NBER WORKING PAPER SERIES

THE EVOLVING IMPACT OF THE OGALLALA AQUIFER: AGRICULTURAL ADAPTATION TO GROUNDWATER AND CLIMATE

Richard Hornbeck
Pinar Keskin

Working Paper 17625
http://www.nber.org/papers/w17625

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
November 2011

For many helpful comments and suggestions, we thank seminar participants at Bocconi, Brown, Columbia, EHA, Harvard, IIES, Kansas, Miami-OH, Michigan, Michigan State, NBER, NEUDC, PERC, Queen's, RES, Santa Barbara, Toronto, Tufts, UPF, Vanderbilt, Wellesley, World Bank, and Yale. For financial support, we thank the Harvard University Center for the Environment and the Harvard Sustainability Science Program. Melissa Eccleston, James Feigenbaum, Jan Kozak, and Jamie Lee provided excellent research assistance. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

The Evolving Impact of the Ogallala Aquifer: Agricultural Adaptation to Groundwater and Climate
Richard Hornbeck and Pinar Keskin
NBER Working Paper No. 17625
November 2011
JEL No. N52,Q54

ABSTRACT

Agriculture on the American Great Plains has been constrained by historical water scarcity. After World War II, technological improvements made groundwater from the Ogallala aquifer available for irrigation. Comparing counties over the Ogallala with nearby similar counties, groundwater access increased irrigation intensity and initially reduced the impact of droughts. Over time, land-use adjusted toward water-intensive crops and drought-sensitivity increased; conversely, farmers in water-scarce counties maintained drought-resistant practices that fully mitigated higher drought-sensitivity. Land values capitalized the Ogallala's value at $26 billion in 1974; as extraction remained high and water levels declined, the Ogallala's value fell to $9 billion in 2002.

Richard Hornbeck
Department of Economics
Harvard University
232 Littauer Center
Cambridge, MA 02138
and NBER
hornbeck@fas.harvard.edu

Pinar Keskin
Department of Economics
Wellesley College
106 Central Street
Wellesley, MA 02481
pkeskin@wellesley.edu

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; FAO 1999; Schoengold and Zilberman 2007; Keskin 2009). 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; Provencher and Oscar 1993; Blomquist 1994; Aggarwal and Narayan 2004; Foster and Rosenzweig 2008; Sekhri 2008; Rosegrant et al. 2009; Ostrom 2011; Libecap 2011).

Groundwater resources are being depleted as agricultural economies grow and become increasingly dependent on groundwater irrigation. Future climate change may affect precipitation, temperature, and the incidence of extreme drought. Yet, it is difficult to identify how agricultural land-use and drought sensitivity adapt to water availability in the short-run and, of more interest, evolve over many decades. In general, the economic impacts of environmental change depend on how economic agents adjust in the long-run to mitigate short-run impacts (Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2006; Deschenes and Greenstone 2007; Guiteras 2009; Schlenker and Roberts 2009; Dell, Jones, and Olken 2011; Olmstead and Rhode 2011; Hornbeck forthcoming). Historical changes in groundwater availability provide a unique opportunity to identify long-run agricultural adjustments and how land-use evolves to accommodate water resources and climates.

This paper analyzes the 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.

The baseline empirical specifications compare counties over the Ogallala with nearby counties in the same state and soil group, controlling for longitude, latitude, average precipitation, and average temperature. Historical county-level data are drawn from the Census of Agriculture and merged with a United States Geological Survey map of the Ogallala's original boundary. Extended empirical specifications estimate the interaction between groundwater and climate, 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.

Groundwater has theoretically distinct short-run and long-run impacts when farmers adjust production methods faster than crop choice. In the short-run, farmers increase irrigation intensity, causing crop yields to become less sensitive to drought. In the long-run, farmers shift land toward water-intensive crops, causing yields to become more sensitive to drought. The net impact of groundwater is theoretically ambiguous, depending on relative adjustment along the intensive (short-run) and extensive (long-run) margins.[1] In each period, the net present value of access to groundwater is capitalized in agricultural land values.

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 non-irrigated 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 allocations increased the impact of drought on corn yields. Conversely, farmers in nearby water-scarce counties have maintained drought-resistant agricultural practices that fully mitigate their naturally higher sensitivity to drought.

Groundwater access remains a valuable agricultural asset, however, improving crops' drought-resistance in the short-run and enabling the production of higher value crops in the long-run. Estimated land value premiums capitalized the Ogallala's peak value at \$26 billion in the 1970's and, as extraction rates remained high and water levels declined, the Ogallala's estimated value fell to \$9 billion in 2002. 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. As the region loses access to groundwater, the estimates predict short-run increases in drought sensitivity before long-run adaptations increase resistance to drought.

The economic impacts of groundwater and its interaction with climate are difficult to observe in modern settings, as short-run data do not capture the extent of long-run agricultural

---

[1] 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.

adaptation. Agricultural adaptation can reverse estimated short-run impacts, as adoption of drought-resistant practices reduces drought impacts in areas lacking groundwater access. Losing access to groundwater is costly, but it need not increase vulnerability to drought in the long-run. For settings in which long-run historical perspective is unavailable, the Ogallala provides a stark example of agricultural adaptation to groundwater and climate.

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 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).[2]

The Ogallala underlies 174,000 square miles of the Great Plains from the Texas panhandle to South Dakota. 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.[3]

The Ogallala was first discovered by the United States Geological Survey in the 1890s, but was considered of limited agricultural importance (Webb 1931; US Department of Commerce 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" (Weakley and Zook 1928). Groundwater irrigation was thought to be of great potential value, particularly in raising corn yields, but pumps were small and/or expensive (Weakly 1932; Weakly 1936). "Most of the pumps are operated by the general-purpose tractor, which is used principally for other farm work;" "irrigation pumps are considered as equipment for emergency use by a large proportion of Nebraska owners" (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 1950's, Nebraska Agricultural Exten-

---

[2] Artificial recharge has been considered but is 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).

[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). As water levels continue to decline, these 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 soil porosity affect the speed of underground water flow, which determines the degree of externality in water withdrawal.

sion 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 et al. (1956) draw 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 capital and labor costs (Bonnen et al. 1952).[4] 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 et al. 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. Originally invented in 1949 by a Colorado farmer, Frank Zybach, the "self-propelled sprinkling apparatus" combined recent advances in turbine pumps, steel and aluminum pipes, and lawn sprinklers.[5] Center pivot technology was particularly suited to the Great Plains: able to direct water to plants with minimal evaporation in dry windy weather and able to accommodate large fields with hilly or sandy land.

Zybach's patent was granted in 1952 and he moved home to Nebraska and partnered with a local businessman to begin manufacturing prototypes. Yet early center pivot machines were unreliable; in 1954, they sold the patent to the Nebraska-based Valley Manufacturing Company, who improved the design and began large-scale production and distribution. Competition increased after Zybach's original patent expired in 1969, though Nebraska remains the hub of the center pivot irrigation industry.

As pumping and center pivot irrigation technologies were improved and adopted, Ogal-

---

[4] From Bonnen et al. (1952), "Use of Irrigation Water on the High Plains," Texas Bulletin 756: "A few operators have attempted to overcome the disadvantage of steep slopes and extremely sandy soils through the use of sprinkler systems. These have the advantage of providing an even distribution of water on land difficult to water by other means. The practice has not been widely adopted partly because of a greatly increased investment, higher pumping costs, the additional labor involved in moving the system over the land, the difficulty of applying water rapidly enough especially during periods of high temperatures, and the uneven wetting of the soil during periods of windy weather."

[5] For first-hand accounts of the technology's introduction and improvement, see http://www.livinghistoryfarm.org/

lala 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 pre-development levels (McGuire et al. 2003; Little 2009).[6] Agriculture accounts for the vast majority of groundwater extraction.[7] Most areas retain sufficient groundwater to supply irrigation pumps, though scattered shallow sections of the Ogallala are beginning to run dry.

Ogallala groundwater has visibly transformed the Plains landscape (Groundwater Foundation 2005). Center pivot irrigation creates distinctive circular crop patterns nested within traditionally square land plots (Appendix Figure 1).[8] Farmers in nearby counties do not access Ogallala groundwater using pipelines or any system of exchange.[9]

Farmers' water extraction draws from the broader Ogallala region such that, over time, there is little marginal effect on farmers' own water levels.[10] Thus, the Ogallala represents a classic "common pool" problem, in which individual water users do not pay the social cost of water extraction. 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.[11] Depletion of the aquifer may encourage reform of water institutions (e.g., Demsetz 1967), though the Ogallala represents a large cross-state coordination problem with strongly diverging interests. Federal tax code allows irrigating farmers to depreciate the value of Ogallala water level declines, essentially magnifying private extraction externalities.[12]

Much economics research has focused on water extraction externalities in India and other developing countries. Relative to smaller aquifers around the world, the magnitude of the Ogallala and speed of underground water flow imply that most local water extraction is

---

[6] 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.

[7] Ogallala groundwater is also used for drinking water, though much of the Plains population has access to alternative drinking water sources. Ogallala water does not meet EPA drinking water standards in a few counties (Guru and Horne 2000).

[8] 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 reach the corners. 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.

[9] There is mixed evidence on whether irrigation broadly affects downwind precipitation (see DeAngelis et al. 2010 for a recent study).

[10] Underground water flows vary in speed throughout the Ogallala, but in no area do individual farmers internalize a meaningful portion of their private water extraction.

[11] See McGuire et al. 2003 for a review of state management policies.

[12] 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).

soon drawn from distant sources. Standard plot sizes begin at 160 acres on the US Plains, much larger than in India, so wells have less temporary effect on neighboring wells.[13] Large plot sizes also imply that fixed costs of digging a well are relatively less important than the marginal costs of water extraction.

Because farmers' water extraction is almost entirely an externality, there is little local variation in the degree of externality, and this paper focuses on other questions concerning land-use adaptation and drought sensitivity. For this set of questions, a relative advantage to studying Ogallala groundwater is that the United States Geological Survey (USGS) has detailed maps on the Ogallala's location; thus, it is not necessary to infer groundwater availability from constructed wells or other agricultural decisions. In addition, the annual availability of groundwater is not directly affected by drought and agricultural land-use, because the Ogallala is a large closed aquifer. Over time, water levels are affected by agricultural activity, so the empirical analysis assigns groundwater availability using USGS pre-development Ogallala boundaries.

II Agricultural Adaptation to Groundwater and Climate

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.

II.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 ($L_1 + L_2 = 1$). 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 the intensive

---

[13] Plot sizes of 160 acres create a natural minimum 0.4 kilometer buffer between wells, which is often the policy goal in developing countries to reduce the immediate impact of farmers' extraction on neighbors' water levels. Over time, aquifer water flows underground to equalize levels.

[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: $\partial^2 y_1/\partial L_1 \partial w_1 \geq \partial^2 y_2/\partial L_2 \partial w_2 > 0$.

and extensive margins:

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

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.[15] Refer to the Theory 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, as after the Dust Bowl in this region (Hornbeck forthcoming). The increase in groundwater availability may also be gradual, as pumping and center pivot irrigation technologies improve. Agricultural rents increase as production adjusts along both margins. Agricultural land values increase immediately in anticipation of later rent increases, to the extent that increases in water endowments are unexpected.

