Farming the Ogallala Aquifer: Short and Long-run Impacts of Groundwater Access

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September 2010

Preliminary and Incomplete

Abstract

Following World War II, central pivot irrigation technology and decreased pumping costs made groundwater from the Ogallala aquifer available for large-scale irrigated agricultural production on the Great Plains. Comparing counties over the Ogallala with nearby similar counties, empirical estimates quantify the short-run and long-run impacts on irrigation, crop choice, and other agricultural adjustments. From the 1950 to the 1978, irrigation increased and agricultural production adjusted toward water-intensive crops with some delay. Estimated differences in land values capitalize the Ogallala's value at $10 billion in 1950, $29 billion in 1974, and $12 billion in 2002 (CPI-adjusted 2002 dollars). The Ogallala is becoming exhausted in some areas, with potential large returns from changing its current tax treatment. The Ogallala case provides a stark example for other water-scarce settings in which such long-run historical perspective is unavailable.

Water scarcity is a critical issue in many areas of the world.[1] Water is becoming increasingly scarce as the demand for water increases and groundwater sources are exhausted. In some areas, climate change is expected to reduce rainfall and increase dependence on groundwater irrigation. The impacts of water shortages are often exacerbated by the unequal or inefficient allocation of water.

The economic value of water for agricultural production is an important component in understanding the optimal management of scarce water resources. Further, as the availability of water changes, little is known about the speed and magnitude of agricultural adjustment. The short-run and long-run economic value of water depends on farmers' adjustments and, in particular, the magnitude of externalities created.

This paper analyzes the economic impacts of the Ogallala aquifer on the Great Plains. Following World War II, groundwater from the Ogallala became available for large-scale agricultural production due to the introduction of center pivot irrigation technology and decreased pumping costs.

The main empirical specifications compare counties over the Ogallala in each year with nearby counties in the same state and soil group, controlling for longitude and latitude. The aquifer has irregular boundaries that cut across natural vegetation regions. Ogallala counties and non-Ogallala counties had similar characteristics in 1920, lending support to the identification assumption that Ogallala counties would otherwise have been similar to non-Ogallala counties.

Irrigated farmland increased substantially from 1950 to 1978 in Ogallala counties, both absolutely and relative to non-Ogallala counties. In that later period, from 1964 to 1978, Ogallala farmers adjusted to more water-intensive crops. Irrigation and water-intensive crop acreages have remained at these higher levels, generating far greater revenue in Ogallala counties than in non-Ogallala counties. Withdrawal of water quickly surpassed the aquifer's very slow rate of natural recharge and, as a result, water levels have declined.

[1] Prominent examples include the Western United States (Hansen, Libecap, and Lowe 2009), India (Keskin 2009), Lebanon, and many other countries.

Land values increased immediately in Ogallala counties, relative to non-Ogallala counties. This difference in land values peaked in the 1960's, capitalizing the production gains from groundwater access at $29 billion (in CPI-adjusted 2002 dollars). The estimated production gains have since declined to $12 billion in 2002, appearing to reflect the unsustainable use of Ogallala groundwater. Indeed, some original Ogallala counties have begun to lose groundwater access.

Water-use management has been minimal. Remarkably, since a legal decision in 1965, federal tax code has been interpreted to allow farmers depreciation allowances for the value of Ogallala water extracted. In this sense, federal tax policy is magnifying the externalities associated with private extraction of this common pool resource. Given the large estimated value of Ogallala groundwater, there are large potential efficiency gains from policy reform.

The historical experience of the Ogallala aquifer illustrates a variety of economic impacts of water on agricultural production. Groundwater is a valuable resource, and it is often used inefficiently due to externalities and public policies. Agricultural production decisions can be quite persistent and respond slowly to changes in water availability, but there are large potential gains from improvements in the management of total water-use and its allocation.

I Background on the Ogallala Aquifer

The Ogallala aquifer is one of the world's largest underground freshwater sources, formed by ancient runoff from the Rocky Mountains and trapped amidst accumulated sand, gravel, clay, and silt (Zwingle 1993; Opie, 2003). The Ogallala is a closed basin, essentially a nonrenewable resource, that receives less than an inch of freshwater recharge annually due to minimal rainfall, high evaporation, and low infiltration of surface water (High Plains Associates, 1982).[2]

The Ogallala aquifer stretches beneath 174,000 square miles of the Great Plains from Western Texas to South Dakota. There is substantial heterogeneity in the aquifer's characteristics

[2] Plans for artificial recharge have been considered but found to be infeasible. For example, the 1968 Texas Water Plan sought to divert 5.8 million acre-feet of water from the Mississippi River. The Army Corps of Engineers found that it would require 50 billion kilowatts of electricity annually to support the water transfer ($5 billion in 2010) and Texas abandoned the plan (Opie 1993).

due to topographic features in the Tertiary Period that have long since been obscured on the surface. By construction, pre-1940's underground water volume is mainly determined by whether an area is located over an ancient valley or hill.

Local irrigation potential from the Ogallala is determined by three main characteristics that vary considerably across the aquifer: (1) depth of water (distance between the ground surface and the surface of the aquifer); (2) saturated thickness (distance from surface of the aquifer to the Triassic clay bottom of the aquifer); (3) specific yield (amount of water that can be extracted from a unit volume of saturated ground).

The aquifer characteristics have important economic implications for water-use. Pumping costs increase with the depth of water. The total available water for irrigation increases in the saturated thickness and specific yield. The specific yield, and the related porosity of soil, affect the speed of underground water flow, which determines how quickly a local area refills with nearby water and the degree of externality in water withdrawal.[3]

The Ogallala formation was first discovered in the 1890's and was initially used for limited agricultural purposes. There was great demand for water in the region once known as the "Great American Desert," but available windmill technologies were limited in effectiveness. Farmers could only reach water within 30 feet of the surface, and even then only obtain "subsistence" amounts of water: enough to irrigate approximately 5 acres or provide for 30 cattle (Cunfer 2005).

After World War II, several important technological developments combined to make large-scale irrigation possible with Ogallala groundwater. New low-cost automobile engines were adapted to power new oil pumps, lifting the groundwater cheaply and in large volumes. Center pivot irrigation systems were developed, which used water more efficiently than previous flood irrigation methods and enabled irrigation of hilly parts of fields (Opie 1993).

Ogallala groundwater became increasingly used for irrigation and, as pump and irrigation

[3] Ogallala water quality is sufficient for irrigation purposes, though in a small number of counties the water does not meet EPA drinking water standards with respect to salinity, chloride, or sulfates (Guru and Horne 2000).

equipment became more powerful, farmers' withdrawals quickly surpassed the aquifer's natural recharge rate.[4] In an early analysis of the region, the United States Geological Service (USGS) estimated that yearly groundwater withdrawals quintupled between 1949 and 1974. In some areas, water tables have declined by 100 feet from predevelopment levels to 2000 (Little 2009).

Appendix Figure 1 illustrates the visible impacts of Ogallala groundwater on agriculture: center pivot irrigation creates distinctive circular land patterns nested within the traditional square land allotments. The impact of groundwater on land values is less clear, however.[5] Agricultural production has presumably adjusted, but the magnitude and speed of adjustment along different dimensions is unclear. Water table declines have begun to make groundwater unavailable for irrigation, which will have unknown short-run and long-run impacts on local economic outcomes.

The Ogallala aquifer represents a classic "common pool" problem, in which individual water users do not pay the social cost of water extraction. There was no initial management of water-use; in fact, tax policy has subsidized Ogallala water-use since 1965. The US Court of Appeals found in 1965 that Ogallala farmers were entitled to depreciation allowances for the value of Ogallala water that they extracted.[6]

There remains no unified strict management of Ogallala water-use. In the last two decades, a variety of state water laws and groundwater management districts have been adopted in the region. Regulations generally prevent "wastage" of water, but the threshold is effectively zero.[7] Rules and laws vary significantly by state and by district. Kansas, New Mexico, and Colorado enforce restrictions on new well spacing. Texas fines users who lose water due to

[4] O'Brien et al. (2001) reviews economic studies on the determinants of Ogallala irrigation technology adoption, which mainly develop and parameterize models of farmers' adoption incentives. Recently, Peterson and Ding (2005) construct a programming model to compare irrigation systems with varying efficiency levels, taking account of important components of crop productivity such as irrigation timing and production risk.

[5] Torrell et al. (1990) compare the market value of irrigated and non-irrigated farms in the Ogallala region, though irrigation decisions may be correlated with unobserved land and farm characteristics.

[6] The legal decision is available here: http://bulk.resource.org/courts.gov/c/F2/347/347.F2d.103.20972.html A 2009 description of this policy is here: http://taxmap.ntis.gov/taxmap/pubs/p225-034.htm

[7] Controversially, oil companies will sometimes use vast amounts of water to push small remaining portions of oil from the ground.

equipment malfunctioning (Peterson et al. 2003).

II Data Construction and County Characteristics by Ogallala Share

County-level data are drawn from the US Censuses of Agriculture (Gutmann 2005; Haines 2005), and the main variables of interest include: the value and acreage of agricultural land, acres of irrigated agricultural land, agricultural revenue, total cropland harvested, and crop-specific harvested acreages and production. The empirical analysis focuses on a balanced panel of 368 Plains counties from 1920 to 2002, for which data on the main variables are available in every period of analysis.[8] To account for county border changes, census data are adjusted in later periods to maintain the 1920 county definitions (Hornbeck 2010).

