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The Impacts of a Local Enhanced Management Area on Groundwater Use for Crop Production

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This study evaluates the impact of groundwater restrictions under Kansas's Local Enhanced Management Area program, focusing on the Sheridan-6 (SD6) region from 2013 to 2023. Using difference-in-differences regressions and well-level panel data, we find that SD6 irrigators reduced water use intensity by 16 percent and pumping costs by \$5.48 per acre on average. No significant changes in irrigated acreage occurred. Differences from the control group decreased after 2018 when irrigators outside SD6 adopted less stringent water use policies. Results suggest that locally governed, farmer-led restrictions can reduce water use without diminishing productivity, though policy diffusion and adaptive responses complicate long-term measurement of conservation outcomes.

Key words: difference-in-differences, groundwater use, irrigation, pumping costs, restrictions

Introduction

The Ogallala Aquifer spans 450,660 km^2 across the U.S. Southern and Central High Plains (Thelin and Heimes, 1987). The aquifer is a critical resource for agriculture but faces depletion due to unsustainable irrigation practices (Lauer et al., 2018). Parts of the Southern and Central High Plains may have insufficient water for irrigation within 20 to 30 years (Haacker et al., 2016). Research has documented an overall decline of 15.4 to 15.8 feet in water levels from 1950 to 2015, corresponding to a reduction of approximately 266.7 to 273.2 million acre-feet in water stored (McGuire, 2014; McGuire, 2017). Some Southern High Plains regions have experienced declines surpassing 150 feet (Pfeiffer and Lin, 2010). Deines et al. (2020) predict that 24 percent of the land currently irrigated by the Aquifer will not support irrigated crop production by 2100. The aquifer's depletion is projected to significantly impact the farm and regional economy as producers adapt to limited water resources by adjusting cropping patterns and input demand (Deines et al., 2021).

Water pricing, irrigated acreage fees, quantity restrictions, and water markets have been implemented to address groundwater overappropriation with varying degrees of success (Hrozencik et al., 2017; Guilfoos et al., 2016). Deficit irrigation, which optimizes groundwater use to match crop evapotranspiration, and restrictions on groundwater use could extend the

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aquifer's life and sustain the region's economic base (Steiner et al., 2021). Voluntary adoption of deficit irrigation by risk-averse and profit-maximizing producers is often considered unlikely. Risk-averse producers may not voluntarily adopt deficit irrigation if doing so increases the downside risk of lower crop yields. Profit-maximizing producers are unlikely to voluntarily adopt it if it means shifting away from high-valued crops to lower-valued, less water-intensive crops. Besides, what one producer conserves today could be used by others tomorrow.

Local governance of water resources is an important component of policies that aim to address overappropriation of groundwater resources since voluntary collective action is unlikely (Perez-Quesada and Hendricks, 2021). Designing and implementing policies that limit water use requires buy-in from users and institutions to support and facilitate the conservation of common-pool resources like aquifers (Ostrom, 1990). Users may be averse to top-down, third-party monitoring of water use, and catching and punishing transgressors can be costly, as can collecting, managing, and sharing information on water withdrawal among appropriators (Ostrom and Gardner, 1993).

Kansas and its Groundwater District legislation exemplifies a local governance solution for redressing groundwater over-extraction in the state's northwest region. In 2012, the state legislature passed Senate Bill No. 310, making Local Enhanced Management Areas (LEMAs) a part of Kansas water law (Kansas Department of Agriculture, Division of Water Resources [KDA], 2013).[1] The legislation aimed to reduce groundwater consumption to conserve the state's groundwater supply and extend the aquifer's life. This law allows groundwater management districts (GMDs) to initiate voluntary public hearings to consider specific water conservation plans that meet local goals.

On December 31, 2012, the Chief Engineer issued an Order of Decision accepting the LEMA proposed by local GMD4 irrigators for the Sheridan-6 (SD6) high-priority area inside GMD4 (LEMA-1) (Supplemental Material Figure 1). GMD4 includes wells in Sheridan and Thomas Counties, Kansas. GMD4 is characterized by high water use and significant, chronic reductions in water table levels. High-priority areas are geographic sections inside the district experiencing the most significant groundwater decline. The voluntary effort led by SD6 irrigators imposed a fixed-quantity-per-right groundwater use restriction of 20 percent less than historical use (Steiner et al., 2024). SD6 irrigators assigned themselves a 5-year allocation of 55 acre-inches per eligible acre. Eligible acres were determined as the maximum acres irrigated during the 2007 to 2010 period, with an allotment of 114,000 acre-feet for all SD6 irrigators over five years (KDA, 2013). Water use is monitored with meters, and monitoring is required by law.

The first SD6 LEMA lasted five years, with the option to extend or terminate it in 2017. On February 17, 2017, SD6 LEMA irrigators requested that the Kansas Division of Water Resources extend the LEMA to 2022, allowing a carryover allotment of up to 5 inches per acre from the first to the second LEMA (LEMA-2) (Northwest Kansas Groundwater Management District [NKGMD], 2021). The second LEMA was initiated and approved directly by the GMD4 Board. When irrigators adopted a district-wide LEMA in 2018, SD6 irrigators could have accepted a less restrictive allocation of 66 acre-inches over five years, but voted to maintain the original allocation of 55 acre-inches over another five years. This request and reluctance to increase the allotment suggest that the SD6 producers believed they could circumvent any negative economic consequences associated with reduced groundwater use and that the benefits of groundwater conservation outweighed the potential costs of self-imposed restrictions.

In 2018, GMD4 producers outside the SD6 boundary initiated a district-wide LEMA. Allocations varied across the district-based aquifer conditions. This LEMA lasted five years, beginning January 1, 2018, and ending December 31, 2022. The updated LEMA included all remaining eligible wells inside GMD4, excluding some vested rights and points of diversion

[1] Details of the policy and its implementation are at https://gmd4.org/SD6.html. For an expanded discussion on Kansas GMDs, see Perez-Quesada and Hendricks (2021).

(wells) whose supply source was 100 percent alluvial.[2] The required reductions in the district-wide GMD4 LEMA were less than those inside the SD6 LEMA. Irrigators in GMD4 areas immediately outside the SD6 LEMA voted for a multi-year allocation of 76 acre-inches over five years, 21 inches more than the allocations for SD6 irrigators[3]. The current GMD4 and SD6 LEMAs are in effect from 2023 to 2027.

This study aims to determine the effect of the second SD6 LEMA of 2018 on groundwater use. The regional focus of this research is well-studied, and the findings across studies are generally consistent. Smith et al. (2017) found that a groundwater tax reduced irrigation intensity by 33 percent for Colorado irrigators. Irrigators also replaced water-intensive crops with ones adapted to rainfed conditions. Ashwell et al. (2016) employed simulation methods to investigate the impact of subsidies that encouraged the adoption of enhanced irrigation technologies and their role in mitigating groundwater depletion. Their study area was the same as this research. Ashwell and coauthors concluded that enhancing irrigation efficiency may increase groundwater use and pumping costs. Golden (2018) used aggregated data in a difference-in-differences analysis (2006-2017) to examine the impact of the SD6 LEMA on applied water. He found that applied water decreased by 23 percent relative to their neighbors. In a nearby region of Kansas, Golden and Leatherman (2017) found that irrigated acres decreased by 20 percent when a GMD adopted water use restrictions. The outcome was accomplished by maintaining or expanding the production of higher-valued crops and adopting efficient irrigation technologies and practices. Drysdale and Hendricks' (2018) study, from 2008 to 2016, analyzed the effects of water quantity restrictions for SD6 irrigators. They found that irrigation intensity decreased by 26 percent after the LEMA's implementation. Dienes et al. (2019) analyzed the same region using aggregated data from 2008 to 2017. They found that producers inside the SD6 LEMA decreased water use by 31 percent. Zwickle et al. (2021) found a similar decrease from 2013 to 2017. Farmers made minor adjustments to irrigated crop acres but remained profitable despite reduced yields. In a follow-up study, Dienes et al. (2021) revised their 2008 to 2017 estimate downward to a 25 percent reduction in groundwater use inside SD6.