II.B Adaptation to Drought Risk and Groundwater

Of further interest is how a farmer adapts to drought risk, 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.[16] Groundwater partially mitigates the negative impact of drought, particularly for the water-intensive crop.[17]

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:

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

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-

---

[15] 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.

[16] 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.

[17] 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: $\partial^2 y_1/\partial w_1 \partial d > \partial^2 y_2/\partial w_2 \partial d > 0$.

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).

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 affect agricultural production more than before. Refer to the Theory Appendix for 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 $w_1 L_1 + w_2 L_2 = \bar{w}$ 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. Refer to the Theory Appendix for a proof of this special case.

The comparative statics are intuitive for a symmetric loss in 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 in groundwater. In the cross-section, areas without groundwater may sufficiently adapt toward non-water-intensive crops to fully mitigate their naturally higher impact of drought.

III Data Construction and County Differences by Ogallala Share

III.A Census Data and Spatial Patterns

Historical county-level data are available every five years from the US Census of Agriculture (Gutmann 2005; Haines 2005).[18] The main variables of interest include: irrigated acres and total acres of agricultural land, harvested acres and bushels of corn and wheat, value of agricultural revenue, and value of agricultural land. 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. 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 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

---

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

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 100km 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 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 group, longitude, latitude, average precipitation, and average temperature. States, mapped in Figure 1, capture differences in region, state agricultural extension services, and other state-level policies.

Figure 4 displays major soil groups in the Plains, as defined by the Soil Conservation Service in 1951. The 1951 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. These soil groups proxy for detailed regional determinants of agricultural production. For example, "Alluvial Soils" occur along major rivers and predict higher irrigation in 1935. Conversely, "Sand and Silt" in North-Central Nebraska is unproductive for agriculture. The Ogallala boundary cuts across major soil groups; importantly, as 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 data on average precipitation and temperature are taken from PRISM data (PRISM 2004). County longitude and latitude are measured using the coordinates of 1920 county centroids (NHGIS).[19] Because non-Ogallala counties surround the Ogallala region, there is variation in Ogallala access within similar climate, longitude, and latitude.

---

[19] 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.

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

Prior to modern improvements in pumping and irrigation technology, the Ogallala may have little impact on agriculture. The Ogallala water table is generally too deep to be accessed by natural vegetation. 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").[20] Columns 3 to 5 include controls to compare Ogallala counties with nearby similar non-Ogallala counties: column 3 includes state fixed effects; column 4 adds controls for the fraction of county land in each soil group; and column 5 adds linear controls for average precipitation, average temperature, 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. 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 farmers and land speculators.

III.C Changes in County Characteristics by Ogallala Group

For a preliminary view of the data, Figure 5 plots average outcomes over time for two groups of sample counties: counties less than 10% over the Ogallala, and counties more than 90% over the Ogallala.[21] By contrast, the main empirical specifications use continuous variation in counties' Ogallala share and control for other differences among sample counties.

---

[20] 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.

[21] 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.

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 1970's. Irrigated corn acreage increased somewhat in Ogallala counties from 1954 to 1964, and was substantially higher by 1978 (Panel B). In contrast, total corn acreage changed similarly from 1920 through 1964, and only became substantially higher in Ogallala counties by 1978 (Panel C).[22] The value of farmland was relatively lower or similar in Ogallala counties from 1920 through the 1940's; after 1950, 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 four county characteristics X_c (average rainfall, average temperature, longitude, and latitude). These cross-sectional specifications are pooled across all time periods, with each coefficient allowed to vary in each time period:

$$Y_{ct} = \beta_t OgallalaShare_c + \alpha_{st} + \gamma_{gt} + \theta_t X_c + \epsilon_{ct} \tag{3}$$

In each time period, the estimated β reports the average difference between counties entirely over the Ogallala and counties never over the Ogallala.[23]

The estimated β's 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 group, precipitation, temperature, longitude, and latitude. 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.

The Ogallala's impact may vary over the analyzed region. For example, the Ogallala may have less impact in areas with unproductive soil and more impact in areas with productive soil and water deficiencies. For simplicity, the analysis reports the impact of the Ogallala on the average acre of land over the Ogallala. For this purpose, the regressions are weighted by county size.

Differences in the estimated β's, from one year to another year, report the average change

---

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

[23] 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.

for an Ogallala county relative to a non-Ogallala county over that time period. Differencing the estimated coefficients is numerically equivalent to estimating equation (3) with county fixed effects.[24] The standard error of the difference is generally 20-40% lower than the standard error of the two cross-sectional coefficients due to positive serial correlation in county-level outcomes. The change in β's 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.

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 approximately 10-30%.[25]

V Results

V.A Irrigation and Farmland: Intensive vs. Extensive Margins

Table 2, column 1, reports the estimated impact of the Ogallala in each year on acres of irrigated farmland per county acre. In 1935, irrigation was a statistically insignificant 0.4 percentage points lower in Ogallala counties than in non-Ogallala counties.[26] By 1950, irrigation was a statistically insignificant 1.3 percentage points higher in Ogallala counties than in non-Ogallala counties. As groundwater irrigation technology improved and agricultural production adjusted, this difference increased to 11.3 percentage points by 1978. Ogallala counties maintained substantially higher irrigation levels through 1997.

Column 2 reports the estimated impact of the Ogallala on acres of total farmland per county acre. The fraction of county land in farms was similar in Ogallala and non-Ogallala counties through 1959, though higher in some periods. Since the 1960's, the fraction of county land in farms has been consistently higher by 5 to 7 percentage points in Ogallala counties. This small relative increase mainly reflects a slower absolute decline in farmland than in non-Ogallala counties.

Comparing the estimates in column 1 and column 2, initial adjustments in agricultural

---

[24] 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. The explanatory variables are fully interacted with time, such that the impact of each variable is allowed to vary in each year. The sample is also balanced in each regression, such that every county has data in every analyzed period. Thus, the estimated coefficients in any one year are not influenced by county outcomes in any other year.

[25] Spatial correlation among counties is assumed to be declining linearly up to a distance cutoff and zero after that cutoff (Conley 1999). For a distance cutoff of 100 miles or 200 miles, the estimated Conley standard errors are approximately 10-30% higher than the standard errors when clustering at the county level, depending on the outcome variable.

[26] Note that the first row of coefficients for each outcome are the same coefficients reported in column 5 of Table 1.

production were mainly on the intensive margin. Farmers increased irrigation of existing farmland, shifting land from dryland farming. Subsequently, farmers both increased irrigation and relatively expanded production along the extensive margin of total farmland.

V.B Corn and Wheat: Irrigated and Total Acreages

Table 3 examines the Ogallala's impact on corn and wheat acreages, which are the two major crops in this region with data availability over many years. Irrigated corn and irrigated wheat acreages became higher in Ogallala counties from 1950 through 1964 (columns 1 and 3). Total corn and wheat acreages did not increase over this period (columns 2 and 4); thus, as in Table 2, initial increases in irrigated corn and wheat represented a shift on the intensive margin away from dryland farming of corn and wheat.

By 1978, however, there was a substantial increase in irrigated corn acreages and total corn acreages. Irrigated wheat acreages continued to increase, while total wheat acreages declined.

In the context of the model, as groundwater became increasingly available, both corn and wheat initially became more water-intensive. After some delay, crop production shifted toward corn, which is typically more water-intensive and drought-sensitive than wheat.

V.C Agricultural Land Values and Revenues

The model predicts that higher land values over the Ogallala capitalize the net present value of agricultural rents from groundwater. In each period, land values reflect: (1) current agricultural rents, (2) expected increases in rents from future improvements in pumping and irrigation technology, (3) expected increases in rents from adjusting agricultural production, and (4) expected decreases in rents from exhaustion of groundwater.

In the 1950's, after the introduction of improved pumping and irrigation technologies, the value of agricultural land and buildings became consistently higher in counties over the Ogallala (Table 4, column 1).[27] The land value premium peaks at 51% in 1964 (0.415 log points), and has since declined to 19% in 2002 (0.178 log points).

Column 2 reports the implied market valuation of Ogallala groundwater in each period, based on the coefficients in column 1 and the total value of land over the Ogallala.[28] Column 3 converts the estimated valuations into constant 2002 dollars using the Consumer Price Index:

---

[27] 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.

[28] The coefficient β implies 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 estimates' t-statistics are approximately the same as in column 1; they would be identical, but the estimated log point differences are converted to percent differences.

the value of Ogallala groundwater rises from \$8.9 billion in 1950 to a peak of \$26 billion in 1974, and declines to \$9.0 billion by 2002. Column 5 converts the estimated valuations into constant 2002 dollars using a regional land value price index: the rise and fall in Ogallala value is similar to column 3, though the Ogallala's value peaks roughly 10 years earlier.[29]

Recent declines in land values over the Ogallala are consistent with expectations that groundwater is being exhausted in many areas. An alternative interpretation is that the marginal value of water has declined in recent periods (e.g., declining relative prices of water-intensive crops). While agricultural rents are not directly observable, agricultural revenues provide a useful proxy.[30] Table 4, column 5, reports that agricultural revenues have been higher over the Ogallala since the late 1940's, but increased substantially in the 1970's as agriculture shifted toward greater corn acreages over the Ogallala. The impact on revenues has increased in recent periods, as land values have declined, suggesting that the marginal return to water remains high and decreased land values reflect market expectations of exhaustion.[31]

The estimated Ogallala premiums in land values and revenues may reflect the combination of a variety of factors, including: (1) increased allocation of land to high value crops, (2) increased crop yields, (3) decreased irrigation costs, (4) general increases in yields of water-intensive crops, and (5) general increases in prices of water-intensive crops. In particular, the introduction of hybrid corn or increased corn prices may increase the Ogallala's value if the Ogallala enables counties to grow corn. It is appropriate that the marginal return to water reflect relative changes in the prices and productivity of water-intensive activities. For example, as policymakers consider the risk of an oil pipeline contaminating Ogallala groundwater, these five factors jointly contribute to the policy-relevant valuation of Ogallala groundwater for agricultural production.

Higher land values over the Ogallala do not appear to reflect increased demand for land in the urban sector. In contrast to other areas of the United States, the sample region is predominately rural and there is less impact of urban expansion on agricultural land values. 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 2500). Further, the estimated

---

[29] The land value price index is 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.

[30] If the agricultural production function were Cobb-Douglas, then percent differences in revenue 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.

[31] 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.

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% urban population in 1920.

V.D Robustness and General Equilibrium Spillovers

The empirical results appear robust to changes in the particular empirical specification, as suggested by the unadjusted data reported in the maps (Figures 2 and 3) and aggregate changes by Ogallala share (Figure 5). The results are generally insensitive to changing the included control variables and/or their functional form. The results are also similar when narrowing the main 368 county sample to 186 counties on the Ogallala boundary, i.e., with Ogallala shares strictly between zero and one.

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.

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 100km 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.