Figure 1 shows the 1920 county borders overlaid with a map of the Ogallala aquifer (USGS).[9] The shaded area represents the USGS's estimated original boundary of the aquifer, prior to intensive use for agriculture. The sample is restricted to counties within 100 kilometers of the aquifer.

Appendix Figure 2 displays major soil groups in the sample region (SCS 1951). To account for regional differences in soil and climate characteristics, state agricultural extension services, and other state-level policies, the empirical specifications control for soil group and state fixed effects (interacted with year). Thus, the empirical analysis focuses on comparisons between Ogallala and non-Ogallala counties within the same state and major soil group.

Table 1, column 1, reports average sample county characteristics in 1920 (or the earliest year available) and prior to intensive agricultural use of the Ogallala. Columns 2 to 5 report estimated differences correlated with the fraction of county area over the Ogallala: column 2 reports basic differences between Ogallala and non-Ogallala counties; column 3 adds state fixed effects; column 4 adds soil group fixed effects; and column 5 adds linear controls for

[8] The 1920 base year reflects a tradeoff between a larger sample size (later base year) and a longer time horizon (earlier base year). Data for fewer counties are available in all years for some crop-specific acreages and production, so the sample size is lower in those specifications.

[9] The United States Geological Service (USGS) provides detailed geographic (GIS) data on the Ogallala aquifer boundaries and characteristics, as well as a set of unique water levels information from selected wells in each state measured annually by numerous Federal, State, and local water-resources agencies dating back to 1930's. These data far surpass the available groundwater data in most other countries and time periods.

the X-coordinate and Y-coordinate of the county centroid.[10]

After controlling for state and soil group fixed effects, there are no substantial or statistically significant differences between Ogallala and non-Ogallala counties in 1920. This lends support to the identification assumption that Ogallala and non-Ogallala counties would have been similar in later years, if not for the availability of the Ogallala.

However, for several possible reasons, Ogallala and non-Ogallala counties are not similar for all characteristics in all periods prior to the increased availability of Ogallala groundwater. First, and of most concern for the empirical analysis, the Ogallala region may have different natural features that affect agricultural production. Appendix Figure 3 shows the Ogallala boundary and a 1924 map of natural vegetation regions (USDA 1924). The Ogallala water table is generally too deep to be accessed by plants or trees, and the Ogallala boundary mainly cuts across the two largest vegetation regions ("Short Grass" and "Tall Grass") and larger river beds ("Oak-Hickory"). However, the Ogallala boundary is more correlated with differences in vegetation region around the southern tip and northwest sections. Thus, it is important that the empirical specifications focus on variation within soil groups (Appendix Figure 1) that capture finer regional groupings than the mapped vegetation regions.

Second, Ogallala and non-Ogallala counties may happen to experience different drought severity or other shocks in particular years. The Great Plains experienced very severe droughts in the 1930's, in which there was massive crop failure and agricultural disruption. Even small differences in drought intensity and its effects could generate large relative effects on agricultural outcomes.[11] Future work will explore controlling for drought, as well as examine the interaction between drought and the Ogallala's impact.

Third, agricultural outcomes could be affected by the Ogallala prior to the 1950's. Ogallala

[10] The means and regressions are weighted by county acres, as the empirical analysis is focused on changes for an average acre of land.

[11] The 1930's Dust Bowl had large short-run and long-run effects (Hornbeck 2009), but controlling for post-Dust Bowl erosion levels has little effect on the results. The Ogallala region is not correlated with erosion levels after narrowing the sample and controlling for state, soil region, longitude, and latitude. Soil regions are measured after the Dust Bowl and partly capture its effects, so for simplicity the Dust Bowl erosion measures are omitted from the main specification.

groundwater was partly available to farmers on a limited scale through the use of early pumps, windmills, and irrigation techniques. In addition, farmers and land speculators would be influenced by expectations over the future availability of the Ogallala. In particular, Ogallala land values might be higher to the extent that pumping and irrigation technological improvements were expected. Settlement, land improvement, and investments might precede the widespread availability of the Ogallala, either due to forward-looking rational behavior or over-optimism. Thus, the empirical analysis does not control for pre-1950's differences in county characteristics because they may be outcomes of the Ogallala.

III Changes in County Characteristics by Ogallala Share

Figure 2 shows aggregate trends in the region, and previews some of the empirical results by plotting average county outcomes over time within two groups of sample counties: those less than 10% over the Ogallala and those more than 90% over the Ogallala.[12]

Ogallala and non-Ogallala counties had similar low levels of irrigated farmland in 1935, before Ogallala counties experienced a gradual increase to 15% of county area by the 1970's (Figure 2a). Total farmland generally increased through the 1930's and Ogallala counties became relatively more settled; this difference persisted and widened as farmland declined less in Ogallala counties during the 1960's and 1970's (Figure 2b).

The value of agricultural land and farm buildings per county acre was lower or similar in Ogallala counties through the 1940's, and after 1950 became greater than in non-Ogallala counties (Figure 2c). Total agricultural revenue initially was lower or similar in Ogallala counties, with a large aggregate drop in the 1930's hitting Ogallala counties slightly more heavily (Figure 2d). Revenue recovered in the 1940's, increased moderately into the 1960's, and then Ogallala counties experienced particularly large relative revenue increases in the 1970's.

Similar to the pattern for revenue, there were initially fewer acres of corn harvested in

[12] Averages for the in-between group of counties generally fall within the averages for these two groups, but are omitted from the figure for increased clarity.

Ogallala counties, with a clear aggregate drop during the 1930's drought and subsequent recovery in the 1940's (Figure 2e). After the 1960's, Ogallala counties experienced a large relative increase in harvested corn acreages. By contrast, wheat acreages were initially higher in Ogallala counties and partially converged to non-Ogallala county levels after the 1960's (Figure 2f).

The aggregate comparisons in Figure 2 do not take advantage of the available finer geographic variation. Figure 3 maps the fraction of county land irrigated in 1935 (Figure 3a) and 1974 (Figure 3b). Irrigation levels are low everywhere in 1935, aside from a few areas with major rivers (see Appendix Figure 2). By 1974, irrigation levels had increased substantially throughout the Ogallala region, both in absolute terms and relative to nearby non-Ogallala counties.

Figures 4a and 4b map county land values in 1920 and 1964, shaded to reflect the county's quintile in each year. In contrast to 1920, land values in 1964 are systematically higher in Ogallala counties than in nearby non-Ogallala counties. Figures 4c and 4d map county farm revenues, which show Ogallala region effects similar to those for land values.

IV Empirical Framework

The empirical analysis is based on comparing counties over the Ogallala with nearby counties that might have otherwise been similar on average. In the main empirical specifications, outcome Y_c in county c is regressed on the fraction of the county's area over the Ogallala, state fixed effects α_s, soil group fixed effects γ_g, and the longitude and latitude of the county center.[13] The effect of the Ogallala is assumed to be uniform across the sample region. These cross-sectional specifications are pooled across all time periods, with each coefficient allowed

[13] In practice, "longitude" and "latitude" are represented by the X and Y coordinates of the county centroid from an equal area map projection of the US. These coordinates reflect exact distances East-West and North-South, rather than exact longitude and latitude degrees whose physical distance varies slightly over the sample area.

to vary in each time period:

$$Y_{ct} = \beta_t OgallalaShare_c + \alpha_{st} + \gamma_{gt} + \theta_t^x Longitude_c + \theta_t^y Latitude_c + \epsilon_{ct} \quad (1)$$

The sample is balanced in each regression, such that every county included has data in every analyzed period. The regressions are weighted by county size to estimate the average effect for an acre of land. Standard errors are clustered at the county level to adjust for heteroskedasticity and within-county correlation over time.

For each time period, the estimated β reports the cross-sectional difference between counties over the Ogallala and not over the Ogallala.[14] Interpreting this estimate as the impact of the Ogallala requires the identification assumption that all counties in the sample region would have had the same average outcome value if not for the Ogallala. In practice, this assumption must hold after controlling for other differences correlated with state, soil group, longitude, and latitude. Thus, the empirical research design exploits the sharp spatial discontinuity created by the irregular borders of the Ogallala.

Year-to-year changes in the estimated β's report the change for an Ogallala county relative to a non-Ogallala county over that time period. Differencing the estimated coefficients is numerically equivalent to estimating equation (1) with county fixed effects. The standard error of the difference is generally 20-40% lower than the standard error of the cross-sectional coefficients due to positive serial correlation in county-level outcomes. Interpreting the change in β as the changing impact of the Ogallala requires an analogous identification assumption: that sample counties would have changed the same on average if not for the changing impact of the Ogallala.

