil Land Capability Class 7	7,355	368	9.0%	17.3%	0.0%	93.4%
Non-Irrigated Soil Land Capability Class 8	7,355	368	0.1%	0.6%	0.0%	7.2%

Table 2. Regression output for percent irrigated acres as the economic outcome

% Irrigated Acres		Share High	Share Med.	Share Low	CO	NE	KS	OK	TX	IA	WY	SD	Rain	Temp.	Long.	Lat.	LCC 1	LCC 2	LCC 3	LCC 4	LCC 5	Constant	R2	N	Wald Test - Shares Equal
1920	Coef	-0.0345	-0.0507	0.0202	0.0532	0.0552	0.0674	0.0313	0.0375		-0.0508	-0.0444	0.0036	0.0136	0.0000	0.0000		-0.0002	0.0003	0.0004	0.0040	-0.4810	0.35	80	2.66
	P > t	33%	14%	58%	28%	39%	21%	57%	36%		46%	60%	20%	23%	8%	14%		64%	51%	45%	81%	15%			7.82%
1925	Coef																								
No Obs	P > t																								
1930	Coef	-0.0399	-0.0613	0.0375	0.0322	0.0577	0.0861	0.0193	0.0485		-0.0786	-0.0863	0.0044	0.0161	0.0000	0.0000	0.0021	-0.0006	0.0002	0.0004	-0.0002	-0.5269	0.38	82	4.94
	P > t	27%	8%	31%	51%	37%	11%	76%	23%		27%	33%	11%	15%	7%	5%	80%	26%	61%	39%	99%	10%			1.02%
1935	Coef	-0.0084	-0.0085	0.0043	0.0240	0.0227	0.0141	0.0117	0.0097	0.0239	-0.0100	0.0091	0.0009	0.0017	0.0000	0.0000	0.0002	0.0001	0.0001	0.0001	0.0002	-0.1121	0.25	354	4.41
	P > t	2%	3%	38%	1%	3%	11%	16%	16%	6%	40%	47%	0%	30%	0%	10%	12%	32%	7%	5%	76%	0%			1.29%
1940	Coef	-0.0056	-0.0080	0.0059	0.0358	0.0295	0.0163	0.0158	0.0136	0.0300	-0.0026	0.0133	0.0010	0.0008	0.0000	0.0000	0.0003	0.0001	0.0002	0.0002	0.0003	-0.1247	0.26	252	1.75
	P > t	36%	24%	47%	1%	8%	25%	24%	19%	20%	89%	53%	4%	77%	0%	46%	21%	16%	1%	17%	76%	5%			17.66%
1945	Coef																								
No Obs	P > t																								
1950	Coef	0.02	0.00	0.01	0.04	0.04	0.02	0.02	0.02	0.03	0.02	0.04	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.06	0.24	354	2.85
	P > t	1%	95%	51%	4%	9%	47%	41%	19%	38%	43%	20%	11%	9%	1%	12%	5%	0%	0%	37%	33%	47%			5.91%
1954	Coef	0.0483	0.0129	0.0180	0.0309	0.0448	0.0121	0.0177	0.0350	0.0190	0.0275	0.0530	0.0012	-0.0116	0.0000	0.0000	0.0008	0.0008	0.0012	0.0002	0.0022	-0.0312	0.33	354	4.96
	P > t	0%	30%	25%	25%	18%	67%	51%	11%	64%	47%	19%	19%	2%	3%	3%	1%	0%	0%	32%	28%	79%			0.75%
1959	Coef	0.0811	0.0277	0.0281	0.0448	0.0689	0.0206	0.0171	0.0413	0.0366	0.0500	0.0740	0.0017	-0.0139	0.0000	0.0000	0.0021	0.0011	0.0016	0.0004	0.0028	-0.0780	0.42	354	8.62
	P > t	0%	6%	13%	16%	8%	53%	59%	11%	44%	27%	12%	11%	2%	1%	1%	0%	0%	0%	12%	25%	58%			0%
1964	Coef	0.0898	0.0343	0.0321	0.0309	0.0627	0.0236	0.0184	0.0447	0.0361	0.0400	0.0704	0.0016	-0.0143	0.0000	0.0000	0.0022	0.0012	0.0017	0.0007	0.0031	-0.0709	0.495	354	10.89
	P > t	0%	1%	7%	30%	9%	45%	54%	7%	42%	34%	12%	11%	1%	1%	1%	0%	0%	0%	1%	17%	59%			0%
1969	Coef	0.12	0.05	0.03	0.03	0.06	0.02	0.02	0.04	0.03	0.04	0.06	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.06	0.56	354	20.06
	P > t	0%	0%	9%	28%	12%	44%	52%	11%	52%	35%	19%	24%	2%	1%	1%	0%	0%	0%	0%	18%	63%			0%
1974	Coef	0.1488	0.0673	0.0319	0.0491	0.0767	0.0311	0.0097	0.0172	0.0449	0.0666	0.0748	0.0010	-0.0122	0.0000	0.0000	0.0031	0.0015	0.0019	0.0009	0.0032	-0.0730	0.58	354	28.08
	P > t	0%	0%	9%	12%	5%	35%	76%	50%	34%	14%	11%	36%	4%	2%	0%	0%	0%	0%	0%	18%	60%			0%
1978	Coef	0.1806	0.0883	0.0359	0.0714	0.1105	0.0432	0.0081	0.0097	0.0647	0.0958	0.0975	0.0009	-0.0130	0.0000	0.0000	0.0037	0.0017	0.0020	0.0011	0.0044	-0.0709	0.61	354	32.65
	P > t	0%	0%	8%	4%	1%	24%	82%	73%	22%	5%	6%	47%	5%	5%	0%	0%	0%	0%	0%	10%	64%			0%
1982	Coef	0.1792	0.0862	0.0274	0.0845	0.1278	0.0515	0.0024	-0.0095	0.0817	0.1147	0.1127	0.0009	-0.0099	0.0000	0.0000	0.0035	0.0016	0.0017	0.0009	0.0048	-0.1032	0.61	354	37.65
	P > t	0%	0%	17%	1%	0%	14%	94%	73%	11%	2%	3%	43%	12%	5%	0%	0%	0%	0%	0%	7%	49%			0%
1987	Coef	0.1545	0.0789	0.0238	0.0821	0.1272	0.0492	-0.0024	-0.0198	0.0834	0.1142	0.1089	0.0010	-0.0066	0.0000	0.0000	0.0033	0.0014	0.0013	0.0009	0.0042	-0.1238	0.62	354	36.67
	P > t	0%	0%	16%	1%	0%	10%	94%	40%	6%	1%	1%	33%	23%	5%	0%	0%	0%	0%	0%	6%	33%			0%
1992	Coef	0.1788	0.0854	0.0281	0.0897	0.1411	0.0543	-0.0032	-0.0180	0.0962	0.1267	0.1258	0.0012	-0.0070	0.0000	0.0000	0.0035	0.0016	0.0015	0.0010	0.0052	-0.1565	0.61	354	36.91
	P > t	0%	0%	16%	1%	0%	13%	93%	52%	6%	1%	1%	30%	28%	4%	0%	0%	0%	0%	0%	5%	29%			0%
1997	Coef	0.187	0.095	0.037	0.090	0.152	0.052	-0.010	-0.010	0.101	0.134	0.130	0.002	-0.008	0.000	0.000	0.004	0.002	0.002	0.001	0.006	-0.174	0.62	354	33.14
	P > t	0%	0%	8%	1%	0%	17%	78%	74%	6%	1%	2%	18%	23%	4%	0%	0%	0%	0%	0%	3%	27%			0%
2002	Coef																								
No Obs	P > t																								
2007	Coef	0.1976	0.1074	0.0405	0.0830	0.1787	0.0484	-0.0214	-0.0199	0.1228	0.1554	0.1339	0.0017	-0.0105	0.0000	0.0000	0.0045	0.0018	0.0014	0.0016	0.0075	-0.1353	0.64	344	29.57
	P > t	0%	0%	7%	4%	0%	23%	58%	53%	4%	1%	2%	19%	16%	14%	0%	0%	0%	0%	0%	1%	43%			0%
2012	Coef	0.1783	0.1029	0.0419	0.0694	0.1600	0.0344	-0.0314	-0.0302	0.0780	0.1382	0.1098	0.0010	-0.0092	0.0000	0.0000	0.0044	0.0017	0.0013	0.0014	0.0065	-0.0735	0.64	344	24.21
	P > t	0%	0%	5%	6%	0%	37%	40%	32%	17%	1%	5%	44%	20%	39%	0%	0%	0%	0%	0%	2%	66%			0%

The table reflects Equation 4 estimated with the percentage of irrigated acres in a county as the economic outcome of interest for each census year. Grayed cells indicate that a variable was omitted due to collinearity. Grayed rows indicate that there were no observations in that year (data gaps). LCC stands for land capability class. The column marked "Wald Test" includes the F-stat and P-value for the test of equivalency among the coefficients for the percent share groups.

Table 3. Difference-in-Difference analysis for select economic outcomes

Era 2 - Era 1	High Counties	Low Counties	Difference-in-Difference
Percent Irrigated	8.3% *0.1%*	2.3% *0.2%*	5.9% *0.30%*
Value of Land / Acre	2.2% *0.4%*	-2.2% *0.6%*	4.4% *0.97%*
Percent Irrigated Wheat	9.3% *0.5%*	-1.0% *0.6%*	10.3% *1.09%*
Percent Irrigated Corn	18.6% *0.6%*	9.8% *0.8%*	8.7% *1.43%*

	From	*To*	Statistic
Era 1	1925	1969	Mean Outcome (for County *i*)
Era 2	1925	2012	Mean Outcome (for County *i*)

Table 3 reflects Equation 4 estimated with the average value for each economic outcome for Era 2 (entire study) differenced from Era 1 (pre-1969) as the dependent variable. These coefficients for High and Low saturated thickness groups are differenced again to understand the changes of the disparities between groups over the course of the study. Italicized numbers reflect the standard error.

Table 4. Regression output for percentage of irrigated wheat as the economic outcome