Table 5 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 200km 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; in 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). In 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.[32]

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).[33] 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 mean 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 non-irrigated crop yields, particularly for corn. These estimates are consistent with expectations that corn is more water-intensive and drought-sensitive than wheat (Brower and Heibloem 1986; Pimentel et al. 1997).

The main empirical specifications use variation in access to Ogallala groundwater, over space and time, to estimate interaction terms between drought and the Ogallala. Based on previous results, the 54 years of 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

---

[32] 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.

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

and third eras, relative to the first era, conditional on a number of control variables.[34]

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 average precipitation, average temperature, longitude, and latitude ($\gamma^3_e X_c$). 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 average precipitation, average temperature, longitude, and latitude ($Drought_{ct} \times \gamma^3_e X_c$). The full empirical specification is:

$$
\begin{aligned}
(4)\quad Y_{ct} &= \beta^1 Ogallala_c \times Drought_{ct} \times 1(e=2) + \beta^2 Ogallala_c \times Drought_{ct} \times 1(e=3) \\
&+ \beta^3 Ogallala_c \times 1(e=2) + \beta^4 Ogallala_c \times 1(e=3) \\
&+ \alpha_c + \gamma^1_{se} + \gamma^2_{ge} + \gamma^3_e X_c \\
&+ \delta^1 Drought_{ct} \times \alpha_c + \delta^2 Drought_{ct} \times 1(e=2) + \delta^3 Drought_{ct} \times 1(e=3) \\
&+ \delta^4 Drought_{ct} \times \gamma^1_{se} + \delta^5 Drought_{ct} \times \gamma^2_{ge} + \delta^6 Drought_{ct} \times \gamma^3_e X_c + \epsilon_{ct}
\end{aligned}
$$

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 6, 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% to 45% productivity advantage over non-Ogallala counties (0.29 log points to 0.38 log

---

[34] 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.

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 (-0.02 log points to -0.05 log points).

In the third era, from 1977 to 1993, the Ogallala lost most of its effect on corn yields during drought (-0.05 log points to 0.08 log points). Yields increased slightly during average weather conditions from the second era to the third era (0.10 log points to 0.13 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.

By comparison, panel B, reports estimates from equation (5) for wheat yields. The Ogallala had little detectable impact on wheat yields, which is more drought-resistant than corn and did not experience the same large changes in acreage.

VII Conclusion

Following engineering improvements in pumping and center pivot irrigation, counties over the Ogallala gained access to groundwater amidst the arid Great Plains. Farmers responded initially on the intensive margin by shifting from dryland farming to increase the irrigation intensity of farmland, corn, and wheat. For corn production, which is relatively water-intensive and drought-sensitive, greater irrigation initially decreased the sensitivity of yields to drought.

Over time, Ogallala farmers expanded corn acreage into new areas and yields again became sensitive to drought. Agricultural revenues increased, along with water extraction rates, and the groundwater table declined. In 2002, the remaining value of Ogallala groundwater had fallen to \$9 billion from a peak of \$26 billion in 1974.

Lacking access to Ogallala groundwater, nearby counties have maintained agricultural practices that are less water-intensive and more drought-resistant. Agricultural production has adapted to groundwater availability such that, over time, non-Ogallala counties are no more sensitive to drought than heavily-irrigated Ogallala counties.

As Ogallala counties lose access to groundwater, corn yields may become more sensitive to drought in the short-run; yet, over time, adoption of neighboring counties' land-use practices can re-establish drought-resistance. Agricultural production will become less valuable without Ogallala groundwater, but neighboring counties illustrate the scope for long-run agricultural adaptation.

In the Great Plains and in other arid regions, groundwater resources are becoming exhausted even as climate change threatens to increase drought. The impact on vulnerable agricultural economies depends on the degree of agricultural adaptation; yet, in modern settings, it is difficult to observe adaptation to groundwater access and climate. The history of farming over the Ogallala aquifer reveals the influence of both short-run and long-run agricultural adaptation to groundwater and climate.

REFERENCES

Aggarwal, R.M. and T.A. Narayan. 2004. "Does inequality lead to greater efficiency in the use of local commons? The role of strategic investments in capacity," *Journal of Environmental Economics and Management*, 47, 163-182.

Blomquist, W. 1994. “Changing Rules, Changing Games: Evidence from Groundwater Systems in Southern California,” in Rules, Games, and Common-Pool Resources, eds. Elinor Ostrom, Roy Gardner, and James Walker, Ann Arbor, MI: University of Michigan Press.

Bonnen, C.A., W.C. McArthur, A.C. Magee, and W.F. Hughes. 1952. “Use of Irrigation Water on the High Plains.” Texas Agricultural Experiment Station, College Station, Texas Agricultural and Mechanical College System, Bulletin 756 (December).

Brackett, E.E. and E.B. Lewis. 1933. “Pump Irrigation Investigations in Nebraska.” Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 282 (July).

Brower, C., and Heibloem, M. 1986. "Irrigation water management: Irrigation water needs," Training Manual 3, Rome 7, FAO.

Coman, K. 1911. "Some Unsettled Problems of Irrigation," *American Economic Review*, 1(1)1-19.

Conley, T. 1999. “GMM estimation with cross sectional dependence.” *J. of Econometrics*, 92 (1)1-45.

Cunfer, G., 2005. On the Great Plains: Agriculture and Environment. Texas A&M University Press, College Station.

DeAngelis, A., F. Dominguez, Y. Fan, A. Robock, M. D. Kustu, and D. Robinson. 2010. "Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States," *Journal of Geophysical Research*, 115.

Dell, M., B. Jones, and B. Olken. 2011. “Temperature Shocks and Economic Growth: Evidence from the Last Half Century.” August, Mimeo.

Demsetz, H. 1967. “Toward a Theory of Property Rights,” *American Economic Review: Papers and Proceedings*, 57, 347-359.

Deschenes, O. and M. Greenstone. 2007. “The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather.” *American Economic Review*, 97(1)354-385.

Epp, A.W. 1954. “The Cost of Pumping Water for Irrigation in Nebraska.” Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 426 (November).

FAO. 1999. Poverty Reduction and Irrigated Agriculture. International Programme for Technology and Research in Irrigation and Drainage. Food and Agricultural Organization of the United Nations, Rome.

Foster, A. and M. Rosenzweig, “Inequality and the Sustainability of Agricultural Productivity Growth: Groundwater and the Green Revolution in Rural India,” mimeo, 2008.

Gertel, K., J.W. Thomas, T.S. Thorfinnson, and H.W. Ottoson. 1956. “Adjusting to Irrigation in the Loup River Area in Nebraska.” Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 434 (February).

Gisser, M. 1983. "Groundwater: Focusing on the Real Issue," *Journal of Political Economy,* 91, 1001-1027.

Groundwater Foundation. 2005. Rainmakers: A Photographic Story of Center Pivots. Lincoln, Nebraska.

Guiteras, R. 2009. “The Impact of Climate Change on Indian Agriculture,” mimeo.

Guru, M.V., and J.E. Horne. 2001. “The Ogallala Aquifer,” *Water Resource Management*, 48, 321-329.

Gutmann, M.P. 2005. Great Plains Population and Environment Data: Agricultural Data. Ann Arbor: University of Michigan and ICPSR.

Haines, M.R. 2005. Historical, Demographic, Economic, and Social Data: The United States, 1790–2000. Hamilton, NY: Colgate University and ICPSR.

Hansen, Z., G. Libecap, and S. Lowe. 2011. "Climate Variability and Water Infrastructure: Historical Experience in the Western United States," in The Economics of Climate Change: Adaptations Past and Present, eds. Gary D. Libecap and Richard H. Steckel, May 2001, NBER, University of Chicago Press.

Hornbeck, R. Forthcoming. “The Enduring Impact of the American Dust Bowl: Short and Long-run Adjustments to Environmental Catastrophe,” *American Economic Review.*

Hornbeck, R. 2010. “Barbed Wire: Property Rights and Agricultural Development,” *Quarterly Journal of Economics*, 125, 767–810.

Keskin, P. 2009. “Thirsty Factories, Hungry Farmers: Intersectoral Impacts of Industrial Water Demand,” *mimeo*, Kennedy School of Government.

Libecap, G. 2011. "Institutional Path Dependence in Climate Adaptation: Coman's 'Some Unsettled Problems of Irrigation,'" *American Economic Review Centenary Symposium*, 101(1)64-80.

Little, J. 2009. “The Ogallala Aquifer: Saving a Vital U.S. Water Source.” *Scientific American*, March.

McGuire, V.L., Johnson, M.R., Schieffer, R.L., Stanton, J.S., Sebree, S.K., and Verstraeten, I.M., 2003, Water in storage and approaches to ground-water management, High Plains aquifer, 2000: U.S. Geological Survey Circular 1243.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The impact of global warming on agriculture: A Ricardian analysis," *American Economic Review*, 84(4)753-771.

Moench, M. 1996. Groundwater policy: Issues and alternatives in India. Colombo: International Irrigation Management Institute.

NHGIS, http://www.nhgis.org/, Minnesota Population Center, University of Minnesota.

O'Brien, D.M., F.R. Lamm, L.R. Stone, and D.H. Rogers. 2001. "Corn-Yield and Profitability for Low- Capacity Irrigation Systems," *Applied Engineering in Agriculture*, 17, 315–21.

Olmstead, A.L. and P. Rhode. 2011. "Adapting North American wheat production to climatic challenges, 1839 - 2009," *PNAS*, 108(2)480-485.

Opie, J. 1993. Ogallala: Water for a Dry Land. Lincoln: University of Nebraska Press.

Ostrom, E. 1990. Governing the commons: The evolution of institutions for collective action. London: University of Cambridge Press.

Ostrom, E. 2011. "Reflections on 'Some Unsettled Problems of Irrigation,'" *American Economic Review Centenary Symposium*, 101(1)49-63.

Peterson, J.M., and Y. Ding. 2005. "Economic adjustments to groundwater depletion in the high plains: Do water-saving irrigation systems save water?" *American Journal of Agricultural Economics*, 87 (1), 147–159.

Peterson, J.M., T.L. Marsh, and J.R. Williams. 2003. "Conserving the Ogallala Aquifer: Efficiency, Equity, and Moral Motives," *Choices*, 1, 15–18.

Pimentel, D., J. Houser, E. Preiss, O. White, H. Fang, L. Mesnick, T. Barsky, S. Tariche, J. Schreck, and S. Alpert. 2007. "Water Resources: Agriculture, the Environment, and Society." *BioScience,* 47(2)97-106.

Pfeiffer, L. and C.-Y.C. Lin. 2010. "The effect of irrigation technology on groundwater use," *Choices*, 25(3).

Porter, K.B., I.M. Atkins, and C.J. Whitfield. 1952. "Wheat Production in the Panhandle of Texas." Texas Agricultural Experiment Station, College Station, Texas Agricultural and Mechanical College System, Bulletin 750 (June).

PRISM Climate Group. 2004. http://prism.oregonstate.edu, Oregon State University.

Rao, K. L. 1979. India's Water Wealth. Orient Longman, New Delhi.