Our interpretation of the results emphasizes the cross-sectional estimates because knowledge of the Ogallala and technological advances came about gradually. For estimated changes

[14] Some counties are partly over the Ogallala, and this specification assumes that the effect of the Ogallala is linear in the share of the county over the Ogallala. The effect appears to be approximately linear, from graphing county residual changes in irrigated farmland against county residual Ogallala shares, after absorbing state-level means of both variables.

in land values, in particular, panel estimates are difficult to interpret due to unknown changes in expectations. However, the cross-sectional estimates are subject to bias from omitted variables at the county level. When farming practices are substantially different in Ogallala counties prior to 1950 (e.g., farmland, cropland, revenue, crop acreages), the implied panel estimates may be a more reliable indication of the Ogallala's effect. The panel estimates also highlight the speed of agricultural adjustment to changes in the availability of Ogallala groundwater.[15]

V Results

V.A Irrigated Farmland and Land Values

The expected primary effect of the Ogallala aquifer is to increase the amount of irrigated farmland. Table 2, column 1, reports the estimated effect of the Ogallala in each year on irrigated farmland. In 1935, irrigation levels were a statistically insignificant 0.5 percentage points lower in Ogallala counties.[16] By 1950, the irrigated fraction of county land had become 1.5 percentage points higher in Ogallala counties than in non-Ogallala counties. By 1978, this difference had risen to 12 percentage points. The 30 year increase in irrigation levels may reflect improvements in pumping and irrigation technology, changes in the marginal return to water, or a typical "s-curve" in technological adoption. Irrigation levels then remained similar through the 1990's.

The main expected secondary effect of the Ogallala aquifer is to increase the value of agricultural land. In each period, the cross-sectional difference in land values should reflect the expected present discounted value of production rents from the Ogallala aquifer. Prior to its widespread availability, land value differences include small contemporaneous improvements in production and some expectation of large future gains. After Ogallala groundwater be-

[15]A concern with the empirical analysis is the potential for spillover effects of Ogallala water on non-Ogallala counties. The estimated changes in agricultural output appear insufficiently large to affect agricultural prices of goods in non-Ogallala counties, when trade often takes place at the national or global level. The water itself is not transferred in large quantities from Ogallala to non-Ogallala counties for agricultural use, though the short-term availability of some production factors (labor, capital) could be affected. We expect that effects on local wages or capital rental prices would be small in the long-run.

[16]Note that coefficients for the first year (1935) are the coefficients reported in column 5 of Table 1.

comes available, land value differences should immediately reflect the full future production gains even if farming practices adjust more slowly. Once the Ogallala's future sustainability becomes in doubt, land values should partly decrease to reflect future more-limited dryland farming.[17]

Prior to 1950, column 2 of Table 2 reports mixed results on the difference in land values between Ogallala and non-Ogallala counties. Ogallala land values were similar in 1920 and 1925, relatively higher in 1930, and then fluctuated through the 1930's drought and recovery.

In the 1950's, after the introduction of new pumping and irrigation technologies, Ogallala county land values became consistently higher than non-Ogallala land values by 30 to 39 log points (35 to 48 percent). Land value differences peaked in the 1960's, declined in the late 1970's, and have since fluctuated between 20 and 30 log points.

Column 3 of Table 2 reports the implied contemporary market valuation of the Ogallala aquifer in each year, based on the coefficient β in column 2.[18] The Ogallala was valued at \$1.3 billion in 1950, \$4.1 billion in 1964, and \$12 billion in 2002.

Column 4 converts the column 3 valuations into constant 2002 dollars using the CPI. The Ogallala value rises from \$9.8 billion in 1950 to a peak of \$29 billion in 1974, declines to \$11 billion in 1987, and remains roughly constant through 2002.

Column 5 converts the column 3 valuations into constant 2002 dollars using a land value price index based on non-Ogallala sample counties.[19] This price index adjusts for any factors that affect regional agricultural land values; thus, changes in the adjusted values correspond more-narrowly to changes in the expected future quantity and marginal return of available Ogallala water. The valuations are similar to those in column 4, but peak roughly 10 years

[17]Data on agricultural rents are unavailable, which could have provided a period-specific measure of the Ogallala's rate of return.

[18]The estimated percent decrease in Ogallala counties' land values without the Ogallala is $\frac{(e^{\beta}-1)}{e^{\beta}}$, which is multiplied by the total value of land over the Ogallala (estimated as the sum of each county's land value multiplied by the share of its area over the Ogallala). The estimates' statistical significance and t-statistics are approximately the same as in column 2, but not exactly the same because the estimated log point changes are converted to percent changes.

[19]The index is defined as the 2002 value of land in counties with zero Ogallala share, divided by the year-specific value of land in counties with zero Ogallala share.

earlier.[20]

V.B Agricultural Adjustment

Table 3 reports estimated changes on more extensive margins of agricultural adjustment: farmland, cropland harvested, and farm revenue. In most years prior to 1960, similar fractions of Ogallala and non-Ogallala counties were in farmland (column 1). During the 1960's, farmland increased relatively in Ogallala counties, mainly reflecting a slower decline than in non-Ogallala counties. From 1969 to 2002, farmland remained roughly 6 percentage points higher in Ogallala counties than in non-Ogallala counties.

Cropland harvested in Ogallala counties was similar to non-Ogallala counties in 1925, and was then higher by 5 percentage points in 1930. Harvested acreages fell during the drought of 1934 (production data reported in 1935), in which many central Plains counties experienced severe crop failure (Sutch 2008). Crop acreages increased again in the 1940's, and remained similar or increased slightly through 2002.

Agricultural revenue in Ogallala counties was similar to non-Ogallala counties in 1920 and 1925, and was higher by 20 log points (22 percent) in 1930. Agricultural revenue data are unavailable in 1935, but presumably fell during the drought along with harvested cropland, and revenue remained at lower non-Ogallala levels by 1940. Revenue recovered to higher levels in 1945 and remained similarly higher than in non-Ogallala counties into the 1960's. Ogallala counties experienced particularly large increases in revenue from 1964 to 1974; an increase of 50 log points or 65 percent.

If the agricultural production function were Cobb-Douglas, then percent differences in revenue would be equal to the percent differences in profits. However, Ogallala counties' large new irrigation expenses (including fuel and electricity for pumps) suggest that factor shares would not be constant and the increase in revenue is likely to overstate the increase in agricultural profits.

[20] As a comparison to the magnitude of these valuations, Hornbeck (2009) estimates that the cost of the 1930's Dust Bowl was \$1.6 billion in CPI-adjusted 2002 dollars and \$2.3 billion in 2002 dollars using the land value index.

Table 4 reports estimated changes on more intensive margins of agricultural adjustment: crop choice. Total acres of harvested corn follow the qualitative pattern of revenue changes, with a clear increase in acres of harvested corn from 1964 to 1978 (column 1). Irrigated corn acres increased to similar but slightly higher levels after 1964, indicating that most of the corn expansion was in irrigation and a small part was substitution away from non-irrigated corn (column 2).

Total acres of wheat had been moderately higher in Ogallala counties since 1925 (column 3). This difference peaked in 1950 and declined somewhat over the years. Irrigated wheat increased after 1950, and in particular after 1964, mainly substituting away from non-irrigated wheat (column 4). Total acres of hay have always been similar or slightly lower in Ogallala counties, though irrigated hay was consistently higher after 1978 (columns 5 and 6).

VI Conclusion and Planned Future Work

Agricultural land values over the Ogallala were substantially higher than in similar nearby areas following the introduction of pumping and irrigation technologies that enabled its widespread use. The Ogallala aquifer is estimated to be valued at $12 billion in 2002, despite concerns that portions will be exhausted under status quo policies.

While land values increased quickly in the early 1950's, irrigated acreages increased only gradually. Revenue and crop choice mainly responded after 15 - 20 years. Future work will explore possible explanations for this delay, including changes in agricultural policy, adjustment costs, or induced innovations in water-intensive technologies. The analysis will explore which area characteristics were correlated with an ability to adopt new irrigation techniques and cropping patterns.

In future work, we also hope to estimate the interaction between drought and the Ogallala's impact, following work by Hansen, Libecap, and Lowe (2009). The Ogallala's impact may be especially large in drought years, so much of the Ogallala's effects may be through minimizing agricultural risk. Experienced drought may also help explain the adoption of agricultural practices that depend on Ogallala groundwater.

Further, we hope to analyze ongoing declines in the Ogallala water table. Our goal is to estimate how declining water tables and increased pumping costs impact land values and adjustment in land-use. Water table declines in a particular county are partly caused by that county's agricultural outcomes, so the analysis will instrument for a county's water table with water-use in other counties and geological information on county-to-county underground water flows.

Finally, to analyze policy implications more directly, we hope to estimate the spatial distribution of agricultural externalities using the estimated value of aquifer water, the private fuel and capital costs of water extraction, and a matrix on cross-county water flows. This would inform potential optimal corrective taxes on water-use, perhaps with a per-acre distribution to landowners. The estimated agricultural value of water may also help improve the efficiency of water allocation between agricultural and residential uses.

