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

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Abstract

After 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 risk from drought. From 1950 to 1978, irrigation gradually increased and crop production increased in water-intensity with some delay. Groundwater access initially decreased the impact of drought on corn yields, before expansion in corn acreage made production more reliant on groundwater access. Land value premiums capitalize the Ogallala's value at $12 billion in 2002, which may understate its potential value due to externalities exacerbated by tax policy. Experiences from the Ogallala provide a stark example for understanding other water-scarce settings in which 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, the short-run and long-run economic impacts of water depend on the speed and magnitude of agricultural adjustment. Historical changes in groundwater availability provide a rare opportunity to observe both short-run and long-run agricultural adjustments.

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 the later period, from 1964 to 1978, Ogallala farmers adjusted to more water-intensive crops. Ogallala groundwater initially reduced the impact of drought on the production of water-intensive crops, though long-run expansion in water-intensive crop acreages made agriculture more dependent on groundwater and more sensitive to drought.

[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 from 1964 to 1974, 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, which appear to reflect expectations of many areas losing access to groundwater in the future.

Strict regulation of water-use has been minimal. Remarkably, since a legal decision in 1965, federal tax code has been interpreted to allow irrigating farmers depreciation allowances for declines in their Ogallala water level. 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 may be large potential efficiency gains from policy reform.

The historical experience of the Ogallala aquifer helps to understand the short-run and long-run impacts of water on agricultural production, and its interactions with drought and agricultural risk. 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 underlies 174,000 square miles of the Great Plains from Western

[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).

Texas to South Dakota. The borders of the aquifer are sharply defined by the location of ancient valleys and hills in the Tertiary Period, which have long since been covered and obscured on the surface.[3] The formation of the Ogallala is unrelated to fossil fuels, and the aquifer borders are not particularly correlated with known locations of oil and natural gas.

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).[4]

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 pumps developed in the oil industry, lifting the groundwater cheaply and in large volumes. Center pivot irrigation systems were developed, which effectively distributed water across farmland (Opie 1993).

Ogallala groundwater became increasingly used for irrigation and, as pump and irrigation equipment became more powerful, farmers' withdrawals quickly surpassed the aquifer's natural recharge rate.[5] In an early analysis of the region, the United States Geological Service

[3] Local irrigation potential from the Ogallala is determined by three main characteristics: (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). These characteristics vary over the aquifer but most counties over the Ogallala have had sufficient water for irrigation for most of their history; thus, this analysis focuses on the basic feature of which counties overlay the original aquifer border. As water levels continue to decline, aquifer characteristics will have increasingly 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.

[4] 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).

[5] 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.

(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 the year 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 plots.[6] The magnitude and speed of agricultural adjustment is less clear, however, in addition to the impact on land values.[7] Water table declines are just beginning to make groundwater unavailable for irrigation in some shallow areas, which will have unknown short-run and long-run impacts on local economic outcomes.

The smallest standard plot sizes are 160 acres on the Plains, which is much larger than in most developing countries. Large plot sizes make the marginal costs of pumping water relatively much larger compared to the fixed cost of digging a well. The 160-acre plots naturally create a minimum 0.4 kilometer buffer between wells, which is often a policy goal in developing countries, so farmers' pumping has less immediate effect on closest neighbors' water levels. Over time, a farmer's water extraction draws from the broader Ogallala region and has little marginal effect on water levels underneath that farmer's particular plot. The Ogallala is a very large closed aquifer in a climate with low average rainfall, so there is relatively less annual fluctuation in water levels and less potential for long-run recharge than in many developing-country contexts.

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 declining water levels under their land.[8] There remains no unified strict management of

[6]Farmers either plant drought-resistant crops in the corners of fields or accept lower yields on their main crop. Farmers sometimes install more-costly irrigation equipment that can also reach corners of fields.

[7]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.

[8]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

Ogallala water-use. In the last two decades, a variety of state water laws and groundwater management districts have been adopted in the region. State and local regulations sometimes restrict the spacing of new wells or aim to prevent water "wastage," but these are loose constraints and have little effect on the large majority of water-use.[9]

II Land-use Adjustment to Groundwater Access and Interactions with Drought

II.A Baseline Model of Land-use Adjustment

The Ogallala substantially increased water available for agriculture. In this simple model, a farmer can adjust the water-intensity of production both within-crops and between-crops. The productive value of water is capitalized in land values. Depending on the relative speed and magnitude of adjustment within-crops and between-crops, access to groundwater has different effects on the sensitivity of agricultural production to drought.

Assume that a farmer uses water and land to produce rents from two crops, $y_1(w_1, L_1)$ and $y_2(w_2, L_2)$. Water and land increase production of both crops, but the first crop is more water-intensive ($\frac{\partial y_1}{\partial w_1} > \frac{\partial y_2}{\partial w_2}$). Both production functions are concave, but the first crop has a slower declining marginal return to water ($\frac{\partial^2 y_2}{\partial w_2^2} < \frac{\partial^2 y_1}{\partial w_1^2} < 0$). Water and land are complementary for both crops, but not more so for the second crop ($\frac{\partial^2 y_1}{\partial L_1 \partial w_1} \geq \frac{\partial^2 y_2}{\partial L_2 \partial w_2} > 0$).[10]

The farmer maximizes total production, subject to a water constraint ($w_1 + w_2 = \overline{w}$) and a land constraint ($L_1 + L_2 = 1$). The farmer's optimal production decisions are functions of the water endowment: $w_1^*(\overline{w}), L_1^*(\overline{w}), w_2^*(\overline{w}), L_2^*(\overline{w})$.

An increase in the water endowment affects agricultural production along each margin. Given the above restrictions on the production function, more water becomes used for the

[9] Controversially, oil companies will sometimes use vast amounts of water to push small remaining portions of oil from the ground. Kansas, New Mexico, and Colorado enforce restrictions on new well spacing. Texas fines users who lose water due to equipment malfunctioning (Peterson et al. 2003).

[10] These conditions are sufficient for the joint production function to be concave, and for the derived water-use solution to be a maximum. An example of this functional form is: $w_i + L_i + w_i L_i - a_i w_i^2 - L_i^2$, where $a_1 = 0.5 + \epsilon$, $a_2 = 0.5 - \epsilon$, and $\epsilon \in (0, 0.25)$.

first crop and land is shifted toward the first crop:[11]

$$\frac{\partial w_1^*(\overline{w})}{\partial \overline{w}} > 0 \qquad \text{and} \qquad \frac{\partial L_1^*(\overline{w})}{\partial \overline{w}} > 0. \tag{1}$$

Agricultural adjustment may be delayed within-crops and/or between-crops, just as after Dust Bowl erosion in this region (Hornbeck 2011). Agricultural rents increase as agricultural production adjusts. Agricultural land values increase more immediately in anticipation of later rent increases, to the extent that the increase in water availability was unexpected.

II.B Interactions Between Groundwater and Drought

Of further interest is how access to groundwater affects the sensitivity of agricultural production to drought. Agricultural production depends on an additional drought term ($y_1(w_1, L_1, d)+ y_2(w_2, L_2, d)$). Drought is unexpected and farmers cannot respond by changing the crop allocation of dry land or irrigated land. Drought decreases the productivity of land for both crops, but drought has a larger negative effect on the first crop ($\frac{\partial^2 y_1}{\partial L \partial d} < \frac{\partial^2 y_2}{\partial L \partial d} < 0$). Drought increases the productivity of water for both crops, but more so for the first crop ($\frac{\partial^2 y_1}{\partial w \partial d} > \frac{\partial^2 y_2}{\partial w \partial d} > 0$).