This analysis extends the previous research in three ways. First, the study uses well meter data from 2003 to 2023. The extended data set facilitates the examination of the LEMA's impact on groundwater use by adding the 2018 to 2023 period. This period is significant because the quota system was reauthorized for another five years, beginning in 2018. During this period, irrigators surrounding SD6 adopted less stringent water use restrictions. We expect that observed differences between irrigators inside SD6 and their counterparts outside the LEMA will decrease with the adoption of less restrictive water use regulations by GMD4 irrigators. Second, like Drysdale and Hendricks, we use a two-way fixed effects (TWFE) difference-in-differences (DiD) estimator to model site-specific and temporal heterogeneity while estimating the effects of the LEMA on irrigation decisions. Omitting sources of heterogeneity associated with sites and years may lead to downward-biased estimates of the treatment effects (i.e., overstated effects from the restriction). We use an augmented TWFE-DiD estimator that Wooldridge (2021, 2023) proposed, called an extended TWFE (ETWFE) estimator. The extended regression improves upon the standard TWFE-DiD estimator by controlling for additional sources of heterogeneity by including multi-way interactions among treatment variables, control variables, time effects, and event study effects. Third, the estimates are used to predict changes in pumping costs for producers inside SD6. We expect that pumping costs decreased for SD6 irrigators compared to their counterparts. However, differences in pumping costs are expected to decline for GMD4 irrigators outside SD6 after they adopted less restrictive water use policies. We aggregate these pumping costs to the SD6 region to proxy changes in net returns following the LEMA's implementation.

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[2] Source: https://www.agriculture.ks.gov/home/showpublisheddocument/6194/638468944198100000
[3] Source: https://gmd4.org/LEMA.html.

Conceptual Framework

The economics of quantity restrictions on groundwater use for irrigation is a particular case of deficit irrigation economics. English's (1990) seminal paper on deficit irrigation economics explained how producers determine optimal irrigation levels when water and land are limiting factors. Moore et al. (1994) used this framework to examine extensive and intensive margin changes for multicrop production functions. Wang and Nair (2013)'s intertemporal solution of deficit irrigation economics was the same as the previous static results: an irrigator will use all the groundwater resources when it is in short supply. Their model also predicted that, under deficit conditions, producers are unresponsive to price signals from the water demand side.

The above framework predicts that a producer chooses a level of irrigation intensity that maximizes profit when land is not a limiting factor, but groundwater is. The theory also predicts that all irrigable land will be used for crop production. When water use is restricted, the producer will irrigate just enough cropland up to the quota by adjusting water use intensity until the marginal value product of irrigation intensity equals the marginal factor cost of delivering the water plus the shadow value of the water resource, i.e., what English called the 'water resource rent' divided by water use intensity in acre-feet/acre.

The previous studies did not discuss the role of the shadow value on the groundwater constraint in the irrigation decision or the shadow value of irrigable land. The economic relationship between the shadow value of groundwater resources and irrigation intensity can be demonstrated by setting up the producer's irrigation problem as a constrained Lagrangian and solving the necessary conditions for the irrigable acres and groundwater constraints. Moore et al. (1994) introduced a land constraint, but it played no role in their analysis. What follows is a stylized problem that includes irrigable land and groundwater constraints. Including a land constraint yields an additional shadow value for irrigable land. The setup only considers one crop, but it can be extended to any number of irrigable crops.

Denote the profit from an irrigated crop produced on a acres of land that can be irrigated as $a \cdot \pi(w) = a \cdot [p \cdot y(w) - c(w)]$, where p is crop price, $\pi(w)$ is profit (\$/acre), $y(w)$ is a concave yield response function, w is applied water (acre-feet/acre), $c(w)$ is the cost to irrigate an acre with $c(0) = 0, c'(w) > 0$, and $c''(w) > 0$. The water manager's decision variable a equals zero when the crop is rainfed, and $y(0)$ is the rainfed yield. The water manager's objective is to maximize profit from irrigated crops subject to a water use restriction. The Lagrangian for this problem is:

$$\max_{a,w} \mathcal{L} = a \cdot \pi(w) + \lambda_A[A - a] + \lambda_{\bar{W}}[\bar{W} - a \cdot w], \tag{1}$$

where A is the irrigable area, λ_A is the shadow value for irrigable acres (\$/acre), $\bar{W}$ is a restriction on groundwater use (the quota, in acre-feet), and $\lambda_{\bar{W}}$ is the shadow value of the quota (\$/acre-foot). Differentiating equation 1 with respect to water use intensity (lower-case letters indicate decision variables):

$$\mathcal{L}_w = p \cdot y_w - c_w - \lambda_{\bar{W}} = 0, \tag{2}$$

and then irrigated acres,

$$\mathcal{L}_a = p \cdot y(w) - c(w) - \lambda_A - w \cdot \lambda_{\bar{W}} = 0. \tag{3}$$

Rearranging terms in equation 2, the value of the marginal product (VMP) of irrigation equals the marginal factor cost (MFC) plus the shadow value of the quantity restriction, i.e., $VMP(w) = MFC(w) + \lambda_{\bar{W}}$.[4] The interpretation is that the producer will adjust water use intensity until the

[4] English (1990), and Wang and Nair (2013), assumed that the quantity restriction was always binding. This assumption may not always be the case as it depends on other things, such as precipitation and crop water demand. Assuming that the quantity restriction is binding and using the first-order conditions, English, Wang

value marginal product earned from doing so equals the provision cost and the economic value of the quota. If groundwater is not a limiting factor, then the producer will maximize profit by applying irrigated water until the marginal value of production equals the cost of irrigation. The producer will apply water until the marginal product value equals the marginal cost of irrigating another acre of land. Paris (2011) derived similar results for joint production processes and input quotas.

When groundwater is a limiting factor, the producer incurs an additional cost equal to the quota's value as water use intensity is adjusted to maximize profit, subject to a binding restriction. Producers adjust the amount of irrigated land and water use intensity until their net return margins are equal. Producers exhaust the allotment to irrigate the crop when the quota is binding. If the allotment is not binding, then the economic value of the quota is zero.

Consider now the second first-order condition. Rearranging terms and using the results of equation 2,

(4) $$\pi(w) = \lambda_A + w \cdot [VMP(w) - MFC(w)].$$

Equation 4 is identical to English's and Wang and Nair's results when water is a limiting factor but for the shadow value on irrigable land when irrigable land is limited. Dividing through by water use intensity yields the restricted profit condition into \$/acre-feet equivalence, $\pi^*(w) = \lambda_A^*(w) + \lambda_{\overline{W}}(w)$. This expression states that when groundwater and irrigable land are limited, the returns to acre-feet of applied water equal the value of irrigated land plus the implicit economic value of the quantity restriction on water availability. If neither constraint is binding, producers will adjust water use intensity and irrigated land such that the value of marginal profit equals the marginal cost of irrigating.

Empirical Model

This study uses Drysdale and Hendricks' (2018) decomposition of the total acre-feet of water used by an irrigator following the implementation of a water use quota into changes in acres irrigated (extensive margin), changes in irrigation intensity for a crop (direct-intensive margin), and land use changes (indirect-intensive margin). The decomposition differs here because it assumes that a binding water use constraint will affect crop choice and how much acre-feet of water is used. Given an irrigation quota, we assume that crop water demand is heterogeneous and will affect irrigation intensity and the number of acres irrigated.