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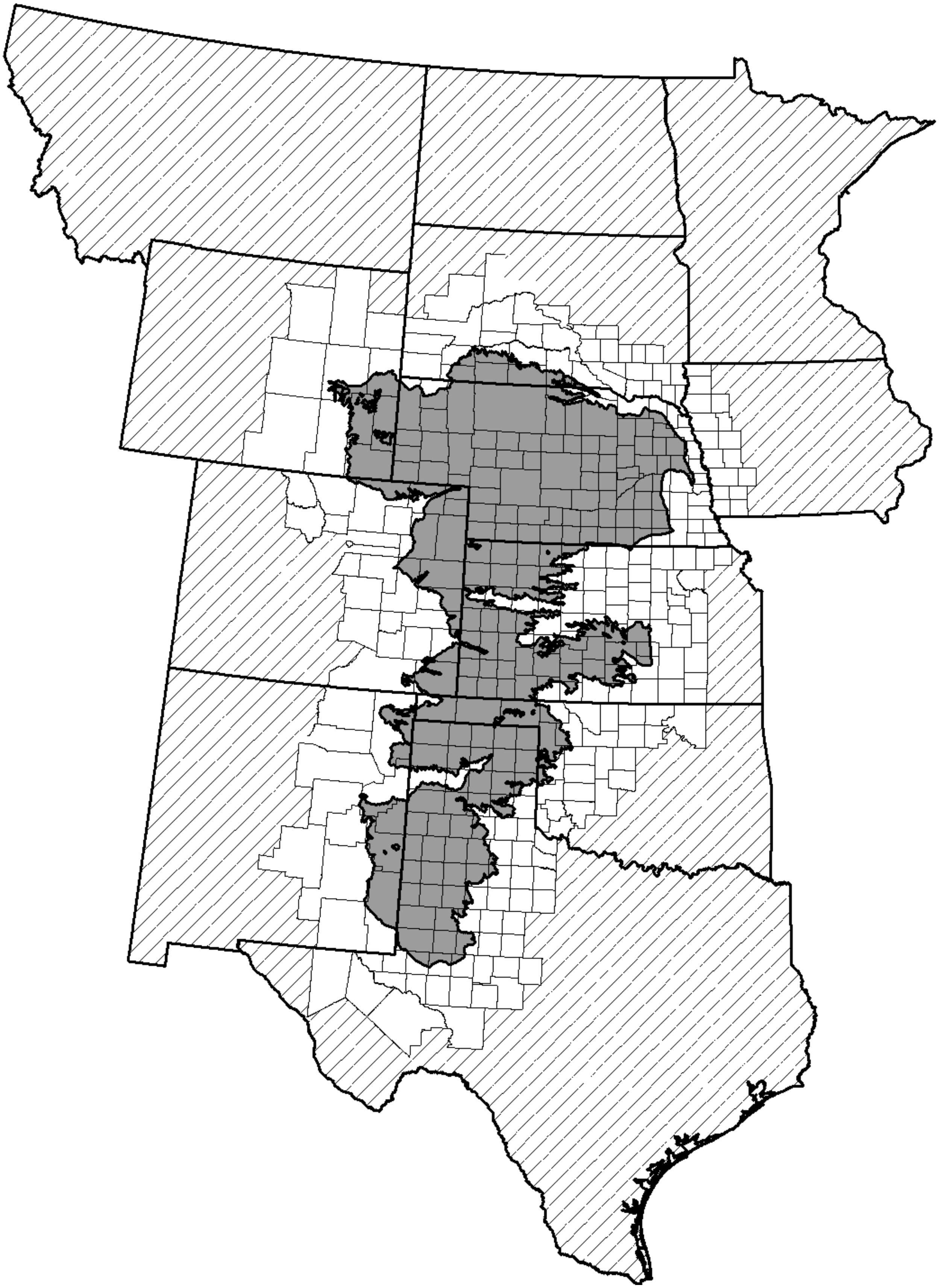
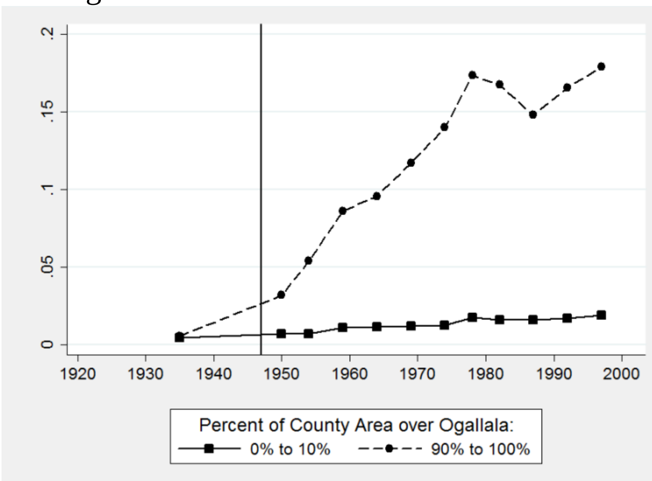
Figure 1. Ogallala Region and Counties Within 100km



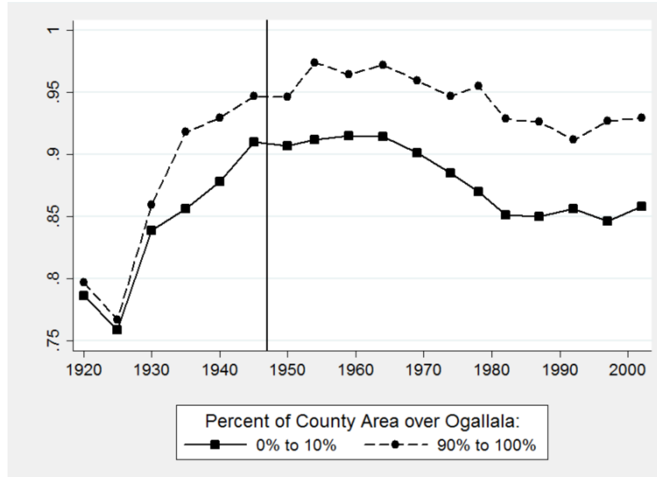
Notes: Figure 1 displays 1920 county borders for counties within 100km of the shaded Ogallala region.