The farmer continues to maximize total production, subject to constraints on water and land. Given optimal allocations of water and land, the impact of drought is ($\frac{\partial y_1(L_1^*, w_1^*, d)}{\partial d} + \frac{\partial y_2(L_2^*, w_2^*, d)}{\partial d}$). An increase in the water endowment has an ambiguous effect on the impact of drought:

$$\frac{d}{d\bar{w}}\left[\frac{\partial y_1}{\partial d} + \frac{\partial y_2}{\partial d}\right] = \underbrace{\left(\frac{\partial^2 y_1}{\partial d \partial w_1}\frac{\partial w_1^*}{\partial \bar{w}} + \frac{\partial^2 y_2}{\partial d \partial w_2}\frac{\partial w_2^*}{\partial \bar{w}}\right)}_{>0} + \underbrace{\left(\frac{\partial^2 y_1}{\partial L_1 \partial d} - \frac{\partial^2 y_2}{\partial L_2 \partial d}\right)\frac{\partial L_1^*}{\partial \bar{w}}}_{<0}. \tag{2}$$

The effect is ambiguous because water mitigates the impact of drought on each crop (the first term), but production shifts toward the more drought-sensitive crop (the second term).

[11] Changes in water for the second crop ($\frac{\partial w_2^*(\overline{w})}{\partial \overline{w}}$) can be positive or negative, depending on the particular production function parameters.

If land allocations are constrained in the short-run, the second term is equal to zero and water access unambiguously mitigates the impact of drought. After land allocations adjust in the long-run, drought has more impact and may affect agricultural production more than in the initial case.[12]

The intuition for these effects is somewhat clearer for a symmetric loss in groundwater. In the short-run, crop choices remain similar and there is less water, so drought has a larger impact on production. In the long-run, crop choices shift toward drought-resistant crops and the impact of drought is lessened. If there is enough shift toward drought-resistant crops, relative to the declines in water for each crop, then the impact of drought may become less than before the loss in groundwater. Note, however, that agricultural rents and land values will still decline after the loss in groundwater.

III Data Construction and County Characteristics by Ogallala Share

Historical 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, and harvested acreages and production for corn and wheat. The empirical analysis focuses initially 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.[13] To account for county border changes, census data are adjusted in later periods to maintain the 1920 county definitions (Hornbeck 2011). For a restricted sample of counties in the post-1940 period, annual county-level data are drawn from the National Agricultural Statistics Service (NASS) and the National Climatic Data Center (NCDC): planted acreages

[12]It is not an unusual case in which drought affects agricultural production more after an increase in groundwater. Consider a plausible special case in which a farmer maximizes $L_1 y_1(w_1) + L_2 y_2(w_2)$ subject to $w_1 L_1 + w_2 L_2 = \bar{w}$ and $L_1 + L_2 = 1$. Crop 1 is more water intensive ($y_1'(w) > y_2'(w) > 0$) and the marginal return to water is declining ($y_1''(w) < 0$ and $y_1''(w) < 0$). Given an increase in the water endowment, the farmer shifts land to crop 1 ($\frac{\partial L_1^*(\overline{w})}{\partial \overline{w}} > 0$ and $\frac{\partial L_2^*(\overline{w})}{\partial \overline{w}} < 0$) but per-acre crop water usage is unchanged ($\frac{\partial w_1^*(\overline{w})}{\partial \overline{w}} = \frac{\partial w_2^*(\overline{w})}{\partial \overline{w}} = 0$). In the extended model with drought, the impact of drought will only strengthen in the long-run through a shift toward the drought-sensitive crop. In the short-run, when land allocations are constrained, the impact of drought will be mitigated as crop water usage increases.

[13]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.

and production for corn and wheat, and annual drought severity.[14]

Figure 1 shows the 1920 county borders overlaid with a map of the Ogallala aquifer (USGS). 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 in each 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 the X-coordinate and Y-coordinate of the county centroid.[15]

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.

The empirical analysis does not control for pre-1950 differences in county characteristics, because these may still be outcomes of the Ogallala. Ogallala groundwater was partly available to farmers on a limited scale through the use of early pumps, windmills, and irrigation techniques. Farmers and land speculators may also have been influenced by expectations over the future availability of the Ogallala. In particular, Ogallala land values may be

[14]We thank Hansen, Libecap, and Lowe (2010) for providing weather data from the NCDC.

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

higher to the extent that pumping and irrigation technological improvements were expected. Settlement and land investments may precede the widespread availability of the Ogallala, influenced by the expected availability of groundwater.

The Ogallala water table is generally too deep to be accessed by plants or trees, but 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 boundary mainly cuts across the two largest vegetation regions ("Short Grass" and "Tall Grass") and more-wooded areas ("Oak-Hickory"), though the Ogallala boundary is more correlated with differences in vegetation regions around the southern tip and northwest sections. The included soil group controls (Appendix Figure 2) capture finer regional groupings than the mapped vegetation regions.

IV Changes in County Characteristics by Ogallala Share

Figure 2 plots average outcomes over time within two groups of sample counties: counties less than 10% over the Ogallala, and counties more than 90% over the Ogallala.[16] 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 (Panel A). The value of farmland was relatively lower or similar in Ogallala counties from 1920 through the 1940's, and after 1950 became consistently greater in Ogallala counties than in non-Ogallala counties (Panel B).

Acres of corn harvested were relatively lower or similar in Ogallala counties from 1920 through 1964, with aggregate temporary declines during the 1930's drought (Panel C). Between 1964 and 1978, Ogallala counties experienced a large relative increase in harvested corn acreages. This change in crop production appears to lag the increase in irrigation and land values.

Figure 3 illustrates the finer geographic variation available in the data. Irrigation levels were low everywhere in 1935 (Panel A), aside from a few areas with major rivers (see

[16] Average outcomes for the in-between counties are generally within the averages for the two groups shown, but this third category is omitted from the figure for increased clarity.

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 (Panel B). Analogously, land values are similar in 1920 and are systematically higher in Ogallala counties than in nearby non-Ogallala counties in 1964 (Figure 4).[17]

V Empirical Framework

The empirical analysis is based on comparing counties over the Ogallala with nearby counties that may 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.[18] These cross-sectional specifications are pooled across all time periods, with each coefficient allowed to vary in each time period:

$$Y_{ct} = \beta_t OgallalaShare_c + \alpha_{st} + \gamma_{gt} + \theta_t^x Longitude_c + \theta_t^y Latitude_c + \epsilon_{ct} \tag{3}$$

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.[19] 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,

[17] Counties are shaded to reflect their land value quintile in each year.

[18] 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.

[19] 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.

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, though 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.

Relative differences in Ogallala counties may not reflect the aggregate impact of the Ogallala if there are spillover effects on non-Ogallala counties. Water is not directly transferred to non-Ogallala counties for agricultural use, though the short-term availability of labor and capital could be affected in non-Ogallala counties.[20] The Ogallala region represents a small share of national and world agricultural production, so estimated impacts on output and land values would not have large indirect effects on the prices of agricultural goods and farmland in non-Ogallala counties.

VI Results

VI.A Agricultural Land-use and Land Values

Table 2, column 1, reports the estimated effect of the Ogallala in each year on acres of irrigated farmland per county acre, controlling in each year for state, soil group, and X/Y county coordinates. In 1935, irrigation levels were a statistically insignificant 0.5 percentage points lower in Ogallala counties than in non-Ogallala counties.[21] By 1950, irrigation had

[20]The physical border of the aquifer is sharp, and oil-industry techniques for horizontal drilling or pipelines are not cost effective for water. In practice, there is not large-scale physical transportation of water to nearby areas for agricultural purposes.

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

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 reflects improvements in pumping and irrigation technology, as well as gradual adjustment in agricultural practices.

