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LETTER

Quantifying irrigation adaptation strategies in response to stakeholder-driven groundwater management in the US High Plains Aquifer

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Abstract

Irrigation enhances agricultural yields and stabilizes farmer incomes, but overexploitation has depleted groundwater resources around the globe. Strategies to address this sustainability challenge differ widely. Socio-ecological systems research suggests that management of common pool resources like groundwater would benefit from localized approaches that combine self-organization along with active monitoring. In 2012, the US state of Kansas established a Local Enhanced Management Area (LEMA) program, empowering farmers to work with local and state officials to develop five-year, enforceable groundwater conservation programs. Here, we assessed the efficacy of the first LEMA implemented from 2013 to 2017 using a causal impact methodology based on Bayesian structural time series that is new to agrohydrology. Compared to control scenarios, we found that the LEMA reduced water use by 31% over the five-year period, with early indications of stabilizing groundwater levels. Three main conservation strategies can lead to reduced water use: (1) reducing irrigated area, (2) reducing irrigation amount applied to existing crops through improved efficiency, and/or (3) switching to crops that require less water. To partition water savings among these strategies, we combined satellite-derived irrigated areas and crop type maps with well records. We found that farmers were able to largely maintain irrigated area and achieved the majority of pumping reductions (72%) from improvements in irrigation efficiency, followed by expansion of crops with lower water demand (19%). The results of this analysis demonstrate that conservation programs that are irrigator-driven with regulatory oversight can provide a path toward sustainability in stressed aquifers.

1. Introduction

Irrigated agriculture helps meet global food demand by enhancing yields and buffering crop productivity and farmer income from climate variability and change (Lobell *et al* 2009, Troy *et al* 2015, Smidt *et al* 2016, Rufin *et al* 2018). Groundwater contributes about half of the world's irrigation water and is often the primary source in arid to semiarid regions (Kustu *et al* 2010, Siebert *et al* 2010, Aeschbach-Hertig and Gleeson 2012), but overuse has depleted aquifers around the globe (Wada *et al* 2010, Gleeson *et al* 2012, Rodell *et al* 2018). In the United States, the High Plains Aquifer (HPA, often labeled by its predominant geologic unit, the Ogallala Formation) supports more than $20 billion in annual economic activity (Ashworth 2006). However, water-level declines threaten the continued viability of irrigated agriculture over much of the aquifer, particularly in areas of low recharge concentrated in the central and southern regions (Scanlon *et al* 2012, Haacker *et al* 2016, Cotterman *et al* 2018).

Policy and management institutions developed to address this sustainability challenge differ widely across the HPA and beyond. Aquifer depletion can be

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costly, since the value of irrigation water should increase over time considering expected future higher yielding varieties and irrigation's ability to mitigate droughts, which are likely to become more frequent and severe with climate change (Zipper *et al* 2016, Foster *et al* 2017, Quintana Ashwell *et al* 2018, USGCRP 2018). At the same time, improved management could boost crop water productivity around the world (Brauman *et al* 2013, Rattalino Edreira *et al* 2018), indicating producers might obtain similar yields using less water and thus slow the rate of aquifer depletion. Top-down approaches to management are typically met with resistance by farmers who are understandably concerned with near-term profit (Wang *et al* 2015). Since groundwater can be considered a common pool resource (Hardin 1968, Ostrom *et al* 1994), approaches that operate on local scales, allow self-organization, and include active monitoring and enforcement are more likely to achieve sustainability (Ostrom 2009).

A management framework with these characteristics has emerged in Kansas, where HPA water levels are rapidly falling and pumping reductions appear to be the only viable option for reducing decline rates over the vast majority of the aquifer (Butler *et al* 2016, Whittemore *et al* 2016). Legislation in 2012 allowed stakeholder groups to establish Local Enhanced Management Areas (LEMAs) and work with local (groundwater management districts or GMDs) and state officials to develop enforceable and monitored water use reduction programs that operate over five year cycles (K.S.A. 82a-1041 2012). The pioneering LEMA started in 2013, following a vote by irrigators within a 256 km^2 highly stressed region in northwestern Kansas referred to as Sheridan 6 (hereafter SD-6, figure 1) (KDA 2013). The group sought to stabilize groundwater levels by reducing the total groundwater pumping over the five year (2013–2017) LEMA period by 20% relative to 2002–2012 levels (NW KS GMD 4 2016). This reduction target was consistent with an assessment based on a water balance approach developed by the Kansas Geological Survey, which estimated that a 21% reduction in annual pumping could have stabilized areally averaged aquifer levels between 1996 and 2013 in the surrounding region (Butler *et al* 2016). Allocations were reduced to a five year total of 139.7 cm (55 inches) per irrigated ha, with areas varying by existing water rights; up to one year of unused water (27.9 cm or 11 inches) can be carried over to subsequent LEMA cycles. In 2017, stakeholders voted to renew the SD-6 LEMA for 2018–2022. In the spring of 2018, a second LEMA was approved for most of the surrounding district (GMD4), and additional LEMAs are being discussed in parts of three other Kansas GMDs.