Figure 2. Average County Characteristics Per County Acre, by Ogallala Share

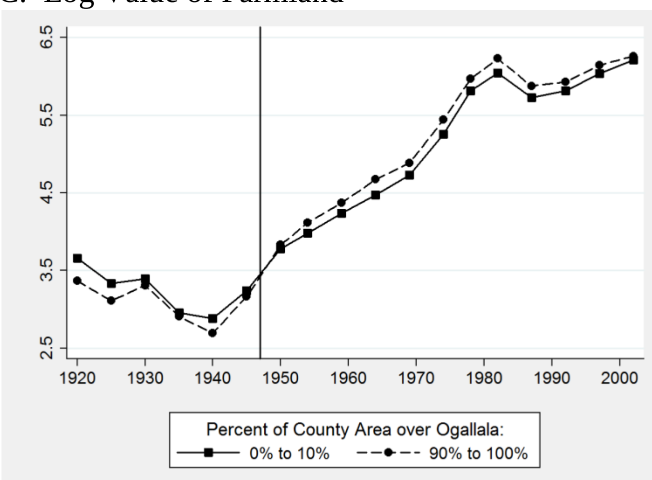
A. Irrigated Farmland Acres



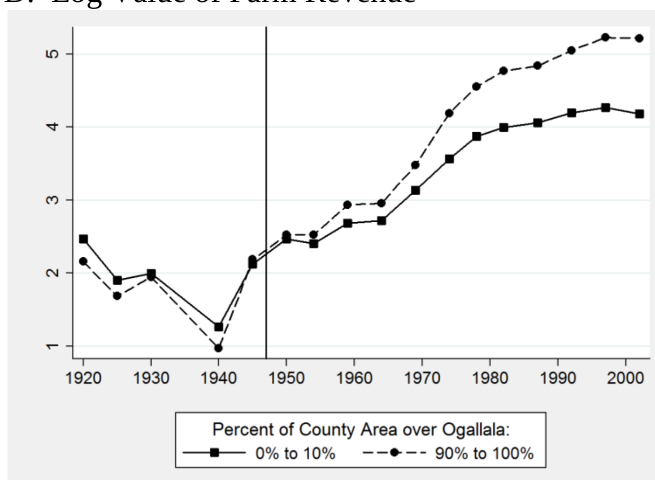
B. Farmland Acres



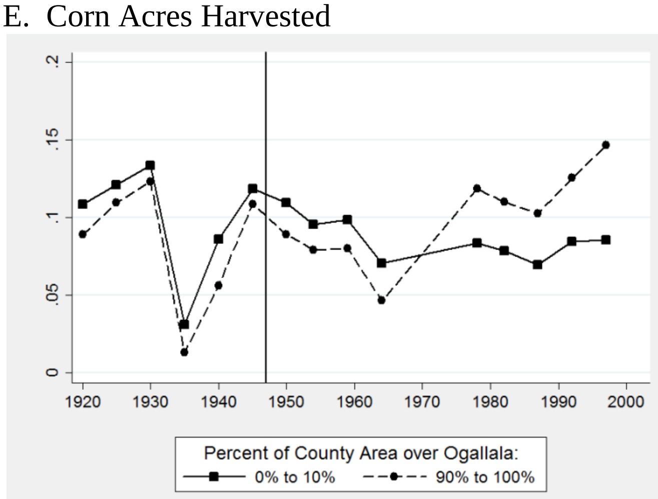
C. Log Value of Farmland



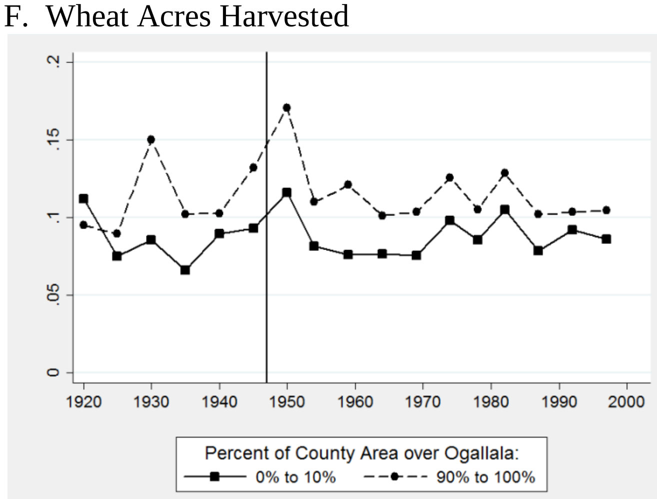
D. Log Value of Farm Revenue



E. Corn Acres Harvested



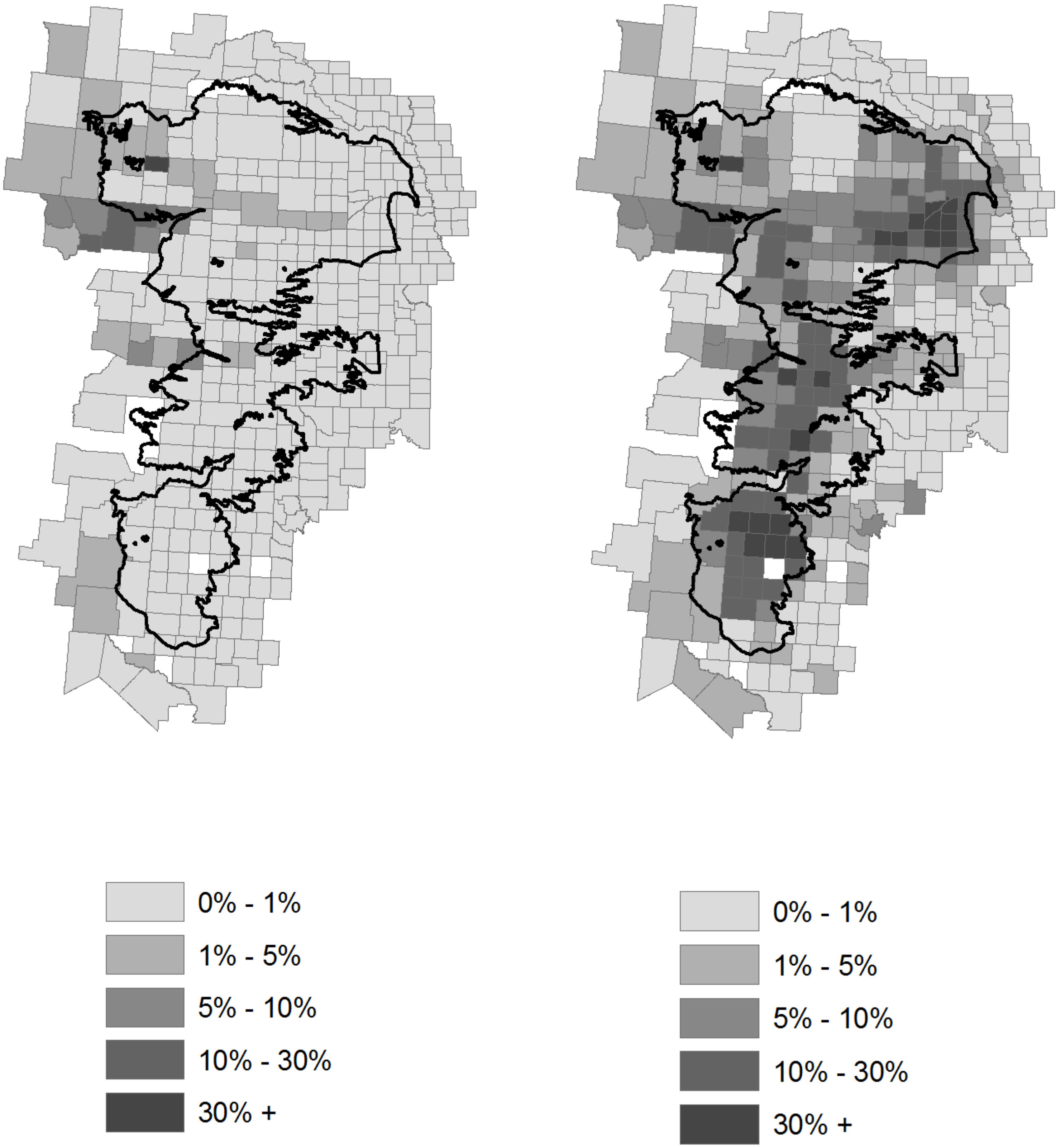
F. Wheat Acres Harvested



Notes: Each panel reports average characteristics for counties in two groups: those less than 10% over the Ogallala and those more than 90% over the Ogallala. Panels A to D include counties from the main 368 county sample. Panel E (Panel F) includes counties from the 356 (333) county sample with corn (wheat) acreage data in every period.

Figure 3. Irrigated Percent of County Area in 1935 and 1974

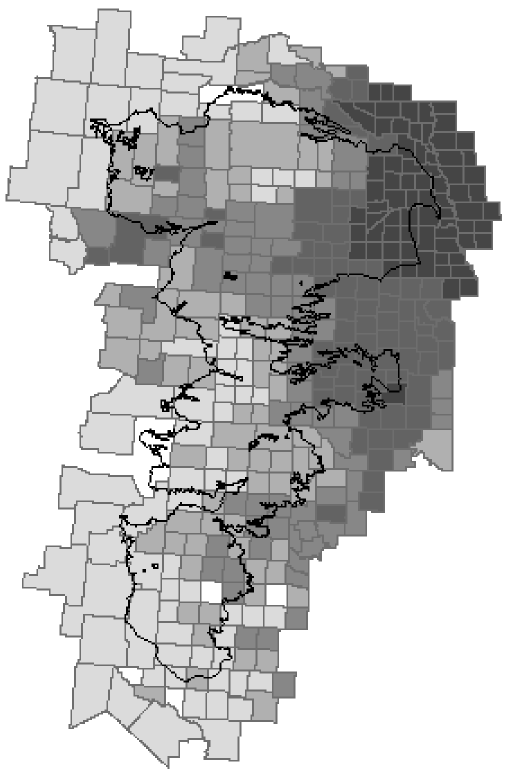
A. Irrigation in 1935 B. Irrigation in 1974



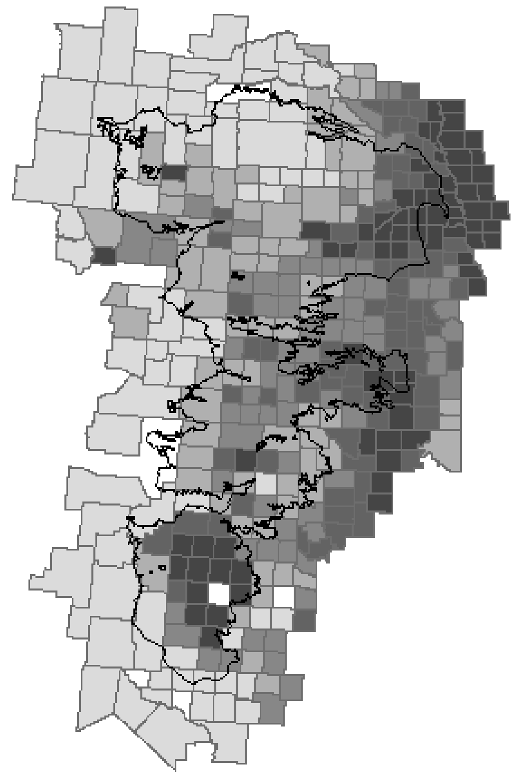
Notes: Figures 3a and 3b show the 368 main sample counties, shaded to reflect the percent of county land irrigated in 1935 (Figure 3a) and 1974 (Figure 3b).