% Irrigated Wheat		Share High	Share Med.	Share Low	CO	NE	KS	OK	TX	IA	WY	SD	Rain	Temp.	Long.	Lat.	LCC 1	LCC 2	LCC 3	LCC 4	LCC 5	Constant	R2	N	Wald Test - Shares Equal
1920	Coef	-0.2053	-0.2299	-0.1629	0.1179	0.3952	0.3374				0.2757	0.3453	-0.0086	-0.0950	0.0000	0.0000	0.0002	-0.0013	0.0003	0.0022	-0.0005	1.6662	0.52	94	0.2
	P > t	3%	1%	17%	49%	9%	7%				27%	24%	21%	0%	83%	0%	96%	45%	87%	19%	97%	6%			81%
1925	Coef																								
No Obs	P > t																								
1930	Coef	-0.0866	-0.1090	-0.1010	0.0874		0.0685				-0.1187		0.0016	-0.0278	0.0000	0.0000	0.0002	-0.0004	-0.0006	0.0009	0.0006	0.2269	0.39	143	0.09
	P > t	12%	1%	7%	30%		16%				36%		69%	26%	41%	18%	95%	50%	38%	39%	93%	72%			91%
1935	Coef	-0.0734	-0.1007	-0.0619	0.0016		0.1057				-0.3032		0.0103	-0.0046	0.0000	0.0000	-0.0025	0.0000	-0.0001	0.0059	0.0005	-0.8128	0.61	134	0.33
	P > t	15%	1%	24%	99%		2%				1%		1%	84%	0%	65%	27%	93%	92%	0%	93%	15%			72%
1940	Coef	-0.1349	-0.1414	-0.1346	0.1618		0.1215				-0.0535		0.0010	0.0184	0.0000	0.0000	-0.0011	-0.0005	-0.0005	0.0019	-0.0031	-0.4077	0.44	143	0.01
	P > t	1%	0%	1%	5%		1%				67%		80%	44%	22%	80%	68%	37%	38%	6%	62%	50%			98%
1945	Coef	-0.0563	-0.0813	-0.0908	0.0085		0.0572				-0.1438		0.0033	-0.0285	0.0000	0.0000	-0.0006	-0.0001	-0.0003	0.0023	0.0013	0.1047	0.43	143	0.24
	P > t	21%	2%	5%	90%		16%				19%		34%	20%	28%	21%	79%	88%	54%	1%	80%	85%			0.79
1950	Coef	-0.0053	-0.0038	-0.0173	0.0346	0.0606	0.0475	0.0394	0.0396	0.0494	0.0701	0.0699	-0.0018	-0.0101	0.0000	0.0000	0.0001	-0.0001	0.0002	-0.0001	-0.0001	0.2170	0.22	306	1.39
	P > t	45%	61%	6%	3%	0%	0%	1%	0%	9%	0%	1%	0%	0%	3%	0%	64%	58%	11%	31%	93%	1%			25%
1954	Coef	-0.0278	-0.0311	-0.0922	-0.4034	-0.2649	-0.3351	-0.4101	-0.4266	-0.2551	-0.2587	-0.2365	-0.0052	-0.0233	0.0000	0.0000	0.0001	-0.0007	-0.0003	-0.0008	-0.0019	1.0766	0.5	306	2.21
	P > t	30%	27%	1%	0%	0%	0%	0%	0%	2%	0%	1%	2%	6%	25%	0%	87%	9%	44%	13%	67%	0%			11%
1959	Coef	-0.0013	-0.0199	-0.0315	0.1409	0.2917	0.2336	0.1981	0.2299	0.2703	0.2698	0.3253	-0.0056	-0.0384	0.0000	0.0000	0.0004	-0.0004	0.0006	-0.0002	0.0004	0.6837	0.35	307	0.52
	P > t	96%	47%	35%	2%	0%	0%	0%	0%	1%	0%	0%	1%	0%	17%	0%	60%	32%	12%	65%	93%	2%			59%
1964	Coef	-0.0523	-0.1057	-0.1661	-0.3785	-0.1761	-0.2165	-0.2939	-0.2462	-0.1740	-0.2223	-0.1824	-0.0115	-0.0593	0.0000	0.0000	0.0009	-0.0007	0.0005	0.0015	-0.0028	1.8428	0.54	309	3.46
	P > t	14%	1%	0%	0%	7%	1%	0%	0%	24%	5%	14%	0%	0%	9%	0%	38%	15%	35%	4%	64%	0%			3%
1969	Coef	-0.0253	-0.0472	-0.0507	0.1323	0.1259	0.1121	0.0754	0.0734		0.1115		0.0053	-0.0033	0.0000	0.0000	0.0002	0.0001	0.0000	0.0011	0.0016	-0.4613	0.29	305	0.96
	P > t	18%	2%	4%	0%	2%	2%	8%	5%		7%		0%	71%	0%	89%	68%	61%	98%	1%	61%	4%			38%
1974	Coef	0.0616	-0.0055	-0.1233	-0.7063	-0.5661	-0.5014	-0.5062	-0.3290	-0.5220	-0.6400		-0.0033	-0.0444	0.0000	0.0000	0.0003	-0.0004	0.0006	0.0019	-0.0004	1.2926	0.56	320	9
	P > t	8%	88%	1%	0%	0%	0%	0%	0%	0%	0%		28%	1%	75%	5%	75%	41%	20%	1%	94%	0%			0%
1978	Coef	0.1000	0.0088	-0.0773	-0.4816	-0.4316	-0.3520	-0.3603	-0.3106	-0.3941	-0.4685	-0.4075	-0.0041	-0.0397	0.0000	0.0000	0.0005	0.0001	0.0009	0.0018	-0.0025	1.1447	0.49	339	13.12
	P > t	0%	77%	4%	0%	0%	0%	0%	0%	0%	0%	0%	7%	0%	67%	1%	54%	73%	3%	0%	60%	0%			0%
1982	Coef	0.1044	0.0064	-0.1082	-0.4378	-0.3237	-0.2529	-0.3052	-0.3002	-0.2511	-0.4382	-0.3098	-0.0044	-0.0368	0.0000	0.0000	0.0006	-0.0001	0.0004	0.0022	-0.0038	1.0519	0.52	345	21.44
	P > t	0%	82%	0%	0%	0%	0%	0%	0%	1%	0%	0%	3%	0%	88%	0%	42%	76%	22%	0%	39%	0%			0%
1987	Coef	0.1240	0.0114	-0.0929	-0.4545	-0.3733	-0.2887	-0.3278	-0.3473	-0.3116	-0.5083	-0.3369	-0.0018	-0.0412	0.0000	0.0000	0.0010	0.0007	0.0013	0.0028	-0.0023	0.8988	0.56	347	29.34
	P > t	0%	64%	0%	0%	0%	0%	0%	0%	0%	0%	0%	33%	0%	18%	0%	10%	4%	0%	0%	57%	0%			0%
1992	Coef	0.1214	0.0144	-0.0924	-0.3498	-0.2459	-0.1655	-0.2031	-0.2168	-0.1801	-0.4093	-0.2214	-0.0027	-0.0419	0.0000	0.0000	0.0006	0.0003	0.0010	0.0024	-0.0015	0.8684	0.49	333	23.57
	P > t	0%	59%	1%	0%	0%	2%	0%	0%	6%	0%	2%	19%	0%	35%	0%	38%	50%	1%	0%	73%	0%			0%
1997	Coef	0.0904	0.0053	-0.0876	-0.2746	-0.1820	-0.1296	-0.1689	-0.1644	-0.1268	-0.3328	-0.1521	-0.0021	-0.0460	0.0000	0.0000	0.0003	0.0001	0.0006	0.0029	-0.0021	0.8700	0.49	330	17.09
	P > t	0%	84%	1%	0%	2%	5%	1%	0%	17%	0%	10%	30%	0%	47%	0%	70%	70%	6%	0%	62%	0%			0%
2002	Coef	0.0825	-0.0319	-0.1080	-0.4129	-0.2829	-0.2218	-0.2816	-0.2361	-0.2175	-0.4951	-0.2807	-0.0049	-0.0530	0.0000	0.0000	0.0002	-0.0004	0.0003	0.0039	-0.0031	1.2952	0.62	257	15.9
	P > t	1%	31%	1%	0%	0%	1%	0%	0%	6%	0%	1%	7%	0%	98%	0%	83%	37%	49%	0%	54%	0%			0%
2007	Coef	0.1944	0.0731	0.0086	0.0894	0.2980	0.2493	0.1630	0.1401				0.0035	-0.0295	0.0000	0.0000	0.0026	0.0000	0.0004	0.0041	0.0057	-0.1439	0.47	274	14.79
	P > t	0%	3%	84%	37%	1%	1%	8%	11%				21%	13%	3%	5%	0%	93%	41%	0%	25%	73%			0%
2012	Coef																								
	P > t																								

The table reflects Equation 4 estimated with the percentage of irrigated wheat in a county as the economic outcome of interest for each census year. Grayed cells indicate that a variable was omitted due to collinearity. Grayed rows indicate that there were no observations in that year (data gaps). LCC stands for land capability class. The column marked "Wald Test" includes the F-stat and P-value for the test of equivalency among the coefficients for the percent share groups.

Table 5. Regression output with percentage of irrigated corn as the economic outcome

% Irrigated Corn		Share High	Share Med.	Share Low	CO	NE	KS	OK	TX	IA	WY	SD	Rain	Temp.	Long.	Lat.	LCC 1	LCC 2	LCC 3	LCC 4	LCC 5	Constant	R2	N	Wald Test - Shares Equal
1920	Coef																								
No Obs	P > t																								
1925	Coef																								
No Obs	P > t																								
1930	Coef																								
No Obs	P > t																								
1935	Coef																								
No Obs	P > t																								
1940	Coef																								
No Obs	P > t																								
1945	Coef																								
No Obs	P > t																								
1950	Coef	0.0701	0.0397	0.1111		0.0235							-0.0046	-0.0283	0.0000	0.0000	0.0013	0.0019	0.0023	0.0009	0.0038	0.4881	0.33	108	0.68
	P > t	22%	49%	19%		72%							57%	58%	65%	54%	15%	1%	1%	37%	59%	57%			50%
1954	Coef	0.0799	0.0701	0.1304		0.0733				0.0894			0.0070	-0.0116	0.0000	0.0000	0.0015	0.0017	0.0012	0.0003	0.0023	-0.5467	0.36	135	0.43
	P > t	12%	20%	10%		53%				56%			19%	81%	1%	100%	11%	1%	13%	73%	69%	42%			64%
1959	Coef	0.1014	0.1103	0.1334		-0.4160	-0.7500	-0.7861		-0.4551	-0.0021		0.0102	0.0872	0.0000	0.0000	0.0037	0.0008	0.0004	-0.0021	-0.0012	-1.3467	0.68	234	0.18
	P > t	3%	2%	3%		1%	0%	0%		1%	99%		1%	0%	0%	3%	0%	18%	52%	5%	84%	1%			83%
1964	Coef	0.1438	0.1170	0.0062	0.2363	0.3510	0.2993	-0.2057	-0.1945	0.3809	0.0463	0.1583	0.0003	-0.0143	0.0000	0.0000	0.0066	0.0039	0.0039	0.0014	-0.0187	-0.3995	0.58	305	1.81
	P > t	1%	6%	94%	8%	4%	4%	15%	8%	6%	82%	45%	95%	64%	0%	15%	0%	0%	0%	27%	7%	51%			16%
1969	Coef	0.1801	0.1212	0.1626	0.1843	-0.0657	-0.6776	-0.8026	-0.8997	-0.1555	0.0000		0.0185	0.0916	0.0000	0.0000	0.0047	0.0010	0.0000	-0.0007	0.0040	-2.0992	0.78	253	1.19
	P > t	0%	1%	1%	8%	53%	0%	0%	0%	24%			0%	0%	0%	8%	0%	12%	99%	47%	58%	0%			30%
1974	Coef	0.2931	0.2424	0.2975	1.1740	1.0059	1.0020	0.3022	0.0487	0.9314	0.8306		-0.0016	0.0519	0.0000	0.0000	0.0048	0.0018	-0.0002	-0.0025	0.0037	-1.3882	0.8	270	1.05
	P > t	0%	0%	0%	0%	0%	0%	0%	56%	0%	0%		68%	2%	0%	72%	0%	0%	75%	1%	63%	0%			35%
1978	Coef	0.2812	0.2451	0.3135	1.1952	1.0699	1.0794	0.3083	0.0469	0.8773	0.8711		-0.0019	0.0465	0.0000	0.0000	0.0048	0.0012	-0.0003	-0.0027	0.0117	-1.2626	0.8	282	0.98
	P > t	0%	0%	0%	0%	0%	0%	0%	57%	0%	0%		62%	4%	0%	54%	0%	4%	61%	0%	9%	1%			38%
1982	Coef	0.2939	0.2312	0.2663	1.2353	1.1291	1.1578	0.3491	1.0363	1.0098	1.0386		0.0024	0.0516	0.0000	0.0000	0.0050	0.0013	-0.0003	-0.0021	0.0122	-1.7083	0.81	255	1.31
	P > t	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%		53%	4%	0%	62%	0%	3%	61%	2%	10%	0%			27%
1987	Coef	0.2748	0.2207	0.1838	0.1661	0.0153	0.0187	0.3117	-1.0539	-0.2424	0.1229		-0.0039	0.0439	0.0000	0.0000	0.0045	0.0007	0.0005	-0.0025	0.0121	-0.0327	0.75	249	1.26
	P > t	0%	0%	1%	15%	92%	89%	2%	0%	18%	49%		36%	12%	1%	58%	0%	31%	46%	2%	16%	95%			29%
1992	Coef	0.2482	0.2094	0.1049	0.0988	0.1396	0.0929	-0.6798	-0.9956	-0.0235	0.1686		-0.0034	0.0427	0.0000	0.0000	0.0046	0.0006	-0.0003	-0.0020	0.0172	-0.1373	0.8	256	3.23
	P > t	0%	0%	9%	37%	32%	44%	0%	0%	88%	30%		40%	11%	0%	99%	0%	36%	64%	3%	2%	79%			4%
1997	Coef	0.2688	0.1733	0.0476	0.1659	0.2108	0.0820	-0.6032	-0.9081	0.1505	0.2668		0.0010	0.0744	0.0000	0.0000	0.0040	0.0008	0.0000	-0.0004	0.0236	-0.9957	0.81	258	10.38
	P > t	0%	0%	40%	13%	10%	45%	0%	0%	31%	10%		78%	1%	0%	44%	0%	18%	96%	61%	0%	6%			0%
2002	Coef	0.4401	0.3228	0.2770	0.0961	-0.0113	-0.1331	-0.6918	-0.9903	-0.0526	-0.6078		0.0059	0.1052	0.0000	0.0000	0.0023	0.0005	-0.0005	-0.0015	0.0213	-1.5934	0.77	251	5.27
	P > t	0%	0%	0%	57%	95%	44%	0%	0%	80%	1%		15%	0%	0%	3%	8%	49%	48%	13%	1%	1%			0%
2007	Coef	0.5318	0.3730	0.1267	-0.3932	-0.4101	-0.5211	-0.9640	-1.1550	-0.4859	-0.2277		0.0050	0.1176	0.0000	0.0000	0.0021	0.0008	-0.0004	-0.0007	0.0182	-1.2808	0.69	244	19.16
	P > t	0%	0%	10%	2%	3%	0%	0%	0%	2%	31%		27%	0%	3%	2%	14%	29%	62%	52%	4%	5%			0%
2012	Coef	0.3484	0.2664	0.1540	0.4445	0.7169	0.4127	0.0977		0.5675	0.2378		0.0073	0.1062	0.0000	0.0000	0.0052	0.0022	0.0014	0.0001	0.0116	-2.4786	0.51	214	3.11
	P > t	0%	0%	10%	0%	0%	0%	43%		0%	33%		22%	2%	3%	14%	0%	4%	18%	95%	28%	0%			4%