Understanding the effectiveness and impact of the SD-6 LEMA is vital as the LEMA program expands and opportunities for stakeholder-driven management spread across Kansas, the United States (e.g. California's recent Sustainable Groundwater Management Act (Kiparsky 2016)), and the world (e.g. Tringali *et al* 2017). Here, we analyzed the effects of this first LEMA on groundwater pumping, water levels, and irrigated crop dynamics to address two main questions: (1) How did the observed pumping volumes following LEMA establishment differ from the pumping that would have occurred in its absence, controlling for climate and evolving management trends?; and (2) What adaptation strategies did producers use to meet required pumping reductions?

To account for climate fluctuations and wider trends in management and/or technology, we used two complementary controls in the absence of a randomized experimental control. First, we established a paired *control region* that matched characteristics of the SD-6 region. Second, we generated a statistical control to estimate a business-as-usual scenario in the absence of the LEMA program (hereafter *BAU scenario*). To calculate the BAU scenario, we used a causal impact analysis which is based on an emerging Bayesian structural time-series method (Brodersen *et al* 2015) new to agrohydrology. We then combined detailed well records, satellite-derived annual irrigation maps (AIM) (Deines *et al* 2017), and annual national crop maps to quantify how pumping reductions were achieved to understand land use impacts and farmer adaptation strategies.

2. Methods

2.1. Control region design

We established the control region by manually demarcating an area analogous to SD-6 during the five years prior to the LEMA (2008–2012, figure 1). We targeted adjacent areas (⩾1.5 km away to reduce direct well effects (Fileccia 2016)) with similar well density and irrigation frequency based on AIM (Deines *et al* 2017). Working in Google Earth Engine (Gorelick *et al* 2017), we iteratively adjusted control region boundaries until the 2008–2012 mean control region statistics were within 10% of SD-6 for the following metrics: (a) total area (0.12% difference); (b) crop area based on the USDA Cropland Data Layers (CDL; 1.38%) (USDA-NASS 2017); (c) annual precipitation derived from GRIDMET 4 km gridded daily climate data (0.01%) (Abatzoglou 2013); and (d) total pumped volume divided by total area based on WIMAS well data (7.1%, data described below). SD-6 and the control region share a similar mix of irrigated crops, with corn, sorghum, soy, and wheat making up 98% of irrigated area in both regions between 2008 and 2017 (Deines *et al* 2017, USDA-NASS 2017).

2.2. Annual crop type, irrigated area, and water use data

The state of Kansas maintains high quality, publicly available groundwater level and well-specific annual