Land value premiums may reflect the expected present discounted value of production rents from the Ogallala aquifer. In the 1950's, after the introduction of new pumping and irrigation technologies, Ogallala land values became consistently higher than non-Ogallala land values (Table 2, column 2). Land value differences peaked in the 1960's and declined in the late 1970's. Recent declines in land values appear to reflect expected future losses in groundwater access, rather than declines in the marginal return to water, as impacts on agricultural revenue have increased in the recent period (Appendix Table 1).[22]

Column 3 reports the implied historical market valuation of the Ogallala aquifer in each year, based on the coefficients in column 2.[23] Column 4 converts these valuations into constant 2002 dollars using the Consumer Price Index: 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 regional land value price index: the valuations are similar to those in column 4, but peak roughly 10 years earlier.[24]

Table 3 reports estimated impacts of the Ogallala on agricultural land-use. The extensive margin of total farmland was similar in Ogallala counties and non-Ogallala counties in most years prior to 1960. Since 1960, the fraction of county land in farms has been consistently

[22] If the agricultural production function were Cobb-Douglas, then percent differences in revenue would equal the percent differences in (unobserved) agricultural rents. However, Ogallala counties' higher irrigation expenses suggest that factor shares may not be constant and higher revenues are likely to overstate the impact on rents.

[23] 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' t-statistics are approximately the same as in column 2; they would be identical, but the estimated log point differences are converted to percent differences.

[24] The land value price index is defined as the 2002 value of land in sample counties with zero Ogallala share, divided by the year-specific value of land in sample counties with zero Ogallala share. This price index adjusts for 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.

5 to 8 percentage points higher in Ogallala counties. This relative increase mainly reflects a slower absolute decline in farmland than in non-Ogallala counties.

Table 3, columns 2 and 3, report impacts on the intensive margins of corn acreage and irrigated corn acreage. Prior to 1950, harvested corn acreages were similar in Ogallala and non-Ogallala counties. In the 1950's and 1960's, there were moderate relative increases in irrigated corn acreages in Ogallala counties and little change in total corn acreages. In the 1970's, there were large increases in irrigated corn acreages and moderately smaller increases in total corn acreages. Most of the expansion in corn acreage was irrigated corn, with some small substitution from non-irrigated corn.

Total wheat acreage has been moderately higher in Ogallala counties since 1925 (column 4). This difference peaked in 1950 and mostly declined through the 1990's. In contrast, irrigated wheat increased somewhat during the 1950's, 1960's, and 1970's, mainly substituting away from non-irrigated wheat (column 5).

As the Ogallala became widely available, both corn and wheat became more water-intensive. Crop production eventually shifted toward corn, which tends to be more water-intensive than wheat and more-sensitive to drought. This delayed shift toward corn may reflect farmers' adjustment costs and high corn prices in the early 1970's.[25]

VI.B Interaction Effects between Drought and the Ogallala

For a restricted sample of counties, this section explores how access to the Ogallala affects the impact of drought on corn yields and wheat yields. Drought mainly varies across years in the sample region, with little cross-sectional variation within years, so it is necessary to use annual data from the NASS on crop acreages and production. The NASS crucially provides data on planted crop acreages, as severely drought-damaged cropland may be left unharvested and not appear in data on harvested crop acreages. Crop yields are defined as the log number of bushels produced per acre planted.

[25]High corn prices directly encourage planting corn, and indirectly encourage planting corn by effectively relaxing government policy disincentives for planting corn.

Drought is defined according to the Palmer Drought Severity Index (PDSI). The PDSI uses cumulative rainfall and temperature to determine dryness/wetness over several months, relative to the local average climate. For the analysis, the PDSI is set equal to zero in wet years and ranges between zero and 7.22 with a 1.16 standard deviation.

As discussed in section II, the impact of groundwater access during drought years may depend on the relative speed and magnitude of adjustment in agricultural land-use. The drought analysis splits the available years of data into three main eras: before widespread use of Ogallala irrigation for corn and wheat (1940-1957), after moderate increases in the water-intensity of corn and wheat (1958-1971), and after a shift toward the more water-intensive corn (1972-1993).[26]

In a preliminary specification, log crop yield (Y_{ct}) in county (c) and year (t) is regressed on the county's Ogallala fraction, the county's Ogallala fraction interacted with drought, county fixed effects (α_c), era fixed effects (γ_e), and drought:

$$
\begin{aligned}
(4) \qquad Y_{ct} &= \beta_e^1 OgallalaShare_c + \alpha_c + \gamma_e \\
&+ \beta_e^2 OgallalaShare_c \times Drought_{ct} + \delta_e Drought + \epsilon_{ct}
\end{aligned}
$$

The main coefficients of interest are β^1 and β^2, which are allowed to vary in each era. The coefficient β^1 reports crop productivity in wet years in Ogallala counties relative to non-Ogallala counties, and relative to this difference in the omitted baseline period (1940-1957). The coefficient β^2 reports in each era how drought affects crop productivity in Ogallala counties relative to the impact of drought in non-Ogallala counties; alternatively, β^2 reports the impact of the Ogallala on crop productivity in drier years relative to the impact of the Ogallala on productivity in wet years.

The sample is balanced in each regression, such that every county included has data in

[26]Before 1940, NASS data is available for few States and the 1930's were otherwise atypical due to extreme drought, the Dust Bowl, and the Great Depression. After 1993, NASS data is available for fewer counties within these States.

each period. There are fewer counties in each sample, and particular States with available data are reported along with the number of county observations. The regressions continue to be weighted by county size, and standard errors are clustered at the county level.

The full specification is an extended version of equation 4 that controls for drought interactions with state, soil group, and X/Y county coordinates, in addition to the controls' main effects:

$$
\begin{aligned}
(5)\quad Y_{ct} &= \beta_e^1 OgallalaShare_c + \alpha_c \\
&+ \gamma_{se}^1 + \gamma_{ge}^2 + \gamma_e^3 Long_c + \gamma_e^4 Lat_c \\
&+ \beta_e^2 OgallalaShare_c \times Drought_{ct} \\
&+ \delta_{se}^1 Drought + \delta_{ge}^2 Drought + \delta_e^3 Long_c \times Drought + \delta_e^4 Lat_c \times Drought + \epsilon_{ct}
\end{aligned}
$$

The coefficients of interest are still β^1 and β^2, which have the same interpretation. The additional controls in equation 5 focus the analysis on the same conditional variation in Ogallala access that identified the earlier empirical analysis, though the sample of counties is more restricted due to NASS data availability.

Table 4, column 1, reports estimates from equation 4 for corn yields. After the first era (1940-1957), corn yields increased 16 log points by the second era (1958-1971) and 71 log points by the third era (1972-1993). The productivity increases were higher in Ogallala counties by 44 and 72 log points, respectively. Drought decreased productivity and had less impact on productivity in Ogallala counties, particularly in the second era.

Column 2 reports estimates from equation 5 for corn yields, controlling for regional variation in Ogallala access. Drought had similar or worse effects on Ogallala counties in the first era, and drought became much less damaging in Ogallala counties in the second era. After corn acreages expanded going into the third era, Ogallala counties' productivity increased in wet years and Ogallala counties lost their relative advantage in drought years. Indeed, corn production in Ogallala counties became more sensitive to drought than in non-Ogallala counties. These estimates are similar if the sample is expanded to include counties with data in the second and third eras only (column 3).

By comparison, columns 4 to 6 report estimates from equations 4 and 5 for wheat yields. Wheat productivity increased over time in Ogallala and non-Ogallala counties, and wheat production was generally less sensitive to drought than corn production (column 4). The Ogallala had relatively little effect on the sensitivity of wheat production to drought in any era (columns 5 and 6).

