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The Historically Evolving Impact of the Ogallala Aquifer: Agricultural Adaptation to Groundwater and Drought[†]

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Agriculture on the American Plains has been constrained historically by water scarcity. Post-WWII technologies enabled farmers over the Ogallala aquifer to extract groundwater for large-scale irrigation. Comparing counties over the Ogallala with nearby similar counties, groundwater access increased agricultural land values and initially reduced the impact of droughts. Over time, land use adjusted toward water intensive crops and drought sensitivity increased. Viewed differently, farmers in nearby water-scarce areas maintained lower-value drought-resistant practices that fully mitigate naturally higher drought sensitivity. The evolving impact of the Ogallala illustrates the importance of water for agricultural production, but also the large scope for agricultural adaptation to groundwater and drought. (*JEL* N51, N52, Q15, Q25, Q54)

Water resources are critical to agricultural development in many arid regions, such as the Western United States (Coman 1911; Hansen, Libecap, and Lowe 2011) and India (Rao 1979; Shah 1993; Moench 1996; Hasnip and Hussein 1999; Schoengold and Zilberman 2007; Keskin 2009).[1] Water availability is determined in part by irrigation and production choices, however, which confounds empirical analysis of agricultural adaptation to water availability.[2] Adaptation is difficult to identify in a cross-section or short panel, but historical changes in groundwater access provide an opportunity to observe how agriculture adapts in the short run and long run to available water resources and the threat of drought.

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[1] Water scarcity is often exacerbated by inefficient water allocation, and much research has focused on common pool externalities and the institutional structure for water allocation (Gisser 1983; Ostrom 1990; Blomquist 1994; Aggarwal and Narayan 2004; Foster and Rosenzweig 2008; Rosegrant, Ringler, and Zhu 2009; Libecap 2011; Ostrom 2011; Sekhri 2011).

[2] In general, the degree of long-run adaptation is central to understanding the environment's economic impacts (Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2006; Deschênes and Greenstone 2007; Guiteras 2009; Schlenker and Roberts 2009; Olmstead and Rhode 2011; Dell, Jones, and Olken 2012; Hornbeck 2012).

This paper analyzes the short-run and long-run impacts of groundwater on agricultural land-use and drought sensitivity, exploiting local variation in Plains counties' access to the Ogallala aquifer. The Ogallala was formed by ancient runoff from the Rocky Mountains, trapped below the modern Great Plains, and it maintains distinct irregular boundaries that cut across modern soil groups and natural vegetation regions. The Ogallala was first discovered in the 1890s, but it remained mainly inaccessible. Following World War II, improved pumps and center pivot irrigation technology made Ogallala groundwater available for large-scale irrigated agriculture.

Increased access to groundwater has theoretically distinct short-run and long-run impacts when farmers are able to adjust production methods faster than land allocations. In the short run, farmers increase irrigation intensity and crop yields become less sensitive to drought. In the long run, farmers also shift land toward water intensive crops and crop yields become more sensitive to drought. The net impact of groundwater on drought sensitivity is theoretically ambiguous, depending on relative adjustment along the intensive (short-run) and extensive (long-run) margins.[3] In each period, the net present value of access to groundwater is capitalized in agricultural land values.

The baseline empirical specifications compare counties over the Ogallala with nearby counties in the same state, controlling for soil characteristics, climate, longitude, and latitude. Historical county-level data are drawn from the Census of Agriculture and merged with a United States Geological Survey map of the Ogallala's boundary. Extended empirical specifications estimate the interaction between groundwater and drought, using annual data on crop yields and drought severity. Ogallala counties and non-Ogallala counties had similar characteristics prior to improved groundwater availability, lending support to the identification assumption that Ogallala counties would otherwise have been similar to non-Ogallala counties.

Following the introduction of improved pumps and center pivot irrigation technology, irrigated farmland increased substantially in counties over the Ogallala, both in absolute terms and relative to nearby similar counties. Farmers increased irrigation first along the intensive margin, shifting nonirrigated farmland to irrigation, before somewhat expanding total farmland.

In the production of crops, farmers' initial response was to increase the irrigation intensity of corn and wheat. Irrigated corn acreages and irrigated wheat acreages increased, while total corn and wheat acreages were mostly unchanged. In later periods, farmers shifted land toward the more water intensive corn.

Consistent with the model, farmers' short-run adjustments reduced the impact of drought on water intensive corn yields. In the long run, changes in land allocation reestablished the impact of drought on corn yields. While groundwater irrigation did not reduce drought sensitivity in the long run, these estimates imply that farmers in nearby water scarce counties have maintained drought-resistant agricultural practices that fully mitigate their naturally higher sensitivity to drought.

Groundwater is a valuable agricultural asset, improving drought resistance in the short run and increasing production of higher value crops in the long run. Estimated

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[3] In the opposite case, when farmers lose access to groundwater, the short-run response is to decrease irrigation intensity and yields become more sensitive to drought. In the long run, farmers shift land from water intensive crops and yields become less sensitive to drought.

land value premiums capitalized the Ogallala's peak value at $25 billion in the 1960s and, as extraction rates remained high and water levels declined, the Ogallala's estimated value fell to $10 billion in 2002.[4] The impact on agricultural revenues has been increasing over time, particularly as farmers adjusted toward high-value water intensive corn. In the modern period, declining land values and rising revenues are consistent with expectations that many areas will lose access to Ogallala groundwater.

The historically evolving impact of the Ogallala aquifer illustrates both the importance of water for agricultural production and the large scope for agricultural adaptation to groundwater and drought. Increased access to groundwater decreased initial sensitivity to drought, but subsequent adjustment toward high-value water intensive crops was associated with no long-run decline in drought sensitivity. Viewed differently, however, farmers in nearby water-scarce areas have maintained lower value drought-resistant practices that fully mitigate their naturally higher sensitivity to drought. Particular agricultural practices differ widely across places and time periods, but historical perspective from the Ogallala aquifer provides a stark example of the potential long-run agricultural adaptation to available water resources and the threat of drought.

I. Background on the Ogallala Aquifer

The Ogallala aquifer is one of the world's largest underground freshwater sources. It was formed by ancient runoff from the Rocky Mountains, trapped amidst accumulated sand, gravel, clay, and silt. The Ogallala's boundaries are sharply defined by the location of ancient valleys and hills, which have long since been covered and obscured on the surface.[5] The Ogallala is a closed aquifer, essentially a nonrenewable resource, that receives less than an inch of annual recharge due to minimal rainfall, high evaporation, and low infiltration of surface water (Zwingle 1993; Opie 1993; McGuire et al. 2003).[6]

The Ogallala was first discovered by the United States Geological Survey in the 1890s, but it was considered of limited agricultural importance (Webb 1931; Bennett et al. 1937). Windmill pumps could only provide small quantities of water, approximately enough to irrigate 5 acres or provide for 30 cattle (Cunfer 2005). In a 1928 bulletin, the Nebraska Agricultural Extension Service highlighted the need for improved irrigation methods to supplement scarce rainfall and streams: while "the underground water supply is abundant," there are insufficient means of "lifting it to the surface and applying it to the land" (Weakly and Zook 1928). Groundwater irrigation was thought to be of great potential value, particularly in raising corn

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[4] These land value premiums are expressed in constant 2002 dollars, based on an index of land values in non-Ogallala areas.

[5] Local irrigation potential from the Ogallala is determined by three main characteristics: depth of water (distance between the ground surface and the surface of the aquifer); saturated thickness (distance from surface of the aquifer to the Triassic clay bottom of the aquifer); and specific yield (amount of water that can be extracted from a unit volume of saturated ground). The loss of saturated thickness will exhaust some areas' potential for large-scale irrigation as water levels continue to decline, though there is not much local variation in these characteristics that could be used in the empirical analysis. Declining water levels are partly endogenous to local water withdrawals, so the empirical analysis focuses on preextraction access to Ogallala groundwater.

[6] Artificial recharge has been considered but found infeasible. The 1968 Texas Water Plan considered diverting water from the Mississippi River, but the Army Corps of Engineers estimated an annual requirement of 50 billion kilowatts of electricity ($5 billion in 2010) and Texas abandoned the plan (Opie 1993).

yields, but pumps were small and expensive (Weakly 1932, 1936; Brackett and Lewis 1933).

After World War II, automobile engines were adapted to power improved pumps, lifting groundwater cheaply and in larger volumes. In the 1950s, Nebraska Agricultural Extension Service bulletins discuss the growing importance of groundwater irrigation pumps (Epp 1954). Thorfinnson and Epp (1953) report that pump irrigation increases corn yields and "serves as partial insurance against the hazards of drought." Rhoades et al. (1954) discuss how, as lands become irrigated, farmers can adjust corn "production practices to take full advantage of irrigation water." To guide adaptation in sub-humid Plains areas, Gertel (1956) draws lessons from a local Nebraska river basin; through production adjustments, irrigation allows a higher-value crop rotation, with an emphasis on corn, and provides partial insurance against drought.

In these early years, groundwater was mainly pumped into open irrigation furrows. Sprinkler systems were not widely adopted due to technical limitations and high costs (Bonnen 1952). In Texas, agricultural bulletins in 1952 focused on wheat production, for which irrigation "is generally a practice of supplementing the natural rainfall and is not an intensive irrigation of the crop" (Porter, Atkins, and Whitfield 1952). "Only a limited amount of corn is grown" and "practically all of the corn acreage is under irrigation because of the low natural rainfall" (Rogers and Collier 1952).

Groundwater irrigation increased substantially with the subsequent introduction and adoption of center pivot technology. This new technology combined recent advances in turbine pumps, steel and aluminum pipes, and lawn sprinklers. Early center pivot machines were unreliable, but larger manufacturing companies improved the designs and increased large-scale production and distribution through the 1950s.

As pumping and center pivot irrigation technologies were improved and adopted, Ogallala groundwater became increasingly used for irrigation and farmers' withdrawals quickly surpassed the aquifer's natural recharge rate. The USGS estimates that groundwater withdrawals quintupled from 1949 to 1974 and water tables have declined substantially from predevelopment levels (McGuire et al. 2003; Little 2009).[7] Most areas retain sufficient groundwater to supply irrigation pumps, though small sections of the Ogallala have started to become unavailable for large-scale irrigation.[8]

The Ogallala represents a classic "common pool" problem, in which individual water users do not pay the social cost of water extraction. Farmers' water extraction draws from broader areas such that, over time, there is little effect on farmers' own water levels.[9] There has been little strict regulation of water use, though some states and local water management districts have increasingly limited new wells, restricted "wastage," and explored well metering.[10] Depletion of the aquifer may encourage

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[7] O'Brien et al. (2001), Peterson and Ding (2005), and Pfeiffer and Lin (2010) analyze Ogallala farmers' adoption of irrigation technology and changes in groundwater extraction. Torell, Libben, and Miller (1990) compare the market value of irrigated and nonirrigated farms in the Ogallala region, though irrigation decisions may be correlated with unobserved land and farm characteristics.