The table reflects Equation 4 estimated with the percentage of irrigated corn in a county as the economic outcome of interest for each census year. Grayed cells indicate that a variable was omitted due to collinearity. Grayed rows indicate that there were no observations in that year (data gaps). LCC stands for land capability class. The column marked “Wald Test” includes the F-stat and P-value for the test of equivalency among the coefficients for the percent share groups.

Table 6. Regression output with the log of avg. value of land and buildings per acre in 2002 dollars as the economic outcome

Ln($/Acre)		Share High	Share Med.	Share Low	CO	NE	KS	OK	TX	IA	WY	SD	Rain	Temp.	Long.	Lat.	LCC 1	LCC 2	LCC 3	LCC 4	LCC 5	Constant	R2	N	Wald Test - Shares Equal
1920	Coef	-0.0984	-0.0223	-0.1186	0.6258	0.1326	-0.3836	-0.4579	-0.0932	0.2119	-0.0178	-0.2343	0.0213	-0.0409	0.0000	0.0000	0.0175	0.0124	0.0085	0.0076	0.0442	3.1211	0.88	368	0.83
	P > t	16%	77%	21%	0%	50%	2%	0%	48%	37%	94%	33%	0%	18%	0%	23%	0%	0%	0%	0%	0%	0%			43%
1925	Coef	-0.0778	-0.0109	0.1129	0.6452	0.2901	-0.1537	-0.2782	0.1494	0.2477	-0.1899	-0.0208	0.0216	-0.0496	0.0000	0.0000	0.0168	0.0138	0.0110	0.0082	0.0463	2.6529	0.88	368	253
	P > t	23%	88%	20%	0%	11%	32%	6%	22%	26%	37%	93%	0%	8%	0%	97%	0%	0%	0%	0%	0%	0%			0.08
1930	Coef	0.0595	0.0600	0.1186	0.6772	0.5035	0.1155	0.1038	0.3631	0.5174	0.0366	0.1840	0.0248	-0.0471	0.0000	0.0000	0.0183	0.0153	0.0127	0.0102	0.0477	1.9465	0.86	368	0.26
	P > t	38%	41%	19%	0%	1%	48%	50%	1%	3%	87%	43%	0%	11%	2%	54%	0%	0%	0%	0%	0%	1%			76%
1935	Coef	-0.0084	-0.0053	0.0203	0.5828	0.5116	0.0931	0.0120	0.2217	0.4931	0.0250	0.0382	0.0238	-0.0464	0.0000	0.0000	0.0182	0.0152	0.0125	0.0093	0.0462	1.5780	0.85	368	0.06
	P > t	90%	94%	82%	0%	1%	56%	94%	8%	3%	91%	87%	0%	11%	6%	28%	0%	0%	0%	0%	0%	2%			94%
1940	Coef	-0.0243	-0.0150	0.0675	0.4257	0.4057	0.1087	0.0404	0.2821	0.7170	0.0221	-0.1008	0.0370	-0.0686	0.0000	0.0000	0.0183	0.0142	0.0102	0.0085	0.0376	1.0529	0.82	368	0.47
	P > t	75%	85%	51%	2%	6%	55%	82%	5%	1%	93%	70%	0%	4%	60%	3%	0%	0%	0%	0%	1%	17%			62%
1945	Coef	0.0630	0.1038	0.1381	0.3505	0.2485	0.0210	-0.0276	0.1753	0.4794	-0.1017	-0.3351	0.0228	-0.0686	0.0000	0.0000	0.0205	0.0156	0.0117	0.0091	0.0312	2.3301	0.84	368	0.36
	P > t	37%	18%	15%	3%	21%	90%	87%	19%	5%	66%	17%	0%	3%	3%	2%	0%	0%	0%	0%	1%	0%			69%
1950	Coef	0.2039	0.2015	0.2426	0.2105	-0.0520	-0.1571	-0.0536	-0.0660	0.2284	-0.4186	-0.4143	0.0134	-0.1029	0.0000	0.0000	0.0193	0.0157	0.0137	0.0092	0.0214	3.9422	0.82	368	0.13
	P > t	0%	1%	1%	17%	78%	31%	72%	59%	31%	5%	7%	1%	0%	1%	0%	0%	0%	0%	0%	7%	0%			87%
1954	Coef	0.2748	0.2699	0.2427	0.0991	-0.1171	-0.2074	-0.0795	0.0163	0.2197	-0.5016	-0.4366	0.0156	-0.0754	0.0000	0.0000	0.0192	0.0153	0.0129	0.0089	0.0189	3.6613	0.81	368	0.07
	P > t	0%	0%	1%	52%	53%	19%	60%	90%	33%	2%	6%	0%	1%	4%	6%	0%	0%	0%	0%	11%	0%			93%
1959	Coef	0.3016	0.2707	0.2905	0.0888	-0.1298	-0.2231	-0.0692	0.0777	0.2713	-0.6167	-0.3598	0.0292	-0.0551	0.0000	0.0000	0.0186	0.0150	0.0127	0.0096	0.0196	2.5982	0.77	368	0.09
	P > t	0%	0%	0%	59%	52%	19%	67%	56%	26%	1%	14%	0%	8%	48%	46%	0%	0%	0%	0%	12%	0%			91%
1964	Coef	0.3571	0.3107	0.3783	0.0781	-0.1846	-0.2115	0.1254	0.1711	0.0722	-0.6942	-0.3696	0.0280	-0.0909	0.0000	0.0000	0.0178	0.0145	0.0129	0.0097	0.0279	3.3714	0.79	368	0.42
	P > t	0%	0%	0%	60%	31%	17%	40%	16%	74%	0%	10%	0%	0%	58%	12%	0%	0%	0%	0%	2%	0%			65%
1969	Coef	0.3415	0.2612	0.2583	0.2717	0.0780	-0.0657	0.2705	0.2140	0.3686	-0.3470	-0.0996	0.0266	-0.1090	0.0000	0.0000	0.0171	0.0134	0.0118	0.0101	0.0193	3.9467	0.82	368	1.03
	P > t	0%	0%	0%	5%	64%	65%	5%	6%	7%	8%	63%	0%	0%	77%	1%	0%	0%	0%	0%	7%	0%			35%
1974	Coef	0.3477	0.2522	0.2465	0.5528	0.4068	0.2531	0.4508	0.1278	0.7209	-0.0951	0.1517	0.0249	-0.1037	0.0000	0.0000	0.0163	0.0130	0.0110	0.0085	0.0117	4.3137	0.82	368	1.57
	P > t	0%	0%	0%	0%	1%	7%	0%	25%	0%	62%	45%	0%	0%	85%	0%	0%	0%	0%	0%	26%	0%			20%
1978	Coef	0.2116	0.1603	0.1787	0.5357	0.5804	0.3124	0.4335	0.1194	0.9816	0.0516	0.1909	0.0191	-0.1136	0.0000	0.0000	0.0170	0.0124	0.0100	0.0079	0.0149	5.4159	0.82	368	0.36
	P > t	0%	1%	3%	0%	0%	3%	0%	29%	0%	79%	35%	0%	0%	46%	0%	0%	0%	0%	0%	16%	0%			69%
1982	Coef	0.2208	0.1509	0.1389	0.6831	0.7768	0.4471	0.6929	0.3097	1.0757	-0.0292	0.3820	0.0231	-0.0957	0.0000	0.0000	0.0159	0.0111	0.0084	0.0079	0.0121	5.0028	0.8	368	0.88
	P > t	0%	2%	8%	0%	0%	0%	0%	1%	0%	88%	6%	0%	0%	51%	0%	0%	0%	0%	0%	25%	0%			41%
1987	Coef	0.1351	0.0789	0.0197	0.5618	0.7228	0.4106	0.5461	0.2737	0.9493	-0.1275	0.4794	0.0179	-0.1255	0.0000	0.0000	0.0131	0.0090	0.0075	0.0073	0.0104	5.5291	0.75	368	1.37
	P > t	1%	18%	79%	0%	0%	0%	0%	1%	0%	48%	1%	0%	0%	60%	0%	0%	0%	0%	0%	29%	0%			25%
1992	Coef	0.171	0.112	0.091	0.615	0.554	0.277	0.395	0.160	0.757	-0.038	0.258	0.013	-0.176	0.000	0.000	0.016	0.011	0.008	0.007	0.016	6.764	0.79	368	0.72
	P > t	0%	8%	25%	0%	0%	5%	0%	15%	0%	84%	21%	0%	0%	6%	0%	0%	0%	0%	0%	13%	0%			48%
1997	Coef	0.1546	0.1044	0.0567	0.7902	0.6823	0.3694	0.3897	0.1599	1.0309	0.1896	0.4705	0.0160	-0.1891	0.0000	0.0000	0.0151	0.0103	0.0082	0.0087	0.0138	6.9361	0.79	368	0.83
	P > t	1%	11%	49%	0%	0%	1%	1%	16%	0%	33%	2%	0%	0%	10%	0%	0%	0%	0%	0%	20%	0%			43%
2002	Coef	0.1058	0.0732	0.0597	0.7152	0.4605	0.1983	0.1669	0.1438	0.6959	0.1622	0.2060	0.0172	-0.2038	0.0000	0.0000	0.0151	0.0098	0.0079	0.0088	0.0148	7.4761	0.77	368	0.18
	P > t	11%	31%	51%	0%	2%	22%	28%	25%	0%	46%	37%	0%	0%	2%	0%	0%	0%	0%	0%	22%	0%			0.83
2007	Coef	0.0201	0.0489	0.0328	0.7716	0.4986	0.0744	0.2441	0.4104	0.8307	0.3599	0.3562	0.0091	-0.1724	0.0000	0.0000	0.0136	0.0083	0.0067	0.0059	0.0136	8.1624	0.82	364	0.15
	P > t	70%	38%	64%	0%	0%	54%	4%	0%	0%	3%	4%	2%	0%	0%	0%	0%	0%	0%	0%	14%	0%			85%
2012	Coef	0.0377	0.0945	0.0274	0.6657	0.7310	0.3621	0.1994	0.3545	0.9811	0.5262	0.5259	0.0008	-0.2351	0.0000	0.0000	0.0148	0.0098	0.0063	0.0060	0.0157	9.9466	0.83	367	0.52
	P > t	55%	17%	75%	0%	0%	2%	17%	0%	0%	1%	2%	88%	0%	0%	0%	0%	0%	0%	0%	17%	0%			59%

The table reflects Equation 4 estimated with the natural log of average value per acre of farmland economic outcome of interest for each census year. Grayed cells indicate that a variable was omitted due to collinearity. Grayed rows indicate that there were no observations in that year (data gaps). LCC stands for land capability class. The column marked “Wald Test” includes the F-stat and P-value for the test of equivalency among the coefficients for the percent share groups.