Rhoades, H.F., O.W. Howe, J.A. Bondurant, and F.B. Hamilton. 1954 "Fertilization and Irrigation Practices for Corn Production on Newly Irrigated Land in the Republican Valley." Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 424 (February).

Rogers, J.S. and J.W. Collier. 1952. "Corn Production in Texas." Texas Agricultural Experiment Station, College Station, Texas Agricultural and Mechanical College System, Bulletin 746 (March).

Rosegrant, M.W., C. Ringler and T. Zhu. 2009. "Water for Agriculture: Maintaining Food Security under Growing Scarcity," *Annual Review of Environment and Resources*, 34, 205-222.

Schlenker, W., W. Hanemann, and A. Fisher. 2006. "The Impact of Global Warming on U.S. Agriculture: An Econometric Analysis of Optimal Growing Conditions." *Review of Economics and Statistics*, 88(1)113-125.

Schlenker, W. and M. Roberts. 2009. "Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change," *PNAS*, 106(37)15594-98.

Schoengold, K. and Zilberman, D. 2007. "The economics of water, irrigation and development," in Evenson R.E., Pingali, P., Schultz, T.P. (eds.), Handbook of Agricultural Economics: Agricultural Development: Farmers, Farm Production and Farm Markets, vol. 3, North-Holland.

Sekhri, S. 2008. "Public Provision and Protection of Natural Resources: Groundwater Irrigation in Rural India," forthcoming, *American Economic Journal, Applied Economics*.

Shah, T. 1993. Groundwater Markets and Irrigation Development: Political Economy and Practical Policy. Bombay: Oxford University Press.

Soil Conservation Service. 1951. Map of Major Soil Groups. National Archives Record Group 114, item 148.

Thorfinnson, T.S. and A.W. Epp. 1953. “Effect of Pump Irrigation on Farms in Central Nebraska.” Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 421 (October).

Torell, L.A., JD Libben, and M.D. Miller. 1990. “The market value of water in the Ogallala aquifer,” *Land Economics*, 66, 163-75.

U.S. Department of Agriculture. 1924. *Atlas of Agriculture, Part I, section E*, Washington, DC: GPO.

U.S. Department of Commerce. 1937. *The Future of the Great Plains: Report of the Great Plains Committee to the House of Representatives*, 75th Cong., 1st session, doc. 144.

Weakly, H. E. and L.L. Zook. 1928. “Pump Irrigation Results.” Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 227 (June).

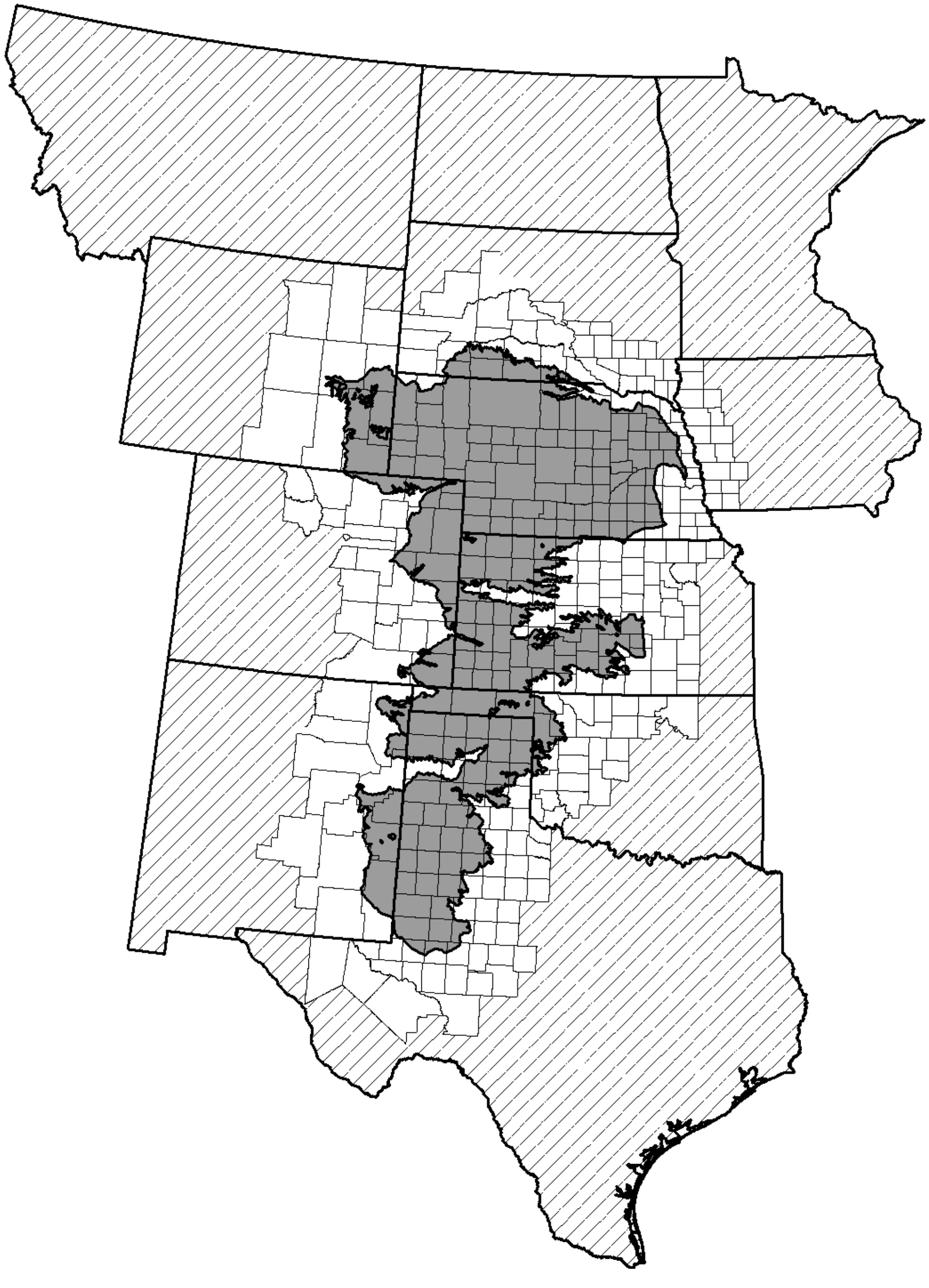
Weakly, H.E. 1932. “Pump Irrigation and Water Table Studies.” Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 271 (May).

Weakly, H.E. 1936. “Pump Irrigation at the North Platte Experimental Substation.” Agricultural Experiment Station, University of Nebraska College of Agriculture, Lincoln, Bulletin 301 (June).

Webb, W.P. 1931. The Great Plains, New York, NY: Grosset & Dunlap.

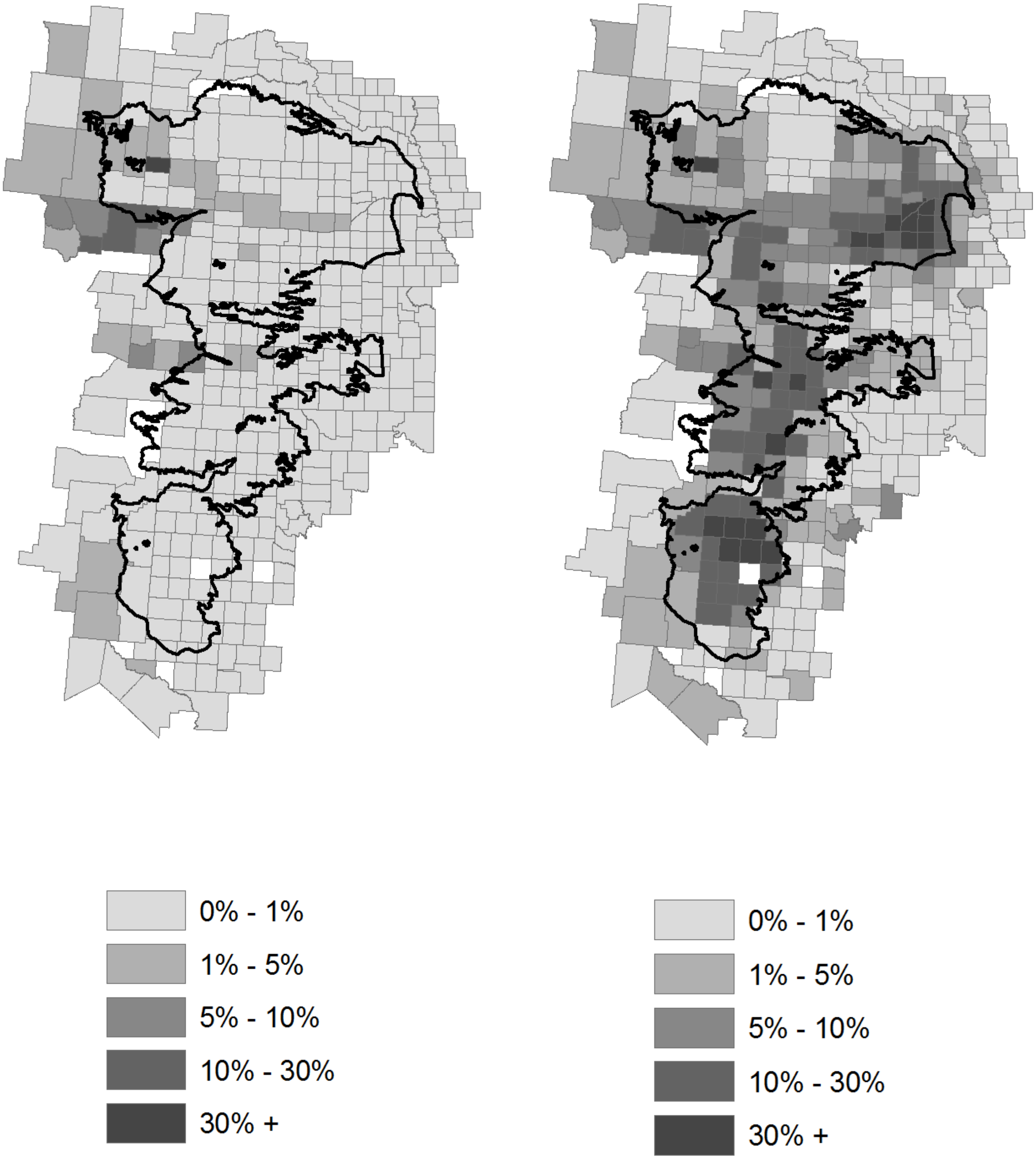
Zwingle, E. 1993. “Wellspring of the High Plains,” *National Geographic*, March, 80-109.