VII Conclusion

Agricultural land values over the Ogallala aquifer were substantially higher than in similar nearby areas, following the introduction of pumping and irrigation technologies that enabled widespread use of the groundwater. The market value of the Ogallala aquifer is estimated to be $12 billion in 2002, down from $29 billion in 1974. The potential current value of the aquifer may be substantially higher, given the absence of strict policies that might mitigate the large common pool externalities encouraging over-extraction of groundwater.

Irrigation increased gradually over the Ogallala from 1950 to 1978. Initial increases in irrigation mainly reflected a shift from dryland farming, while later increases accompanied some expansion along the extensive margin of total farmland.

Crop cultivation adjusted slowly, but initial adjustments increased the water-intensity of existing cultivation. This increased use of groundwater decreased the impact of drought on the production of water-sensitive crops in Ogallala counties. Cultivation then shifted toward more water-intensive crops, and production became more sensitive to drought.

In the reverse case, following a loss in groundwater access, farmers may experience increased risk from drought as the baseline crops are produced with less water. Farmers may then adjust cultivation toward drought-resistant crops, reducing the risk from drought. Crop choice may adjust sufficiently that agricultural production becomes less sensitive to drought than when there was groundwater, though land values and total agricultural rents would still fall.

The short-run and long-run impacts of groundwater on agricultural risk are especially important in developing countries, where imperfect insurance and capital markets leave farmers vulnerable to weather shocks. Unfortunately, future research will likely be able to analyze the impacts of lost groundwater access over the Ogallala and many irrigated regions around the world.

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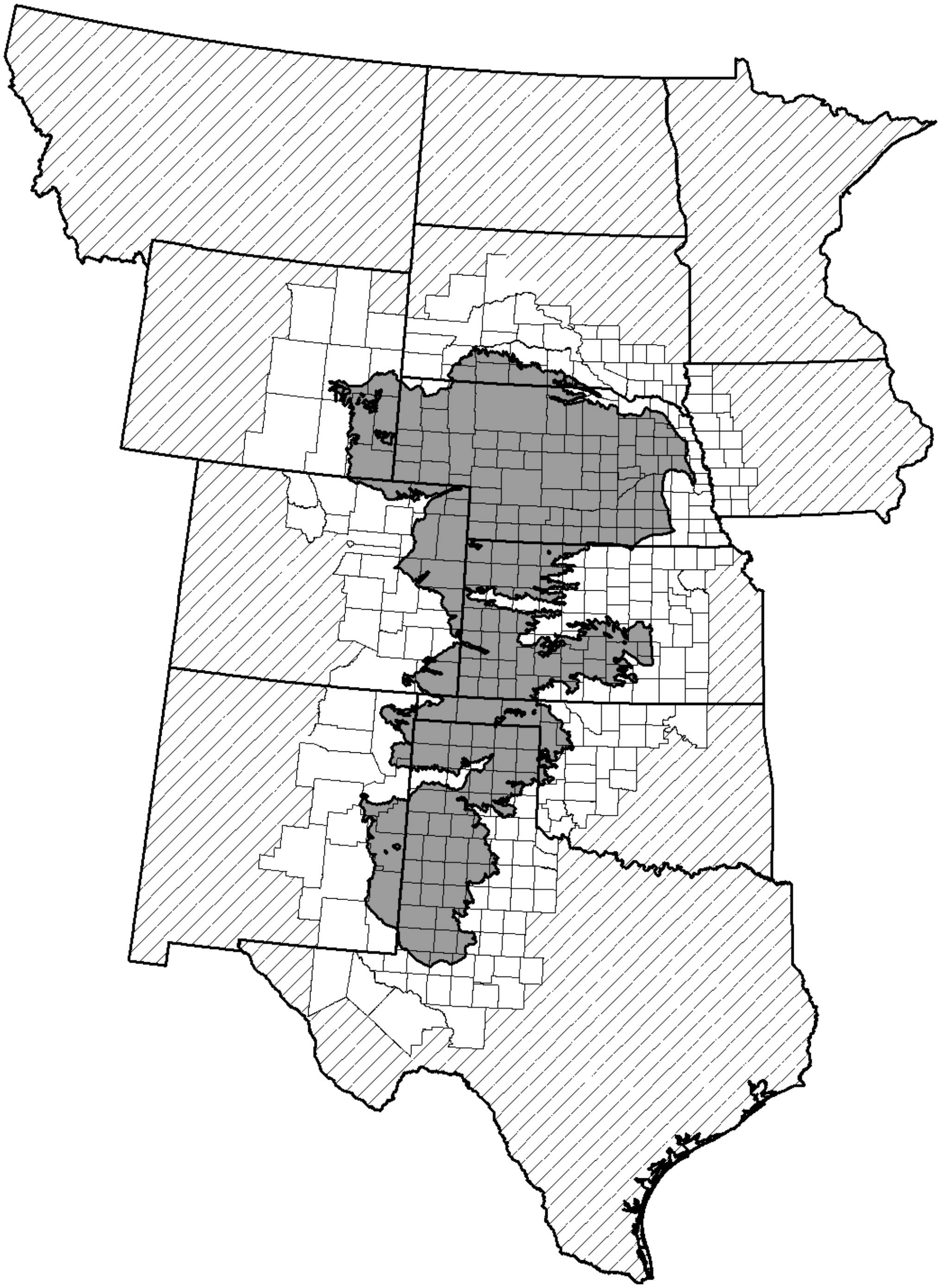
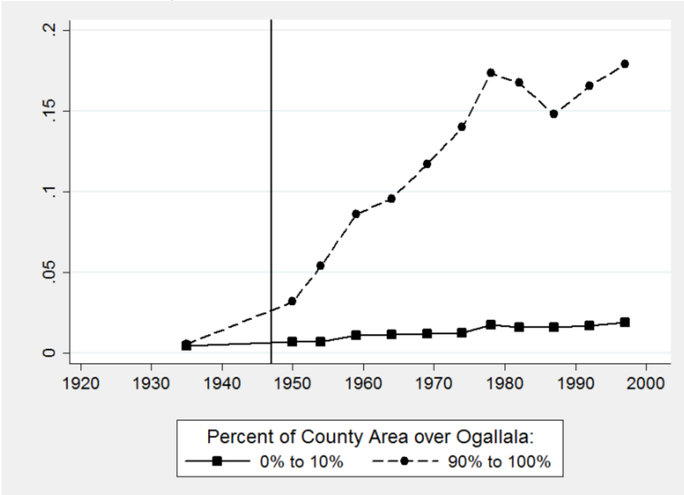
Figure 1. Ogallala Region and Counties Within 100km



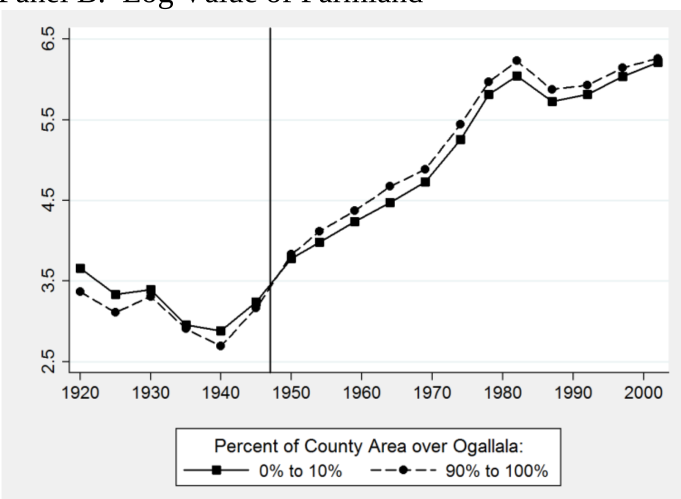
Notes: Figure 1 displays 1920 county borders for counties within 100km of the shaded Ogallala region.