[8] Irrigation costs increase as water levels decline, but the increase in pumping costs does not appear to be of first-order importance for areas that retain a saturated thickness above the minimum threshold.

[9] Underground water flows vary in speed throughout the Ogallala, but in no area would individual farmers internalize a meaningful portion of their private water extraction. This feature of the Ogallala aquifer precludes an analysis of how water use decisions vary with the magnitude of the externality.

[10] See McGuire et al. (2003) for a review of state management policies.

reform of water institutions (e.g., Demsetz 1967), though states have competing interests and federal tax code magnifies the externality by allowing irrigating farmers to depreciate the value of Ogallala water level declines.[11]

Ogallala groundwater has visibly transformed the Plains landscape above the aquifer, as center pivot irrigation creates distinctive circular crop patterns nested within traditionally square land plots.[12] While irrigation infrastructure channels river water over long distances in the Western United States, farmers outside the Ogallala do not have direct access to Ogallala groundwater.[13]

II. Agricultural Adaptation to Groundwater and Drought

Technological innovations substantially increased water availability for agriculture over the Ogallala. In this simple model, farmers can adjust the water intensity of production on the intensive margin (within crops) and the extensive margin (between crops). Depending on the relative speed and magnitude of adjustment on the intensive and extensive margins, groundwater access has different short-run and long-run impacts on the sensitivity of agricultural production to drought. The overall productive value of groundwater is capitalized in land values.

A. *Baseline Model of Agricultural Adaptation to Groundwater*

Assume that a farmer uses water and land to produce rents from two crops, according to two concave production functions, $y_1(w_1, L_1)$ and $y_2(w_2, L_2)$. Water and land increase production of both crops, but the first crop is more water intensive.[14]

The farmer maximizes total rents, subject to a water constraint $(w_1 + w_2 = \overline{w})$ and a land constraint $(L_1 + L_2 = 1)$.[15] 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, i.e., a technological improvement in access to Ogallala groundwater, affects agricultural production along the intensive and extensive margins:

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

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[11] Since a legal decision in 1965, Ogallala groundwater has been declared a nonrenewable resource and treated similarly to timber and minerals (US Court of Appeals, http://bulk.resource.org/courts.gov/c/F2/347/347.F2d.103.20972.html). The depreciation allowance is given to farmers extracting water, based on estimated declines in the general water table (http://taxmap.ntis.gov/taxmap/pubs/p225-034.htm).

[12] In the corners of plots, farmers either accept lower yields or plant less water intensive crops. Less often, farmers install more costly irrigation equipment that also reaches the corners.

[13] For example, pumped Ogallala groundwater is not diverted to non-Ogallala areas through pipelines. There is mixed evidence, however, on whether irrigation broadly affects downwind precipitation (see DeAngelis et al. 2010 for a recent study).

[14] In particular, we introduce three assumptions. First, the marginal product of water is higher for the first crop, $\partial y_1/\partial w_1 > \partial y_2/\partial w_2 > 0$. Second, the marginal product of water declines slower for the first crop, $\partial^2 y_2/(\partial w_2)^2 < \partial^2 y_1/(\partial w_1)^2 < 0$. Third, water and land are complementary for both crops, but weakly more so for the first crop, $\partial^2 y_1/\partial L_1 \partial w_1 \geq \partial^2 y_2/\partial L_2 \partial w_2 > 0$.

[15] While water availability is not actually subject to a hard constraint, this simplified model captures the intuition of cases where the costs of obtaining water for irrigation are lowered by improved technological access to Ogallala groundwater.

On the intensive margin, the farmer uses more water for the water intensive crop. On the extensive margin, land is shifted toward the water intensive crop.[16] Refer to the online Appendix for a proof of the comparative statics in equation (1).

In a dynamic setting, agricultural adjustment may be delayed on the intensive margin and/or extensive margin.[17] Agricultural land use adjustment may be delayed by switching costs, or otherwise constrained by agricultural policy. Agricultural rents increase as production adjusts along both margins. Agricultural land values increase immediately in anticipation of later rent increases, to the extent that the increase in groundwater availability is unexpected.

B. *Adaptation to Drought Risk and Groundwater*

Of further interest is how a farmer adapts to the threat of drought, particularly when there is a change in groundwater availability. Assume that a risk-neutral farmer's agricultural production function depends on an additional drought term, $y_1(w_1, L_1, d) + y_2(w_2, L_2, d)$. Drought d is unexpected, reflecting deviations from average weather conditions, and farmers cannot respond by changing water or land inputs.[18] Groundwater partially mitigates the negative impact of drought, particularly for the water intensive crop.[19]

The farmer continues to maximize total rents, subject to constraints on water and land. Given optimal allocations of water and land, the impact of drought is given by $\partial y_1(L_1^*, w_1^*, d)/\partial d + \partial y_2(L_2^*, w_2^*, d)/\partial d$. Of particular interest, an increase in the water endowment has an ambiguous effect on the impact of drought:

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

On the intensive margin, an increase in water mitigates the impact of drought on each crop (the first term). On the extensive margin, however, land shifts toward the more drought sensitive crop (the second term). The water intensive crop may also become more sensitive to drought as the land allocation shifts (e.g., growing corn in the Texas panhandle).

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[16] Changes in water usage for the less water intensive crop $(\partial w_2^*(\overline{w})/\partial \overline{w})$ can be positive or negative, depending on the production function parameters.

[17] The increase in groundwater availability may also be gradual, as pumping and center pivot irrigation technologies improve.

[18] In practice, a farmer may partially adjust inputs when a drought occurs. For the model, it is only necessary that a farmer is less able to adjust inputs after a drought is known than before the season began.

[19] In particular, we introduce two additional assumptions. First, drought decreases the productivity of land for both crops, but drought has a larger negative effect on the water intensive crop, $\partial^2 y_1/\partial L_1 \partial d < \partial^2 y_2/\partial L_2 \partial d < 0$. Second, drought increases the productivity of water for both crops, but more so for the water intensive crop, $\partial^2 y_1/\partial w_1 \partial d > \partial^2 y_2/\partial w_2 \partial d > 0$.

If land allocations are constrained in the short run, an increase in the water endowment only increases water usage on the intensive margin and mitigates the impact of drought. In the long run, however, as land allocations adjust, drought has more impact and may even reduce agricultural production more than before. The online Appendix provides a proof of this general case.

For a stark example, consider a plausible special case in which a farmer maximizes $L_1 y_1(w_1, d) + L_2 y_2(w_2, d)$, subject to $w_1 L_1 + w_2 L_2 = \overline{w}$ and $L_1 + L_2 = 1$. After an increase in the water endowment, in the short run, per acre crop water usage increases and the impact of drought is mitigated. In the long run, however, the farmer shifts land to the water intensive crop $(\partial L_1^*(\overline{w})/\partial \overline{w} > 0)$ and per acre crop water usage is unchanged $(\partial w_1^*(\overline{w})/\partial \overline{w} = \partial w_2^*(\overline{w})/\partial \overline{w} = 0)$. Thus, in the long run, an increase in the water endowment magnifies the impact of drought. The online Appendix provides a proof of this special case.

The comparative statics are intuitive for a symmetric loss of access to groundwater. In the short run, crop choice remains fixed and there is less available water, so drought has a larger impact on production. In the long run, crop choice shifts toward the drought-resistant crop and the impact of drought is mitigated. If there is sufficient change in crop choice, then the impact of drought may become even less than before the loss of groundwater. Similarly, areas without groundwater may sufficiently adapt toward non-water intensive crops to fully mitigate their naturally higher sensitivity to drought.

III. Data Construction and County Differences by Ogallala Share

A. *Census Data and Spatial Patterns*

Historical county-level data are available every five years from the US Census of Agriculture (Gutmann 2005; Haines 2010).[20] The main variables of interest include: irrigated acres and total acres of farmland, irrigated and nonirrigated acres of corn and wheat, value of agricultural land and buildings, and value of agricultural revenue. The empirical analysis focuses on a balanced panel of 368 Plains counties, from 1920 to 2002, for which data are available in every period of analysis.[21] To account for occasional changes in county borders, census data are adjusted in later periods to maintain 1920 county definitions (Hornbeck 2010).

Figure 1 maps the Ogallala aquifer, overlaid with county borders in 1920. The shaded area reflects a United States Geological Survey (USGS) map of the aquifer's boundary prior to intensive use for agriculture. The empirical analysis focuses on this fixed original boundary, as subsequent declines in water levels are endogenous to agricultural activity. The sample is restricted to counties within 100 kilometers of the aquifer boundary.

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[20] We thank Haines and collaborators for providing additional data.

[21] The census does not report each outcome variable in each year for a broad geographic area, but the analysis for each outcome variable is restricted to a sample of years and counties for which data are available in each year.