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. Irrigated Percent of County Area in 1935 and 1974

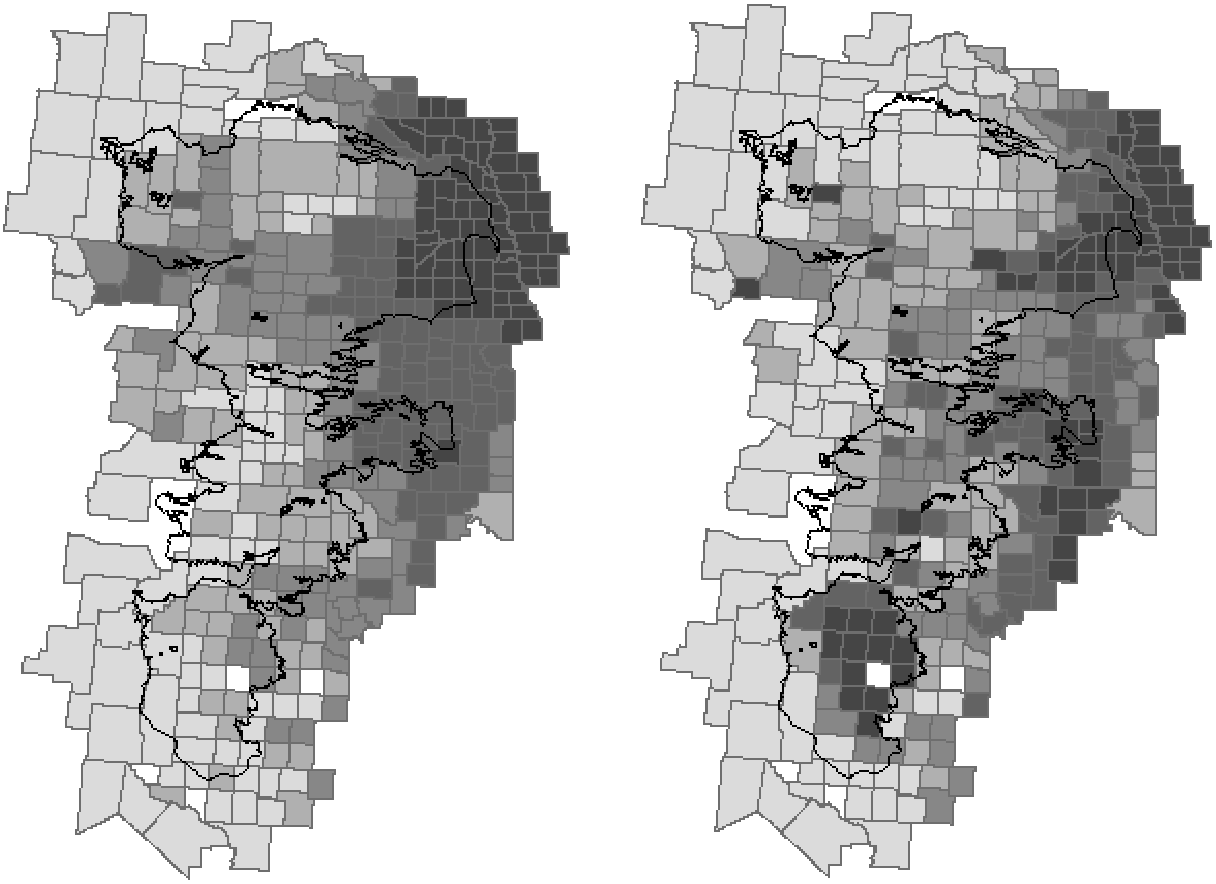


A. Irrigation in 1935

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). White areas are omitted from the sample.

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

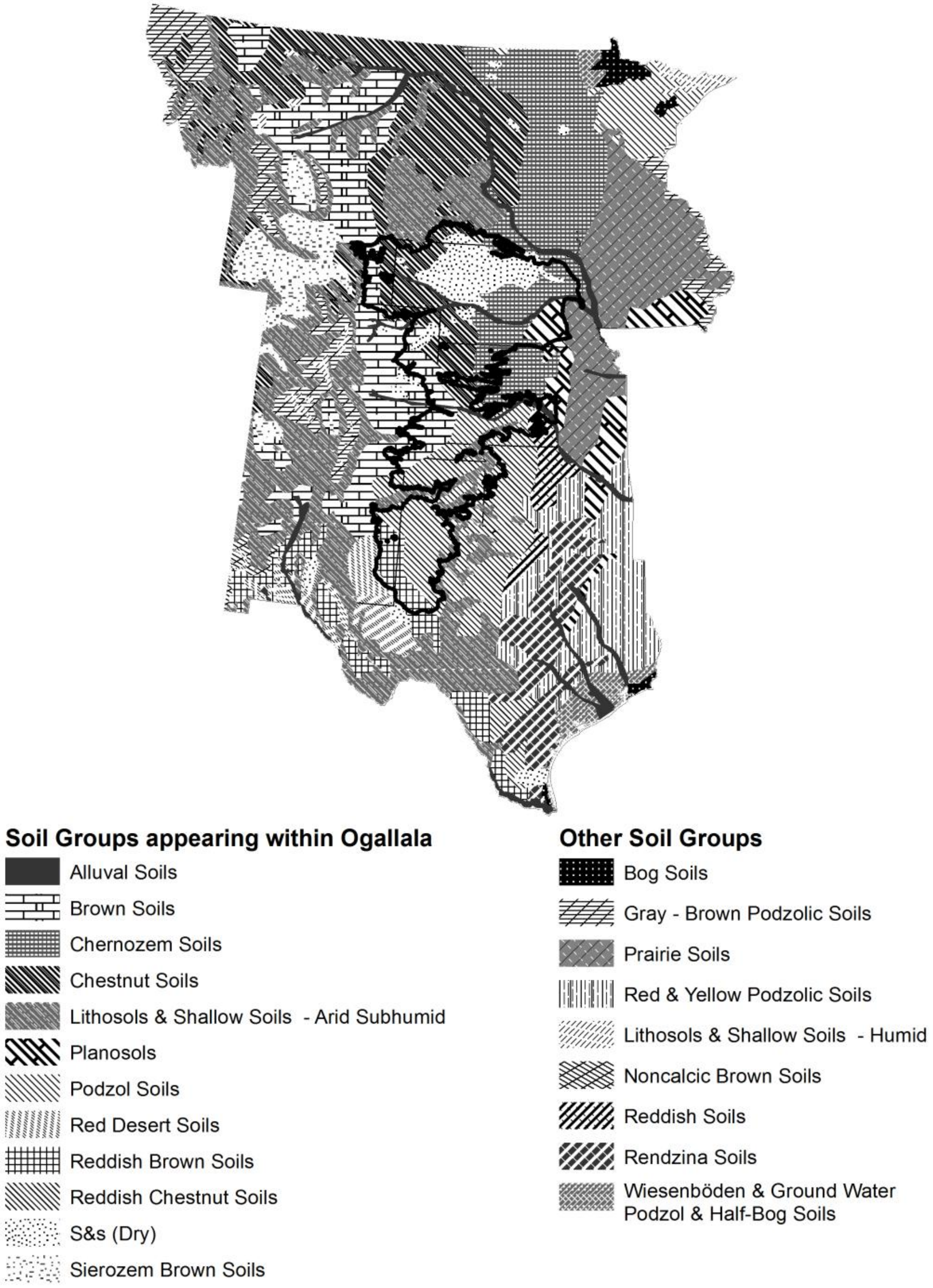


A. Land Value in 1920

B. Land Value in 1964

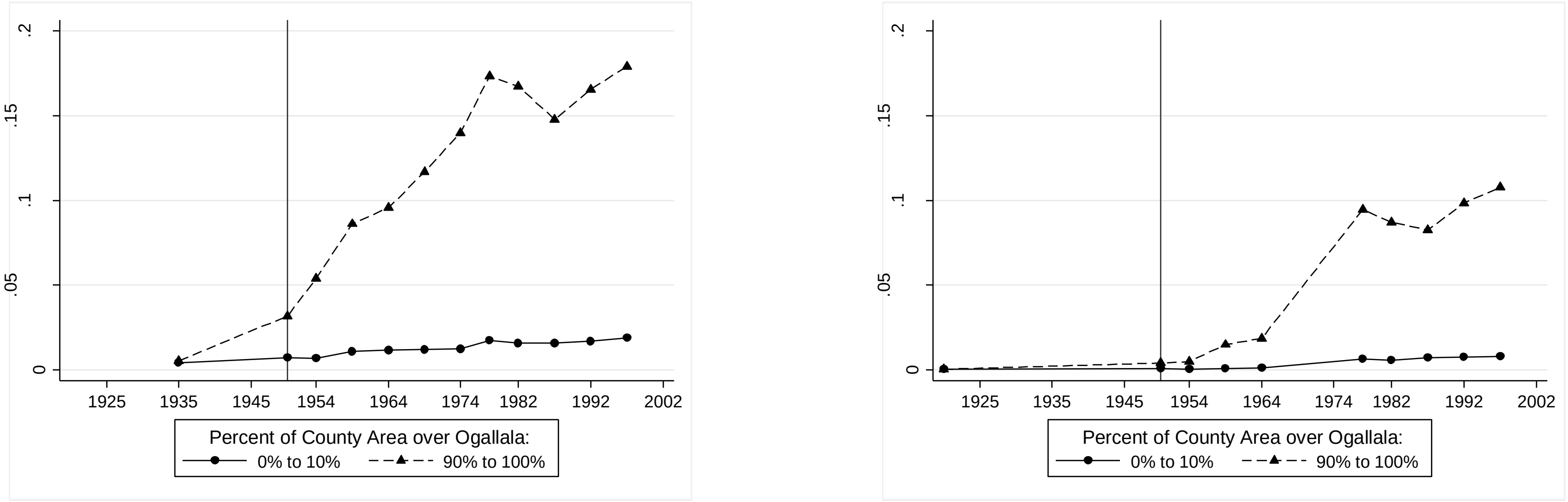
Notes: The 368 sample counties are shaded to reflect their quintile in the distribution of counties' average value of agricultural land per county acre in 1920 (Panel A) and 1964 (Panel B). The lightest gray represents the 20% least valuable counties, while the darkest gray represents the 20% most valuable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

Figure 4. Ogallala Boundary and Soil Group Control Variables



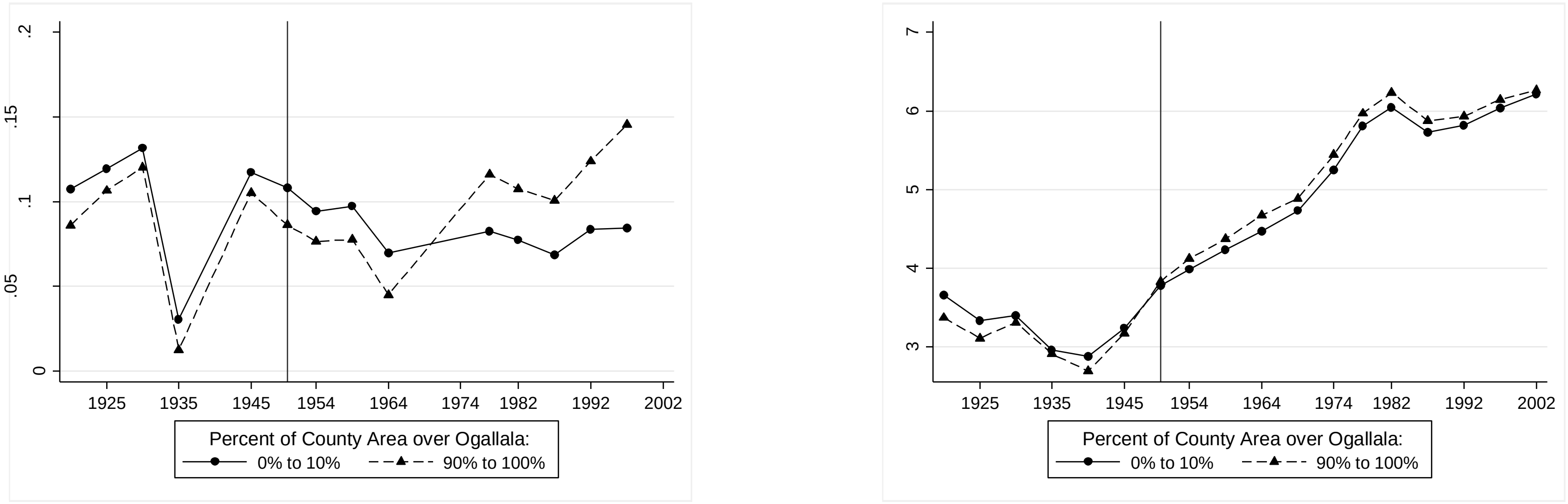
Notes: The Ogallala boundary (USGS) is overlaid with major soil groups, as mapped by the Soil Conservation Service (SCS 1951).