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

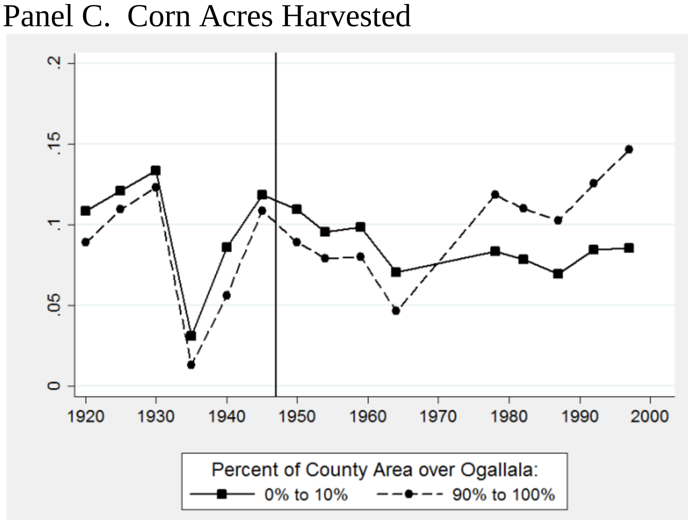
Panel A. Irrigated Farmland Acres



Panel B. Log Value of Farmland



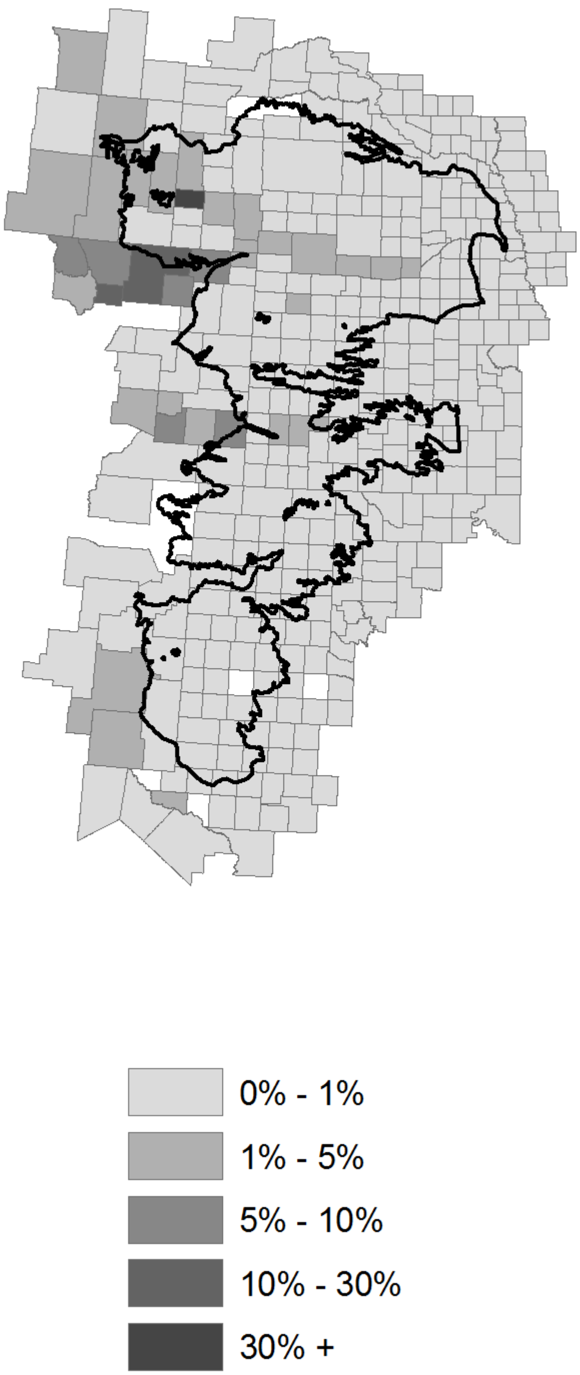
Panel C. Corn Acres Harvested



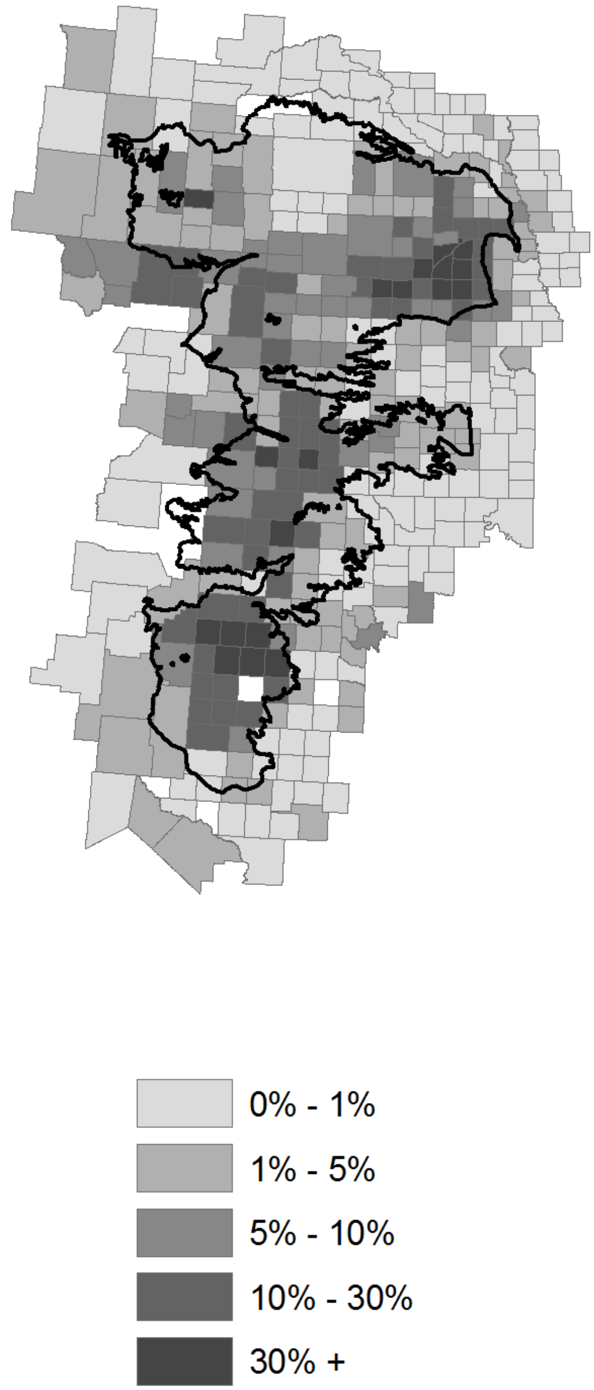
Notes: Each panel reports average characteristics for counties in two groups: those less than 10% over the Ogallala and those more than 90% over the Ogallala. Panels A and B include counties from the main 368 county sample. Panel C includes counties from the 356 county sample with corn acreage data in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