Figure 4. Farmland Value and Farm Revenue, Shaded by Quintile in Each Year

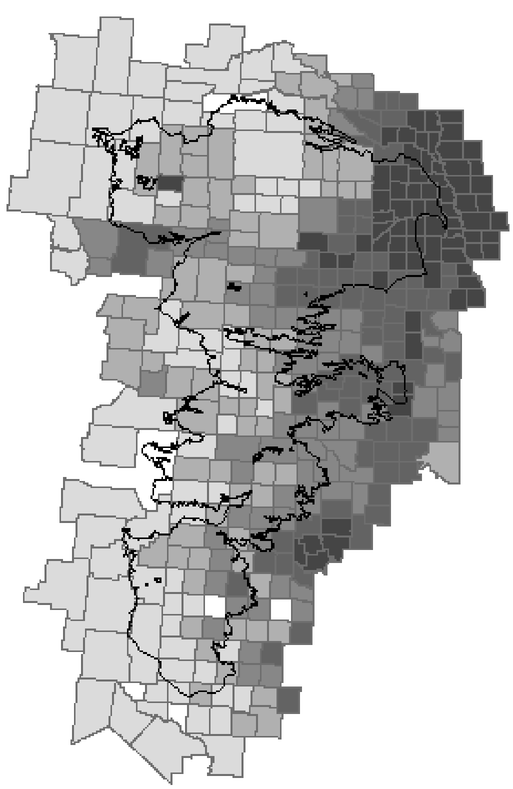
A. Farmland Value in 1920



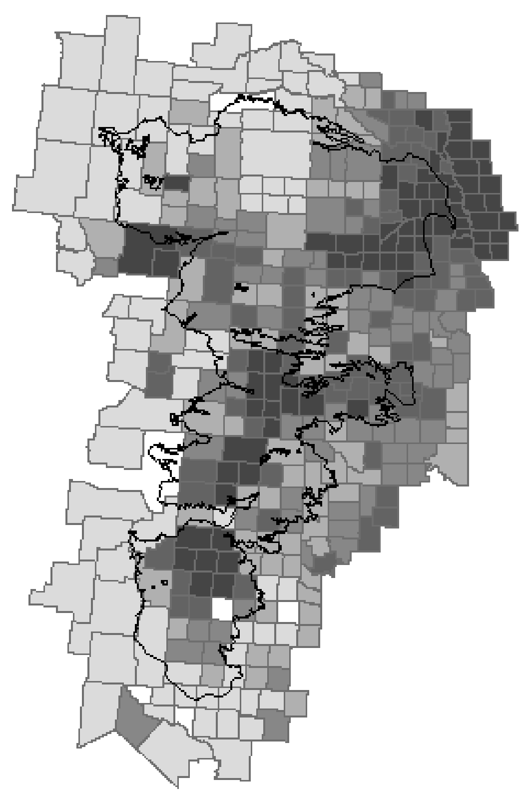
B. Farmland Value in 1964



C. Farm Revenue in 1920

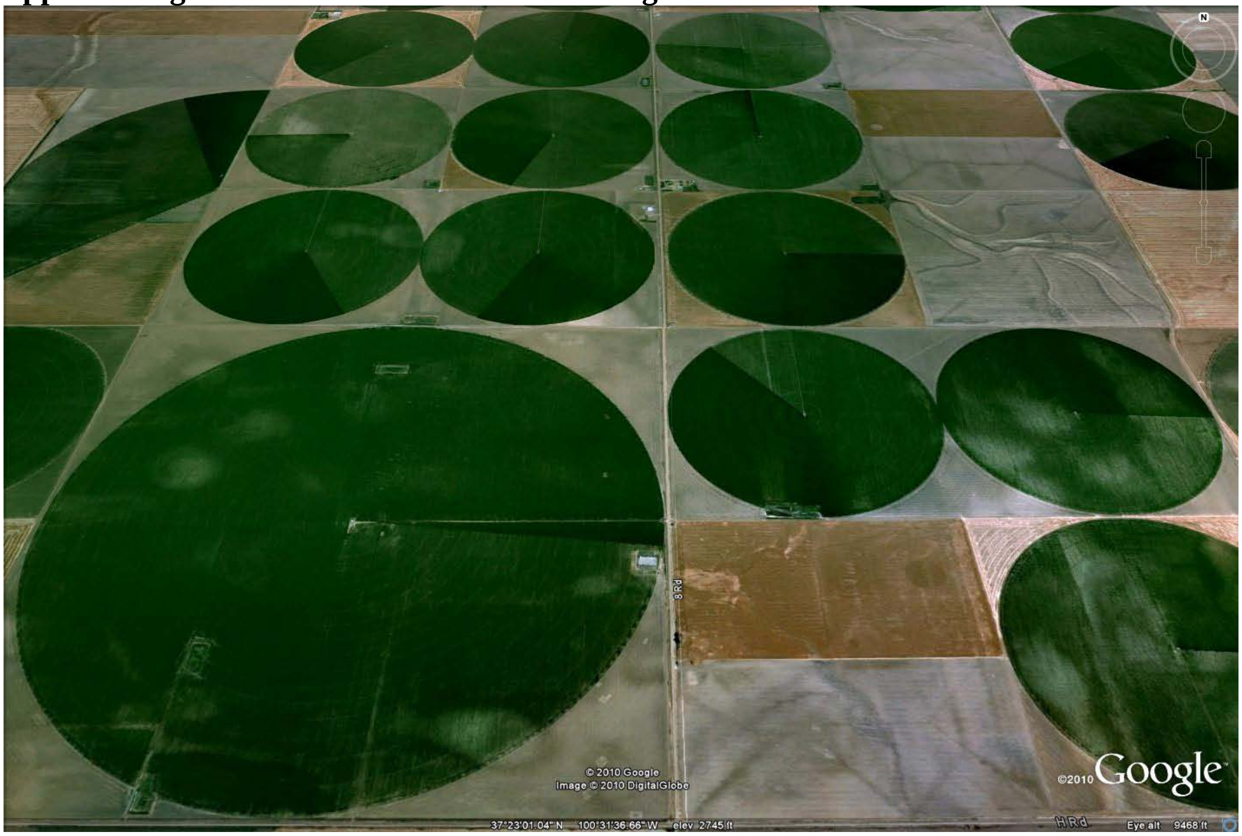


D. Farm Revenue in 1978

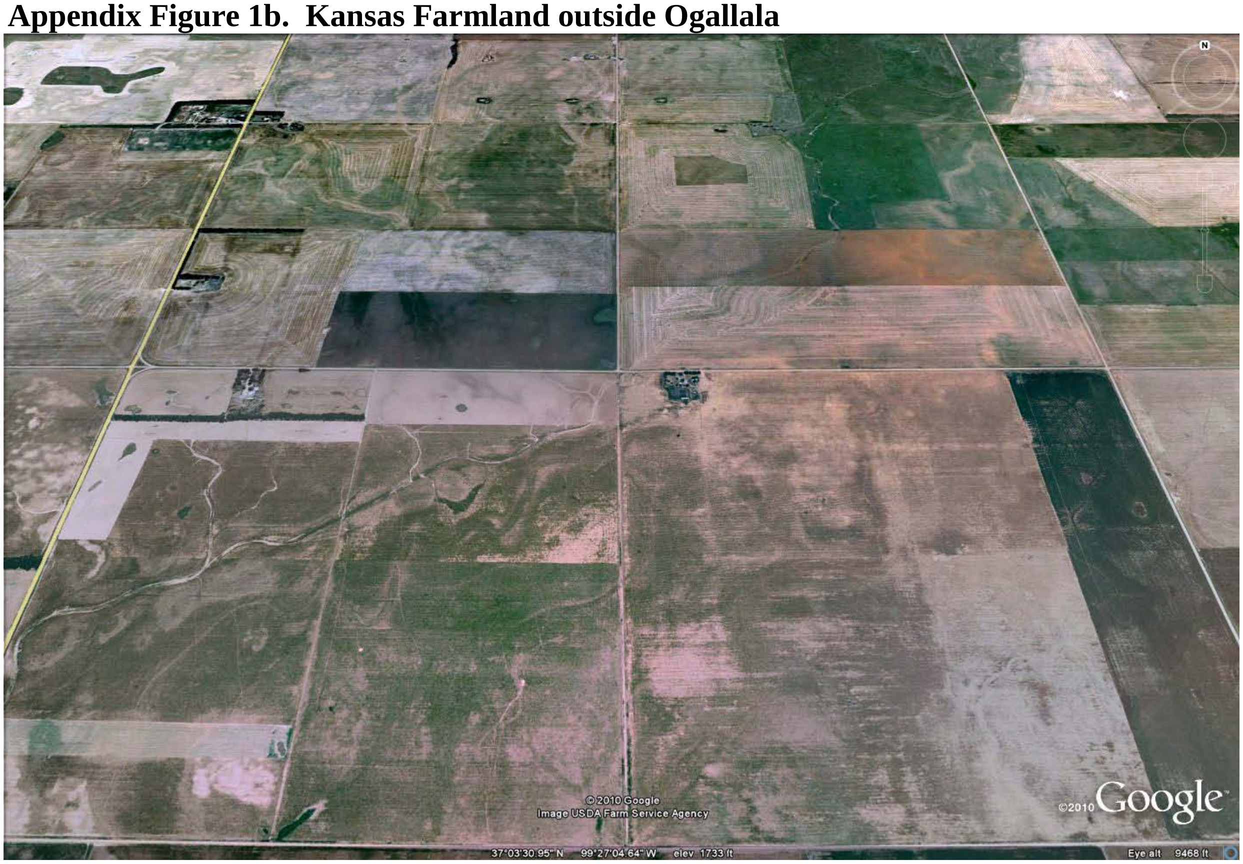


Notes: For the 368 sample counties, figures shade counties to reflect outcome quintiles in each year (darker is higher).