Figure 5. Average County Characteristics Per County Acre, by Ogallala Group



Panel A. Irrigated Farmland Acres

Panel B. Irrigated Corn Acres Harvested



Panel C. Corn Acres Harvested

Panel D. Log Value of Farmland

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 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.

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

		Coefficient on Ogallala Share:			
	County Means	No Controls	State Fixed Effects	State and Soil Group	State, Soil, Climate, X/Y
Per county acre:	(1)	(2)	(3)	(4)	(5)
Farmland	0.706	0.140**	0.020	-0.001	-0.003
	[0.249]	(0.039)	(0.032)	(0.034)	(0.038)
Irrigated Farmland, 1935	0.007	-0.0013	-0.0013	-0.0026	-0.0039
	[0.020]	(0.0024)	(0.0022)	(0.0027)	(0.0034)
Log Value of Farmland and Farm Buildings	2.87	0.432*	-0.203	-0.057	-0.038
	[1.30]	(0.194)	(0.155)	(0.120)	(0.135)
Log Value of Farm Revenue	1.75	0.306	-0.224	-0.102	-0.010
	[1.18]	(0.177)	(0.147)	(0.117)	(0.128)
Corn Acres	0.054	0.0066	-0.0347**	0.0006	-0.0043
	[0.088]	(0.0098)	(0.0075)	(0.0067)	(0.0075)
Irrigated Corn Acres	0.0003	0.00007	-0.00006	-0.00024	-0.00029
	[0.0011]	(0.00015)	(0.00012)	(0.00018)	(0.00019)
Wheat Acres	0.077	0.017	-0.008	-0.003	0.001
	[0.113]	(0.013)	(0.011)	(0.011)	(0.012)
Irrigated Wheat Acres	0.001	-0.00016	-0.00007	-0.00059	-0.00083
	[0.003]	(0.00027)	(0.00031)	(0.00051)	(0.00067)

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 (Figure 4). Column 5 also controls for linear functions of county average precipitation, average temperature, longitude, and latitude. The regressions are weighted by county acres, and robust standard errors are reported in parentheses. ** denotes statistical significance at the 1% level, * at the 5% level.

Table 2. Estimated Differences by Ogallala Share and Year: Irrigation and Farmland

	Irrigated Farmland Acres per county acre	Farmland Acres per county acre
Coefficient in year:	(1)	(2)
1920		-0.003
		(0.038)
1925		-0.015
		(0.036)
1930		0.044
		(0.032)
1935	-0.004	0.054*
	(0.003)	(0.023)
1940		0.013
		(0.029)
1945		0.052
		(0.029)
1950	0.013	0.016
	(0.007)	(0.029)
1954	0.030**	0.039
	(0.009)	(0.032)
1959	0.051**	0.008
	(0.010)	(0.030)
1964	0.062**	0.043
	(0.010)	(0.027)
1969	0.080**	0.055*
	(0.010)	(0.024)
1974	0.097**	0.052**
	(0.012)	(0.020)
1978	0.113**	0.060**
	(0.014)	(0.019)
1982	0.104**	0.071**
	(0.013)	(0.020)
1987	0.093**	0.058**
	(0.012)	(0.020)
1992	0.105**	0.051*
	(0.013)	(0.022)
1997	0.114**	0.064**
	(0.014)	(0.023)
Sample Counties	368	368

Notes: Columns 1 and 2 report estimates from equation (3). The indicated outcome variable is regressed on the share of county area over the Ogallala, state fixed effects, the fraction of county area in each soil group, state by year fixed effects, soil group by year fixed effects, and linear functions of county average precipitation, average temperature, longitude, and latitude. All coefficients are allowed to vary in each year. 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 3. Estimated Differences by Ogallala Share and Year: Corn and Wheat Acreages

	Corn Acres Harvested per county acre		Wheat Acres Harvested per county acre	
	Irrigated Corn	All Corn	Irrigated Wheat	All Wheat
Coefficient in year:	(1)	(2)	(3)	(4)
1920	-0.0003	-0.0036	-0.0009	0.0108
	(0.0002)	(0.0075)	(0.0007)	(0.0122)
1925		0.0108		0.0262*
		(0.0086)		(0.0114)
1930		0.0112		0.0645**
		(0.0096)		(0.0144)
1935		-0.0074*		0.0311**
		(0.0035)		(0.0115)
1940				
1945		0.0117		0.0340*
		(0.0081)		(0.0136)
1950	0.0021*	0.0035	0.0012*	0.0733**
	(0.0010)	(0.0080)	(0.0006)	(0.0139)
1954	0.0032**	0.0033	0.0016*	0.0340**
	(0.0012)	(0.0069)	(0.0006)	(0.0105)
1959	0.0097**	0.0046	0.0035**	0.0515**
	(0.0026)	(0.0075)	(0.0012)	(0.0099)
1964	0.0120**	-0.0020	0.0072**	0.0264**
	(0.0027)	(0.0052)	(0.0017)	(0.0095)
1969				0.0261**
				(0.0091)
1974				0.0332**
				(0.0115)
1978	0.0651**	0.0446**	0.0133**	0.0236*
	(0.0097)	(0.0097)	(0.0020)	(0.0105)
1982	0.0578**	0.0381**	0.0187**	0.0315*
	(0.0094)	(0.0090)	(0.0026)	(0.0125)
1987	0.0544**	0.0374**	0.0163**	0.0276**
	(0.0084)	(0.0081)	(0.0025)	(0.0104)
1992	0.0670**	0.0499**	0.0171**	0.0156
	(0.0099)	(0.0099)	(0.0027)	(0.0114)
1997	0.0762**	0.0652**	0.0140**	0.0146
	(0.0106)	(0.0110)	(0.0022)	(0.0115)
Sample Counties	333	365	313	367

Notes: Columns 1-4 report estimates from equation (3). The indicated outcome variable is regressed on the share of county area over the Ogallala, state fixed effects, the fraction of county area in each soil group, and linear functions of county average precipitation, average temperature, longitude, and latitude. All coefficients are allowed to vary in each year. 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 4. Estimated Differences by Ogallala Share and Year: Land Value and Revenue

	Log Value Farmland	Implied Ogallala Value in millions:			Log Farm Revenue
	per county acre	$	$CPI	$LV	per county acre
Coefficient in year:	(1)	(2)	(3)	(4)	(5)
1920	-0.038	-151	-1360	-1530	-0.010
	(0.135)				(0.128)
1925	-0.035	-103	-1056	-1543	0.044
	(0.112)				(0.131)
1930	0.223*	633	6817	9432	0.207
	(0.103)				(0.107)
1935	0.160	306	4016	7334	-0.080
	(0.093)				(0.112)
1940	-0.024	-41	-525	-1041	
	(0.104)				
1945	0.096	241	2407	4393	0.355**
	(0.093)				(0.105)
1950	0.273**	1192	8911	13255	0.423**
	(0.085)				(0.112)
1954	0.360**	1982	13269	17950	0.382**
	(0.084)				(0.121)
1959	0.352**	2499	15421	18033	0.480**
	(0.090)				(0.116)
1964	0.415**	3907	22659	22729	0.464**
	(0.081)				(0.129)
1969	0.394**	4531	22233	20146	0.584**
	(0.076)				(0.126)
1974	0.369**	7248	26439	19097	0.888**
	(0.072)				(0.133)
1978	0.239**	8544	23559	12663	0.813**
	(0.072)				(0.129)
1982	0.219**	10168	18951	12143	0.935**
	(0.073)				(0.132)
1987	0.158*	5257	8321	9028	0.880**
	(0.069)				(0.130)
1992	0.209**	7252	9296	11146	1.016**
	(0.076)				(0.145)
1997	0.245**	10538	11809	12706	1.177**
	(0.068)				(0.150)
2002	0.178*	9002	9002	9002	1.291**
	(0.080)				(0.155)
Sample Counties	368				368

Notes: Columns 1 and 5 report estimates from equation (3), as described in notes to Table 2. Column 2 reports the implied Ogallala value in contemporary millions of dollars, based on coefficients in column 1. The implied percent decline in land values is multiplied by the total value of land over the Ogallala, estimated as the sum of county land values multiplied by Ogallala shares. Column 3 converts column 2 into 2002 dollars using the CPI. Column 4 converts column 2 into 2002 dollars using a land value price index: in counties with zero Ogallala share, the 2002 value of land divided by that year's value of land.