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

A. Irrigation in 1935



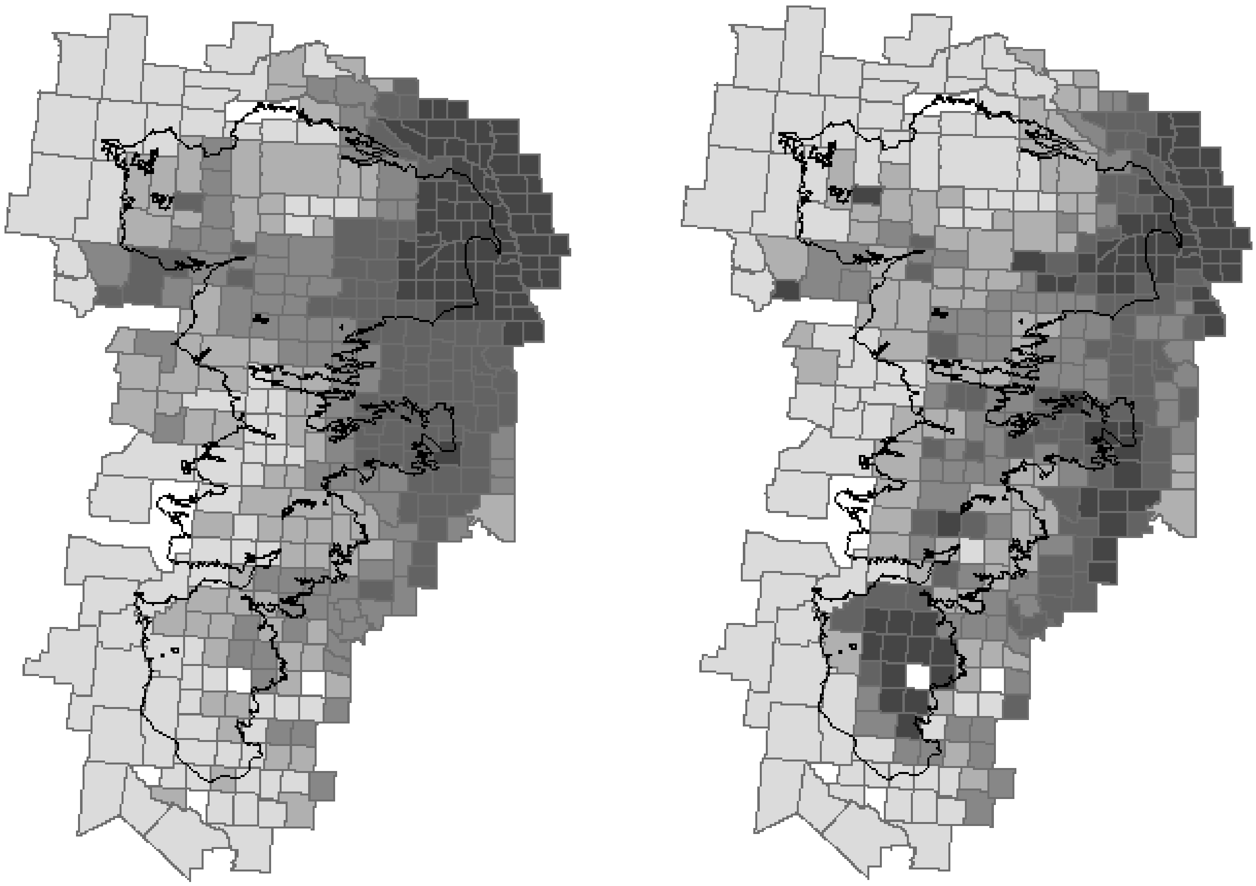
B. Irrigation in 1974



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).

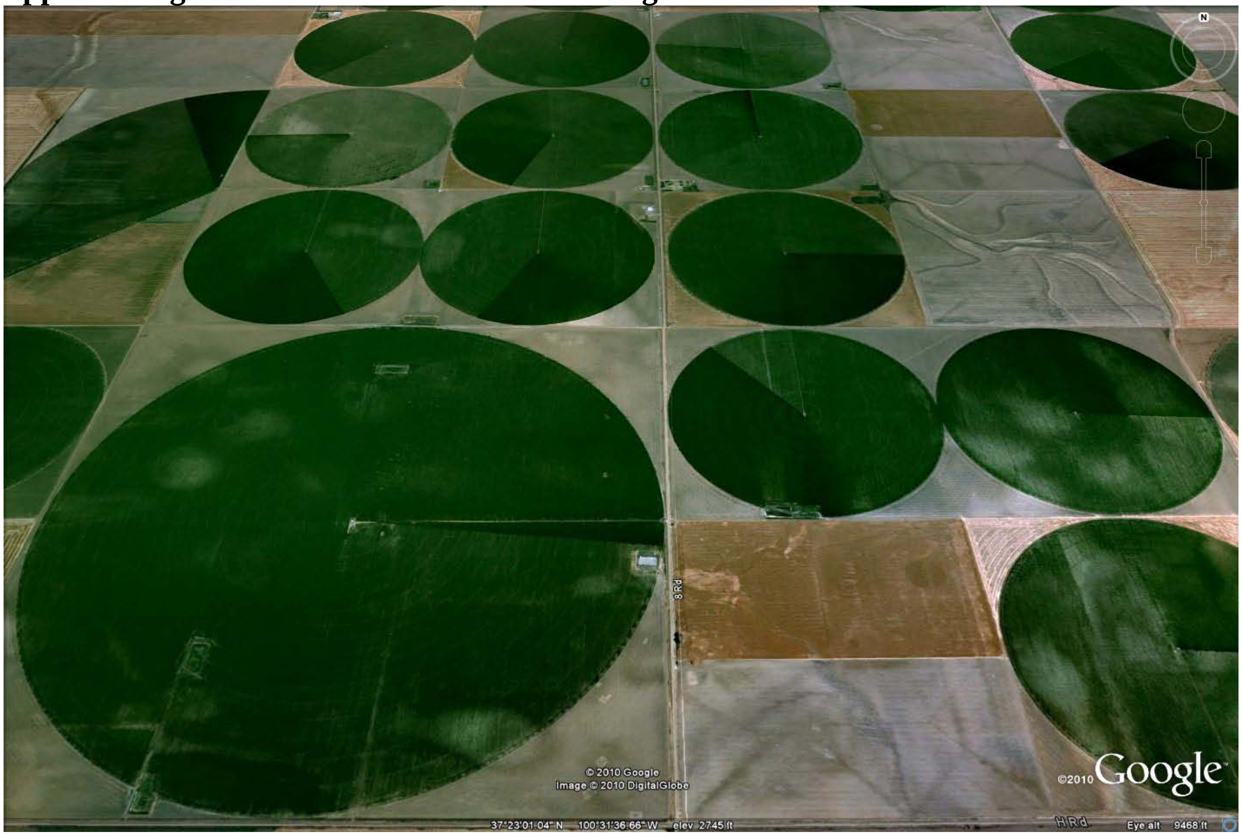
Figure 4. Farmland Value, Shaded by Quintile in Each Year