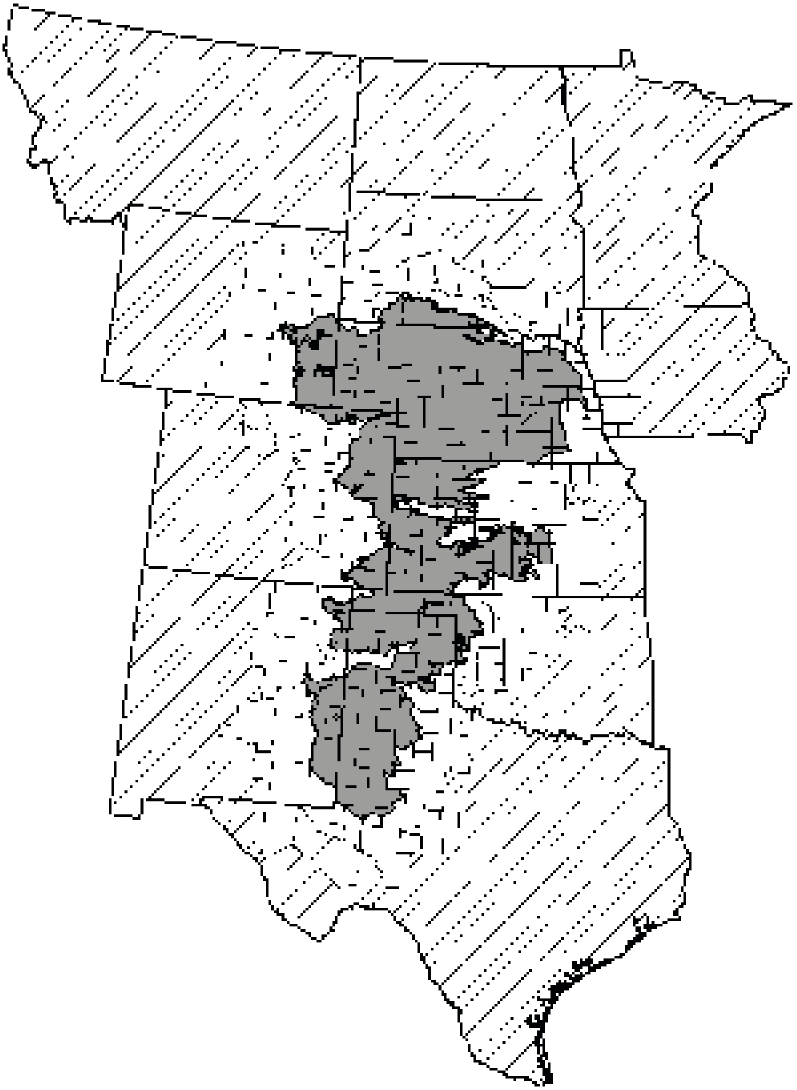

Figure 1. Ogallala Region and Counties within 100km

Notes: The shaded area represents the original boundary of the Ogallala Aquifer, as mapped by the United States Geological Survey. This map is overlaid with county borders, as defined in 1920, for all counties within 100km of the Ogallala boundary.

Figure 2 maps the 368 sample counties, shaded to reflect the irrigated percent of county land in 1935 (panel A) and 1974 (panel B). In 1935, there was little irrigation in all sample counties, aside from a few counties on major rivers. By 1974, irrigation increased substantially in counties over the Ogallala, while counties within 100 km were relatively unchanged.

Spatial patterns in agricultural land values are consistent with large economic impacts of groundwater access. Figure 3 shows counties in 1920 (panel A) and 1964 (panel B), shaded in each year to reflect their quintile in the distribution of counties' average value of agricultural land per county acre. There are strong regional

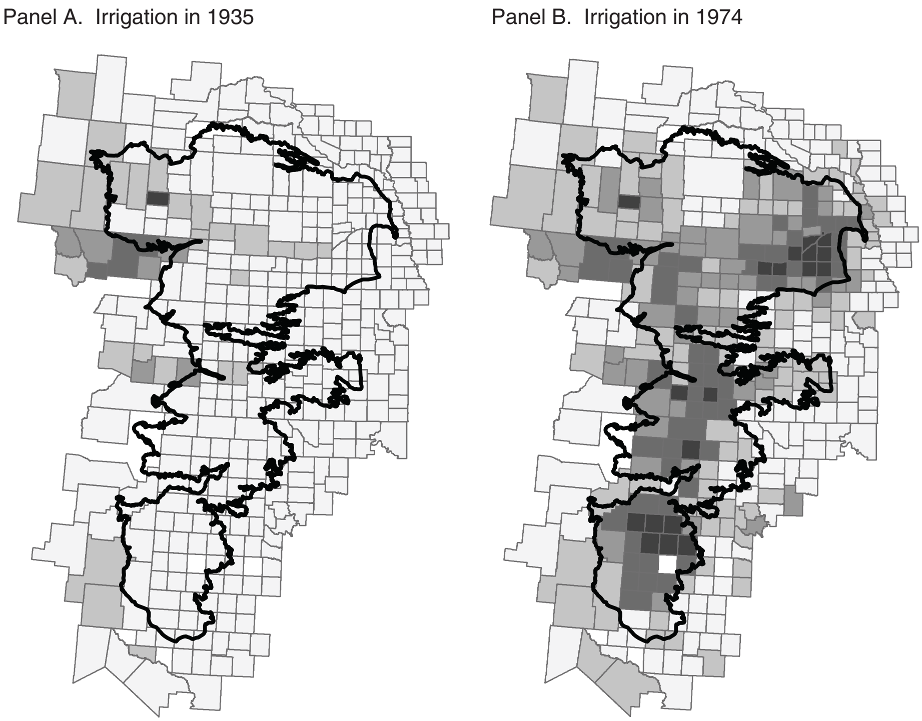

Figure 2. Irrigated Percent of County Area in 1935 and 1974

Notes: The 368 main sample counties are shaded to reflect the percent of county land irrigated in 1935 (panel A) and 1974 (panel B). The five shades of gray correspond to: less than 1 percent (lightest gray), 1 percent to 5 percent, 5 percent to 10 percent, 10 percent to 30 percent, and more than 30 percent (darkest gray). White areas are omitted from the sample.

determinants of land values. Within local areas, however, Ogallala counties and non-Ogallala counties had similar land values in 1920. By 1964, land values are generally higher over the Ogallala than in nearby counties not over the Ogallala.

The empirical research design exploits spatial variation in access to Ogallala groundwater, comparing counties over the Ogallala with nearby similar counties. To focus on comparisons among "nearby similar counties," the empirical specifications control for average differences by state, soil characteristics, climate, longitude, and latitude. Controlling for state allows for differences by region, state agricultural extension services, and other state-level policies. Controlling for major soil groups, mapped in the online Appendix (Figure 1), allows for more detailed regional determinants of agricultural production.[22] Additional controls for the soil's suitability for corn and wheat allow for changes in technology, prices, or government policies

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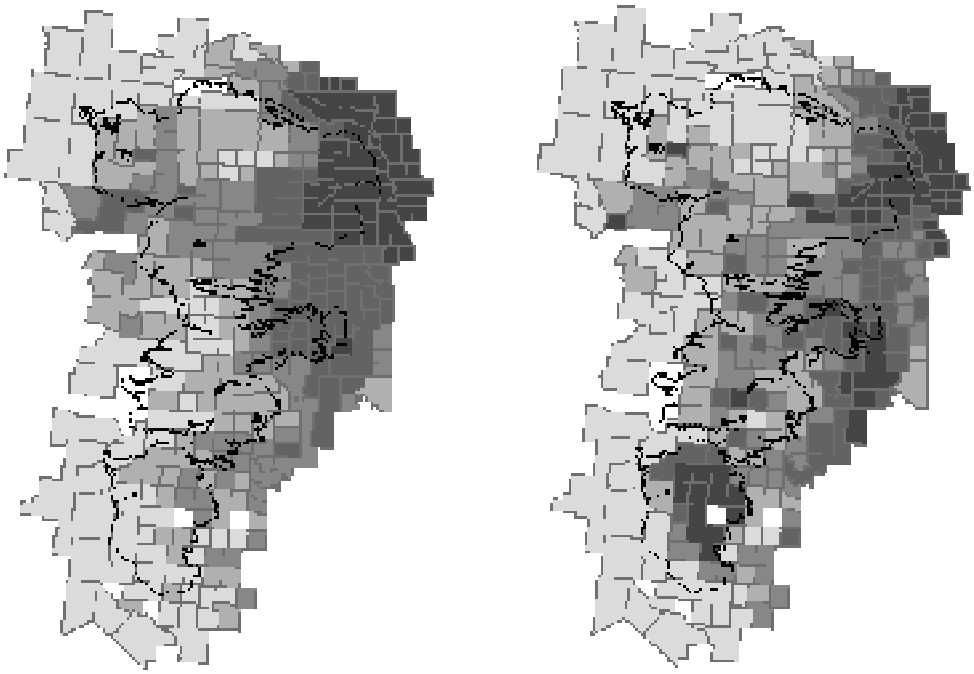
[22] For example, "Alluvial Soils" occur along major rivers and predict higher irrigation in 1935, while "Sand and Silt" in North-Central Nebraska is unproductive for agriculture. This 1951 Soil Conservation Service (SCS) map was scanned, traced in GIS software, and merged to 1920 county borders to assign each county the fraction of its area in each soil group.



Panel A. Land value in 1920

Panel B. Land value in 1964

Figure 3. Value of Agricultural Land per County Acre, Shaded by Quintile in Each Year

Notes: The 368 sample counties are shaded to reflect their quintile in the distribution of counties' average value of agricultural land per county acre in 1920 (panel A) and 1964 (panel B). The lightest gray represents the 20 percent least valuable counties, while the darkest gray represents the 20 percent most valuable counties. White areas are omitted from the sample.

that differentially affect areas suitable for different crops.[23] The Ogallala boundary cuts across major soil groups, which is important because the analysis effectively compares Ogallala and non-Ogallala counties within the same soil group.

Climate and geographic location may also influence agricultural production, even within-state and within-soil group. County-level climate data include average precipitation and average temperature (PRISM 2004), in addition to degree days between 10° C and 29° C and degree days above 29° C (Schlenker and Roberts 2009).[24] County longitude and latitude are measured using the coordinates of 1920 county centroids (MPC 2011).[25] Because non-Ogallala counties surround the Ogallala region, there is variation in Ogallala access within similar climate, longitude, and latitude.

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[23] Corn and wheat suitability reflect the maximum potential yield of each crop, as calculated by the FAO using data on climate, soil type, and ideal growing conditions for that crop. The FAO's Global Agro-Ecological Zone maps (version 3.0) are used to create county-level average crop suitability for corn and wheat. Potential yields are calculated using climate averages from 1961 to 1990 and rain-fed conditions with high inputs.

[24] Degree days are a sum over time spent within each temperature range during the growing season (March to August) multiplied by the difference between the temperature and the lower bound of that temperature range. We thank Wolfram Schlenker for providing these county-level data, which are averaged over weather from 1950 to 2000.

[25] 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 United States. 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.