The empirical model begins with the groundwater constraint in Equation 1 and considers the parameter of groundwater availability ($\overline{W}$) to be a function of the decision variables: how much land to irrigate (a) and water use intensity (w). Total irrigated acre-feet of water used is a function of a quantity restriction (q) and crop choice $\mathbf{y} \in (y_1 \cdots y_m)$:

(5) $$\overline{W}(a, w, q) \geq a(\mathbf{y}, q) \cdot w(\mathbf{y}, q)$$

where $a(\mathbf{y}, q)$ is the total crop acres irrigated and $w(\mathbf{y}, q)$ is the acre-feet of water applied. Totally differentiating equation 1, rearranging terms, and dividing both sides of the derivative by $\overline{W}$ decomposes the effects of the quota on water use into extensive and intensive margins as proportional changes:

(6) $$\frac{1}{\overline{W}} \cdot \frac{\partial \overline{W}}{\partial q} = \frac{1}{a} \cdot \left[\frac{\partial a}{\partial q} + \sum_{m=1}^{M} \frac{\partial a}{\partial y_m} \cdot \frac{\partial y_m}{\partial q}\right] + \frac{1}{w} \cdot \left[\frac{\partial w}{\partial q} + \sum_{m=1}^{M} \frac{\partial w}{\partial y_m} \cdot \frac{\partial y_m}{\partial q}\right]$$

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and Nair, find that $w[VMP - MFC] = \pi(w)$. Dividing through by water use intensity yields an equivalent expression with $\frac{\pi(w)}{w} = \lambda_{\overline{W}}$.

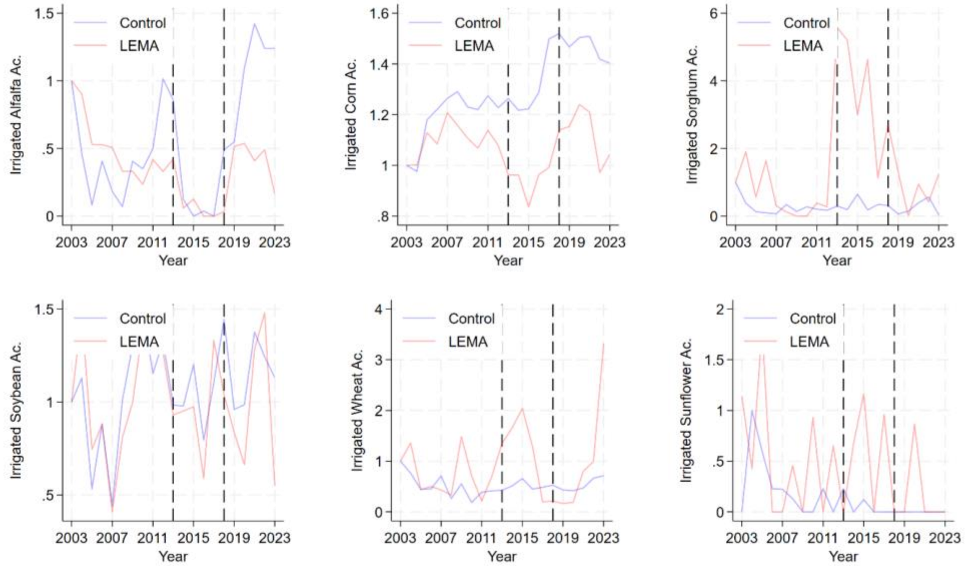

Figure 1. Relative Changes in Acres Allocated to Crops
Notes: The base year is 2003.

The change in irrigated acres (extensive margin) and the changes in land use (indirect-intensive margin) is the first term on the right-hand side of the derivative. The first term inside the bracket is the direct effect of the restriction on total irrigated acres (direct, extensive effect). The second term inside the bracket is the summation of the indirect effects of the restriction on total land use as determined by crop choice. The quantity restriction will affect crop choice when binding because crops have different water requirements. Multiplying through by $1/a$ yields the relative, proportional change in irrigated acres when the restriction is in effect. Producers will irrigate fewer acres if the restriction is binding, holding revenue and all other input costs constant. However, more acres of less water-intensive crops could displace relatively water-intensive, higher-valued crops.

The change in irrigation intensity (direct, intensive margin) is the second term on the right-hand side of equation 6. The first term inside the bracket is the direct effect of the quota on water use intensity (acre-feet/acre). The second term inside the bracket is the summation of the indirect effects of the quota on water use intensity, given crop choice and the quota. Multiplying through by $1/w$ yields the relative, proportional change (percentage) in water use intensity when the quota is in force. Holding revenue and all other input costs constant, producers will adjust water use intensity subject to crop choice if the quota is or near binding.

The decomposition of total water use into its components suggests some testable hypotheses. Irrigators will develop adaptive strategies to avoid potential revenue losses when water use is restricted or the restriction is binding. Buller (1988) and Wu, Bernardo, and Mapp (1996) suggest that producers will change the crop mix by shifting from high water-use crops, such as alfalfa and corn, to crops with lower consumptive use, possibly even converting to nonirrigated production or deficit irrigation.

Data

The Kansas Water Right Information System (WRIS) provided data on groundwater used and crop acres irrigated. Producer-generated annual water use reports are the basis for the WRIS dataset, which provides data on each point of diversion (PDIV) from 2003 to 2023. PDIVs are typically a single well in an irrigated field. We use "site" interchangeably with PDIV.

The WRIS data reports the acres irrigated for corn, soybeans, sorghum, alfalfa, sunflower, and wheat. Occasionally, producers reported irrigating two or more crops at the same PDIV. We call this category 'mixed crops.' A mixed crop allocation table was used to allocate acres to individual crops. For example, if the crop code was '23' (corn 2) and soybean (3), the reported irrigated acres were assumed to have 50 percent corn and 50 percent grain sorghum (Dysdale and Hendricks, 2018). As a result, all fields consisting of either a single crop or two or more crops were included in the calculation for crop-specific acreage. Aggregate trends in land allocated to irrigated crops are in Figure 1. The number of irrigated corn acres decreased after the first SD6 LEMA, and sorghum and wheat acres briefly increased. Trends in land use changes between LEMA and non-LEMA PDIV for the other crops are unclear.

We use 'treated' to refer to PDIV inside the SD6 LEMA and 'controls' for the PDIV outside the SD6 boundary (Supplemental Material Figure 1). Control PDIVs are in GMD4 and inside a three-mile buffer surrounding the SD6 LEMA (Golden, 2018). The three-mile buffer was set in consultation with the local irrigators, the GMD board, and the Kansas Geological Survey to identify the areas of similarity and provide relatively equal numbers of observations in each area. We are less confident that the conditions are like those inside the SD6 LEMA beyond the three-mile buffer. Data at each PDIV includes the total annual acre-foot groundwater usage ($afused$), total acres irrigated ($acirr$), and crop type. Acre-feet of water applied per acre (afa) was calculated by dividing the total acres irrigated by the acre-feet used. Before data cleaning, the total number of observations was 7,659. Aggregated across PDIV, there were 23,597 eligible acres inside SD6.

From 2013 to 2018, GMD4 irrigators outside the SD6 boundary were not under any groundwater restrictions. SD6 irrigators allotted themselves 55 acre-inches/acre from 2013 to 2017. Thus, during the first LEMA, any differences in acres planted, acre-feet used, or acre-feet applied attributable to the implementation of the LEMA are relative to GMD4 irrigators outside the LEMA boundary whose water use was unrestricted. In 2018, GMD4 producers outside the LEMA boundary adopted a water use restriction of 76 acre-inches/acre from 2018 to 2023. The second SD6 LEMA maintained the restriction implemented from 2013 to 2017 of 55 acre-inches over five years.

While GMD4 irrigators outside SD6 initially served as an unrestricted control group (2013 to 2017), adopting a less restrictive water use policy in 2018 introduced a partial constraint on this group. The restriction imposed on control PDIVs from 2018 onwards—76 acre-inches/acre per five years—remained less stringent than the 55 acre-inches over five years restriction retained by the SD6 irrigators. This distinction in policy intensity allows us to preserve the control group's comparative role, though with recognition of its partial regulatory alignment starting in 2018. Therefore, any observed changes in acre-foot water use, acres irrigated, or water use per acre still reflect meaningful contrasts in water management outcomes under differential policy intensity, supporting the continued validity of the difference-in-differences approach. The interpretation of post-2018 differences between treated and control groups should consider this contextual shift. We expect that after 2018, the difference between the SD6 irrigators' water use and the PDIV outside the LEMA boundary will decrease if GMD4 irrigators in the control group adhere to their policy.