Table 7. Regression output with population per square mile as the economic outcome

Pop. / Sq. Mile		Share High	Share Med.	Share Low	CO	NE	KS	OK	TX	IA	WY	SD	Rain	Temp.	Long.	Lat.	LCC 1	LCC 2	LCC 3	LCC 4	LCC 5	Constant	R2	N	Wald Test - Shares Equal
1920	Coef	-11.216	-10.711	-4.714	1.720	1.910	-14.698	-12.274	-10.424	-11.278	3.385	-14.870	0.094	-1.890	0.000	0.000	0.061	0.213	0.128	0.081	-0.203	53.094	0.17	354	0.34
	P > t	8%	12%	59%	91%	92%	34%	41%	39%	61%	87%	50%	85%	50%	22%	54%	74%	2%	15%	54%	86%	41%			71.00%
1925	Coef																								
No Obs	P > t																								
1930	Coef	-12.079	-11.578	-3.914	2.261	3.037	-16.000	-10.696	-7.603	-12.009	4.199	-14.756	0.166	-1.746	0.000	0.000	0.066	0.252	0.159	0.086	-0.304	46.561	0.17	354	0.4
	P > t	11%	15%	70%	90%	89%	37%	53%	59%	64%	86%	57%	77%	59%	33%	60%	75%	2%	12%	58%	82%	54%			66.00%
1935	Coef																								
No Obs	P > t																								
1940	Coef	-12.901	-12.150	-3.480	0.508	2.080	-16.614	-12.730	-7.188	-13.010	2.519	-16.356	0.135	-2.106	0.000	0.000	0.040	0.249	0.147	0.098	-0.389	53.679	0.12	354	0.46
	P > t	11%	16%	75%	98%	93%	39%	49%	63%	64%	92%	55%	83%	55%	35%	59%	86%	3%	18%	55%	78%	51%			62.00%
1945	Coef																								
No Obs	P > t																								
1950	Coef	-14.167	-13.631	-4.279	2.486	4.212	-15.560	-14.513	-5.684	-14.552	5.233	-15.456	0.082	-2.571	0.000	0.000	0.047	0.273	0.156	0.098	-0.601	63.319	0.09	354	0.38
	P > t	13%	17%	73%	91%	87%	49%	50%	75%	65%	86%	63%	91%	53%	39%	54%	86%	4%	23%	61%	71%	50%			68.00%
1954	Coef																								
No Obs	P > t																								
1959	Coef	-18.470	-17.588	-5.019	5.604	8.658	-14.269	-16.655	-3.116	-18.200	8.061	-15.177	0.053	-3.561	0.000	0.000	0.064	0.309	0.172	0.107	-0.802	80.231	0.07	354	0.44
	P > t	12%	17%	75%	84%	80%	61%	54%	89%	65%	83%	71%	95%	49%	44%	49%	85%	6%	29%	66%	70%	50%			64%
1964	Coef																								
No Obs	P > t																								
1969	Coef	-21.652	-21.622	-6.860	10.109	10.685	-16.477	-16.967	-2.923	-27.517	8.157	-17.607	0.045	-5.475	0.000	0.000	0.001	0.373	0.193	0.102	-1.012	108.552	0.07	354	0.43
	P > t	11%	14%	71%	75%	78%	61%	58%	91%	55%	85%	71%	97%	35%	43%	41%	100%	5%	30%	71%	67%	42%			64%
1974	Coef	-23.674	-23.972	-7.934	12.792	12.045	-16.985	-16.638	-1.924	-30.322	7.628	-18.585	0.078	-6.243	0.000	0.000	-0.020	0.397	0.199	0.102	-1.116	117.691	0.07	354	0.44
	P > t	10%	12%	68%	70%	77%	62%	61%	94%	54%	87%	71%	94%	32%	45%	40%	96%	5%	31%	73%	66%	42%			64%
1978	Coef																								
No Obs	P > t																								
1982	Coef	-24.270	-24.918	-8.607	16.126	15.231	-14.650	-13.954	0.585	-27.314	9.523	-15.271	0.221	-6.407	0.000	0.000	0.002	0.398	0.194	0.108	-1.185	108.434	0.07	354	0.46
	P > t	9%	10%	65%	62%	71%	67%	67%	98%	58%	84%	76%	84%	30%	52%	37%	100%	5%	32%	71%	63%	45%			63%
1987	Coef	-26.400	-27.267	-9.143	20.603	19.160	-12.914	-11.724	2.581	-27.358	12.017	-12.976	0.234	-7.046	0.000	0.000	-0.007	0.413	0.193	0.099	-1.285	115.570	0.07	354	0.5
	P > t	8%	9%	65%	56%	65%	72%	74%	93%	60%	81%	80%	84%	28%	54%	34%	99%	5%	35%	75%	63%	45%			60%
1992	Coef	-27.57865	-28.84477	-10.56013	22.78212	20.1105	-12.97558	-13.27902	2.392413	-30.45134	11.62758	-12.88745	0.2950671	-7.642144	0.0000507	-0.0000673	-0.017179	0.4305721	0.1978529	0.0946532	-1.434822	119.9604	0.07	354	0.46
	P > t	8%	9%	62%	53%	65%	73%	71%	94%	57%	82%	81%	81%	26%	56%	33%	97%	5%	36%	77%	60%	45%			63%
1997	Coef	-29.309	-31.039	-11.774	26.185	22.240	-13.114	-12.982	3.365	-31.977	12.427	-12.084	0.301	-8.479	0.000	0.000	-0.014	0.462	0.210	0.099	-1.521	130.748	0.07	354	0.46
	P > t	7%	8%	59%	49%	63%	74%	73%	91%	57%	82%	83%	81%	24%	57%	31%	98%	5%	35%	77%	60%	43%			63%
2002	Coef																								
No Obs	P > t																								
2007	Coef	-34.101	-36.505	-14.025	30.568	22.651	-17.159	-14.440	3.776	-44.856	13.666	-17.384	0.181	-10.629	0.000	0.000	-0.028	0.543	0.236	0.096	-1.858	173.340	0.08	350	0.47
	P > t	7%	7%	58%	48%	67%	70%	74%	92%	49%	82%	79%	90%	20%	50%	29%	96%	4%	37%	81%	57%	37%			62%
2012	Coef	-37.285	-39.464	-15.123	33.071	24.710	-17.421	-14.213	4.945	-49.292	14.644	-19.050	0.140	-11.403	0.000	0.000	-0.032	0.554	0.239	0.086	-2.065	189.613	0.07	353	0.49
	P > t	6%	7%	58%	48%	67%	72%	76%	90%	48%	82%	79%	93%	20%	49%	28%	95%	5%	39%	84%	56%	35%			61%

The table reflects Equation 4 estimated with the population per square mile in a county as the economic outcome of interest for each census year. Grayed cells indicate that a variable was omitted due to collinearity. Grayed rows indicate that there were no observations in that year (data gaps). LCC stands for land capability class. The column marked “Wald Test” includes the F-stat and P-value for the test of equivalency among the coefficients for the percent share groups.

Table 8. Percentage increase in land values over time by saturated thickness

	Coefficient			Percent Interpretation		
Year	**High**	**Med**	**Low**	**High**	**Medium**	**Low**
1950	0.204	0.201	0.243	22.6%	22.3%	27.5%
1954	0.2748	0.2699	0.2427	31.6%	31.0%	27.5%
1959	0.3016	0.2707	0.2905	35.2%	31.1%	33.7%
1964	0.3571	0.3107	0.3783	42.9%	36.4%	46.0%
1969	0.3415	0.2612	0.2583	40.7%	29.8%	29.5%
1974	0.3477	0.2522	0.2465	41.6%	28.7%	28.0%
1978	0.2116	0.1603	0.1787	23.6%	17.4%	19.6%
1982	0.2208	0.1509		24.7%	16.3%	
1987	0.1351			14.5%		
1992	0.171			18.7%		
1997	0.1546			16.7%		
2002						
2007						
2012						

The three columns on the right side of the table reflect the percentage increase in land values that can be interpreted from the coefficients in Table 5, transformed as: $(e^{\beta} - 1)$. This is necessary as our dependent value was the natural log of the average value of land and buildings per acre in 2002. Omitted years and blank cells reflect coefficients that are not statistically significant at the 5-percent level.