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

		Coefficient on Ogallala Share:			
Per county acre:	County means (1)	No controls (2)	State fixed effects (3)	State and soil group (4)	State, soil, climate, X/Y (5)
Farmland	0.706 [0.249]	0.140*** (0.039)	0.020 (0.032)	−0.001 (0.034)	−0.032 (0.039)
Irrigated farmland, 1935	0.007 [0.020]	−0.0013 (0.0024)	−0.0013 (0.0022)	−0.0026 (0.0027)	−0.0019 (0.0041)
log value of farmland and farm buildings	2.87 [1.30]	0.432** (0.194)	−0.203 (0.155)	−0.057 (0.120)	−0.028 (0.132)
log value of farm revenue	1.75 [1.18]	0.306 (0.177)	−0.217 (0.147)	−0.102 (0.117)	0.095 (0.129)
Corn acres	0.054 [0.088]	0.0066 (0.0098)	−0.0347*** (0.0075)	0.0006 (0.0067)	0.0027 (0.0064)
Irrigated corn acres	0.0003 [0.0011]	0.00007 (0.00015)	−0.00006 (0.00012)	−0.00024 (0.00018)	−0.00033 (0.00020)
Wheat acres	0.077 [0.113]	0.017 (0.013)	−0.008 (0.011)	−0.003 (0.011)	0.017 (0.012)
Irrigated wheat acres	0.001 [0.003]	−0.00016 (0.00027)	−0.00007 (0.00031)	−0.00059 (0.00051)	−0.00068 (0.00078)

Notes: Column 1 reports average county characteristics in 1920, except for irrigated farmland for which data are first available in 1935. Corn and wheat data refer to acreages harvested. 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 fraction of county area over the Ogallala. Column 2 reports the unconditional difference. Column 3 controls for state fixed effects. Column 4 also controls for the fraction of county area in each soil group. Column 5 also controls for linear functions of county soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10º C and 29º C, average degree days above 29º C, longitude, and latitude. The regressions are weighted by county acres, and robust standard errors are reported in parentheses.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

B. *Pre-Differences in County Characteristics by Ogallala Share*

Prior to modern improvements in pumping and irrigation technology, the Ogallala had little impact on agriculture. The Ogallala water table is generally too deep to be accessed by natural vegetation. The online Appendix (Figure 2) shows the Ogallala boundary, overlaid with a 1924 map of natural vegetation regions (USDA 1924). The Ogallala boundary cuts across the two largest vegetation regions (“Short Grass” and “Tall Grass”) and more wooded river areas (“Oak-Hickory”).

Table 1 reports estimated differences between Ogallala counties and non-Ogallala counties, prior to the increased availability of Ogallala groundwater for intensive agricultural use. Column 1 reports average sample county characteristics in 1920, or in the earliest year available. From a regression of each outcome on the fraction of county land over the Ogallala and a constant, column 2 reports the estimated average difference between counties entirely over the Ogallala (“Ogallala counties”) and counties entirely not over the Ogallala (“non-Ogallala counties”).[26] Columns 3 to

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[26] In later years, residual scatterplots indicate that the Ogallala’s impact is roughly linear in the fraction of county land over the Ogallala. The county means and regressions are weighted by county acres, as the empirical analysis is focused on changes for an average acre of land over the Ogallala.

5 include controls to compare Ogallala counties with nearby similar non-Ogallala counties. Column 3 includes state fixed effects. Column 4 adds soil group fixed effects. Column 5 adds linear controls for soil suitability for corn and wheat, average precipitation, average temperature, degree days between 10° C and 29° C, degree days above 29° C, longitude, and latitude.

After controlling for state and soil group, there are no substantial or statistically significant differences between Ogallala counties and non-Ogallala counties in 1920. These estimates lend support to the identification assumption that Ogallala and non-Ogallala counties would have been similar in later years, if not for access to Ogallala groundwater.

The empirical specifications do not control for pre-differences in county agricultural outcomes, as early differences may be partly attributed to the Ogallala.[27] Ogallala groundwater was available to farmers on a limited scale through the use of early pumps, windmills, and irrigation techniques. Expected improvements in Ogallala access may also influence land values and investment decisions.

C. *Changes in County Characteristics by Ogallala Group*

For a preliminary view of the data, Figure 4 plots average outcomes over time for two groups of sample counties: counties less than 10 percent over the Ogallala, and counties more than 90 percent over the Ogallala.[28] By contrast, the main empirical specifications use continuous variation in counties' Ogallala share and control for other differences among sample counties.

Counties in both groups had similar low levels of irrigated farmland in 1935 (panel A). As pumping and irrigation technology improved, counties over the Ogallala increased irrigation through the 1970s. Irrigated corn acreage increased somewhat in Ogallala counties from 1954 to 1964, and was substantially higher by 1978 (panel B). By contrast, total corn acreage changed similarly from 1920 through 1964, and only became substantially higher in Ogallala counties by 1978 (panel C).[29] The value of farmland was relatively lower in Ogallala counties from 1920 into the 1940s. After the 1940s, land values became consistently higher in Ogallala counties than in non-Ogallala counties (panel D).

IV. Empirical Framework

In the main empirical specifications, outcome Y in county c is regressed on the fraction of county area over the Ogallala, state fixed effects α_s, the fraction of county area in each soil group γ_g, and linear functions of eight fixed county characteristics $\mathbf{X}_c$ (soil suitability for corn and wheat, average rainfall and temperature, degree

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[27] The empirical results are robust, however, to controlling for a county's initial value of the outcome variable, interacted with each year.

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

[29] Harvested corn acreages fell substantially during the 1930s drought and widespread crop failure.

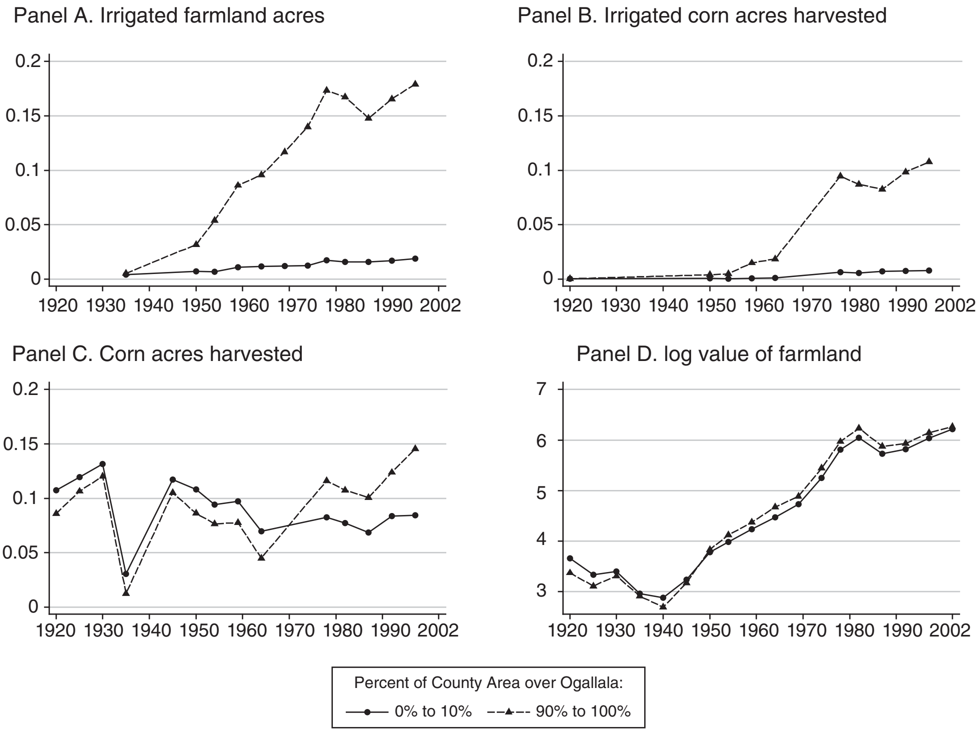

Figure 4. Average County Characteristics per County Acre, by Ogallala Group

Notes: Each panel reports average characteristics for counties in two groups: those less than 10 percent over the Ogallala and those more than 90 percent over the Ogallala. Panels A and D include counties from the main 368 county sample. Panel B (panel C) includes counties from a restricted 333 county sample (365 county sample) with irrigated corn acreage (total corn acreage) data in every period shown.

days between 10° C and 29° C, degree days above 29° C, longitude, and latitude).[30] These cross-sectional specifications are pooled across all time periods, with each coefficient allowed to vary in each time period:

$$Y_{ct} = \beta_t Ogallala_c + \alpha_{st} + \gamma_{gt} + \theta_t \mathbf{X}_c + \epsilon_{ct}. \tag{3}$$

In each time period, the estimated β reports the average difference between counties entirely over the Ogallala and counties not over the Ogallala.[31] While Ogallala water levels have declined over time, counties' Ogallala share is defined using fixed predevelopment boundaries, so that it is not affected by subsequent endogenous water use.[32]

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[30] The empirical results are robust to controlling for erosion severity following the 1930s Dust Bowl (Hornbeck 2012), though the main empirical specifications only include controls that are fixed county characteristics over the sample period.

[31] Some counties are partly over the Ogallala, and this specification assumes that the effect of the Ogallala is linear in the fraction of county area over the Ogallala. From graphing county residual changes in irrigated farmland against county residual Ogallala shares, the effect of the Ogallala appears roughly linear in the share of county area over the Ogallala.

[32] When defining counties' Ogallala share in this way, interpretation of the results must take into account that the estimated impact of the Ogallala may decline over time as some small areas lose access to groundwater and larger areas expect to lose access to groundwater in future periods.

The estimated β coefficients can be interpreted as the impact of the Ogallala in each year, under the identification assumption that sample counties would have had the same average outcomes in each year if not for the Ogallala. In practice, this identification assumption must hold after controlling for other differences correlated with state, soil, and climate. In this way, the research design exploits the sharp spatial discontinuity created by the Ogallala's irregular boundary. Robustness checks limit the sample to counties that intersect the Ogallala boundary, while other specifications test for local spillover effects of the Ogallala on nearby non-Ogallala counties.

Differences in the estimated β coefficients, from one year to another year, report the average change for an Ogallala county relative to a non-Ogallala county over that time period.[33] The change in β coefficients can be interpreted as the changing impact of the Ogallala, under the weaker identification assumption that sample counties would have had the same average changes if not for the Ogallala. Note that the standard error of the difference is generally 10–30 percent lower than the standard error of the two cross-sectional coefficients due to positive serial correlation in county-level outcomes.

The regressions are weighted by county size, which focuses the empirical analysis on the average impact of the Ogallala on lands above. Extended specifications analyze how the Ogallala's impact varies over the sample region, as Ogallala groundwater may have greater benefit in areas with less rainfall or in areas with both less rainfall and better soil.

For the statistical inference, standard errors are clustered at the county level to adjust for heteroskedasticity and within-county correlation over time. When allowing for spatial correlation among sample counties, the estimated standard errors increase by 10–15 percent, on average.[34]

V. Results

A. *Irrigation and Farmland: Intensive versus Extensive Margins*

From estimating equation (3), Figure 5 displays the estimated impact of the Ogallala in each year on acres of irrigated farmland per county acre (panel A). After the introduction of improved groundwater irrigation technologies, counties over the Ogallala became substantially more irrigated relative to nearby similar counties. Counties over the Ogallala had increased irrigation by 11 percentage points in the 1970s and maintained these higher levels through 1997.