The panel was unbalanced, and some PDIV gaps existed due to reporting variations. After removing duplicate records (51) and observations with missing data, there were 7,222 observations for the analysis. There were 169 PDIVs in the target group (3,491 observations) and 199 PDIVs in the control group (3,731 observations). Corn was the primary crop reported in the WRIS data (62 percent), followed by soybeans (19 percent) and wheat (8 percent) (Table 1). About seven percent of the crop observations were classified as mixed crops. Only 50 (131) cases included irrigated sunflower (alfalfa). Producers only report total acre-feet of groundwater usage

Table 1. Summary Statistics (N = 7,222) (1)

Variable	Units	Mean	Std. dev.	Min	Max
Irrigated acres	Acres	136.61	54.78	1	488
Acre-feet used	acre-feet	130.44	62.99	0.01	506
Acre-feet/ac.	acre-feet/acre	1.00	0.43	0.01	5
Corn dummy	(=1, n = 5,717)	0.79		0	1
Soybean dummy	(=1, n = 1,712)	0.24		0	1
Wheat dummy	(=1, n = 731)	0.10		0	1
Alfalfa dummy	(=1, n = 131)	0.02		0	1
Sorghum dummy	(=1, n = 250)	0.03		0	1
Sunflower dummy	(=1, n = 50)	0.01		0	1
Mixed crop dummy	(=1, n = 611)	0.08		0	1
Corn	Irrigated acres	103.28	67.94	0	480
Soybean	Irrigated acres	13.32	31.92	0	300
Wheat	Irrigated acres	5.03	19.75	0	250
Alfalfa	Irrigated acres	2.00	13.29	0	238
Sorghum	Irrigated acres	0.83	10.25	0	240
Sunflower	Irrigated acres	1.29	11.02	0	180
Mixed crop	Irrigated acres	10.05	37.95	0	440
Precipitation	Inches	21.37	5.09	10.52	32.53

Notes: (1) There are 169 and 199 treated and control points of diversion (PDIV).

for a mixed crop yield, and no reasonable method was developed to allocate the total groundwater usage in acre-feet to individual crops.

Annual precipitation data were extracted from PRISM (Daly et al., 2023). The areal units for PRISM are 4-km grids. A nearest-neighbor matching algorithm was used to pair the geocoordinates of the PDIV with the closest grid centroid. Our calculated average of 21.37 inches/year is close to the average precipitation the National Oceanic and Atmospheric Administration calculated over the same period for Sheridan and Thomas Counties (20.56 inches, NOAA (2024)). NOAA estimated the average annual precipitation to be 20.23 inches from 2013 to 2023. The average annual rainfall calculated with the PRISM data over the same period is 21.78 inches. Precipitation was uncorrelated with irrigated acres ($p = 0.54$) but negatively correlated with acre-feet applied ($r = -0.35$, $p < 0.0001$) and water use intensity ($r = -0.38$, $p < 0.0001$).

Methods and Procedures

We use difference-in-differences (DiD) regression to identify a causal relationship between acres irrigated, acre-feet of water pumped, and acre-feet applied/acre after the SD6 LEMA implementation. DiD regression uses a quasi-experimental control group to identify the causal effect of the LEMA implementation on water use and irrigated acres (Angrist and Piscke, 2008). The analysis compares trends in water use across the study area.

Absent water use restrictions, differences in water use trends between the PDIV located inside SD6 and those outside are conditional on irrigated crop types, precipitation, and other sources of site-specific and temporal heterogeneity. Suppose the agronomic parameters in the treated and control groups are comparable before implementing SD6. In that case, the treatment effect of the SD6 LEMA is any statistically significant difference in crop mix, water use, and water use intensity after its implementation. For example, if the target and control areas had comparable irrigated acreage before the LEMA was implemented, and then the target area had fewer acres than the control area after the LEMA was implemented, it is assumed that the adoption of the LEMA likely caused the reduction in the number of irrigated acres in the target area. The scenario above, the parallel trend hypothesis, is testable (discussed below).

Pumping Costs

We calculated the pumping costs at each irrigation PDIV by year based on the irrigation water applied, natural gas prices, pumping efficiency, and total dynamic head (tdh) to measure the impact of the SD6 LEMA on irrigation costs. Pumping costs are a proxy for expected changes in net returns, assuming yields, prices, and other input costs remain constant for both groups. We expect pumping-cost externalities to decrease by adopting water use limits (Negri,1989). The tdh is a measurement used in fluid dynamics. It indicates the total equivalent height at which groundwater will be lifted and transported to the irrigation emitter at the required pressure. The tdh is the sum of the static water level, well drawdown, and additional head required at the center pivot nozzle.

We used the 2003 to 2023 annual average water levels (in feet) below the land surface of the groundwater monitoring station located in Sheridan County, Kansas, as a proxy for the static water level (Supplemental Materials Figure 2) (Kansas Geological Survey, 2024). The well drawdown was set to 40 feet, assuming a pumping capacity of 400 gallons per minute (gpm) (Ramaswamy, 2016). The additional head is 80.85 ft because a lower pressure center pivot usually requires a pressure of 35 pounds per square inch (psi) (or 35 psi × 2.3 ft/psi = 80.85 ft) to pump water through sprinklers.

The parameter c_{it}, the pumping cost per acre (dollars) at irrigation location i in year t, is calculated as $c_{it} = afa_{it} \times e_t \times pg_t$, where afa is the irrigation application rate (acre-ft per acre), and e is the energy required (thousand cubic feet, mcf) to lift one acre-foot of water in year t. The parameter pg is the natural gas price in \$ per mcf for year t. Supplemental Material Figure 3 presents the Kansas price (\$ per thousand cubic feet) of natural gas sold to commercial consumers from 2003 to 2020 (EIA, 2024).

The amount of natural gas required (e) is a function of the given well capacity (wc) in gallons per minute (gpm), total dynamic head (tdh), the pumping efficiency (θ), hours needed to pump one acre-ft of water, d, and hydraulic horsepower (whp) per mcf of natural gas (γ): $e_t = \frac{wc \cdot tdh_t}{3{,}960 \cdot \theta} \times \left(\frac{d}{\gamma}\right)$. Supplemental Material Table 1 presents the values of these parameters. The pumping efficiency (θ) is 75 percent (Tsoodle, 2019), well capacity (wc) is set to 400 gpm, and d is calculated as (325,851 gallons/acre-ft)/[400 gpm/(60 min /hour)] = 13.58 hrs/acre-ft. The parameter γ is 61.7 whp per mcf. The ratio $\frac{wc \cdot tdh_t}{3{,}960}$ calculates hydraulic horsepower (whp) using wc (gpm) and tdh_t (feet)[5]. Changes in pumping costs are calculated using the average treatment effects estimates from the DiD regressions.

Difference-in-Differences Regression

The two-way fixed effect DiD estimator has come under considerable scrutiny recently because of its inability to address staggered interventions (Calloway and Sant'Anna, 2021; Sun and Abraham, 2021), pre-intervention anticipatory effects (Angrist and Pischke, 2008), and its ability to detect violations of the parallel trend assumption (Wooldridge, 2020). We employ an extended two-way fixed effects estimator (ETWFE) to estimate the impact of implementing the SD6 LEMA on water use, acres irrigated, and acre-feet applied (Wooldridge, 2021, 2023). The ETWFE procedure is one of several methods in the recent heterogeneity robust DiD literature (Hull, 2018; Callaway and Sant'Anna, 2021; Sun and Abraham, 2021; de Chaisemartin and D'Haultfoeuille,

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[5] https://water.mecc.edu/courses/ENV110/lesson25_3.htm

2023; Wooldridge, 2023). The ETWFE approach allows for considerable heterogeneity in treatment effects across treatment intensity, periods, and covariates (Wooldridge, 2021). Staggered entry is not a concern here because a common, clearly defined treatment event occurred in 2013. However, it is possible to control for additional sources of unobserved heterogeneity by including dynamic treatment effects, time-treatment, treatment-covariate, covariate-time interactions, and location and yearly effects.