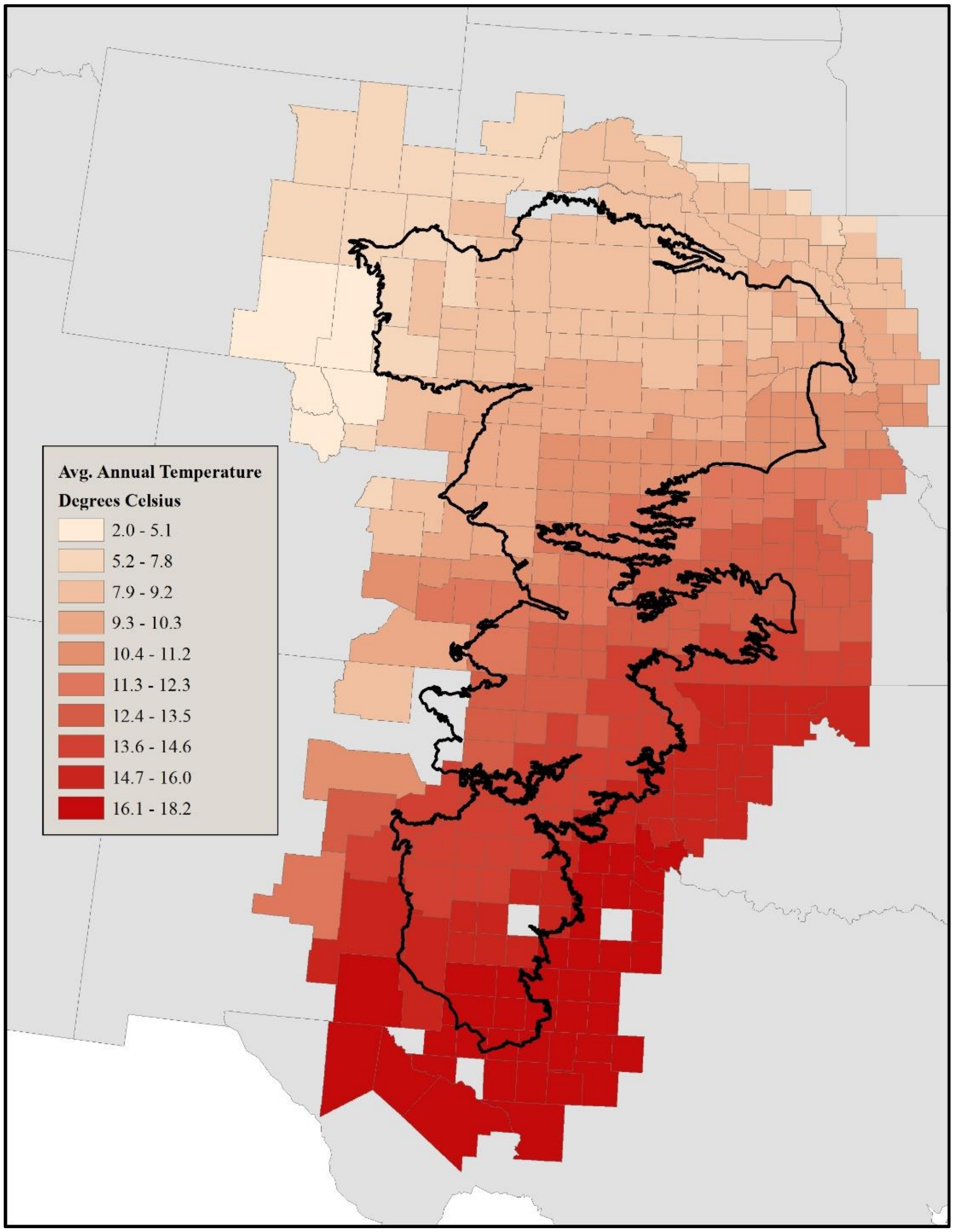

Figure 1. Average annual temperature in the High Plains

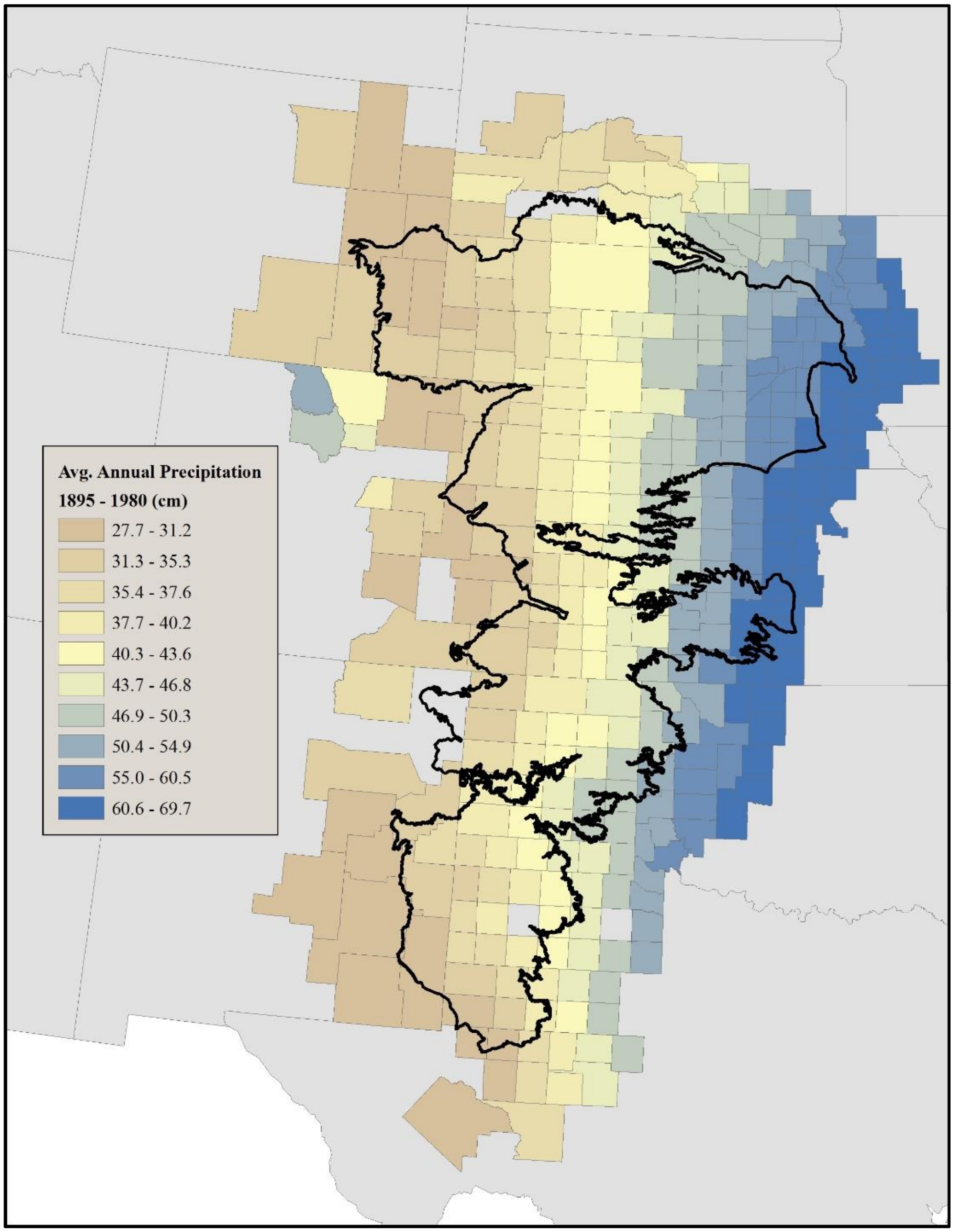

Figure 2. Average annual precipitation in the High Plains

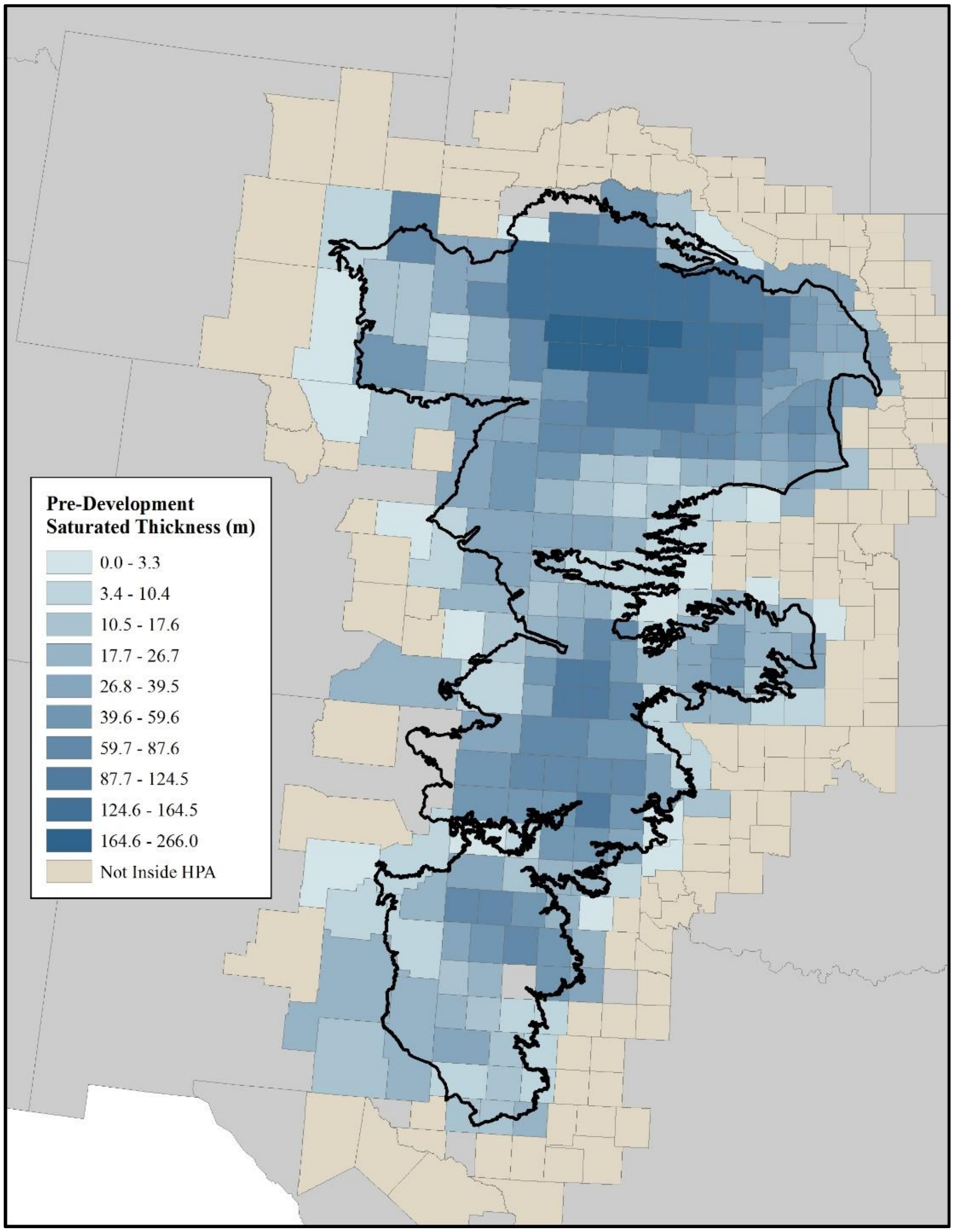

Figure 3. Pre-development (1935) saturated thickness in the High Plains Aquifer

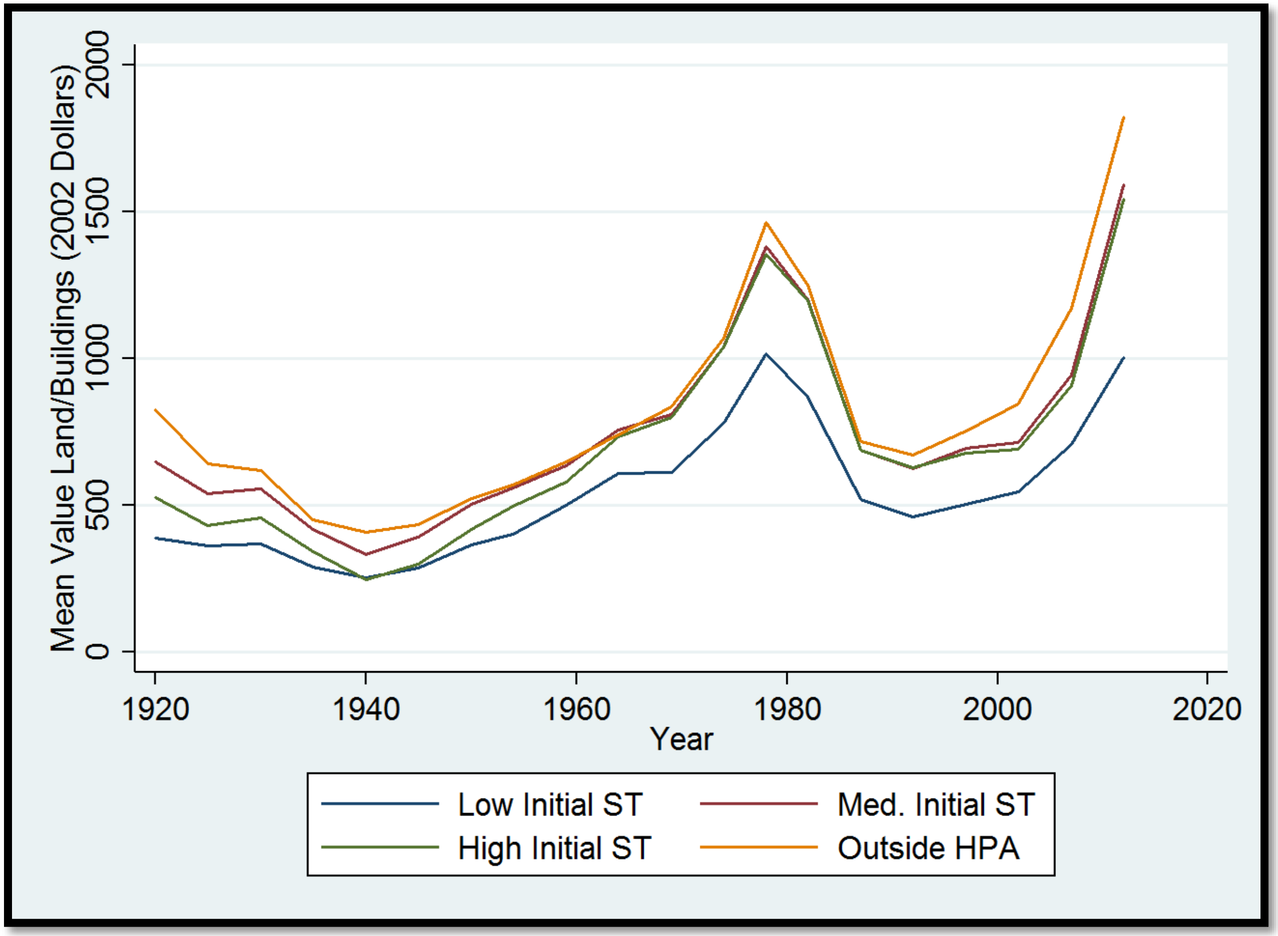

Figure 4. Average land values over time according to initial saturated thickness groups