Appendix Figure 1a. Kansas Farmland over Ogallala

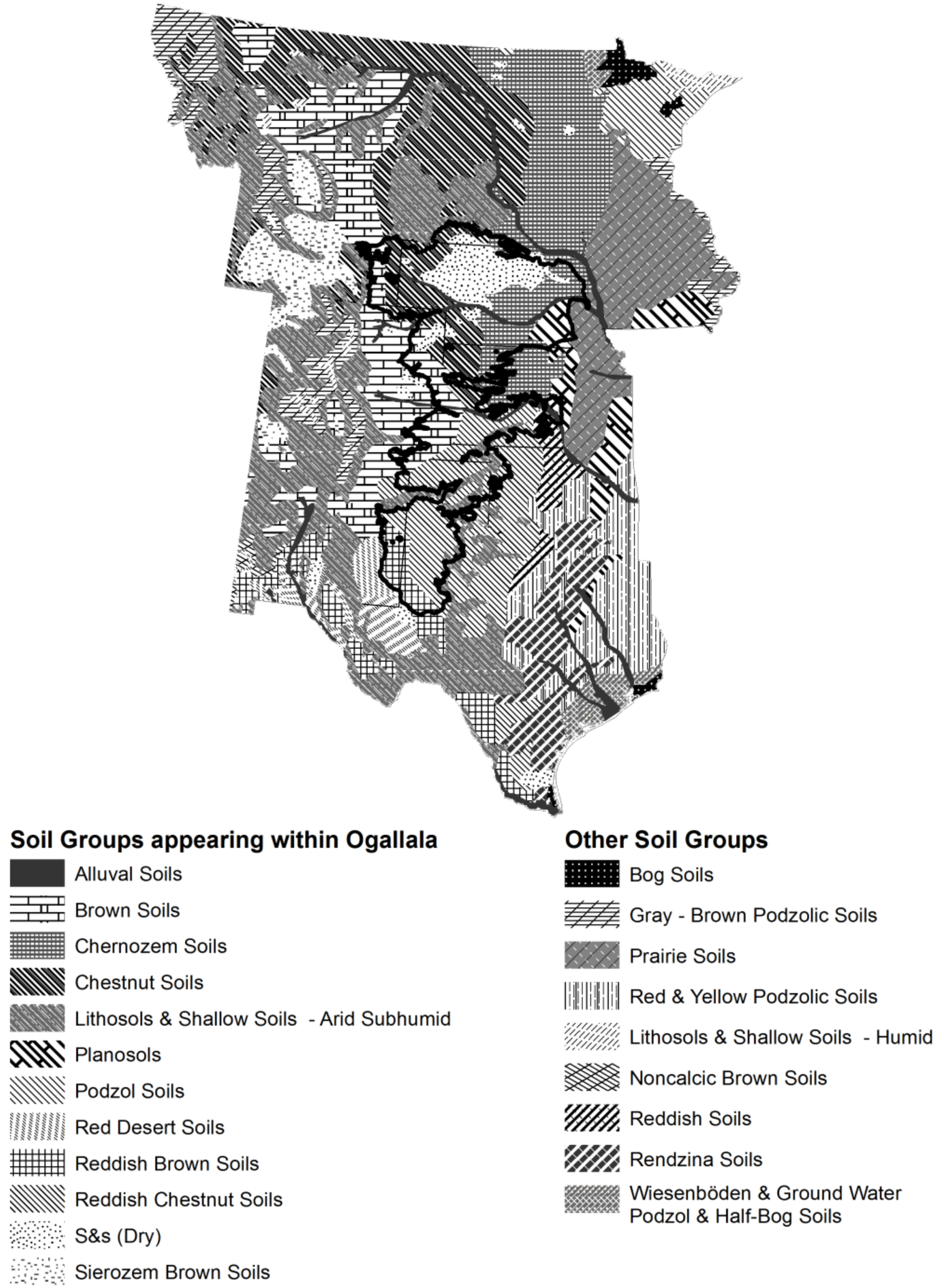


Appendix Figure 1b. Kansas Farmland outside Ogallala



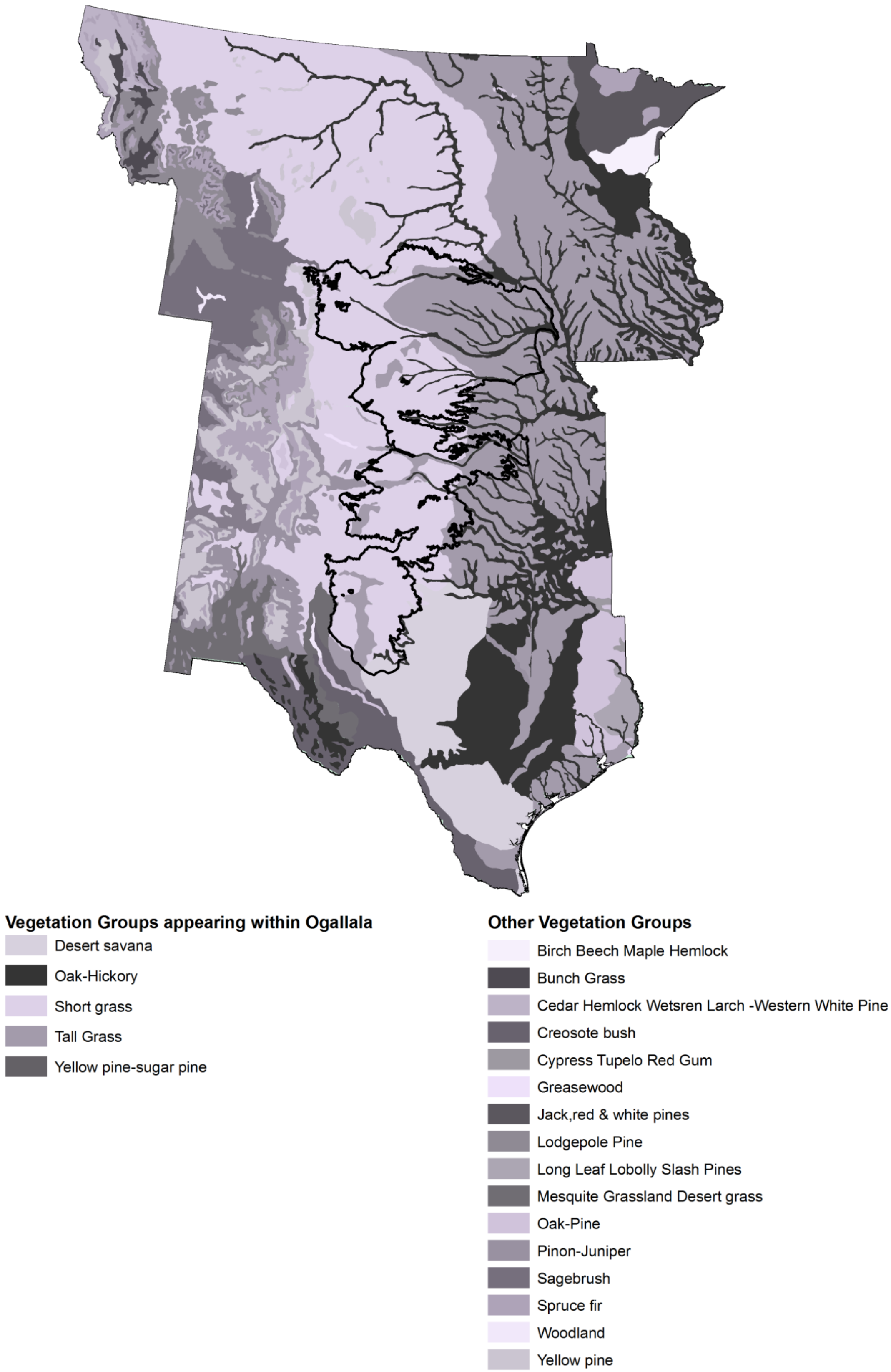
Notes: Appendix Figures 1a and 1b display recent Google Earth images from nearby counties in south central Kansas.

Appendix Figure 2. Ogallala Region and Soil Groups (Fixed Effects)



Notes: Appendix Figure 2 displays major soil groups in the region (SCS 1951).

Appendix Figure 3. Natural Vegetation Regions (1924 Atlas of Agriculture)



Notes: Appendix Figure 3 displays natural vegetation regions, as mapped by the 1924 Atlas of Agriculture (USDA 1924).

Table 1. Average County Characteristics in 1920 and Differences by Ogallala Share

		Coefficient on Ogallala Share:			
	County Averages:	No Controls	State FE	State FE and Soil Group FE	State FE and Soil Group FE, X-Y controls
Per county acre:	(1)	(2)	(3)	(4)	(5)
Farmland	0.706	0.140**	0.020	- 0.001	0.017
	[0.249]	(0.039)	(0.032)	(0.034)	(0.035)
Irrigated Farmland (1935)	0.007	- 0.001	- 0.001	- 0.003	- 0.005
	[0.020]	(0.002)	(0.002)	(0.003)	(0.003)
Log Value of Farmland	2.868	0.432*	- 0.203	- 0.057	0.015
and Farm Buildings	[1.303]	(0.194)	(0.155)	(0.120)	(0.127)
Log Value of Farm	1.750	0.306	- 0.224	- 0.102	- 0.025
Revenue	[1.179]	(0.177)	(0.147)	(0.117)	(0.121)
Cropland (1925)	0.244	0.0625*	- 0.035	- 0.003	0.014
	[0.223]	(0.0287)	(0.022)	(0.019)	(0.018)
Corn Acres	0.054	0.007	- 0.035**	0.001	0.007
	[0.088]	(0.010)	(0.007)	(0.007)	(0.007)
Irrigated Corn Acres	0.0003	0.0001	- 0.0001	- 0.0002	- 0.0003
	[0.0011]	(0.0002)	(0.0001)	(0.0002)	(0.0002)
Wheat Acres	0.077	0.017	- 0.008	- 0.003	0.001
	[0.113]	(0.013)	(0.011)	(0.011)	(0.011)
Irrigated Wheat Acres	0.001	- 0.0002	- 0.0001	- 0.001	- 0.001
	[0.003]	(0.0003)	(0.0003)	(0.001)	(0.001)
Hay Acres	0.058	0.015*	- 0.013**	- 0.001	- 0.001
	[0.051]	(0.007)	(0.004)	(0.004)	(0.004)
Irrigated Hay Acres	0.00004	- 0.00004*	- 0.00002	- 0.00002	- 0.00002
	[0.00010]	(0.00002)	(0.00002)	(0.00002)	(0.00002)

Notes: Column 1 reports average county characteristics in 1920; except for cropland and irrigated farmland, for which data are first available in 1925 and 1935. All cropland data correspond to acreages harvested (total and crop-specific). County averages are weighted by county acres, and standard deviations are reported in brackets.