The ETWFE saturates the standard TWFE-DiD estimator with heterogeneous time effects modeled as interactions between cohorts, control variables, intervention leads and lags, intervention periods, and continuous or discrete time-varying effects (Nagengast, Rios-Avila, and Yotov, 2024). The model is:

$$(7) \quad y_{igt} = a_i + b_t + \sum_{t=2003}^{2011} d_{igt}^{pre} \cdot \tau_t^{pre} + \sum_{t=2013}^{2023} d_{igt}^{post} \cdot \tau_t^{post} + \boldsymbol{x}_{igt}^{D}\boldsymbol{\beta} + \sum_{t=2003}^{2011} d_{igt}^{pre} \cdot \boldsymbol{x}_{igt}^{D}\boldsymbol{\beta}_t^{pre} + \sum_{t=2013}^{2023} d_{it}^{post} \cdot \boldsymbol{x}_{igt}^{D}\boldsymbol{\beta}_t^{post} + \sum_{t=2004}^{2023} dT_{igt} \cdot \boldsymbol{x}_{igt}^{D}\boldsymbol{\delta}_t + u_{igt},$$

where y_{igt} is an outcome (irrigated acres, acre-feet of groundwater applied, or acre-feet applied per acre) (in logs to proxy proportional changes) for group g (SD6 irrigators, other GMD4 irrigators), $\boldsymbol{x}_{igt}^{D}$ are unit-demeaned covariates, the a_i are fixed effects for PDIV i = 1,…368, the b_t are yearly fixed effects for t = 2003,…2023, $dT_{ig2004} \ldots dT_{ig2023}$ are yearly dummy variables and d_{igt}^{pre} and d_{igt}^{post} equal '1' for SD6 PDIVs in year t, with "pre" ("post") indicating periods before (after) the intervention. The base year was 2012. Therefore, the yearly pre- and post-intervention ATET are relative to 2012 and PDIV outside the SD6 LEMA.

The a_i account for systematic differences between PDIVs that are constant over time, such as soil quality, field topography, farmer skill, and other unobserved factors associated with a site. The yearly fixed effects are aggregate time effects that capture external factors such as annual differences in variable costs and prices and other unobserved variables that potentially vary annually and whose shocks are common to all PDIVs. Additional time-varying control variables are included in the vector $\boldsymbol{x}_{igt}^{D}$, depending on which dependent variable is estimated (discussed below). The expected value of the variable u_{igt} is zero with variance σ_u^2. It comprises all other excluded variables, which are assumed to be uncorrelated with the yearly and PDIV fixed effects and the additional covariates in $\boldsymbol{x}^{D}$. Each regression estimates 175 parameters in addition to the 368 site and 17 yearly fixed effects.

Parallel Trend Tests

When decision-making units anticipate the implementation of an intervention, they might change their behavior before the policy is implemented. This Granger effect (Granger, 1969), which is related to the parallel trend assumption, confounds the identification of causal effects after an intervention is implemented. Violating this assumption means the average treatment effect on the treated (ATET) cannot be identified. In other words, a parallel trend signifies that irrigated acres and acre-feet applied were similar for SD6 irrigators and irrigators outside the SD6 LEMA boundary before the intervention. In the counterfactual case, absent the implementation of SD6, the irrigated acres and the acre-feet of water used by treated and control PDIV would continue along the same trend.

The ATET of interest are the τ_t^{post}, whereas the τ_t^{pre} are anticipatory effects (Angrist and Pischke, 2008). The control group includes PDIV inside the three-mile buffer surrounding the SD6 LEMA. The null hypothesis that treated and untreated PDIV had parallel trends in irrigated water and land use before the intervention is a joint test, H_0: $\tau_{2004}^{pre} = \cdots = \tau_{2012}^{pre} = 0$ (Nagengast, Rios-Avila, and Yotov, 2024). Rejection of this null hypothesis implies that a causal relationship between the intervention and water use cannot be identified.

We use a Bonferroni multiple comparison procedure to test this hypothesis graphically. The procedure controls the family-wise error rate by reducing the likelihood of detecting false-positive differences in trends or anticipatory effects. There are nine pre-treatment periods. The adjusted p-value is 0.05/9 = 0.0056 for a type 1 error rate at the five percent significance level. This p-value corresponds with a critical z-value of 2.78. The adjusted confidence interval is calculated as $\hat{\tau}_t^{pre} \pm 2.78 \cdot \mathrm{se}(\hat{\tau}_t^{pre})$. Suppose at least one of the confidence intervals for the pre-treatment effects excludes zero. In that case, the parallel trends null hypothesis is rejected.

We also used the Bonferroni procedure to adjust the confidence intervals for multiple comparisons of the raw data. The confidence intervals for the ATET and the raw acre-feet used and acre-feet/acre plots spanning 2003 to 2023 were adjusted as 0.05/17 = 0.0029, corresponding with a critical z-value of 2.97.

We conduct falsification tests to check the robustness of the parallel trend test results and whether the estimated treatment effects might be driven by something other than the intervention. The falsification test rules out the possibility that the treatment and control groups were already on different trajectories before the treatment occurred, which would bias the treatment effect estimates.

We used 2003 to 2012 data (one year before the LEMA's establishment) to conduct falsification tests. We then varied a fake first-treated period from 2006 to 2009 and calculated the percentage change in the treatment effect on each outcome variable. We calculated the Bonferroni-adjusted 95 percent confidence intervals (CI) adjusted for four hypotheses (2006, 2007, 2008, and 2009).

Irrigated Acres, Acre-Feet Used, and Acre-Feet/Acre Regressions

The outcome variables of interest are irrigated acres ($accir$), total acre-feet used ($afused$), and acre-feet/acre applied (afa). The dependent variables enter the regression models as natural logs. This transformation facilitates inference as relative percentage changes. We use Kennedy's (1981) approximation for the percent change in the outcome variables pre- and post-LEMA. The ATET are calculated in percentage form as $100 \times \left[\exp\left(\hat{\tau}_t - 0.5 \cdot \mathrm{var}(\hat{\tau}_t)\right) - 1\right]$. We use the delta method to estimate the standard errors for the ATET and other relevant summary variables included in the regressions.

The control variables included in the $accir$ regression are dummy variables for corn, wheat, soybean, sorghum, alfalfa and sunflower, and mixed crops. The variation of these control variables identifies this regression since we include site and yearly fixed effects. Alfalfa and sunflower were combined into a single crop due to the relatively sparse appearance of these crops. Annual precipitation is included in this regression. For the $accir$ regression, the total number of parameters estimated is 175, in addition to the PDIV and yearly fixed effects.

The control variables included in the $afused$ regressions are irrigated corn, soybean, wheat, sorghum, alfalfa/sunflower, and mixed crop acres. These additional sources of variation identify the ATET since we include site and annual fixed effects. In addition to identifying an ATET for acre-feet used, the $afused$ regression establishes a relationship between the total water applied and water used by each crop. Annual precipitation is also included as a control variable.

The afa regressions include the same control variables as those included in the $accir$ regression. Like the $accirr$ regression, dummy variables are used to indicate irrigated crops served by the PDIV. Continuous crop acres are excluded because the dependent variable is a function of those acres. The total number of ETWFE parameters estimated for the afa and $afused$ regressions is also 175, in addition to the year and PDIV fixed effects. The post-treatment ATET of the afa ETWFE regression is used to calculate the *ex-post* changes in irrigation costs per acre for SD6 irrigators.