A. Farmland Value in 1920 B. Farmland Value in 1964

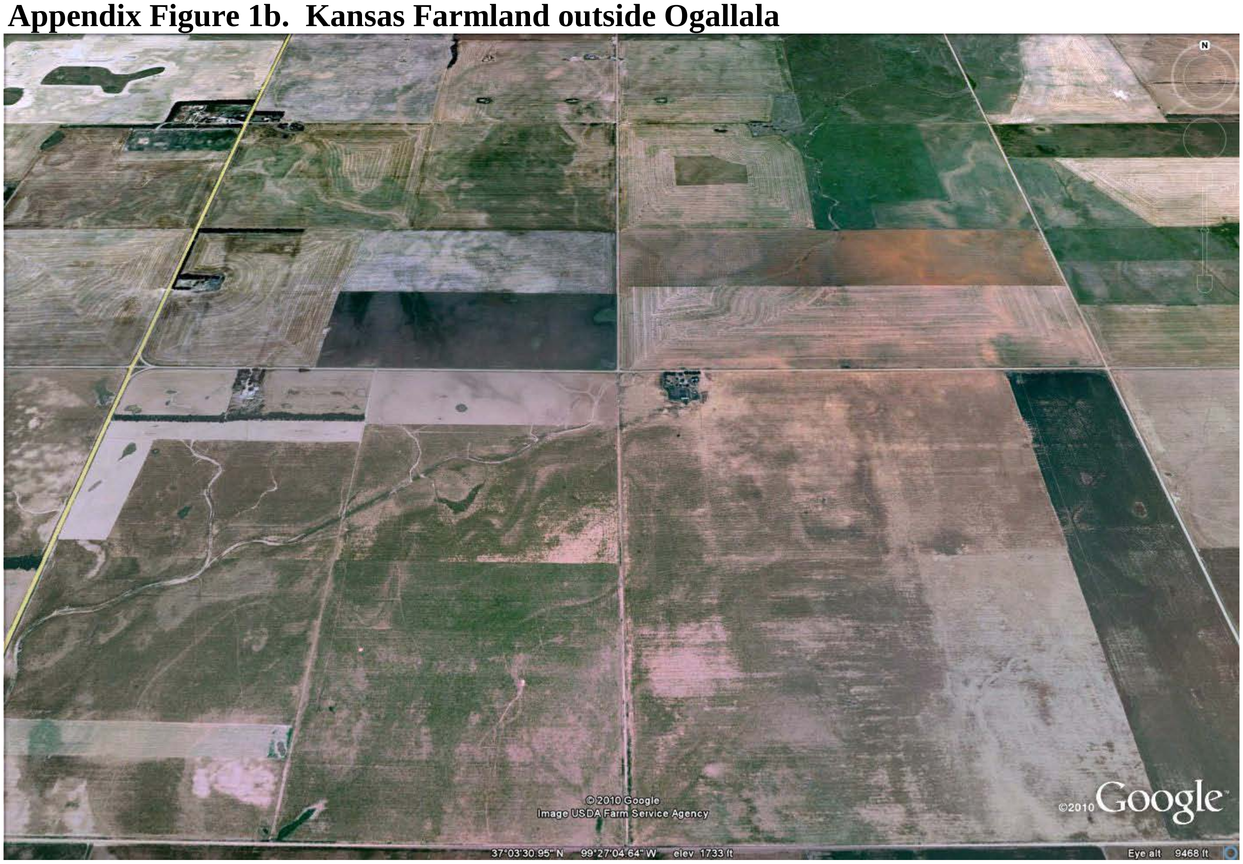


Notes: For the 368 sample counties, figures shade counties to reflect outcome quintiles in each year (darker is higher).

Appendix Figure 1a. Kansas Farmland over Ogallala

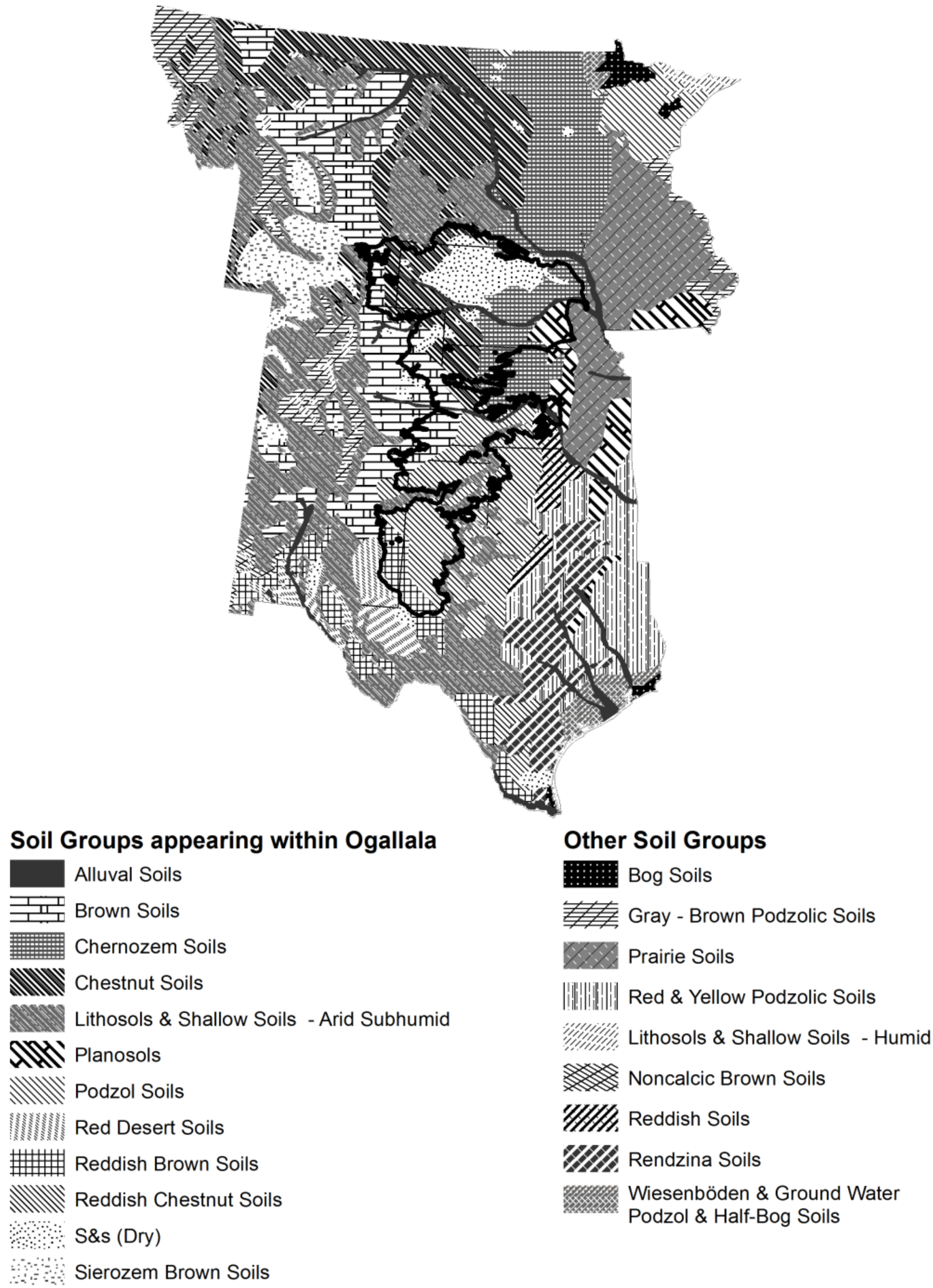


Appendix Figure 1b. Kansas Farmland outside Ogallala



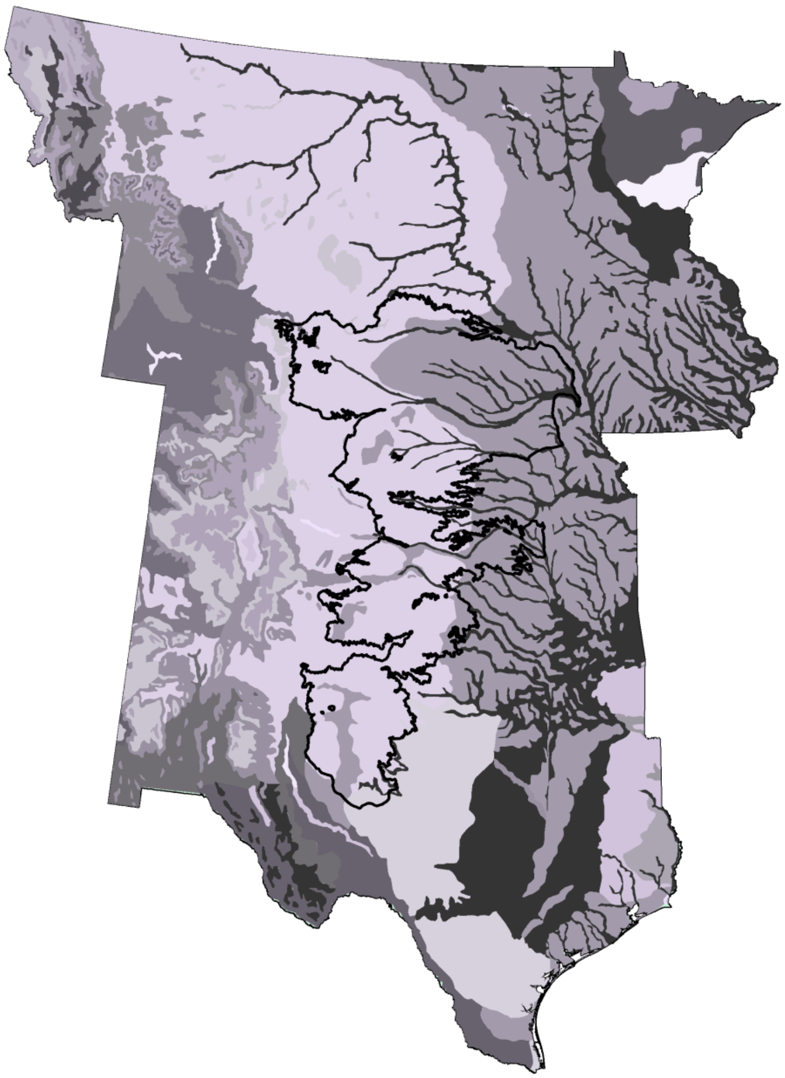
Notes: Appendix Figures 1a and 1b display recent Google Earth images from nearby counties in south central Kansas.