Figure 5, panel B, displays the estimated impact of the Ogallala on acres of total farmland per county acre. Total farmland was similar in Ogallala and non-Ogallala

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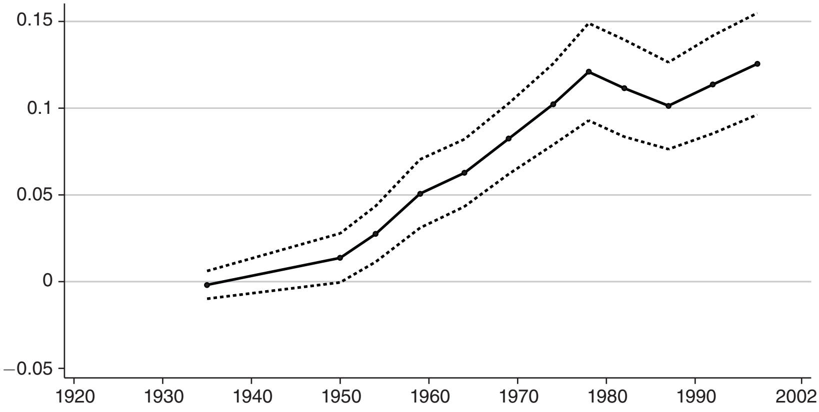
[33] Differencing the estimated coefficients is numerically equivalent to estimating equation (3) in differences or with county fixed effects. Differencing and fixed effects are equivalent for two time periods. For this multi-period regression, the specification is essentially separable for any two time periods because the explanatory variables are fully interacted with time and the sample is balanced.

[34] Spatial correlation among counties is assumed to be declining linearly up to a distance cutoff and zero after that cutoff (Conley 1999; Hsiang 2010). For a distance cutoff of 100 km or 200 km, the estimated Conley standard errors are 10 percent or 15 percent higher than the standard errors when clustering at the county level, averaging across the outcome variables and years.

Panel A. Irrigated farmland acres per county acre



Panel B. Farmland acres per county acre

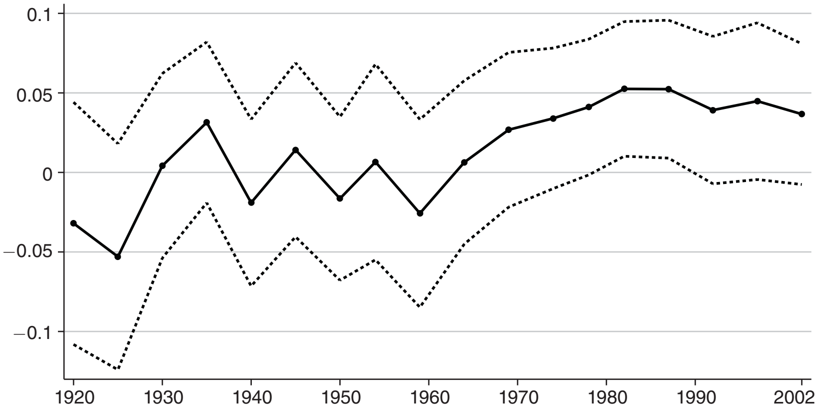


Figure 5. Estimated Differences by Ogallala Share and Year: Irrigation and Farmland

Notes: Panels A and B report estimates from equation (3) in the text: the indicated outcome variable is regressed on the share of county area over the Ogallala, state fixed effects, fraction of county area in each soil group, and linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10º C and 29º C, average degree days above 29º C, longitude, and latitude. All coefficients are allowed to vary in each year. The regressions are weighted by county acres. The dashed lines show 95 percent confidence intervals around the coefficients, based on robust standard errors clustered by county.

counties through the 1950s, but has been consistently higher, by 5 percentage points, in Ogallala counties since the 1970s.[35]

For conciseness, Table 2 reports estimated coefficients that collapse the 18 periods analyzed into 3, 6-period eras: before the Ogallala was widely available (1920–1945), as the Ogallala was becoming increasingly used (1950–1974), and after Ogallala use plateaued (1974–2002). The estimating equation is the same as

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[35] While the relative difference in total farmland is initially variable, there is a small and statistically insignificant relative trend in Ogallala counties from 1920 to 1940 or from 1920 to 1945.

TABLE 2—ESTIMATED DIFFERENCES BY OGALLALA SHARE AND ERA: IRRIGATION AND FARMLAND

Coefficient in era:	Irrigated farmland acres per county acre (1)	Farmland acres per county acre (2)	Nonirrigated farmland acres per county acre (3)
1920–1945	−0.002	−0.009	0.033
	(0.004)	(0.024)	(0.026)
1950–1974	0.057***	0.005	−0.051**
	(0.009)	(0.023)	(0.025)
1978–2002	0.115***	0.044**	−0.069***
	(0.014)	(0.020)	(0.024)
Sample counties	368	368	368

Notes: Each column reports estimates from a modified version of equation (3) in the text: the indicated outcome variable is regressed on the share of county area over the Ogallala (interacted with each era), state by year fixed effects, soil group by year fixed effects, and year-interacted linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10º C and 29º C, average degree days above 29º C, longitude, and latitude. Data for some outcome variables are only available in some years (shown in Figure 5). The regressions are weighted by county acres. Robust standard errors clustered by county are reported in parentheses.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

equation (3), except that the coefficient on Ogallala share is only allowed to vary by era rather than by year.[36] The estimated coefficients reflect the average difference between Ogallala counties and non-Ogallala counties in each era, controlling for other differences associated with the included measures of region, soil, and climate.

As Ogallala groundwater became accessible, agricultural adaptation focused initially on the intensive margin (Table 2, column 1) with little change on the extensive margin (Table 2, column 2).[37] In later periods, farmers both increased irrigation and relatively expanded total farmland.[38] Table 2, column 3, reports directly estimated changes in nonirrigated farmland that highlight this initial shift from dryland farming to irrigated farming.

B. *Corn and Wheat: Irrigated and Total Acreages*

Figures 6 and 7 show the estimated impact of the Ogallala in each year on corn and wheat acreage, which are the two major crops in this region with data availability over many years.[39] Irrigated corn and irrigated wheat acreages increased somewhat

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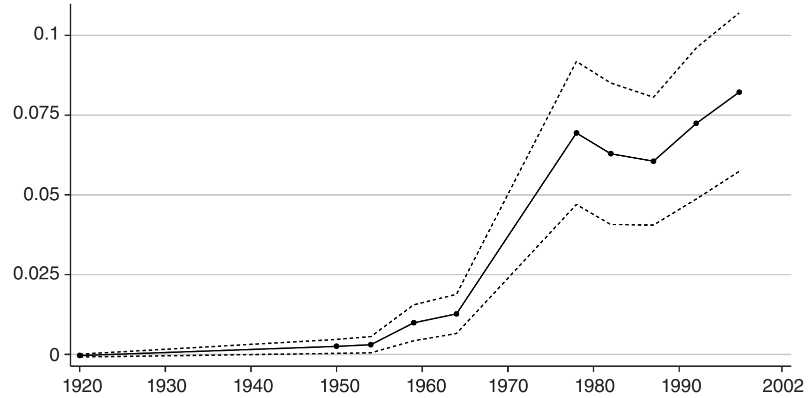
[36] In particular, note that the coefficients on the control variables are allowed to vary in each year.

[37] Estimated relative increases in irrigation are large compared to average values of irrigation per county acre in non-Ogallala counties in the 1950–1974 era (0.009) and the 1974–2002 era (0.015).

[38] Estimated relative increases in total farmland are large compared to the average amount of county land not in farms in the 1950–1974 era (0.089) and the 1974–2002 era (0.140).

[39] The empirical analysis focuses on corn (relatively more water intensive) and wheat (relatively less water intensive), which have the best available data among common crops on the US Plains. Sorghum is relatively drought resistant, but is cultivated for several purposes, and it is difficult to construct land-use and production variables that are comparable over time. Hay may be water intensive or not water intensive, depending on the variety cultivated, and varietal data are often unavailable. Cotton is mainly confined to the Southern Plains, and soybeans are mainly confined to the modern era.

Panel A. Irrigated corn acres per county acre



Panel B. Corn acres per county acre

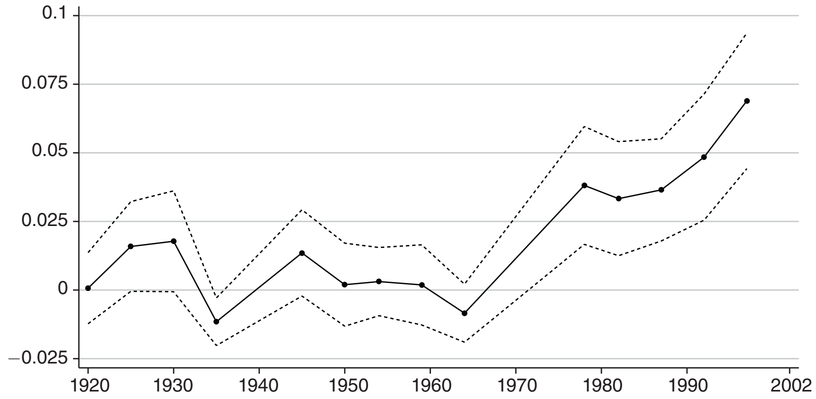


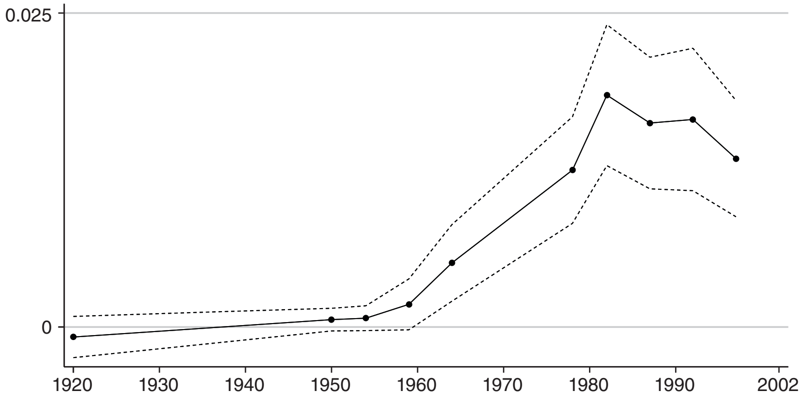
Figure 6. Estimated Differences by Ogallala Share and Year: Corn Acres Harvested

Notes: Panels A and B report estimates from equation (3) in the text: the indicated outcome variable is regressed on the share of county area over the Ogallala, state fixed effects, fraction of county area in each soil group, and linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10° C and 29° C, average degree days above 29° C, longitude, and latitude. All coefficients are allowed to vary in each year. The regressions are weighted by county acres. The dashed lines show 95 percent confidence intervals around the coefficients, based on robust standard errors clustered by county.

in Ogallala counties from 1950 through 1964 (panel A of Figures 6 and 7), but total corn and wheat acreages did not increase over this period (panel B of Figures 6 and 7). By 1978, however, there were substantial increases in both irrigated corn acreage and total corn acreage. Irrigated wheat acreage continued to increase over time, while total wheat acreage declined.