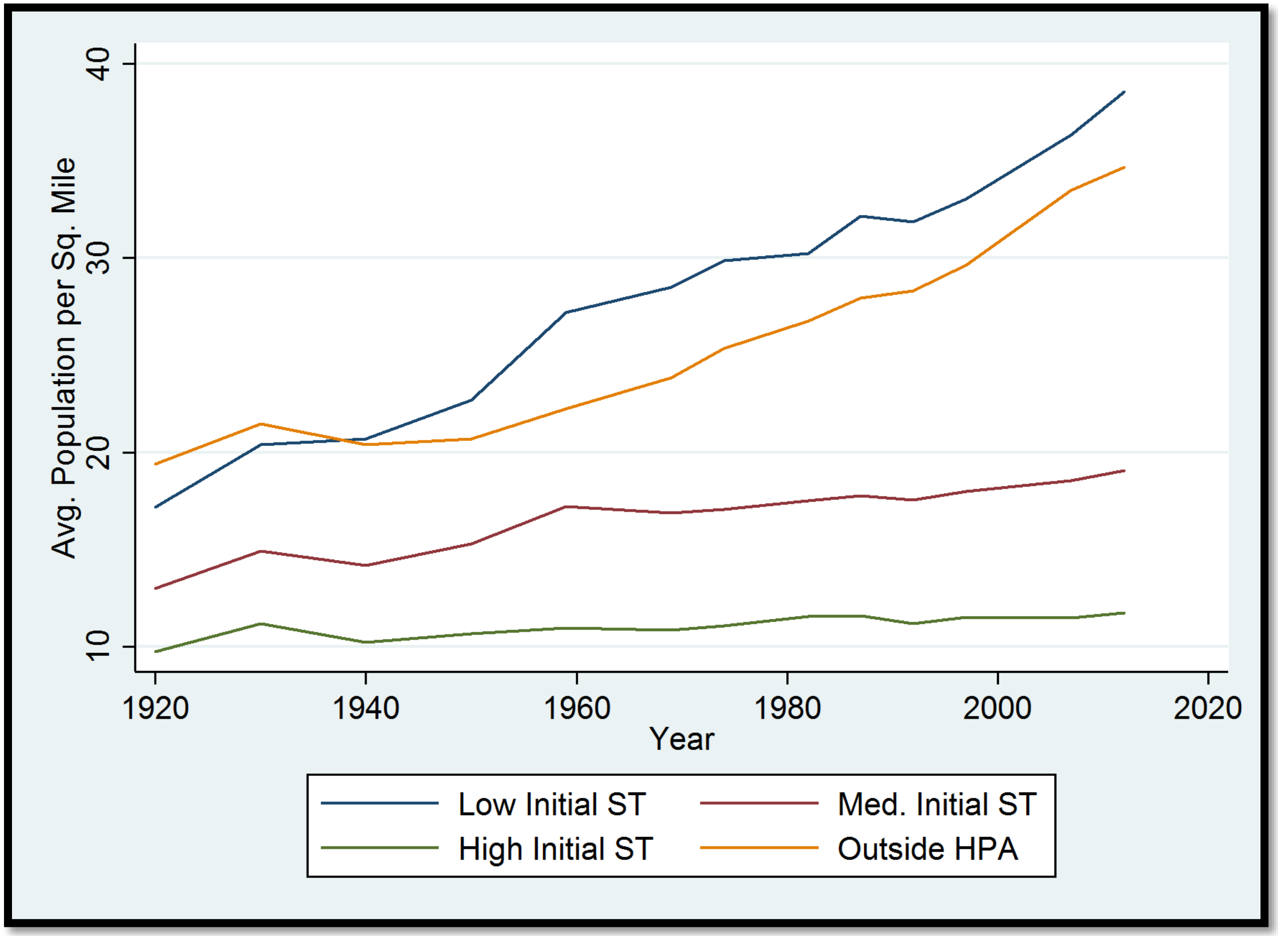

Figure 5. Population density over time according to initial saturated thickness groups

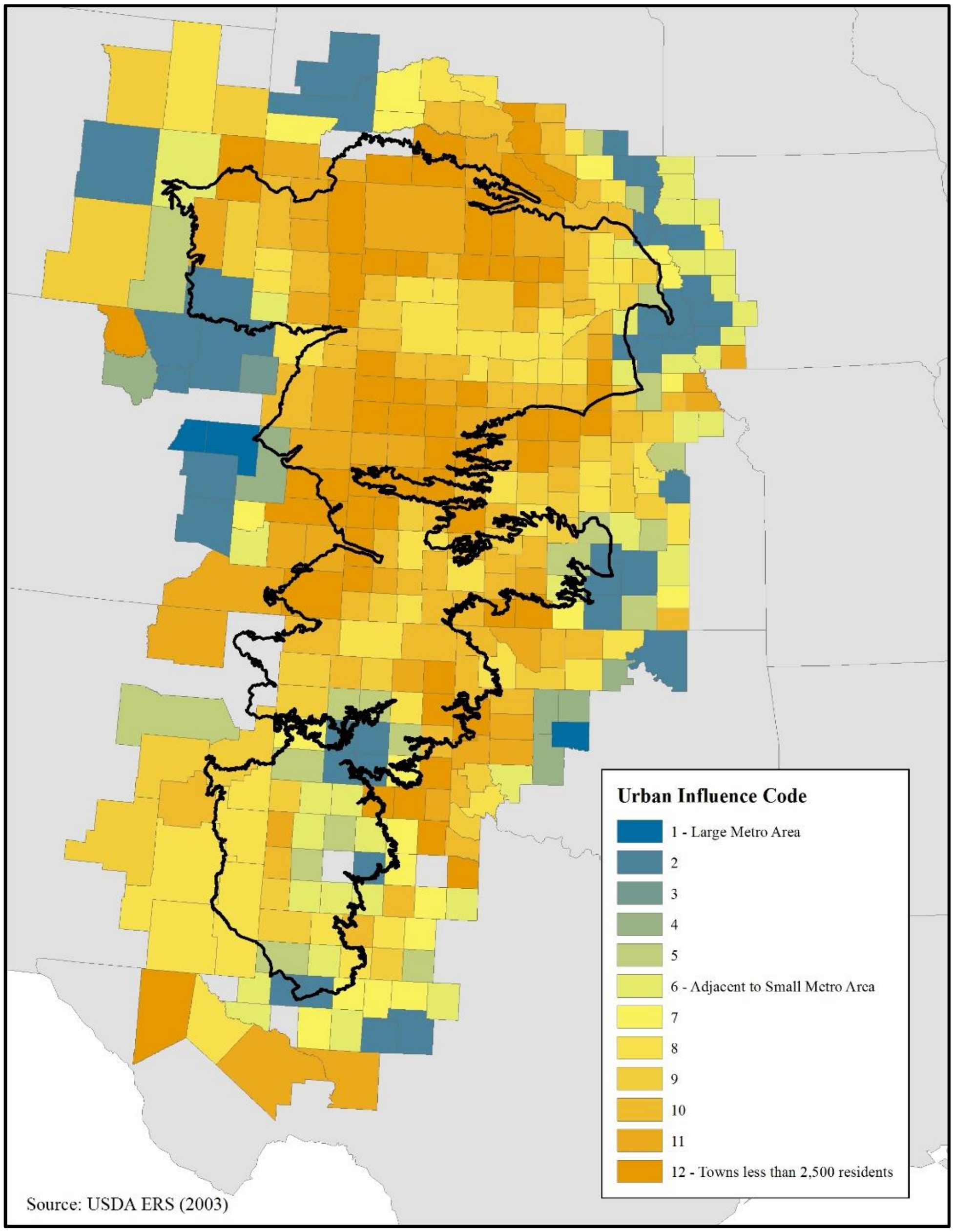

Figure 6. Urban Influence Codes as of 2003

Class 1: 3 Counties
Class 2: 41 Counties
Class 3: 1 Counties
Class 4: 6 Counties
Class 5: 19 Counties
Class 6: 36 Counties
Class 7: 21 Counties
Class 8: 49 Counties
Class 9: 35 Counties
Class 10: 61 Counties
Class 11: 36 Counties
Class 12: 60 Counties