Table 2. Aggregate Changes in Water Use

	-------------Sheridan-6-------------		-------------Control-------------	
Period	Acre-feet used	Acre-inch/ac.	Acre-feet used	Acre-inch/ac.
2008-2012	126,200	64	120,231	58
2013-2017	85,361	43	113,924	55
2018-2022	88,674	45	110,593	53
Eligible acres	23,597		24,862	

Notes: Eligible acres are the maximum acres irrigated between 2007 and 2010, as stipulated by the LEMA rules (KDA, 2013). The same rubric is used to determine "eligible acres" for comparison in the control group.

Changes in Pumping Costs

We estimate changes in pumping costs with the estimated marginal effect of the LEMA on water use intensity (the ATET) and the predicted values of acre-feet/acre using Kennedy's procedure and the rule for log-linear derivatives (Chiang, 1984)[6]. The predicted values of acre-feet/acre are estimated as $\widehat{afa}_{igt} = \exp(\widehat{\ln afa}_{igt} + 0.5 \cdot \hat{\sigma}_u^2)$. The change in acre-feet/acre is estimated as $\Delta\widehat{afa}_{igt} = \widehat{afa}_{igt} \cdot \widehat{ATET}_t$. Changes in pumping costs after the adoption of water use restrictions are estimated as $\Delta c_{igt} = \Delta\widehat{afa}_{igt} \times e_t \times pg_t$.

We find the lower 2.5 and upper 97.5 Bonferroni-adjusted confidence intervals using the delta method and evaluated at each observation. Next, we calculate the change in pumping costs, acre-feet/acre, and the corresponding lower and upper CI. After doing this for each observation, we report the average point estimates for the change in pumping costs and the lower and upper CI over the treated units for each year.

Estimation

The ETWFE regressions are estimated with the jwdid procedure in STATA (StataCorp, 2020; Nagengast, Rios-Avila, and Yotov, 2024). Standard errors were clustered on PDIV (Cameron and Trivedi, 2005). Cluster-robust standard errors allow for unrestricted forms of heteroscedasticity and serial correlation between model residuals for each panel unit (Wooldridge, 2010).

Results and Discussion

The raw data depicting changes in cropping patterns, water use (acre-feet used), and irrigation intensity (acre-feet/acre applied) are discussed first. Comparisons are made between SD6 irrigators and the other GMD4 irrigators outside the LEMA after aggregating over all PDIV and then at the level of the PDIV. Aggregate total acre-feet used and total eligible acres irrigated across all observations are used to calculate an aggregated acre-feet/acre applied, 2003 to 2023 (Table 2). Examination of the raw data is informative, but unadjusted for field size and variation at the PDIV level.

The DiD regressions are discussed next. They adjust for variation between PDIV and periods and other unobserved sources of heterogeneity. The primary objective of the DiD regressions was to estimate how the average behavior of SD6 irrigators changed regarding cropping patterns, water

[6] $\Delta\widehat{afa} = \frac{1}{\widehat{afa}} \cdot \frac{\partial \widehat{afa}}{\partial Lema}$ implies $\frac{\partial \widehat{afa}}{\partial Lema} = \widehat{afa} \cdot \frac{\partial \widehat{\ln afa}}{\partial Lema}$.

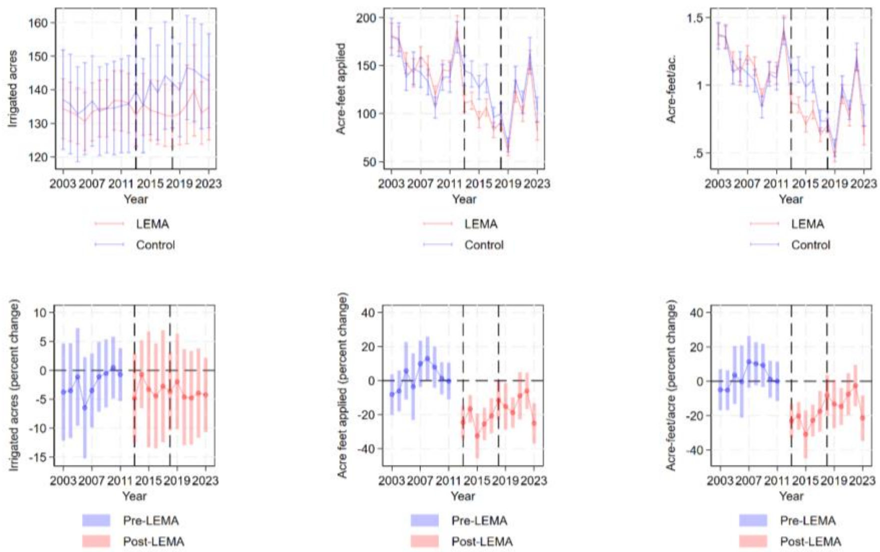

Figure 2. Means of PDIV Data for Irrigated Acres, Acre-Feet Used, and Acre-Feet/Acre, and ATET, 2003 to 2023

Notes: PDIV, points of diversion. The first vertical dashed line is 2013, when the Sheridan-6 LEMA became active. The second hashed line is 2018, when the SD LEMA was reauthorized. Top row: The blue line is the average for the control group. The red line is the average for LEMA fields. The bars are 95-percent confidence intervals adjusted for multiple comparisons using Bonferroni's procedure.

use, and use intensity compared to GMD4 irrigators outside the LEMA before computing acre-feet per acre. The main parameters of interest are the dynamic post-treatment effects (the $\boldsymbol{\tau}$). These ATET are *ceteris paribus* and conditional on the control variables, their interactions, and unobserved site-specific and time heterogeneity.

Observed Changes in Irrigated Acres and Water Use

From 2008 to 2012, and aggregating over all PDIV, SD6 irrigators applied 64-acre inches/acre (Table 2). GMD4 irrigators outside the LEMA applied 58-acre inches/acre during the same period. Aggregate water use intensity in SD6 decreased by 32 percent (43 acre-inches/acre) during the LEMA-1 period, compared to the total acre-inches/acre applied in the five years before its implementation. The same percentage change was observed for water pumped. Dienes et al. (2019), who used aggregated simulated data, reported a similar decline in water pumped (31 percent) during LEMA-1 but for a shorter period. Using different simulation procedures, Dienes et al. (2021) revised their estimate to a 25 percent reduction in water pumped for SD6 irrigators. Whittemore et al. (2023) found a 36 percent decrease in the LEMA's water use from 2013 to 2022 using aggregated data before adjusting for climatic conditions. The total acre-inches/acre applied during the second LEMA remained well below that observed from 2008 to 2012 and below the 55-acre-inches/acre allotment. Aggregate water use intensity for the GMD4 producers outside SD6 remained relatively unchanged from 2013 to 2017, at 53 acre-inches per acre.

The fact that aggregate water use over the ten years of the SD6 LEMA never exceeded the allotment of 114,000 acre-feet suggests that the restriction was never binding. As stated differently and generalized across all PDIV, the shadow value on the water use constraint was effectively zero. If the constraint had been binding, then the shadow value would at least be as much as the penalty for exceeding an allocation (KDA, 2013)[7]. SD6 irrigators quickly learned that they could use deficit irrigation without compromising profitability. They adapted to the water use restriction by temporarily shifting acres from corn to less water-intensive crops such as sorghum and wheat, an aggregate change in the intensive margin. In the aggregate, and during LEMA-1, the number of irrigated acres shifted from corn to sorghum and, briefly, wheat (Figure 1). During the second LEMA, irrigated corn acres remained lower than the control PDIV, but irrigated sorghum and wheat acres returned to pre-2013 levels.

Figure 2 summarizes the disaggregated trends of irrigated acres, acre-feet used, and acre-feet/acre from 2003 to 2023 at the PDIV level. The figure reports the raw data averages and adjusted confidence intervals for each year's SD6 and control PDIVs. The variability in acres irrigated across PDIV is evident. Irrigated corn acres drive the trend, as Figure 1 suggests, but there is no statistical difference between SD6 and control PDIVs concerning acres irrigated before or after the LEMA's establishment. A remarkable and significant difference exists between the acre-feet used and the acre-feet applied per acre after the LEMA's implementation in 2013. As explained in the discussion below, the gap in water use intensity between the SD6 and control PDIVs narrowed after the LEMA was reauthorized in 2018.