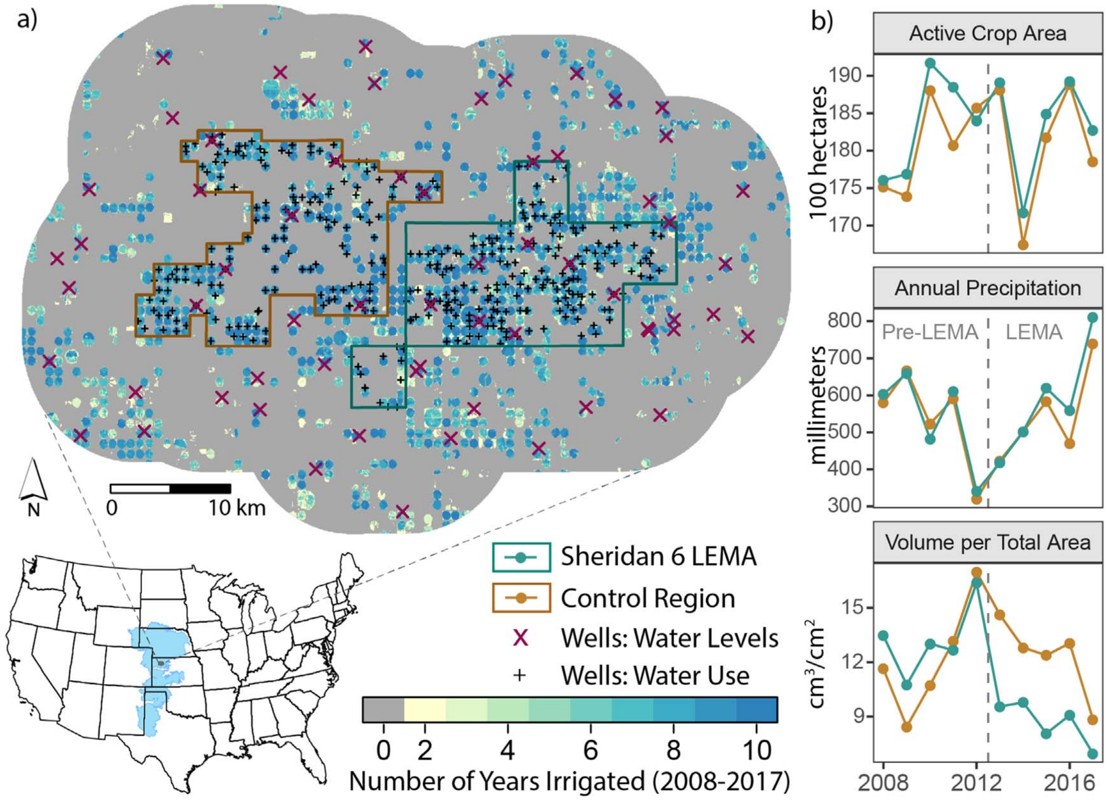

Figure 1. Study area map and regional characteristics. (a) Locations of the Sheridan 6 Local Enhanced Management Area (LEMA), paired control region, and a combined 10 km buffer within the High Plains Aquifer. Wells used to generate annual aquifer level maps are depicted with X's, and wells with irrigation extraction volumes are shown with +'s. Irrigated areas are colored by irrigation frequency between 2008 and 2017 from Deines *et al* (2017). (b) Variables used to select control region boundaries. A vertical dashed line divides the pre-LEMA and LEMA periods. Top: annual active crop area by region (USDA-NASS 2017). Center: Annual precipitation by region (Abatzoglou 2013). Bottom: Annual total pumping volume divided by total area. Symbology for both (a) and (b) is detailed in the central legend.

pumping data. The WIZARD well database contains water depth measurements that have been curated by the Kansas Geological Survey since 1996 (KGS 2018). To translate these irregularly located wells into geostatistically robust groundwater levels, we used R software (R Core Team 2014) to extract 1996–2017 well measurements within a 10 km buffer around the study regions, filtered for observations recorded between 10 December and 28 February (~50 annual observations from 64 wells, figure 1(a)). These winter measurements provided consistent timing for water tables to partially recover following the active pumping season, which typically ends by mid-September. We kriged these measurements with the gstat R package (Pebesma 2004, Gräler *et al* 2016) to produce annual water table elevation maps at 250 m resolution. Due to high longitudinal anisotropy in groundwater levels, we used universal kriging with an easterly trend. With this approach, the longitudinal trend was first modeled using a first-order polynomial. Residuals from the linear trend model were then kriged and combined with the trend surface to produce the estimated water table surface. Annual Gaussian variograms for model residuals were automatically fit with gstat, with mean variogram parameters of 0.83 m, 32.4 m, and 12.5 km for nugget, partial sill, and range respectively. The mean water level for each region was calculated and attributed to the year of the preceding active growing season to represent post-growing season conditions for each year.

Annual groundwater pumping for each region was calculated based on the WIMAS water use database maintained by the Division of Water Resources (DWR) of the Kansas Department of Agriculture (KDA DWR 2017), which documents annual pumping for 203 and 162 wells within SD-6 and the control region during 1996–2017, respectively (figure 1(a)). The WIMAS data also reports well-specific crop mixes and irrigated areas.

To track land use changes in crop type and irrigation status, we used a novel fusion of satellite-derived annual crop type (CDL) and AIM at 30 m resolution from 2008 to 2017 to capture the 5 year periods before and after LEMA establishment. To our knowledge, no other data set for this region is able to track crop-specific irrigated area at this spatial and temporal resolution. Because the previously-published AIM dataset ends in 2016, we used the method and classifier described in Deines *et al* (2017) to extend the irrigation map product to 2017 in order to cover the full five year LEMA cycle (2013–2017). Briefly, this involved assembling all Landsat satellite imagery for the study region in 2017, combining 9 Landsat-derived variables (e.g. maximum greenness) with 11 climate and soil covariates, and applying a random forest classifier that has been validated for multi-year use to create a binary map of irrigation presence for 2017 (Deines *et al* 2017). To minimize misclassification in the satellite-derived maps, the AIM product was filtered by removing irrigated pixels outside allowable place-of-use tracts maintained by the Kansas DWR (KS DWR 2017). Both CDL and AIM map datasets were accessed and processed through Google Earth Engine.