Summarizing these estimates, Table 3 reports the estimated impact of the Ogallala on corn and wheat acreage in each era. Initial adjustments to corn and wheat production focused on increasing the irrigation intensity of production, similar to the results for total irrigated land and total farmland. In the context of the model, as groundwater became increasingly available, production of both crops became more water intensive. After some delay, land allocations shifted toward the crop that is

Panel A. Irrigated wheat acres per county acre



Panel B. Wheat acres per county acre

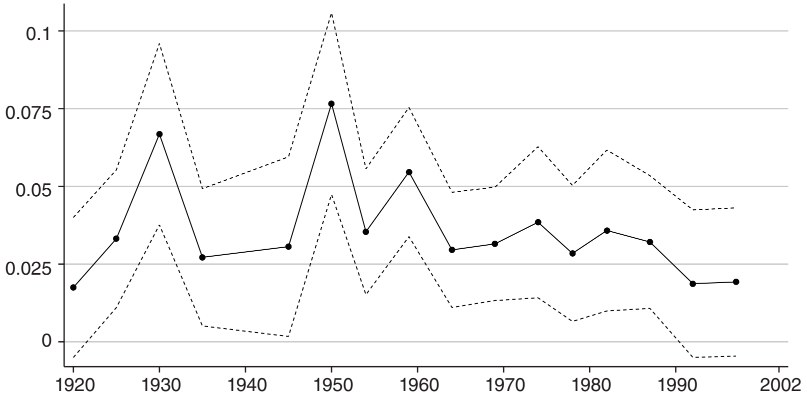


Figure 7. Estimated Differences by Ogallala Share and Year: Wheat Acres Harvested

Notes: Panels A and B report estimates from equation (3) in the text: the indicated outcome variable is regressed on the share of county area over the Ogallala, state fixed effects, fraction of county area in each soil group, and linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10° C and 29° C, average degree days above 29° C, longitude, and latitude. All coefficients are allowed to vary in each year. The regressions are weighted by county acres. The dashed lines show 95 percent confidence intervals around the coefficients, based on robust standard errors clustered by county.

both more water intensive and more drought sensitive.[40] The later adjustments on the extensive margin may reflect higher adjustment costs on the extensive margin, government agricultural policies that restricted adjustment in crop acreages, and/or commodity price increases in the 1970s that encouraged land use adjustment.

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[40] Estimated relative increases in irrigated corn and wheat are large compared to average values of irrigated corn and wheat per county acre in non-Ogallala counties in the 1950–1974 era (0.0007 for corn, 0.0002 for wheat) and the 1974–2002 era (0.0043 for corn, 0.0007 for wheat). Estimated relative changes in total corn and wheat acreage are large, but smaller relative to average corn and wheat acres per county acre in non-Ogallala counties in the 1950–1974 era (0.095 for corn, 0.081 for wheat) and the 1974–2002 era (0.082 for corn, 0.083 for wheat).

TABLE 3—ESTIMATED DIFFERENCES BY OGALLALA SHARE AND ERA: CORN AND WHEAT ACREAGES

	Corn acres harvested per county acre		Wheat acres harvested per county acre	
Coefficient in era:	Irrigated corn (1)	All corn (2)	Irrigated wheat (3)	All wheat (4)
1920–1945	−0.0004 (0.0002)	0.007 (0.007)	−0.0008 (0.0008)	0.035*** (0.011)
1950–1974	0.0070*** (0.0020)	−0.000 (0.006)	0.0021** (0.0008)	0.044*** (0.010)
1978–2002	0.0695*** (0.0115)	0.045*** (0.011)	0.0154*** (0.0025)	0.027** (0.012)
Sample counties	333	365	313	367

Notes: Each column reports estimates from a modified version of equation (3) in the text: the indicated outcome variable is regressed on the share of county area over the Ogallala (interacted with each era), state by year fixed effects, soil group by year fixed effects, and year-interacted linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10º C and 29º C, average degree days above 29º C, longitude, and latitude. Data for some outcome variables are only available in some years (shown in Figures 6 and 7). The regressions are weighted by county acres. Robust standard errors clustered by county are reported in parentheses.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

C. *Agricultural Land Value*

Figure 8, panel A, shows that the value of agricultural land and buildings became consistently higher in counties over the Ogallala after the introduction of improved pumping and irrigation technologies.[41] Land values were initially sometimes higher in Ogallala counties, which may reflect expectations of future groundwater availability, but land values became consistently higher in the 1950s.[42] The estimated premium in land values over the Ogallala peaked in the 1960s and has since declined through 2002. Table 4, column 1, reports the estimated land value premium in Ogallala counties in each of the three main eras.[43]

Our main interpretation of the decline in land value premium is that it reflects expected decreases in rents from exhaustion of groundwater. The decreased land value premium might also reflect decreased returns from water availability, though changes in commodity prices and technology have generally had the opposite effect. Agricultural rents are not directly observable, though agricultural revenues provide

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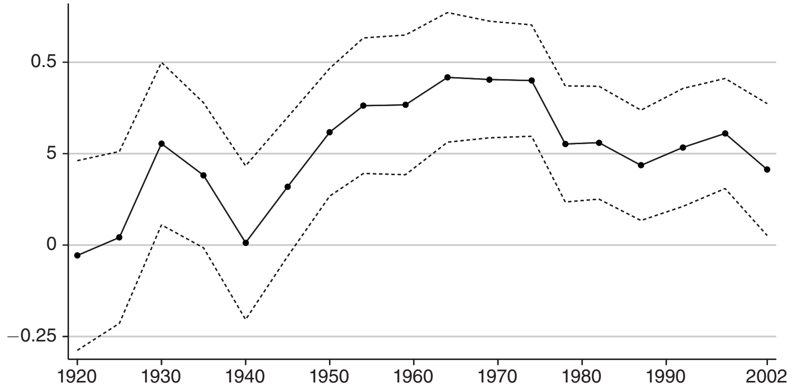
[41] Over this long time period, data are only available for the combined value of agricultural land and buildings. From 1900 to 1940, when data are available separately for land and buildings, the value of land is the much larger component. The estimates are not sensitive to whether the value of land and buildings is normalized by county acres or by "potential farmland," defined as the maximum acres of farmland in the county over the sample period.

[42] Agricultural land values are on a small and statistically insignificant relative trend in Ogallala counties from 1920 to 1940, and a larger but statistically insignificant trend from 1920 to 1945. There is no exact date, however, at which land values would switch from reflecting no impact from Ogallala access to the full impact of Ogallala access.

[43] Higher land values over the Ogallala do not appear to reflect increased demand for land in the urban sector. The Ogallala is not estimated to increase log county population or the fraction of population living in urban areas (i.e., places with population greater than 2,500). Further, the estimated land value premiums are similar or higher when restricting the sample to 253 counties with zero urban population in 1920 or 287 counties with less than 25 percent urban population in 1920.

Panel A. log farmland value per county acre



Panel B. log farmland revenue per county acre

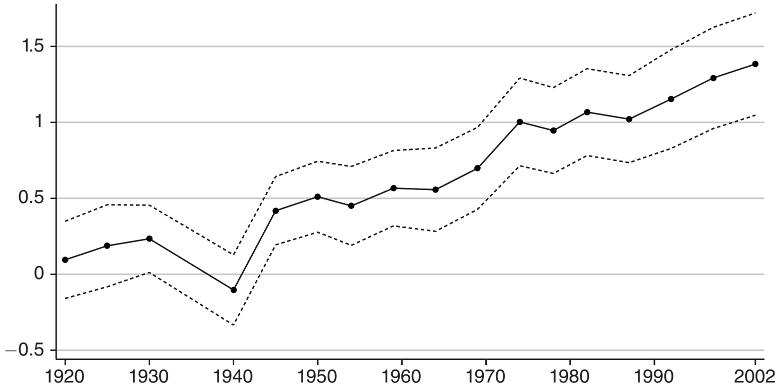


FIGURE 8. ESTIMATED DIFFERENCES BY OGALLALA SHARE AND YEAR: LAND VALUE AND REVENUE

Notes: Panels A and B report estimates from equation (3) in the text: the indicated outcome variable is regressed on the share of county area over the Ogallala, state fixed effects, fraction of county area in each soil group, and linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10° C and 29° C, average degree days above 29° C, longitude, and latitude. All coefficients are allowed to vary in each year. The regressions are weighted by county acres. The dashed lines show 95 percent confidence intervals around the coefficients, based on robust standard errors clustered by county.

a useful proxy.[44] Figure 8, panel B, shows that the value of agricultural revenue has been increasing over time in Ogallala counties relative to non-Ogallala counties. Revenue was also trending higher in Ogallala counties from 1920 to 1945, but there is little indication of declining agricultural revenue in recent periods as the estimated land value premium declined.[45] Table 4, column 2, reports the estimated relative difference in agricultural revenue in Ogallala counties for each of the three main eras.

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

[45] There are difficulties in creating a consistent measure of agricultural revenue, particularly before 1950, which would affect the results to the extent that changes in measurement vary across Ogallala and non-Ogallala areas. After 1945, questions about agricultural revenue shift to the market value of products sold from the value of products sold, traded, or used by the farm. From 1920 through 1935, the value of animal products must be imputed based on the value of livestock in each year and the 1940 ratio between the value of animal products and the value of livestock.