Table 5. Estimated Local Spillover Impacts: Nearby Non-Ogallala Counties vs. Counties 100km from the Ogallala

	Irrigated		Corn Acres Harvested		Wheat Acres Harvested		Log Farm	Log Farm
	Farmland	Farmland	Irrigated Corn	All Corn	Irrigated	All Wheat	Value	Revenue
Coefficient in:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1920		0.134**	-0.0002	0.0111	-0.00004	0.0249	0.277	0.210
		(0.048)	(0.0004)	(0.0179)	(0.00059)	(0.0176)	(0.172)	(0.184)
1935	0.000	0.092		0.0086		0.0119	0.285	
	(0.006)	(0.056)		(0.0111)		(0.0133)	(0.213)	
1945		0.009		0.0162		0.0176	0.268	0.232
		(0.054)		(0.0203)		(0.0176)	(0.189)	(0.187)
1950	-0.002	-0.048	0.0008	0.0182	-0.00020	-0.0029	0.085	0.054
	(0.009)	(0.049)	(0.0016)	(0.0202)	(0.00022)	(0.0213)	(0.138)	(0.170)
1954	-0.001	-0.044	0.0017	0.0091	-0.00016	0.0041	0.0754	-0.036
	(0.009)	(0.060)	(0.0017)	(0.0189)	(0.00013)	(0.0157)	(0.159)	(0.194)
1959	-0.005	-0.016	0.0036	0.0078	-0.00020	0.0153	0.102	0.007
	(0.010)	(0.051)	(0.0037)	(0.0206)	(0.00019)	(0.0144)	(0.115)	(0.192)
1964	-0.004	-0.030	0.0037	-0.0012	-0.00004	0.0004	0.061	0.020
	(0.010)	(0.050)	(0.0031)	(0.0148)	(0.00043)	(0.0142)	(0.118)	(0.209)
1969	-0.002	0.021				0.0022	0.073	0.111
	(0.010)	(0.043)				(0.0164)	(0.117)	(0.223)
1978	0.003	0.018	0.0102	0.0068	-0.00024	0.0122	-0.022	0.204
	(0.013)	(0.049)	(0.0076)	(0.0162)	(0.00085)	(0.0208)	(0.122)	(0.257)
1982	0.003	0.019	0.0083	0.0054	-0.00003	-0.0059	-0.015	0.234
	(0.012)	(0.053)	(0.0083)	(0.0154)	(0.00116)	(0.0244)	(0.144)	(0.235)
1987	0.000	0.036	0.0065	0.0044	-0.00004	-0.0042	-0.042	0.181
	(0.010)	(0.047)	(0.0062)	(0.0129)	(0.00083)	(0.0199)	(0.106)	(0.262)
1992	0.004	0.042	0.0104	0.0066	0.00002	-0.0011	0.117	0.298
	(0.012)	(0.056)	(0.0087)	(0.0160)	(0.00114)	(0.0222)	(0.116)	(0.277)
1997	-0.001	-0.004	0.0081	0.0049	-0.00066	-0.0215	0.078	0.190
	(0.012)	(0.052)	(0.0070)	(0.0145)	(0.00176)	(0.0217)	(0.119)	(0.271)
Sample Counties	136	136	114	133	99	135	136	136

Notes: For counties with zero area over the Ogallala, each column reports estimates from a modified equation (3): coefficients report the impact of "Negative Distance to Ogallala Boundary," measured in 100km units. Coefficients reflect average outcomes in counties next to the Ogallala boundary, relative to counties 100km away. Otherwise, the specifications are as described in Tables 2-4. For conciseness, some coefficients are omitted from 1925, 1930, 1940, 1974, and 2002. ** denotes statistical significance at the 1% level, * at the 5% level.

Table 6. Estimated Impacts of Ogallala and Drought on Yields, Relative to 1940 - 1956

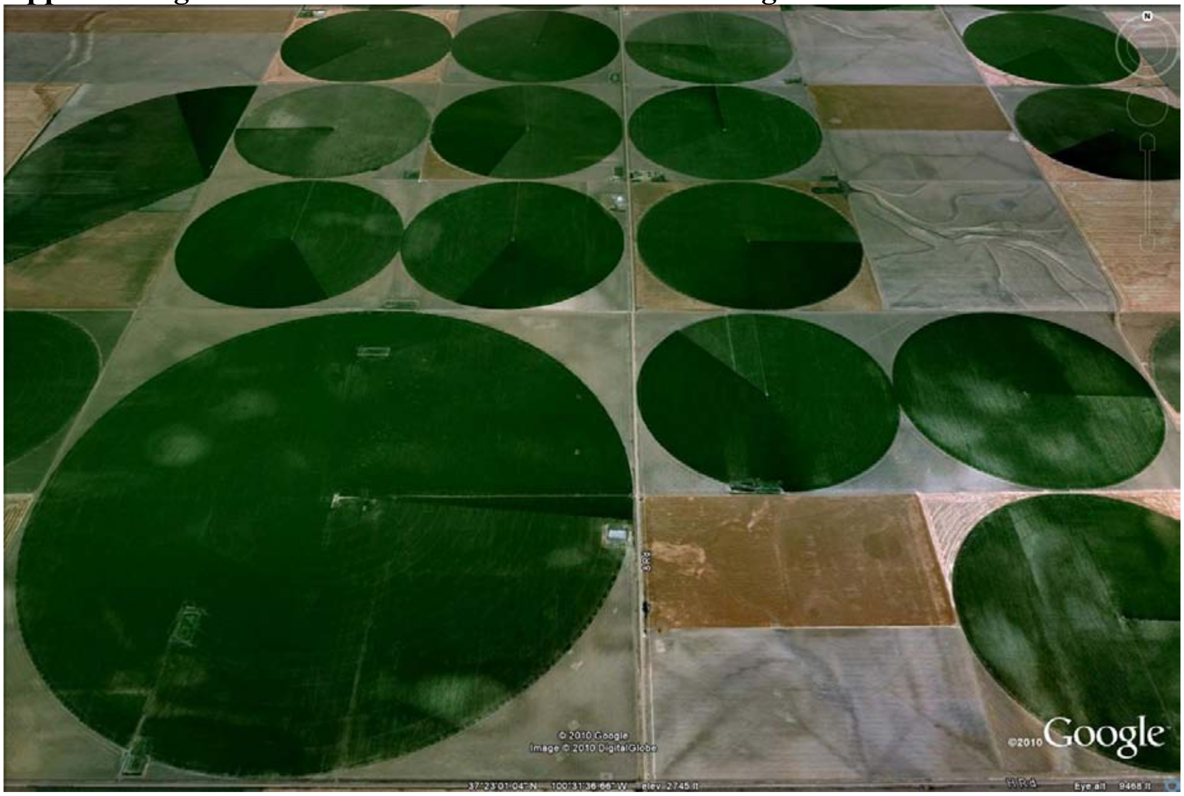
	(1)	(2)	(3)
Panel A. Log Corn Yield			
Ogallala * Drought * (1958 - 1975)	0.375**	0.353**	0.292*
	(0.101)	(0.098)	(0.121)
Ogallala * Drought * (1976 - 1993)	0.077*	-0.050	-0.036
	(0.038)	(0.065)	(0.080)
Ogallala * (1958 - 1975)	-0.034	-0.023	-0.053
	(0.145)	(0.151)	(0.151)
Ogallala * (1976 - 1993)	0.084	0.082	0.082
	(0.139)	(0.137)	(0.139)
Sample Counties	134	134	134
Panel B. Log Wheat Yield			
Ogallala * Drought * (1958 - 1975)	0.008	0.075	0.067
	(0.052)	(0.045)	(0.054)
Ogallala * Drought * (1976 - 1993)	0.057	0.045	-0.024
	(0.055)	(0.057)	(0.076)
Ogallala * (1958 - 1975)	0.052	0.047	0.046
	(0.042)	(0.042)	(0.042)
Ogallala * (1976 - 1993)	0.094	0.074	0.060
	(0.072)	(0.073)	(0.075)
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: Columns 1-3 report estimates from versions of equation (4). 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 average precipitation, average temperature, 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 interactions between drought and state fixed effects and interactions between drought and soil group shares. Column 3 also controls for interactions between drought and linear functions of average precipitation, average temperature, 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, and robust standard errors are reported in parentheses. ** denotes statistical significance at the 1% level, * at the 5% level.

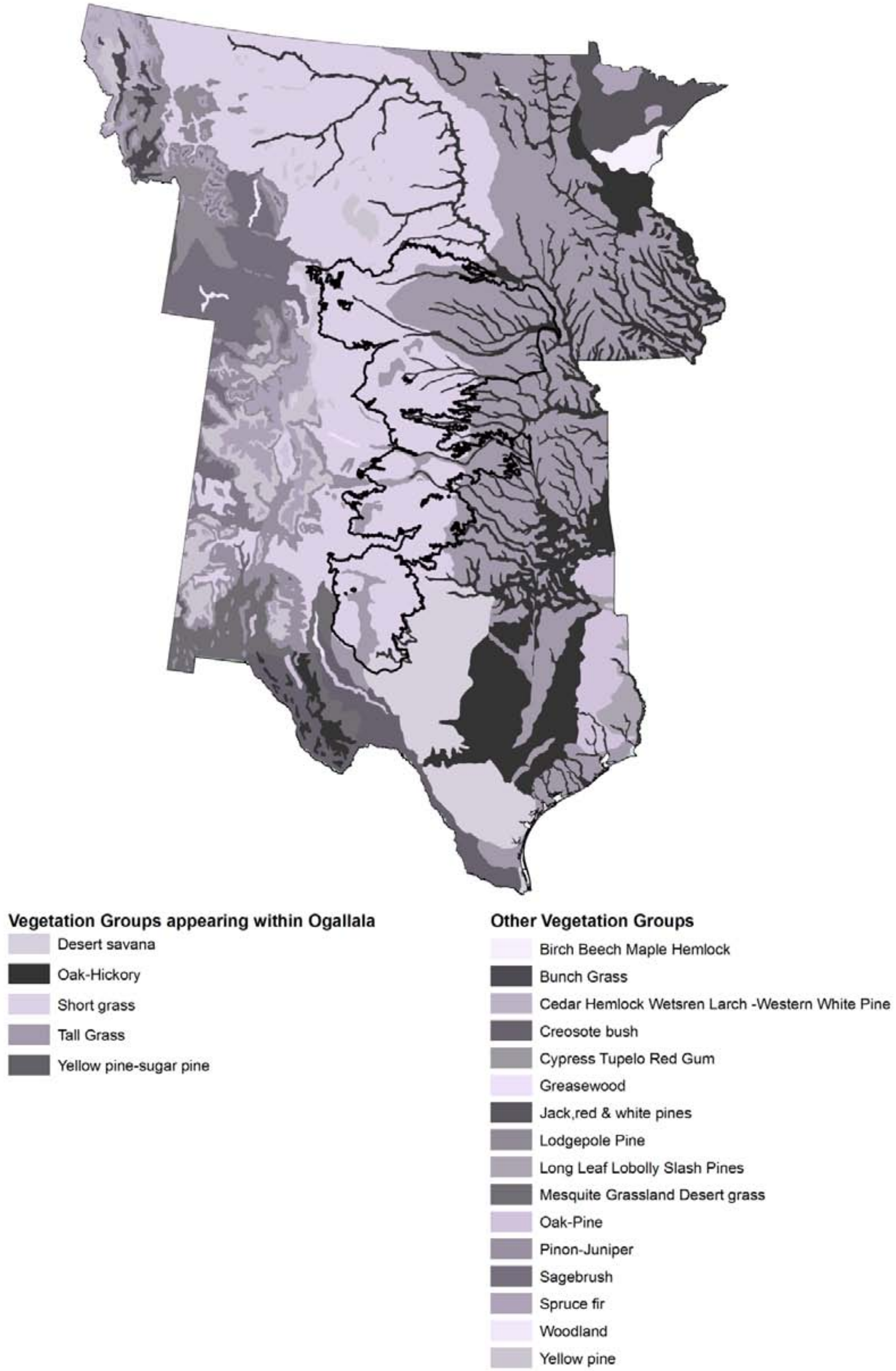
Appendix Figure 1. Panel A. Kansas Farmland over Ogallala



Appendix Figure 1. Panel B. Kansas Farmland outside Ogallala

Notes: Panels A and B display recent Google Earth images from nearby counties in south central Kansas.

Appendix Figure 2. Ogallala Boundary and Natural Vegetation Regions



Notes: The Ogallala boundary (USGS) is overlaid with natural vegetation regions, as mapped by the 1924 Atlas of Agriculture (USDA 1924).