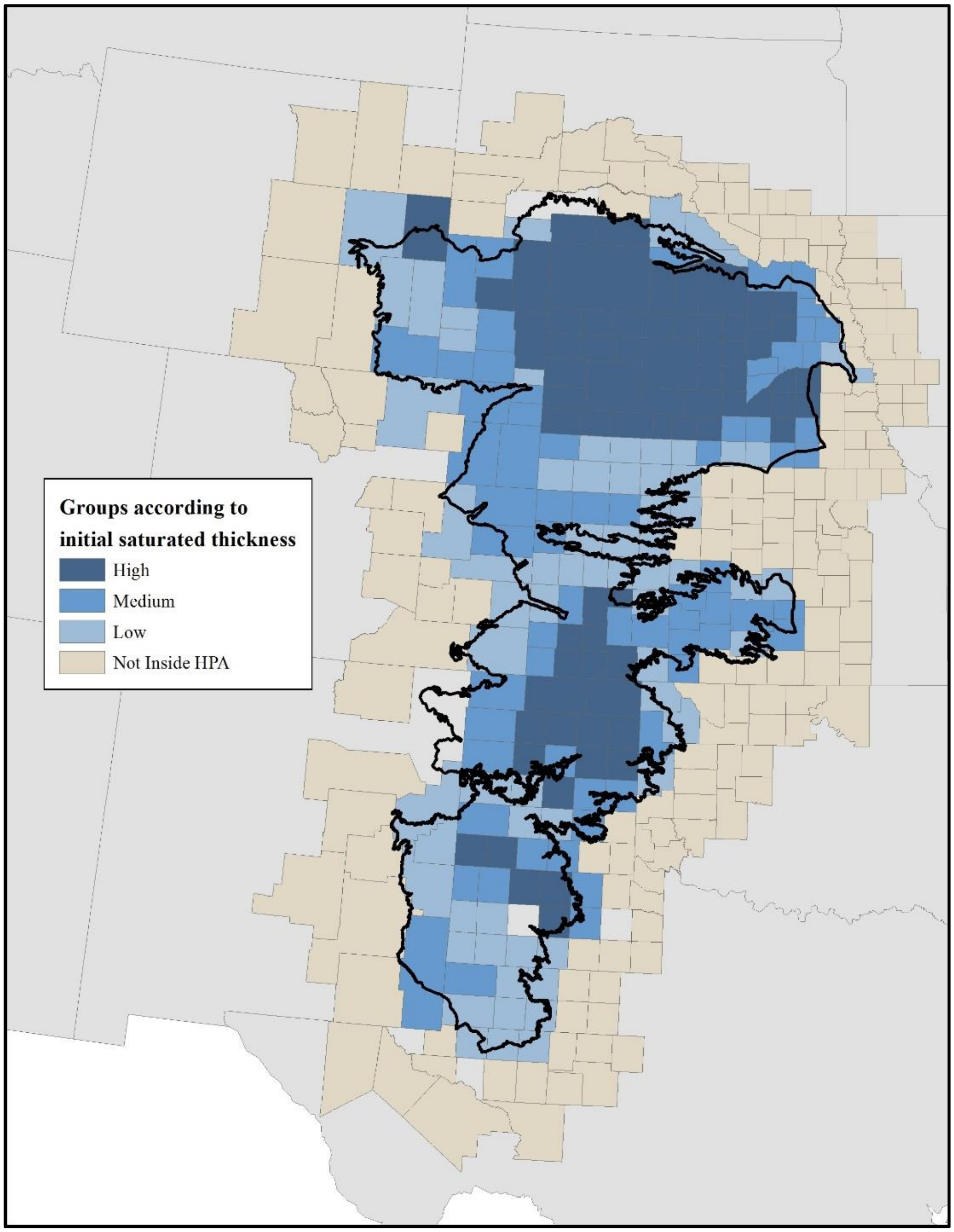

Figure 7. Counties grouped according to initial saturated thickness

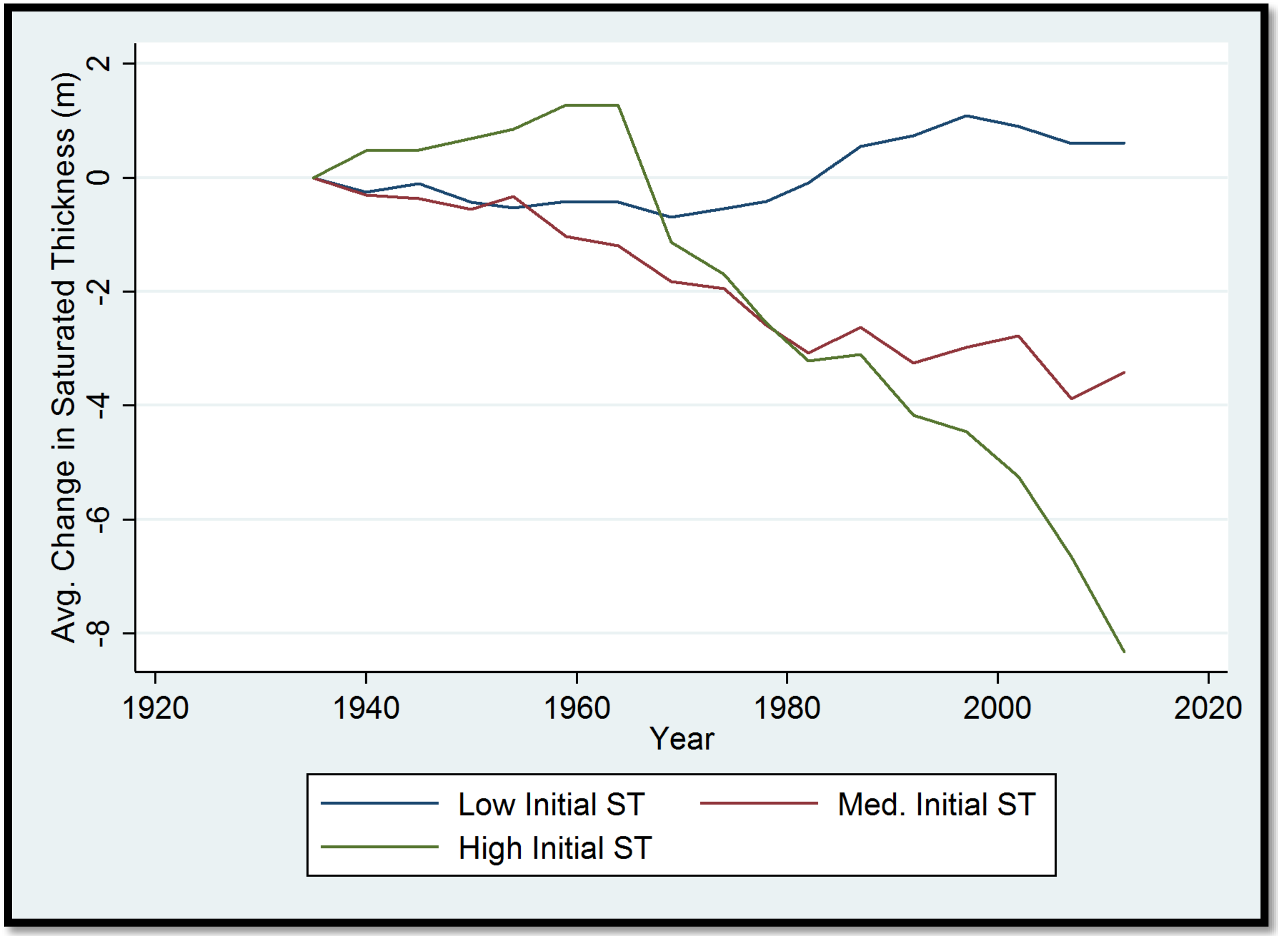

Figure 8. Average change in saturated thickness according to initial saturated thickness groups

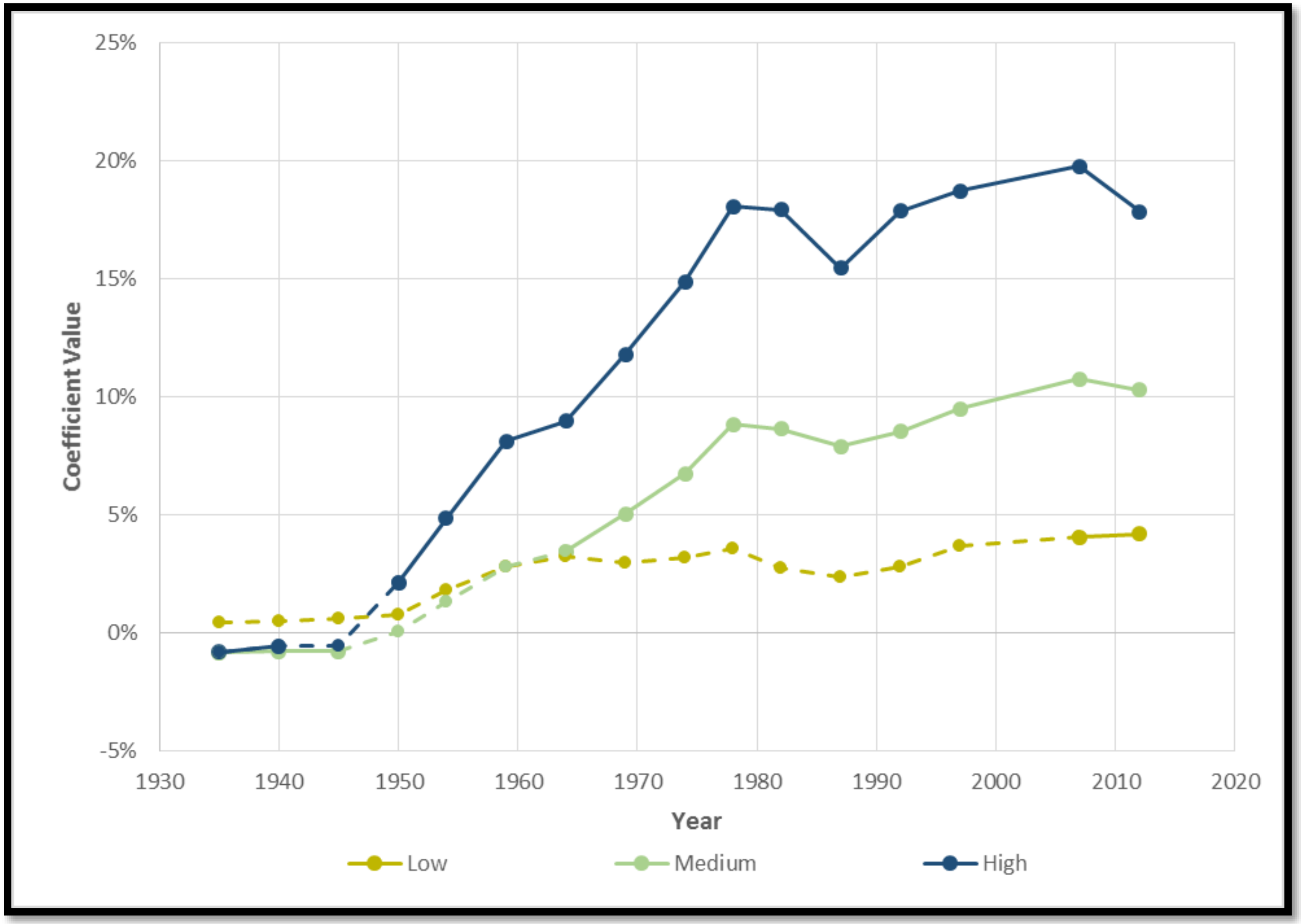

Figure 9. Coefficient values for High, Medium, and Low groups from Table 2 (Percent Irrigated)

Dashed lines represent coefficients which are not significant at the 5-percent level.

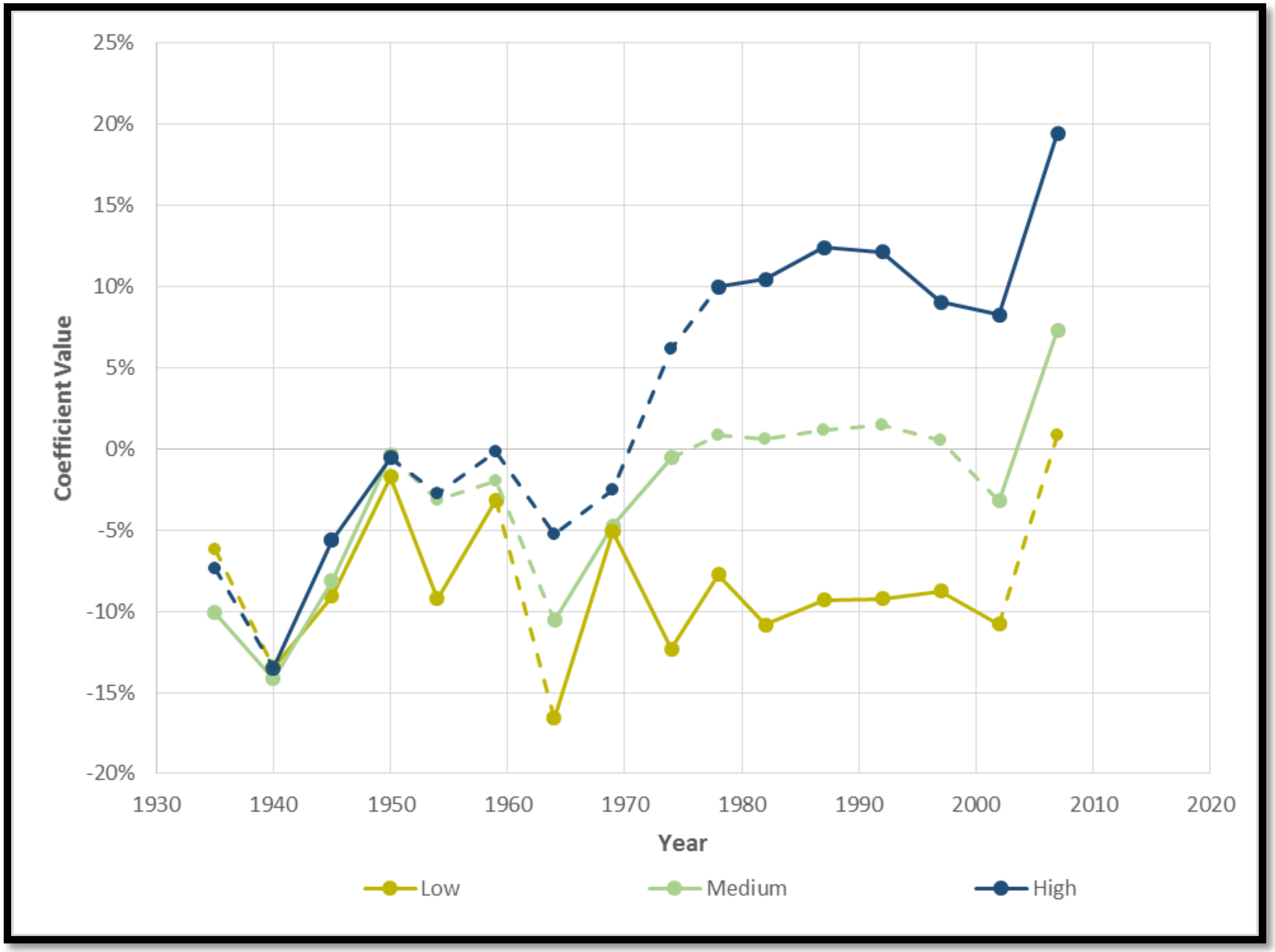

Figure 10. Coefficient values for High, Medium, and Low groups from Table 3 (Percent Irrigated Wheat)

Dashed lines represent coefficients which are not significant at the 5-percent level.