TABLE 4—ESTIMATED DIFFERENCES BY OGALLALA SHARE AND ERA: LAND VALUE AND REVENUE

Coefficient in era:	log value farmland per county acre (1)	log farm revenue per county acre (2)
1920–1945	0.104 (0.104)	0.166 (0.115)
1950–1974	0.406*** (0.083)	0.631*** (0.126)
1978–2002	0.259*** (0.075)	1.144*** (0.153)
Sample counties	368	368

Notes: Each column reports estimates from a modified version of equation (3) in the text: the indicated outcome variable is regressed on the share of county area over the Ogallala (interacted with each era), state by year fixed effects, soil group by year fixed effects, and year-interacted linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10º C and 29º C, average degree days above 29º C, longitude, and latitude. Data for some outcome variables are only available in some years (shown in Figure 8). The regressions are weighted by county acres. Robust standard errors clustered by county are reported in parentheses.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

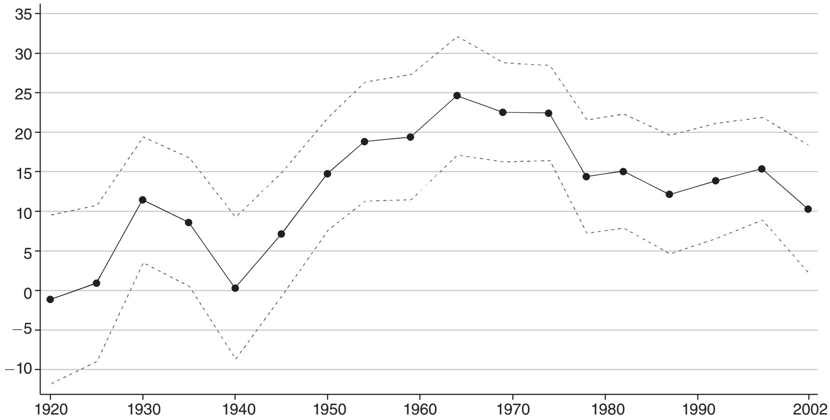

FIGURE 9. IMPLIED VALUE OF THE OGALLALA, IN BILLIONS OF 2002 DOLLARS

Notes: The implied total value of the Ogallala is shown in each year, based on the estimated land value premiums shown in panel A of Figure 8 (and the dashed lines reflect corresponding 95 percent confidence intervals). The estimated valuations are converted into constant 2002 dollars using a regional land value price index.

As a summary measure of the Ogallala's impact on agricultural production, Figure 9 shows the total valuation of Ogallala groundwater in constant 2002 dollars implied by the estimated land value premium in each year.[46] The value of Ogallala groundwater peaked at $25 billion in 1964 and has since declined to $10 billion in

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[46] The β coefficients shown in panel A of Figure 8 imply that land values would decline by $\frac{(e^{\beta}-1)}{e^{\beta}}$ percent, on average, in the absence of Ogallala groundwater. This percent decline is multiplied by the total value of land over the Ogallala, estimated as the sum of each county's total land value multiplied by its share of land over the Ogallala. The estimated valuations are converted into constant 2002 dollars using a regional land value price index, defined as the 2002 value of land in sample counties with zero Ogallala share divided by that year's value of land in sample counties with zero Ogallala share.

2002.[47] Ogallala access is estimated to raise the value of 160 acres by $14,425 in 1950 and by $38,962 in 1978 (in 2002 dollars), though the implied valuation would be higher for areas that farmers choose to irrigate.[48]

The analysis focuses on the average impact of the Ogallala, but there may also be interesting heterogeneity in the Ogallala's impact across the region. Ogallala groundwater might be expected to have the greatest benefit in areas with less rainfall and, in particular, areas with both less rainfall and better soil. To consider these effects, we extend estimating equation (3) to include an interaction between counties' Ogallala share and counties' average precipitation (normalized to have a mean of zero and a standard deviation of negative one). Figure 10, panel A, shows the estimated coefficients on this interaction term and, indeed, the Ogallala's impact on land values is greater in areas with less rainfall. We then extend estimating equation (3) to include an interaction between Ogallala share and an index of county soil quality, along with the triple interaction between Ogallala share, average precipitation, and soil quality.[49] Figure 10, panel B, shows the estimated coefficients on the triple interaction term: the Ogallala's larger impact on rainfall-deficient areas is more pronounced in areas with otherwise productive soil, though this effect is only marginally statistically significant in periods when the Ogallala's impact on land values is greatest.[50]

D. *Robustness and General Equilibrium Spillovers*

The empirical results are robust to changes in the empirical specification, as suggested by the maps (Figures 2 and 3) and aggregate changes by Ogallala share (Figure 4).[51] The results are also robust to narrowing the main 368 county sample to 186 counties that intersect the Ogallala boundary.

The estimated relative differences in Ogallala counties may not reflect the aggregate impact of the Ogallala if there are spillover effects on non-Ogallala counties. There are minimal direct spillovers in access to water, as Ogallala water is not directly transferred to non-Ogallala counties for agricultural use. The Ogallala may also have limited indirect effects on agricultural prices because the Ogallala region represents a small share of national and world agricultural production. However, to the extent that some markets are more local, nearby non-Ogallala counties may be affected by changes in factor availability and terms-of-trade.

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[47] The estimated market valuation of the Ogallala may understate its potential value, to the extent that groundwater extraction externalities induce inefficient water use. The estimates may overstate the value of groundwater, to the extent that groundwater access encourages greater fixed investments that are capitalized in the value of agricultural land and buildings.

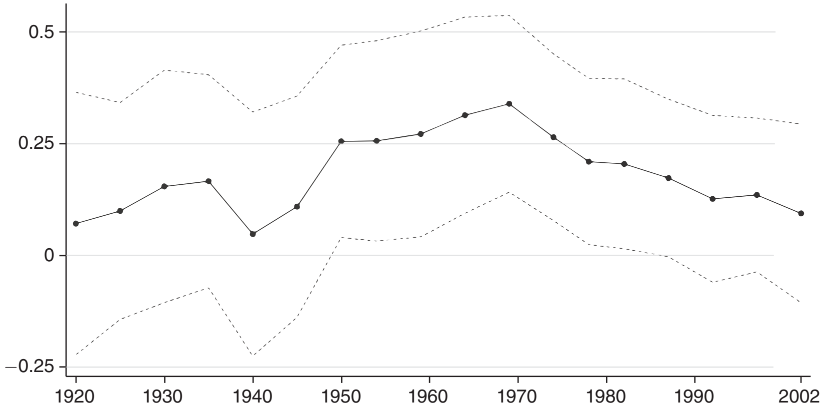
[48] Nutt-Powell and Landers (1979) report that the first center pivot irrigation machines cost $52,000 around 1952, and between $90,000 and $154,000 in 1978, in constant 2002 dollars, though the increase in land values already reflects any required capital expenditures.

[49] We create an index of county soil quality based on the coefficients from regressing pre-1950 county land values on the fraction of county land in each soil group, controlling for the other nonsoil variables in equation (3). The predicted value of each county's soil is then normalized to have a mean of zero and a standard deviation of one.

[50] The Ogallala does not have a greater impact on areas with better soil, on average, which is consistent with findings that technological change over the twentieth century has not systematically benefited areas with better or worse soil in this region (Hornbeck 2012).

[51] In particular, the estimates are not sensitive to restricting the set of included control variables, i.e., the eight fixed county characteristics that are interacted with year.

Panel A. Ogallala share interacted with rainfall deficiency



Panel B. Ogallala share interacted with rainfall deficiency and soil quality

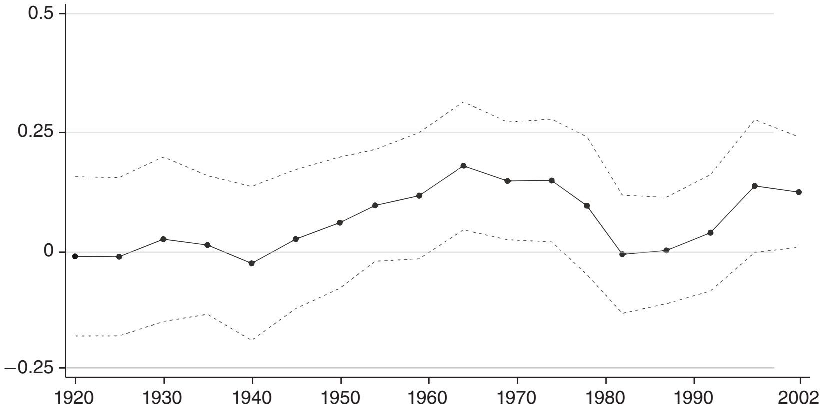


Figure 10. Estimated Heterogeneity in the Ogallala's Impact on log Farmland Value

Notes: Panel A reports estimates from a modified version of equation (3), in which a county's Ogallala share is interacted with the county's average precipitation (normalized to have a mean of zero and a standard deviation of negative one). The interaction term coefficients are shown and dashed lines reflect 95 percent confidence intervals based on robust standard errors clustered by county. Panel B reports estimates from a further extension, in which the above interaction term is also interacted with the county's predicted soil quality (normalized to have a mean of zero and a standard deviation of one). The specification controls for the double interaction between a county's Ogallala share and predicted soil quality. The triple interaction coefficients are shown, and the dashed lines reflect 95 percent confidence intervals based on robust standard errors clustered by county.

To explore local spillover effects, a placebo test compares counties near the Ogallala to counties further from the Ogallala. Restricting the sample to counties with zero Ogallala share, equation (3) is modified to estimate the impact in each year of distance to the Ogallala boundary. For ease of interpretation, distance is measured in units of 100 km and made negative. The estimated coefficients are interpreted as the impact of the Ogallala on the nearest sample counties, relative to the impact of the Ogallala on the furthest sample counties.

The online Appendix (Table 1) reports estimates from this placebo test. For each of the main outcome variables, there is no substantial or statistically detectable relative impact of the Ogallala on nearby non-Ogallala counties. When expanding the sample to counties 200 km from the Ogallala boundary for increased statistical power, there remains little detectable impact of the Ogallala on nearby counties relative to further counties.

VI. Groundwater and Drought: Short-Run and Long-Run Interaction Effects

The impact of groundwater on drought sensitivity depends on the relative speed and magnitude of land-use adjustment on the intensive and extensive margins. In response to increased availability of Ogallala groundwater, farmers are estimated to have initially increased water use mainly on the intensive margin. Irrigated farmland, irrigated corn acreage, and irrigated wheat acreage became higher in Ogallala counties. By contrast, there was little initial change in total farmland, total corn acreage, and total wheat acreage. In later periods, farmers increased total corn acreage, with some small increases in total farmland and small decreases in wheat acreage.

Given these findings, the model predicts an initial decline in the sensitivity of corn yields to drought. This effect is predicted to dissipate once total corn acreage increases, expanding into arid drought sensitive lands. An alternative interpretation is that non-Ogallala counties have adapted to water scarcity by maintaining acreage in drought-resistant crops.