VIII Theory Appendix

This appendix contains proofs of the theoretical results discussed in section II.

VIII.A Model Setup

The maximization problem of our representative farmer is

$$\max_{L_1,L_2,w_1,w_2} y_1(L_1,w_1,d)+y_2(L_2,w_2,d)$$

subject to the constraints

$$\begin{aligned} w_1+w_2 &= \bar{w} \\ L_1+L_2 &= \bar{L} \end{aligned}$$

The production functions are globally concave, with five additional assumptions:

1. The marginal product of water is higher for the first crop:

   $\partial y_1/\partial w_1 > \partial y_2/\partial w_2 > 0.$

2. The marginal product of water declines slower for the first crop:

   $\partial^2 y_2/(\partial w_2)^2 < \partial^2 y_1/(\partial w_1)^2 < 0.$

3. Water and land are complementary for both crops, but weakly more so for the first crop:

   $\partial^2 y_1/\partial L_1 \partial w_1 \geq \partial^2 y_2/\partial L_2 \partial w_2 > 0.$

4. Drought decreases the productivity of land for both crops, but drought has a larger negative effect on the water-intensive crop:

   $\partial^2 y_1/\partial L_1 \partial d < \partial^2 y_2/\partial L_2 \partial d < 0.$

5. Drought increases the productivity of water for both crops, but more so for the water-intensive crop:

   $\partial^2 y_1/\partial w_1 \partial d > \partial^2 y_2/\partial w_2 \partial d > 0.$

VIII.B Comparative Statics Without Drought

Initially, suppress the impact of drought (d) on production. The first order conditions for the farmer's maximization problem are given by:

$$\begin{aligned} \frac{\partial y_1\left(L_1^*, w_1^*\right)}{\partial w_1} - \frac{\partial y_2\left(\bar{L} - L_1^*, \bar{w} - w_1^*\right)}{\partial w_2} &= 0 \\ \frac{\partial y_1\left(L_1^*, w_1^*\right)}{\partial L_1} - \frac{\partial y_2\left(\bar{L} - L_1^*, \bar{w} - w_1^*\right)}{\partial L_2} &= 0. \end{aligned}$$

Of interest is how optimal factor allocation responds to a change in the available water ($\bar{w}$).
Proposition 1. *Water and land allocated to the water intensive crop are increasing in total water availability.*

Proof Totally differentiating the first order conditions with respect to $\bar{w}$, we obtain

$$\begin{aligned} \frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1}\frac{\partial L_1^*}{\partial \bar{w}} + \frac{\partial^2 y_1(\cdot)}{\left(\partial w_1\right)^2}\frac{\partial w_1^*}{\partial \bar{w}} - \frac{\partial^2 y_2(\cdot)}{\left(\partial w_2\right)^2}\left(1 - \frac{\partial w_1^*}{\partial \bar{w}}\right) + \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}\frac{\partial L_1^*}{\partial \bar{w}} &= 0, \text{ and} \\ \frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1}\frac{\partial w_1^*}{\partial \bar{w}} + \frac{\partial^2 y_1(\cdot)}{\left(\partial L_1\right)^2}\frac{\partial L_1^*}{\partial \bar{w}} + \frac{\partial^2 y_2(\cdot)}{\left(\partial L_2\right)^2}\frac{\partial L_1^*}{\partial \bar{w}} - \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}\left(1 - \frac{\partial w_1^*}{\partial \bar{w}}\right) &= 0. \end{aligned}$$

Rewriting, we obtain

$$\begin{aligned} [\frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1} + \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}]\frac{\partial L_1^*}{\partial \bar{w}} + [\frac{\partial^2 y_1(\cdot)}{(\partial w_1)^2} + \frac{\partial^2 y_2(\cdot)}{(\partial w_2)^2}]\frac{\partial w_1^*}{\partial \bar{w}} &= \frac{\partial^2 y_2(\cdot)}{(\partial w_2)^2}, \text{ and} \\ [\frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1} + \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}]\frac{\partial w_1^*}{\partial \bar{w}} + [\frac{\partial^2 y_1(\cdot)}{(\partial L_1)^2} + \frac{\partial^2 y_2(\cdot)}{(\partial L_2)^2}]\frac{\partial L_1^*}{\partial \bar{w}} &= \frac{\partial^2 y_2(\cdot)}{\partial w_2 \partial L_2}. \end{aligned}$$

The solution to this system is

$$\begin{aligned} \frac{\partial L_1^*}{\partial \bar{w}} &= \frac{\left(\frac{\partial^2 y_1(\cdot)}{\left(\partial w_1\right)^2} + \frac{\partial^2 y_2(\cdot)}{\left(\partial w_2\right)^2}\right)\frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2} - \left(\frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1} + \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}\right)\frac{\partial^2 y_2(\cdot)}{\left(\partial w_2\right)^2}}{\left(\frac{\partial^2 y_1(\cdot)}{\left(\partial w_1\right)^2} + \frac{\partial^2 y_2(\cdot)}{\left(\partial w_2\right)^2}\right)\left(\frac{\partial^2 y_1(\cdot)}{\left(\partial L_1\right)^2} + \frac{\partial^2 y_2(\cdot)}{\left(\partial L_2\right)^2}\right) - \left(\frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1} + \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}\right)^2} \\ \frac{\partial w_1^*}{\partial \bar{w}} &= \frac{\left(\frac{\partial^2 y_1(\cdot)}{\left(\partial L_1\right)^2} + \frac{\partial^2 y_2(\cdot)}{\left(\partial L_2\right)^2}\right)\frac{\partial^2 y_2(\cdot)}{\left(\partial w_2\right)^2} - \left(\frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1} + \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}\right)\frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}}{\left(\frac{\partial^2 y_1(\cdot)}{\left(\partial w_1\right)^2} + \frac{\partial^2 y_2(\cdot)}{\left(\partial w_2\right)^2}\right)\left(\frac{\partial^2 y_1(\cdot)}{\left(\partial L_1\right)^2} + \frac{\partial^2 y_2(\cdot)}{\left(\partial L_2\right)^2}\right) - \left(\frac{\partial^2 y_1(\cdot)}{\partial w_1 \partial L_1} + \frac{\partial y_2(\cdot)}{\partial w_2 \partial L_2}\right)^2} \end{aligned}$$

Global concavity of the revenue function ($y_1 + y_2$) ensures that the denominators in $\partial L_1^*/\partial \bar{w}$ and $\partial w_1^*/\partial \bar{w}$ are positive. Under assumptions 1 - 3, above, the numerators are also positive. Thus, $\partial L_1^*/\partial \bar{w} > 0$ and $\partial w_1^*/\partial \bar{w} > 0$. ▮

VIII.C General Case: Comparative Statics With Drought

Proposition 2. *When the land allocation is held constant, an increase in water availability reduces the (negative) impact of drought:*

$$\frac{\mathrm{d}}{\mathrm{d}\bar{w}}\left[\frac{\partial y_1\left(L_1^*, w_1^*\left(\bar{w}\right), d\right)}{\partial d}+\frac{\partial y_2\left(L_2^*, w_2^*\left(\bar{w}\right), d\right)}{\partial d}\right]>0.$$

Conversely, when the land allocation can respond to changes in $\bar{w}$, an increase in water availability has an ambiguous effect on the impact of drought.

Proof Consider the effect of $\bar{w}$ on the derivative of the revenue function with respect to d.

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

Assumption 5 and Proposition 1 imply that the first term is positive. Assumption 4 and Proposition 1 imply that the second term is negative. Thus, an increase in water availability has an ambiguous effect on the impact of drought. If the land allocation is held fixed ($\partial L_1^*/\partial \bar{w}=0$), then the impact is unambiguously positive. In addition, the effect of water availability on the impact of drought is more positive than when the land allocation is free to adjust. ■

VIII.D Special Case: Comparative Statics With Drought

Consider the special case of constant returns to land, in which the farmer maximizes

$$L_1 y_1(w_1, d)+L_2 y_2(w_2, d).$$

Proposition 3. *When the production technology displays constant returns to land:*

1. *If the land allocation can adjust to $\bar{w}$, then an increase in water availability increases the (negative) impact of drought:*

$$\frac{\mathrm{d}}{\mathrm{d}\bar{w}}\left[L_1^*\left(\bar{w}\right)\frac{\partial y_1\left(w_1^*\left(\bar{w}\right), d\right)}{\partial d}+L_2^*\left(\bar{w}\right)\frac{\partial y_2\left(w_2^*\left(\bar{w}\right), d\right)}{\partial d}\right]<0.$$

2. *If the land allocation is fixed, then an increase in water availability reduces the (negative) impact of drought.*

Proof The first order conditions simply to:

$$\begin{aligned}\frac{\partial y_1(w_1,d)}{\partial w_1} &= \frac{\partial y_2(w_2,d)}{\partial w_2} \\ y_1(w_1,d) - y_2(w_2,d) &= \frac{\partial y_2(w_2,d)}{\partial w_2}(w_1 - w_2).\end{aligned}$$

Assumption 1 and global concavity imply that

$$w_1^* > w_2^*.$$

In deriving the impact of $\bar{w}$, total differentiation of the first order conditions yields:

$$\begin{aligned}\frac{\partial^2 y_1(w_1,d)}{(\partial w_1)^2}\frac{\partial w_1}{\partial \bar{w}} &= \frac{\partial^2 y_2(w_2,d)}{(\partial w_2)^2}\frac{\partial w_2}{\partial \bar{w}} \\ \frac{\partial y_1(w_1,d)}{\partial w_1}\frac{\partial w_1}{\partial \bar{w}} - \frac{\partial y_2(w_2,d)}{\partial w_2}\frac{\partial w_2}{\partial \bar{w}} &= \frac{\partial^2 y_2(w_2,d)}{(\partial w_2)^2}\frac{\partial w_2}{\partial \bar{w}}(w_1 - w_2) + \frac{\partial y_2(w_2,d)}{\partial w_2}\left(\frac{\partial w_1}{\partial \bar{w}} - \frac{\partial w_2}{\partial \bar{w}}\right).\end{aligned}$$

Using the first order conditions to simply the second expression:

$$\frac{\partial^2 y_2(w_2,d)}{(\partial w_2)^2}\frac{\partial w_2}{\partial \bar{w}}(w_1 - w_2) = 0.$$

Because $w_1^* \neq w_2^*$, the only solution is $\partial w_1/\partial \bar{w} = \partial w_2/\partial \bar{w} = 0$. That is, increased water availability does not cause the farmer to use more water per acre; instead, the farmer shifts land toward the more water-intensive crop. Because w_1 and w_2 are constants,

$$L_1^*(\bar{w}) = \frac{\bar{w} - w_2}{w_1 - w_2},$$

and L_1^* is increasing in $\bar{w}$. Substituting this special case into the general solution:

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

Thus, when land allocations can adjust and the production technology displays constant returns to land, an increase in water availability increases the (negative) impact of drought. If the land allocation is fixed, however, increased water availability can only be allocated on the intensive margin and the (negative) impact of drought declines. ▮