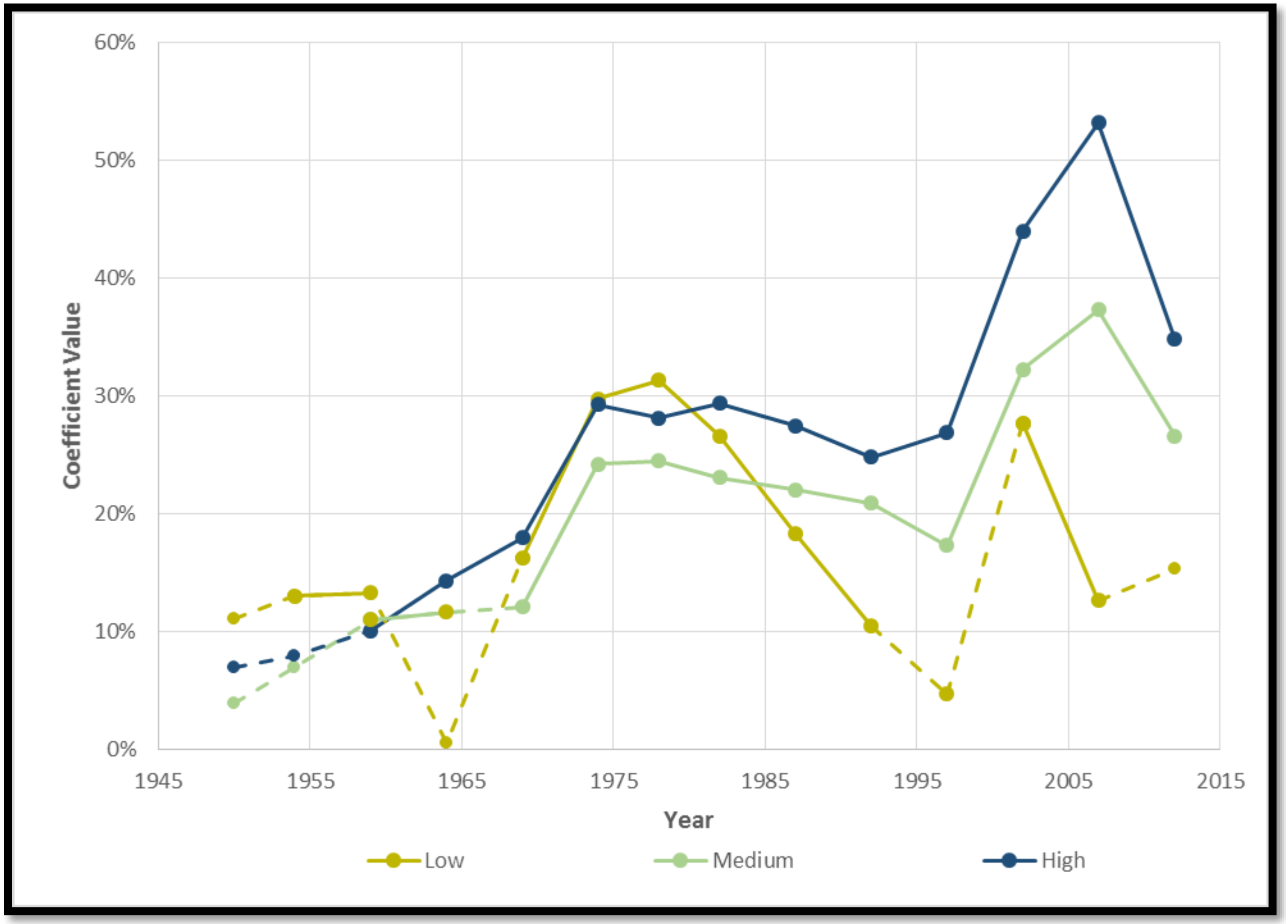

Figure 11. Coefficient values for High, Medium, and Low groups from Table 4 (Percent Irrigated Corn)

Dashed lines represent coefficients which are not significant at the 5-percent level.

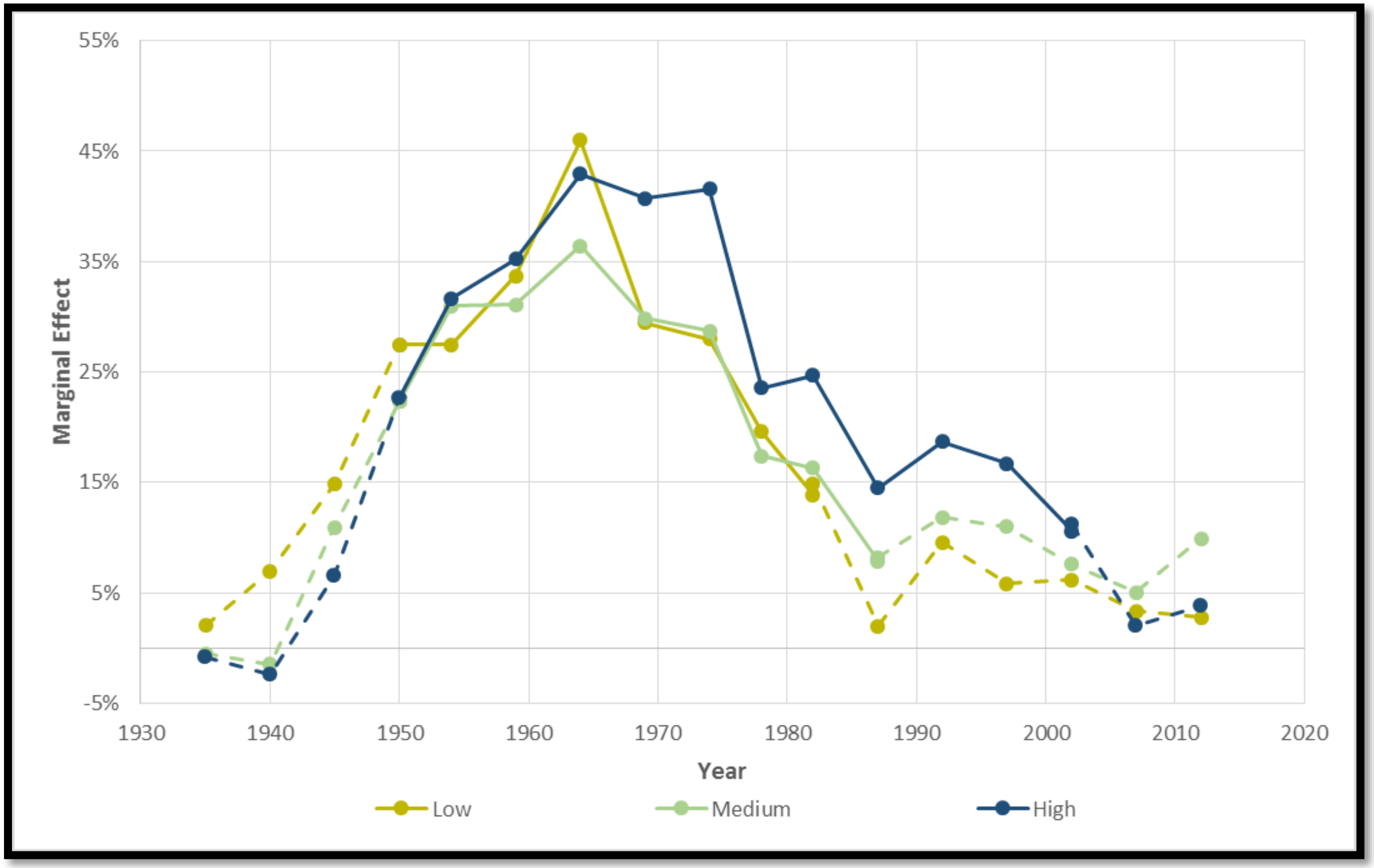

Figure 12. Coefficient values for High, Medium, and Low groups from Table 5 (Natural Log of Land Value)

Dashed lines represent coefficients which are not significant at the 5-percent level.

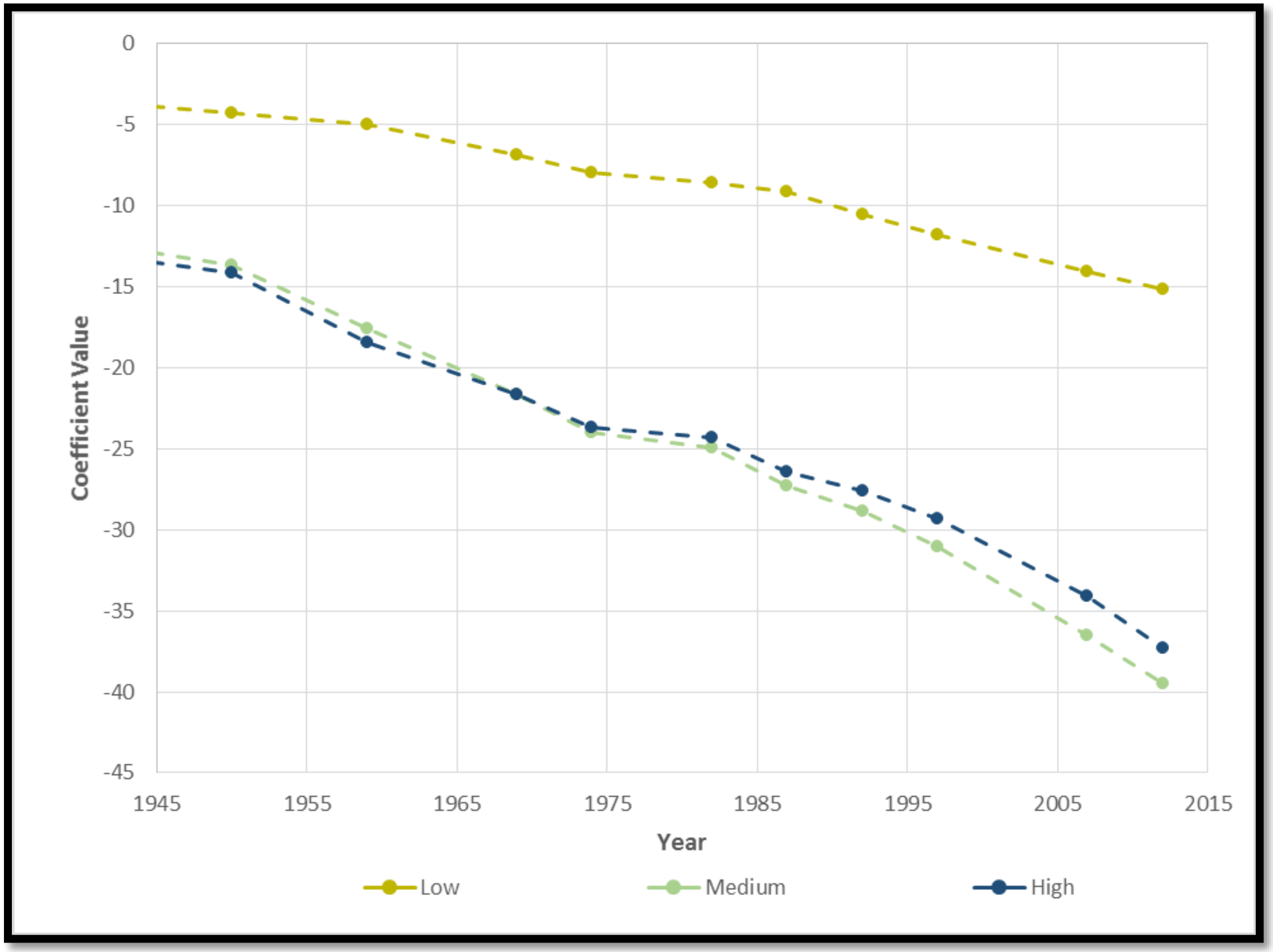

Figure 13. Coefficient values for High, Medium, and Low groups from Table 6 (Population per Square Mile)

Dashed lines represent coefficients which are not significant at the 5-percent level.

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