To explore the short-run and long-run impact of groundwater on drought sensitivity of corn and wheat yields, annual county-level data are drawn from the National Agricultural Statistics Service (NASS). By contrast to census data on harvested acreages, the NASS provides data on planted acreages of corn and wheat. Drought-damaged cropland is often not harvested, so it is important to define crop yields as the log number of bushels produced per planted acre. In the sample region, corn and wheat yields are only available in each year for a limited number of counties between 1940 and 1993.[52]

Drought is defined according to the Palmer Drought Severity Index (PDSI), and annual county-level PDSI data are drawn from the National Climatic Data Center (NCDC).[53] The PDSI uses cumulative rainfall and temperature to determine dryness or wetness, relative to the local average climate. To focus on drought, the PDSI is set equal to zero in wet years, and the index ranges between zero and 7.22 with a 1.16 standard deviation. For ease of interpreting the empirical estimates, we normalize this drought measure to have a mean of zero and a standard deviation of one.

Focusing initially on non-Ogallala counties, from 1940 to 1993, background specifications regress log crop yields on drought, with year fixed effects or state-by-year fixed effects. Drought is estimated to have a large negative impact on corn yield and a moderate negative impact on wheat yield. Irrigated crop yields are less-affected by drought than nonirrigated crop yields, particularly for corn. These estimates are consistent with expectations that corn is more water intensive and drought sensitive than wheat (Brouwer and Heibloem 1986; Pimentel et al. 1997).

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[52] Before 1940, NASS data is available for few states and the 1930s 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.

[53] We thank Hansen, Libecap, and Lowe (2011) for providing PDSI data.

The main empirical specifications use variation in access to Ogallala groundwater, over space and time, to estimate interaction terms between drought and the Ogallala. The 54 years of available data are split into three 18-year eras: before widespread use of Ogallala irrigation for corn and wheat (1940–1957), after increases in the water-intensity of corn and wheat (1958–1975), and after a shift toward the more water intensive corn (1976–1993). Of particular interest is how the Ogallala affects the impact of drought in the second and third eras, relative to the first era, conditional on a number of control variables.[54]

Formally, log crop yield Y in county c and year t is regressed on the triple interaction between a county's Ogallala share, normalized drought index, and a dummy for the second era or third era ($Ogallala_c \times Drought_{ct} \times 1(e = 2)$ and $Ogallala_c \times Drought_{ct} \times 1(e = 3)$). The change in impact of Ogallala access on yield during average weather is captured by the double interaction between a county's Ogallala share and a dummy for the second era or third era ($Ogallala_c \times 1(e = 2)$ and $Ogallala_c \times 1(e = 3)$). As controls, the regression includes county fixed effects (α_c) and era-specific controls for state (γ^1_{se}), soil group (γ^2_{ge}), and linear functions of eight fixed county characteristics ($\gamma^3_e \mathbf{X}_c$).[55] The effect of drought is allowed to vary in each county by controlling for interactions between drought and county fixed effects ($Drought_{ct} \times \alpha_c$). The effect of drought is allowed to vary in each era ($Drought_{ct} \times 1(e = 2)$ and $Drought_{ct} \times 1(e = 3)$). In some specifications, the effect of drought is also allowed to vary in each era and state ($Drought_{ct} \times \gamma^1_{se}$), each era and soil group ($Drought_{ct} \times \gamma^2_{ge}$), or each era and linear functions of the included county characteristics ($Drought_{ct} \times \gamma^3_e \mathbf{X}_c$). The full empirical specification is:

$$
\begin{aligned}
(3) \qquad Y_{ct} = {} & \beta^1 Ogallala_c \times Drought_{ct} \times 1(e = 2) \\
& + \beta^2 Ogallala_c \times Drought_{ct} \times 1(e = 3) \\
& + \beta^3 Ogallala_c \times 1(e = 2) + \beta^4 Ogallala_c \times 1(e = 3) \\
& + \alpha_c + \gamma^1_{se} + \gamma^2_{ge} + \gamma^3_e \mathbf{X}_c \\
& + \delta^1 Drought_{ct} \times \alpha_c + \delta^2 Drought_{ct} \times 1(e = 2) \\
& + \delta^3 Drought_{ct} \times 1(e = 3) \\
& + \delta^4 Drought_{ct} \times \gamma^1_{se} + \delta^5 Drought_{ct} \times \gamma^2_{ge} \\
& + \delta^6 Drought_{ct} \times \gamma^3_e \mathbf{X}_c + \varepsilon_{ct}.
\end{aligned}
$$

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[54] Drought mainly varies across years in the sample region, so it is not feasible to exploit only within-year variation in drought intensity and access to Ogallala groundwater.

[55] As before, these county characteristics are: soil suitability for corn and wheat, average rainfall and temperature, degree days between 10° C and 29° C, degree days above 29° C, longitude, and latitude.

The main coefficients of interest are β^1 and β^2, which indicate how the Ogallala affects the impact of drought in the second and third eras, relative to the first era. In addition, the coefficients β^3 and β^4 indicate how the Ogallala affects yields during average weather in the second and third eras, relative to the first era. The sample is balanced in each regression, such that every county included has data in each period. There are fewer counties in each sample, and the 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.

Table 5, panel A, reports estimates from equation (5) for corn yields. In the second era, from 1958 to 1976, the Ogallala substantially mitigated the impact of drought on corn yields. In years when drought was one standard deviation higher, Ogallala counties experienced a 34 percent to 47 percent productivity advantage over non-Ogallala counties (0.295 log points to 0.387 log points), relative to average county-level differences in drought sensitivity. Because the sample is restricted to 134 counties over 54 years in Nebraska, South Dakota, and Iowa, Column 1 imposes a restriction on the control variables that $\delta^4 = \delta^5 = \delta^6 = 0$, column 2 restricts only $\delta^6 = 0$, and column 3 presents the full specification from equation (5). During this second era, there was little change in corn yields during average weather conditions (-0.023 log points to -0.082 log points).

In the third era, from 1976 to 1993, the Ogallala lost most of its effect on corn yields during drought (-0.027 log points to 0.091 log points). Yields increased slightly during average weather conditions from the second era to the third era (0.067 log points to 0.073 log points). During this third era, as revenues increased substantially, the Ogallala's main impact was enabling expansion of high-value corn cultivation without inducing severe drops in yields during average weather conditions or droughts. Similarly, by limiting corn cultivation, non-Ogallala counties have maintained average yields and drought resistance despite higher water scarcity.

As a comparison, panel B reports estimates from equation (5) for wheat yields. The Ogallala had less impact on the drought sensitivity of wheat, which is more drought resistant than corn.

VII. Conclusion

Agriculture on the American Great Plains has been constrained historically by water scarcity. In the latter half of the twentieth century, technological improvements enabled farmers over the Ogallala aquifer to extract groundwater for large-scale irrigation. Increased access to Ogallala groundwater increased agricultural land values and initially reduced the impact of droughts. Over time, land use adjusted toward high-value water intensive crops and drought sensitivity increased.

Lacking access to Ogallala groundwater, nearby counties have maintained lower-value agricultural practices that are less water intensive and more drought resistant. While agricultural land values remain lower in nearby counties, agricultural production has adapted to water availability such that non-Ogallala counties are no more sensitive to drought than heavily irrigated Ogallala counties.

Scarce water resources have an important role in shaping agricultural production, particularly in arid drought-prone areas. In modern settings, however, it is

Table 5—Estimated Impacts of Ogallala and Drought on Yields, Relative to 1940–1956

	(1)	(2)	(3)
Panel A. log corn yield			
Ogallala × drought × (1958–1975)	0.387***	0.382***	0.295**
	(0.101)	(0.102)	(0.126)
Ogallala × drought × (1976–1993)	0.073	−0.027	0.091
	(0.038)	(0.051)	(0.071)
Ogallala × (1958–1975)	−0.030	−0.023	−0.082
	(0.155)	(0.166)	(0.167)
Ogallala × (1976–1993)	0.070	0.073	0.067
	(0.151)	(0.149)	(0.150)
Sample counties	134	134	134
Panel B. log wheat yield			
Ogallala × drought × (1958–1975)	0.007	0.100**	0.080
	(0.052)	(0.043)	(0.052)
Ogallala × drought × (1976–1993)	0.057	0.040	0.012
	(0.055)	(0.053)	(0.067)
Ogallala × (1958–1975)	0.066	0.062	0.059
	(0.043)	(0.042)	(0.042)
Ogallala × (1976–1993)	0.104	0.074	0.066
	(0.070)	(0.068)	(0.069)
Additional controls:			
Drought × county fixed effects	Yes	Yes	Yes
Drought × era	Yes	Yes	Yes
Drought × era × state & soil	No	Yes	Yes
Drought × era × climate & X/Y	No	No	Yes
Sample counties	165	165	165

Notes: Each column reports estimates from versions of equation (4) in the text. In panel A, log corn yield is regressed on the triple interaction between a county's Ogallala share, normalized Palmer Drought Severity Index, and a dummy for the second era (1958–1975) or third era (1976–1993). Also reported is the double interaction between Ogallala share and era. All specifications control for county fixed effects and era-specific controls for state, soil group, and linear functions of eight fixed county characteristics: soil suitability for corn and wheat, average precipitation, average temperature, average degree days between 10º C and 29º C, average degree days above 29º C, longitude, and latitude. In addition, all specifications control for interactions between drought and county fixed effects and interactions between drought and era fixed effects. The sample is limited to 134 counties in Nebraska, South Dakota, and Iowa with data available in each of the 54 years between 1940 and 1993. Column 2 also controls for triple interactions between: drought, era, and state fixed effects; drought, era, and soil group shares; and drought, era, and soil suitability for corn and wheat. Column 3 also controls for triple interactions between: drought, era, and linear functions of average precipitation, average temperature, average degree days between 10º C and 29º C, average degree days above 29º C, longitude, and latitude. Panel B reports estimated impacts on wheat yields. The sample is limited to 165 counties in Colorado, Kansas, Oklahoma, South Dakota, and Wyoming with wheat yield data in each of the 54 years between 1940 and 1993.The regressions are weighted by county acres. Robust standard errors clustered by county are reported in parentheses.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

difficult to observe how agriculture adapts over time to available water resources and the threat of drought. The particular pattern of agricultural land-use adjustment observed in this setting may reflect the influence of US agricultural policy and other context-specific factors. For settings in which such historical perspective is unavailable, however, the historically evolving impact of the Ogallala aquifer provides a stark example of the importance of water for agricultural production and also the large scope for long-run agricultural adaptation to groundwater and drought.

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