Columns 2 through 5 report estimates from regressing each outcome on the share of county area over the Ogallala. Column 2 reports the unconditional difference. Column 3 controls for state fixed effects. Column 4 controls for state fixed effects and soil group fixed effects (figure 1b). Column 5 controls for state fixed effects, soil group fixed effects, and linear functions of the county centroid's X and Y coordinates from an equal area map projection (i.e., distance East-West and North-South). The regressions are weighted by county acres, and robust standard errors are reported in parentheses. ** denotes statistical significance at the 1% level, * at the 5% level.

Table 2. Estimated Differences Between Ogallala and Non-Ogallala Counties: Irrigated Farmland and the Value of Farmland and Farm Buildings

	Irrigated Farmland Acres per county acre	Log Value Land and Farm Buildings per county acre	Implied Ogallala Value in millions:		
			$	$2002 (CPI)	$2002 (LV)
Coefficient in year	(1)	(2)	(3)	(4)	(5)
1920		0.015	59	531	598
		(0.127)			
1925		- 0.015	- 42	- 429	- 627
		(0.103)			
1930		0.211*	603	6,496	8,988
		(0.096)			
1935	- 0.005	0.154	296	3,883	7,091
	(0.003)	(0.085)			
1940		- 0.051	- 89	- 1,136	- 2,250
		(0.092)			
1945		0.079	200	2,001	3,651
		(0.081)			
1950	0.015*	0.305**	1,310	9,791	14,565
	(0.007)	(0.077)			
1954	0.034**	0.390**	2,117	14,167	19,165
	(0.009)	(0.081)			
1959	0.058**	0.363**	2,566	15,840	18,523
	(0.011)	(0.088)			
1964	0.068**	0.440**	4,091	23,728	23,802
	(0.011)	(0.077)			
1969	0.089**	0.424**	4,807	23,587	21,372
	(0.011)	(0.069)			
1974	0.107**	0.409**	7,885	28,765	20,777
	(0.012)	(0.067)			
1978	0.125**	0.279**	9,794	27,007	14,517
	(0.014)	(0.067)			
1982	0.114**	0.242**	11,097	20,682	13,253
	(0.013)	(0.070)			
1987	0.100**	0.209**	6,792	10,751	11,664
	(0.011)	(0.067)			
1992	0.113**	0.272**	9,134	11,709	14,039
	(0.013)	(0.075)			
1997	0.123**	0.304**	12,716	14,250	15,333
	(0.014)	(0.067)			
2002		0.240**	11,751	11,751	11,751
		(0.078)			
R-squared	0.525	0.945			
Sample Counties	368	368			

Notes: Columns 1 and 2 report estimates from equation (1) in the text. The indicated outcome variable is regressed on the share of county area over the Ogallala, state by year fixed effects, soil group by year fixed effects, and linear functions of the X- and Y-coordinate of the county centroid interacted with year. The regressions are weighted by county acres. Reported in parentheses are robust standard errors clustered by county. ** denotes statistical significance at the 1% level, * at the 5% level.

Column 3 reports the implied Ogallala value in contemporary millions of dollars, based on the coefficient β in column 2. The estimated percent decrease in land values without the Ogallala is $(e^{\beta} - 1)/e^{\beta}$, which is multiplied by the total value of land over the Ogallala, estimated as the sum of each county land value times its Ogallala share.

Column 4 converts column 3 into 2002 dollars using the CPI. Column 5 converts column 3 into 2002 dollars using a land value price index based on non-Ogallala sample counties. The index is defined as the 2002 value of land in counties with zero Ogallala share, divided by that year's value of land in counties with zero Ogallala share.

Table 3. Estimated Differences Between Ogallala and Non-Ogallala Counties: Farmland, Cropland Harvested, and Farm Revenue

Coefficient in year	Acres of Farmland per county acre (1)	Acres of Cropland Harvested per county acre (2)	Log Farm Revenue per county acre (3)
1920	0.017		- 0.025
	(0.035)		(0.121)
1925	- 0.001	0.014	- 0.008
	(0.036)	(0.018)	(0.123)
1930	0.040	0.054**	0.200*
	(0.031)	(0.020)	(0.099)
1935	0.053*	- 0.019	
	(0.022)	(0.017)	
1940	0.009	0.027	- 0.100
	(0.027)	(0.017)	(0.103)
1945	0.041	0.073**	0.360**
	(0.025)	(0.020)	(0.098)
1950	0.019	0.094**	0.417**
	(0.026)	(0.021)	(0.107)
1954	0.042	0.085**	0.382**
	(0.029)	(0.020)	(0.116)
1959	0.012	0.100**	0.517**
	(0.028)	(0.020)	(0.111)
1964	0.048*	0.055**	0.502**
	(0.024)	(0.017)	(0.123)
1969	0.059**	0.077**	0.670**
	(0.021)	(0.018)	(0.120)
1974	0.059**	0.092**	1.005**
	(0.018)	(0.020)	(0.129)
1978	0.067**	0.109**	0.934**
	(0.018)	(0.020)	(0.128)
1982	0.077**	0.108**	1.054**
	(0.018)	(0.020)	(0.129)
1987	0.064**	0.080**	1.011**
	(0.019)	(0.020)	(0.129)
1992	0.054**	0.079**	1.149**
	(0.019)	(0.021)	(0.147)
1997	0.066**	0.113**	1.305**
	(0.020)	(0.021)	(0.150)
2002	0.063**		1.399**
	(0.019)		(0.152)
R-squared	0.562	0.801	0.888
Sample Counties	368	368	368

Notes: Columns 1-3 report estimates from equation (1) in the text. The indicated outcome variable is regressed on the share of county area over the Ogallala (reported coefficient is multiplied by 100 to interpret as percents or percentage points), state by year fixed effects, soil group by year fixed effects, and linear functions of the X- and Y-coordinate of the county centroid interacted with year. The regressions are weighted by county acres. Reported in parentheses are robust standard errors clustered by county. ** denotes statistical significance at the 1% level, * at the 5% level.

Table 4. Estimated Differences Between Ogallala and Non-Ogallala Counties: Corn, Wheat, and Hay (Total and Irrigated)

	Corn Harvested per county acre		Wheat Harvested per county acre		Hay Harvested per county acre	
	All Corn	Irrigated Corn	All Wheat	Irrigated Wheat	All Hay	Irrigated Hay
Coefficient in year	(1)	(2)	(3)	(3)	(3)	(3)
1920	0.0090	- 0.0003	- 0.0002	- 0.0010	- 0.0012	- 0.00002
	(0.0068)	(0.0002)	(0.0113)	(0.0007)	(0.0044)	(0.00002)
1925	0.0203*		0.0231*		- 0.0039	
	(0.0080)		(0.0109)		(0.0040)	
1930	0.0233**		0.0690**		- 0.0046	
	(0.0088)		(0.0148)		(0.0034)	
1935	- 0.0021		0.0316**		- 0.0057	
	(0.0029)		(0.0117)		(0.0034)	
1940	0.0011		0.0259*		- 0.0035	
	(0.0065)		(0.0102)		(0.0030)	
1945	0.0210*		0.0379**		- 0.0066	
	(0.0086)		(0.0138)		(0.0038)	
1950	0.0138	0.0020*	0.0742**	0.0016*	- 0.0048	
	(0.0083)	(0.0010)	(0.0138)	(0.0007)	(0.0042)	
1954	0.0121	0.0030*	0.0295**	0.0022**		
	(0.0073)	(0.0012)	(0.0100)	(0.0007)		
1959	0.0137	0.0095**	0.0532**	0.0048**	- 0.0057	
	(0.0079)	(0.0026)	(0.0097)	(0.0014)	(0.0042)	
1964	0.0043	0.0120**	0.0218*	0.0090**		
	(0.0053)	(0.0028)	(0.0093)	(0.0019)		
1969			0.0235**		- 0.0034	
			(0.0089)		(0.0032)	
1974			0.0325**		- 0.0025	
			(0.0113)		(0.0033)	
1978	0.0528**	0.0665**	0.0225*	0.0162**	- 0.0055	0.0035*
	(0.0106)	(0.0101)	(0.0103)	(0.0021)	(0.0031)	(0.0015)
1982	0.0460**	0.0591**	0.0312*	0.0223**	- 0.0058	0.0031*
	(0.0099)	(0.0098)	(0.0123)	(0.0027)	(0.0030)	(0.0014)
1987	0.0449**	0.0562**	0.0285**	0.0193**	- 0.0057	0.0035*
	(0.0090)	(0.0089)	(0.0102)	(0.0026)	(0.0031)	(0.0014)
1992	0.0581**	0.0686**	0.0147	0.0206**	- 0.0071*	0.0045**
	(0.0110)	(0.0105)	(0.0114)	(0.0028)	(0.0033)	(0.0016)
1997	0.0730**	0.0778**	0.0139	0.0166**	- 0.0063	0.0043*
	(0.0121)	(0.0111)	(0.0116)	(0.0022)	(0.0034)	(0.0017)
R-squared	0.791	0.545	0.728	0.479	0.766	0.513
Sample Counties	356	333	333	313	362	368

Notes: Columns 1-6 report estimates from equation (1) in the text, see notes to Table 3. ** denotes statistical significance at the 1% level, * at the 5% level.