The differences in acre-feet applied/acre are primarily driven by the acre-feet used, as there were no statistical differences between irrigated acres. The acre-feet applied/acre decreased for the control group shortly after SD6's implementation. A noticeable gap existed between the intensity of SD6 and control PDIV water use during the first LEMA. SD6 irrigators reauthorized the LEMA in 2018 for another five years. The difference between the SD6 and control PDIVs quickly closed and was indistinguishable from 2019 to 2023. The narrowing of this gap is likely due to GMD4 irrigators adopting less restrictive water use rules outside the SD6 LEMA and SD6 producers applying carryover allotments. The acre-feet applied peaked during the 2011 drought for both groups but steadily declined until 2019. The DiD regressions examine these unadjusted, aggregate trends more closely by controlling for sources of PDIV panel heterogeneity and irrigated cropping decisions.

Difference-in-Differences Regressions

The regression estimates, including the treatment effects, the control variables, and their temporal interactions, are reported in Supplemental Material Table 2. The acres irrigated, acre-feet used, and acre-feet/acre applied regressions explained 90, 79, and 63 percent of the variation in their respective outcome variables. Collinearity did not appear to be an issue.[8] The ATET are the primary focus, reported in Figure 2, because we are interested in how SD6 irrigators changed their behavior relative to other GMD4 irrigators and whether their behavior changed after the LEMA's reauthorization in 2018. First, we discuss the parallel trend tests.

Parallel Trend Tests

The null hypothesis of parallel trends could not be rejected for any regression because none of the pre-treatment ATETs were significant, as indicated by the inclusion of '0' for all CI (Figure 2, left panel, row two). Failure to reject the null hypothesis suggests that trends in irrigated crop acres, acre feet used, and acre-feet/acre applied were statistically similar for SD6 and control PDIV before the LEMA's implementation.

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[7] The maximum penalty in Sheridan-6 is $1,000/day (KDA, 2013).

[8] The VIF average for the covariates included the $accir$ regression was 1.18. The collinearity diagnostic was 11.78. The VIF and collinearity diagnostic for the covariates included in the $afused$ and afa regressions were 1.31 and 13.18, respectively. Collinearity does not appear to be a concern. We first discuss the parallel trend and falsification test results.

Table 3. Post-LEMA Percent Changes in Acres Irrigated, Acre-Feet Used, and Acre-Feet/Acre

	Acres irrigated	Acre-feet used	Acre-feet/acre
A: 2013 to 2022	-3.50	-18.04***	-16.02***
p-value	0.073	0.000	0.000
B: 2013 to 2017	-3.21	-23.95***	-22.84***
p-value	0.129	0.000	0.000
C: 2018 to 2022	-3.79	-12.12***	-9.20**
p-value	0.073	0.000	0.002
Difference (C - B)	-0.59	11.83***	13.65***
p-value	0.722	0.000	0.000

Notes: (1) significance determined by a *z*-test; ***, **, * significant at the 0.1, 1, and 5 percent level. Entries are calculated using regression estimates. Entries are the average of the treatment effects over the period. Standard errors are calculated using the delta method.

The falsification test results are reported in Supplemental Table 3. All point estimate CIs include zero. The evidence suggests that the actual effects on acre-feet used and water use intensity after 2013 are likely due to the LEMA and no other coincidental factors. The falsification results also support the parallel trends test results, which show that preexisting differences or trends were not driving the treatment effects identified by the full-sample model. We can conclude with some confidence that without the implementation of the LEMA, trends in water use and irrigation decisions would have been the same for SD6 irrigators and those outside the area. The result is encouraging regarding inference about the LEMA's effect on irrigator decision-making.

Changes in Cropping Patterns and Water Use

The ATET estimates are in Figure 2 (bottom row). Consider first the changes in irrigated acres after 2013. These ATETs are the percent change in irrigated acres compared to the irrigated acres at GMD4 PDIV outside the SD6 LEMA. The adjusted confidence intervals of these ATET include '0.' The quantity restriction on water use did not affect the acres SD6 producers irrigated compared to GMD4 irrigators outside the LEMA boundary. Averaging over the ATET from 2013 to 2022, irrigated acres declined by 3.5 percent for SD6 irrigators (Table 3), but this decrease is not different from that of the other GMD4 irrigators. Nor were there any differences in the percentage change in irrigated acres for LEMA-1 (2013 to 2017) or LEMA-2 (2018 to 2022). The average decrease in irrigated acres, or the indirect-intensive margin, is insignificant. The finding is similar to Whittemore et al. (2023) and Dienes et al. (2019). They reported modest changes in irrigated acres following the implementation of the LEMA. Consistent with the economic model's prediction, SD6 irrigators changed their crop mix between LEMA-1 and 2, shifting irrigated acres from corn to less water-intensive wheat (briefly) and sorghum crops without significantly reducing irrigated acres. Expanding the extensive margin is not an option for the SD6 producers because eligible, irrigable acres are fixed at pre-LEMA levels.

The average of the post-treatment ATET for the acre-feet of water used from 2013 to 2022 was significant (Table 3). The acre-feet used decreased, on average, by 18 percent for SD6 irrigators relative to the PDIV outside its boundary during this period. During the first LEMA, SD6 irrigators reduced their acre-feet pumped by an average of 23.95 percent. This estimate is near those of Dienes et al.'s (2021) and Whittemore et al.'s (2023) findings after they adjusted for weather conditions. After 2017 and at the beginning of LEMA-2, the ATET for water used increased but remained negative except for 2021 and 2022. The rate at which SD6 irrigators

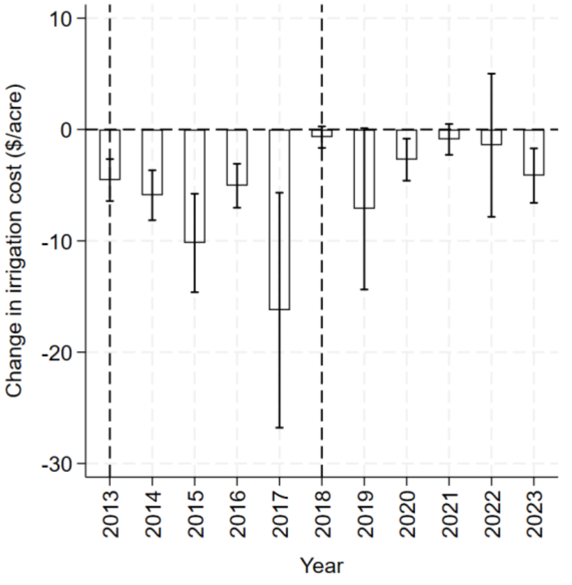

Figure 3. Change in Pumping Costs
Notes: Capped lines are 95-percent confidence intervals adjusted for multiple comparisons using Bonferroni's procedure. The hashed lines indicate the implementation of Sheridan-6 LEMA-1 (2013) and LEMA-2 (2018).

conserved groundwater declined after the first reauthorization of the LEMA. The difference in pumped water for the LEMA-1 and LEMA-2 periods was significant at 9.67 percent (Table 3).

Consider the acre-feet applied/acre ATET in Figure 2, row two, right panel. From 2013 to 2022, SD6 irrigators decreased their water use intensity (direct, intensive margin) by an average of 16.02 percent relative to irrigators outside the LEMA (Table 3). This estimate is lower than the 23 percent estimated by Whittemore et al. (2023) using aggregated data. On average, pumping costs decreased for these irrigators by $5.48/irrigated acre as water use intensity decreased during this period (Figure 3). The decrease in water use intensity was much higher for the LEMA-1 period (-22.84 percent) than the LEMA-2 period (-9.20 percent). Our estimate of the reduction in water use intensity is close to Golden's (2018) and Drysdale's and Hendrick's (2018) findings (23 and 26 percent). Pumping costs decreased by $8.33/acre over the LEMA-1 period for savings of about $2 million. Dienes et al. (2021) estimated that pumping costs decreased by $2.85 million during the same period.