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)
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)

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 Year Differences by Ogallala Share: Irrigation and Land Value

Coefficient in year	Irrigated Farmland Acres per county acre (1)	Log Value Farmland per county acre (2)	Implied Ogallala Value in millions: $ (3)	$CPI (4)	$LV (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 (3) 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 Year Differences by Ogallala Share: Farmland, Corn, and Wheat

	Farmland Acres per county acre	Corn Acres Harvested per county acre		Wheat Acres Harvested per county acre	
		All Corn	Irrigated Corn	All Wheat	Irrigated Wheat
Coefficient in year	(1)	(2)	(3)	(4)	(5)
1920	0.017	0.0090	- 0.0003	- 0.0002	- 0.0010
	(0.035)	(0.0068)	(0.0002)	(0.0113)	(0.0007)
1925	- 0.001	0.0203*		0.0231*	
	(0.036)	(0.0080)		(0.0109)	
1930	0.040	0.0233**		0.0690**	
	(0.031)	(0.0088)		(0.0148)	
1935	0.053*	- 0.0021		0.0316**	
	(0.022)	(0.0029)		(0.0117)	
1940	0.009	0.0011		0.0259*	
	(0.027)	(0.0065)		(0.0102)	
1945	0.041	0.0210*		0.0379**	
	(0.025)	(0.0086)		(0.0138)	
1950	0.019	0.0138	0.0020*	0.0742**	0.0016*
	(0.026)	(0.0083)	(0.0010)	(0.0138)	(0.0007)
1954	0.042	0.0121	0.0030*	0.0295**	0.0022**
	(0.029)	(0.0073)	(0.0012)	(0.0100)	(0.0007)
1959	0.012	0.0137	0.0095**	0.0532**	0.0048**
	(0.028)	(0.0079)	(0.0026)	(0.0097)	(0.0014)
1964	0.048*	0.0043	0.0120**	0.0218*	0.0090**
	(0.024)	(0.0053)	(0.0028)	(0.0093)	(0.0019)
1969	0.059**			0.0235**	
	(0.021)			(0.0089)	
1974	0.059**			0.0325**	
	(0.018)			(0.0113)	
1978	0.067**	0.0528**	0.0665**	0.0225*	0.0162**
	(0.018)	(0.0106)	(0.0101)	(0.0103)	(0.0021)
1982	0.077**	0.0460**	0.0591**	0.0312*	0.0223**
	(0.018)	(0.0099)	(0.0098)	(0.0123)	(0.0027)
1987	0.064**	0.0449**	0.0562**	0.0285**	0.0193**
	(0.019)	(0.0090)	(0.0089)	(0.0102)	(0.0026)
1992	0.054**	0.0581**	0.0686**	0.0147	0.0206**
	(0.019)	(0.0110)	(0.0105)	(0.0114)	(0.0028)
1997	0.066**	0.0730**	0.0778**	0.0139	0.0166**
	(0.020)	(0.0121)	(0.0111)	(0.0116)	(0.0022)
R-squared	0.562	0.791	0.545	0.728	0.479
Sample Counties	368	356	333	333	313

Notes: Columns 1-5 report estimates from equation (3) 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.

Table 4. Estimated Impacts of Drought and Ogallala on Crop Yields

	Log Corn Yield			Log Wheat Yield		
	1940 to 1993		1958 to 1993	1940 to 1993		1958 to 1993
	(1)	(2)	(3)	(4)	(5)	(6)
(1958 - 1971)	0.162			0.447**		
	[0.089]			[0.038]		
(1972 - 1993)	0.705**			0.619**		
	[0.080]			[0.033]		
Ogallala * (1958 - 1971)	0.439**	- 0.148		0.040	- 0.022	
	[0.110]	[0.143]		[0.065]	[0.041]	
Ogallala * (1972 - 1993)	0.716**	0.126	0.264*	0.206**	0.104*	0.041
	[0.090]	[0.165]	[0.113]	[0.058]	[0.052]	[0.040]
Drought * (1940 - 1957)	- 0.197**			- 0.124**		
	[0.018]			[0.021]		
Drought * (1958 - 1971)	- 0.449**			- 0.163**		
	[0.090]			[0.015]		
Drought * (1972 - 1993)	- 0.163**			- 0.145**		
	[0.036]			[0.023]		
Ogallala * Drought * (1940 - 1957)	0.0570*	- 0.071*		- 0.108**	- 0.064	
	[0.023]	[0.032]		[0.037]	[0.035]	
Ogallala * Drought * (1958 - 1971)	0.371**	0.287*	0.145*	- 0.085*	0.003	- 0.044
	[0.101]	[0.118]	[0.062]	[0.042]	[0.037]	[0.038]
Ogallala * Drought * (1972 - 1993)	0.169**	- 0.177*	- 0.119*	- 0.036	- 0.027	0.001
	[0.046]	[0.076]	[0.0535]	[0.034]	[0.027]	[0.020]
County Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
State-Soil-X/Y * Time Period	No	Yes	Yes	No	Yes	Yes
State-Soil-X/Y * Time Period * Drought	No	Yes	Yes	No	Yes	Yes
R-squared	0.756	0.794	0.733	0.522	0.603	0.470
Sample Counties	134	134	200	165	165	243
States Included	NE-OK-SD-IA	NE-OK-SD-IA	NE-OK-SD-IA KS-CO-WY-NM	OK-SD KS-CO-WY	OK-SD KS-CO-WY	NE-OK-SD KS-CO-WY

Notes: To Come, see discussion of equations 4 and 5 in the text on pages 14 and 15.

Appendix Table 1. Estimated Year Differences by Ogallala Share: Farm Revenue

Coefficient in year	Log Farm Revenue per county acre (3)
1920	- 0.025
	(0.121)
1925	- 0.008
	(0.123)
1930	0.200*
	(0.099)
1935	
1940	- 0.100
	(0.103)
1945	0.360**
	(0.098)
1950	0.417**
	(0.107)
1954	0.382**
	(0.116)
1959	0.517**
	(0.111)
1964	0.502**
	(0.123)
1969	0.670**
	(0.120)
1974	1.005**
	(0.129)
1978	0.934**
	(0.128)
1982	1.054**
	(0.129)
1987	1.011**
	(0.129)
1992	1.149**
	(0.147)
1997	1.305**
	(0.150)
2002	1.399**
	(0.152)
R-squared	0.888
Sample Counties	368

Notes: To Come, see notes to Table 3