The rate at which irrigators reduced their water use intensity during LEMA-1 diminished after the 2018 reauthorization of SD6. The change in pumping costs from 2018 to 2023 was -$2.81/acre, an increase of $5.51/acre above that of LEMA-1 (Figure 3), totaling $0.63 million. The difference in water use intensity between LEMA-1 and LEMA-2 was positive and significant at 13.65 percent (Table 3). This period corresponds with the increasing (but still negative) pumping costs/acre estimates from 2019 to 2022. Aggregating across the SD6 LEMA's duration, the total savings in pumping costs were $2.63 million.

What explains the SD6 LEMA's waning impact after its 2018 reauthorization? The positive increase (less negative) in the acre-feet used and acre-feet/acre applied ATET may be attributable to the implementation of the GMD4 LEMA by irrigators outside the SD6 (that is, the control group was eventually "contaminated" with their adoption of a less restrictive policy), the

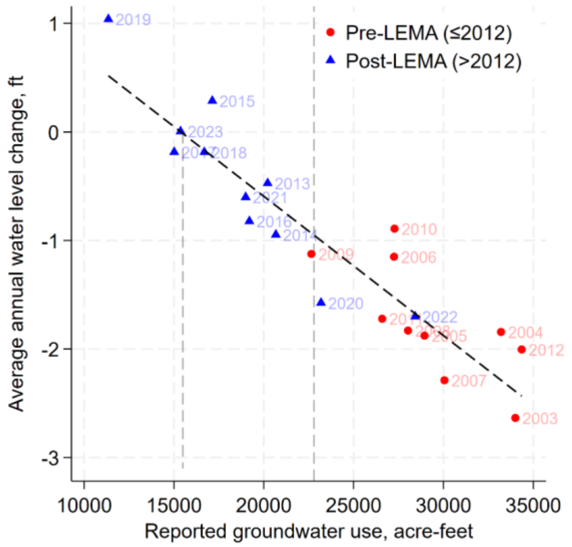

Figure 4. Aggregate Annual Change in Aquifer Water Level, Pre- and Post-Sheridan 6 LEMA

Notes: Data provided by Brownie Wilson, Kansas Geological Survey. The grey vertical line around 15,000 is the Q-stable estimate for the Sheridan-6 LEMA. The second grey vertical line is the 5-year average of the 114,000 acre-feet allotment.

carryover allotments added to the second LEMA, or other reasons not captured by the regression or observed in the data. The introduction of carryover allotments in LEMA-2 may have changed the incentives of some irrigators regarding water use. Instead of a strict annual cap, some irrigators may have optimized their pumping behavior over multiple years, using more in dry years and conserving more in wet years. If there were a sequence of drier years after 2017, irrigators may have needed to pump more to sustain yields. The economic return to irrigation depends on crop prices, input costs, and expected yields. If crop prices increased during LEMA-2 (particularly in dry years), irrigators might have been willing to use more water despite restrictions or increase use to the restricted limit. The negative correlation between acre-feet/acre applied and precipitation is consistent with this reasoning.

Some irrigators might have over-conserved during LEMA-1, fearing strict enforcement, only later adjusting to a more optimal water use strategy during LEMA-2 as they adapted to the rules and enforcement mechanisms or took advantage of carryover allotments. Irrigators could have anticipated future restrictions or had unused carryover. They might have adjusted their pumping behavior to use more water in the present rather than risk losing access to it later. If GMD4 irrigators also reduced their pumping, as expected with their adopted allotment of 76 acre-inches/5-years, it would narrow the difference between SD6 and control PDIV, making SD6's water reductions appear relatively smaller.

How has the SD6 LEMA impacted changes in the aquifer water level, and what are the implications for the aquifer's sustainability? Producers started pumping less groundwater before the LEMA's implementation, with some exceptions during dry years. After irrigators adopted the LEMA, the aggregate acre-feet pumped fell below 28,000, the average of the total 5-year allotment of 114,000 acre-feet, with 2020 and 2022 exceptions. The two exceedances might be explained by a carryover allotment clause added to the 2017 SD6 law (NKGMD, 2021).

The KGS provided data from 2003 to 2023 on groundwater use (in acre-feet) and the average annual water level recorded at wells. These data are plotted in Figure 4. The relationship between acre-feet pumped and the average annual water level change is linear and downward sloping, with an intercept of 2.1 and a slope of -0.00013. A net-zero yearly change in the aquifer water level, or Q-stable (Steiner et al., 2024), occurs around 15,500 acre-feet used, more than half the current restriction. This quantity amounts to an 18.7 percent reduction from LEMA-period pumping rates, which, if sustained over several decades, would extend the aquifer's lifetime by a factor of two (Whittemore et al., 2023). To the extent that no change in the aquifer's water level is sustainable, whether irrigation would remain profitable at this withdrawal rate and the impact this reduction would have on the region's economy is unknown.

Conclusions

This research quantified the impact of a Local Enhanced Management Area (LEMA) in conserving groundwater resources in northwestern Kansas since its adoption in 2013 using disaggregated water-use data. The study focused on the effectiveness of the LEMA on irrigators' water use and irrigated crop decisions from 2013 to 2017 and during the reauthorization of the LEMA, 2018 to 2023. There was a significant 24 percent reduction in groundwater use during the first LEMA period (2013-2017), relative to irrigators outside the LEMA boundary. The gap between water use and water use intensity narrowed during the second LEMA (2018 to 2023) because producers outside the LEMA boundary adopted less restrictive water policies, and irrigators in the LEMA used carryover allotments authorized during LEMA-2.

Our findings are generally consistent with previous research. Individual voluntary action is insufficient to curtail water use, but mutually agreed-upon restrictions by irrigators can reduce groundwater use (Perez-Quesada and Hendricks, 2021; Zwickle et al., 2021; Steiner et al., 2024). Combined with technical and legal support from state agencies, local governance of water use by irrigators may be a sufficient condition for the long-term sustainability of row crop operations that depend on aquifers for irrigation.

Our research could not estimate differences in profitability between SD6 irrigators and those outside the LEMA. Still, the reauthorization of the first LEMA in 2018 and its third reauthorization for 2023 to 2027 suggest that SD6 irrigators perceive that the water use restrictions did not negatively affect net returns. Other regional producers also perceive the LEMA's success as a model, as evidenced by the adoption of water use restrictions in other GMDs.

Several limitations warrant consideration. The quasi-experimental approach assumes that observed differences are attributable to SD6 policy effects. However, other unobserved factors, such as more efficient irrigation technologies, drought-resistant crops, or changing market conditions, could also impact groundwater use. The original control group eventually adopted less restrictive water use restrictions, decreasing the water use gaps observed during the first LEMA. Additionally, this study focuses on a single geographical area and policy intervention, limiting the generalizability of findings to other regions where agricultural practices, aquifer conditions, local governance, or regulatory frameworks may differ.

Future studies could enhance the understanding of groundwater conservation in several ways. First, extending the analysis to other LEMAs or similar conservation initiatives across different states could shed light on the adaptability and effectiveness of similar policies or regulatory structures in other contexts. Another area of research is the impacts of water restrictions on net returns at the field level and their link to the regional economy. The changes in pumping costs give some indication of how the LEMA's implementation affected net returns, but the results are incomplete. Estimating changes in net returns at the field level requires information about how yields changed after the LEMA's implementation. Adopting a water quota could also affect the regional economy by lowering yields, switching to lower-valued crops, and possibly reducing demand for agricultural inputs. The regional economic impacts of the LEMA on Sheridan and Thomas Counties are an area of new research.

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