2.3. Business as usual (BAU) scenario and causal impact analysis on pumping and water levels

We generated the BAU scenario using a causal impact analysis based on Bayesian diffusion-regression state space models as implemented via the CausalImpact R package (Brodersen *et al* 2015). This approach originated in marketing and website analytics to provide robust analysis of time series data to assess market interventions when appropriate control groups are unavailable. It has since been applied widely, including to assess aviation fuel tax impact on aircraft emissions (González and Hosoda 2016) and population-level vaccine effects (Bruhn *et al* 2017), but has not to our knowledge been applied in the agriculture or hydrology literature. This causal impact analysis implements a Bayesian structural time series model, which uses supplied covariates to construct a BAU estimate with uncertainty bounds to enable causal attribution in the absence of a randomized experiment (Brodersen *et al* 2015). This state-space model approach is preferred over often-used Ordinary Least Squares regression or difference-in-difference methods because it addresses autocorrelations in time series data, incorporates changes in external conditions that can affect the response variable, flexibly allows regression coefficients to vary over time while avoiding overfitting, and provides inference about the temporal evolution of the response rather than simply comparing before and after conditions (Bertrand *et al* 2004, Brodersen *et al* 2015).

To evaluate how the LEMA affected groundwater use and water levels in SD-6, we used the CausalImpact package with default priors to separately model the BAU scenario for two response variables: (1) total pumping volume from 1996 to 2017 based on WIMAS well data, and (2) mean water levels from 1996 to 2017 based on the kriged annual water levels. For covariates, we used the following annual time series: (1) GRIDMET-derived annual precipitation, growing season (May through August) precipitation, and pre-season through harvest precipitation (January through August); (2) seasonal aridity, defined as accumulated potential evapotranspiration/precipitation for May through August; (3) corn prices as a proxy for all commodity prices (correlations between corn and sorghum, soybean, and wheat prices are $r = 0.96$, $r = 0.92$, and $r = 0.90$, respectively, between 1996 and 2017) (USDA-NASS 2017); and (4) year. These are suitable covariates since they correlate with the response variables but are not themselves affected by the LEMA program (Brodersen *et al* 2015). The model then uses the response variable's observed time series behavior, the relationships among the response and covariate time series variables from 1996 through 2012, and the covariate time series during the LEMA period to construct the posterior distribution of the response variable's BAU behavior. If observed values fall outside of this estimate and the 95% confidence interval at alpha $= 0.05$, it can be concluded that the LEMA program had a statistically significant impact on the response variable. We then used the same approach to generate a BAU scenario in the control region. If no differences between observed responses and BAU scenarios are found in the control region, then any significant changes in SD-6 are considered due to the LEMA program and not external regional-scale drivers such as altered management, technology adoption, and cropping trends unrelated to LEMA establishment.

2.4. Identifying farmer adaptation strategies and evaluating relative contributions to total water savings

Farmers can decrease water use by three primary ways: (1) reduce irrigated area, (2) reduce irrigation volume per area (hereafter, irrigation depth) applied to existing crops, and/or (3) switch to crops with lower irrigation demand (Hendricks and Peterson 2012). To partition water savings among these three conservation strategies, we used the fused AIM-CDL annual maps of crop type and irrigation status along with WIMAS data that specifies well-specific pumping volume, crop mix, and area irrigated (section 2.1).

First, we assessed changes in total irrigated area within SD-6 and the control regions to compare the five-year LEMA period (2013–2017) against the preceding five years (2008–2012, hereafter the pre-LEMA period), using both AIM and WIMAS as complementary lines of evidence. WIMAS is a well-curated data source, but irrigated area is self-reported. It is unclear how producers may vary in reporting year-specific *active* irrigated area compared to allowable irrigable area, or if reports include or omit area that received some irrigation but was then abandoned due to drought-induced water constraints. On the other hand, AIM is satellite-derived and is thus an independent data source, but it may not detect subtle differences between some rainfed and irrigated areas (Deines *et al* 2017). To overcome these potential issues, we chose to compare statistics from both datasets.

Second, we evaluated changes in irrigation depths for SD-6 and the control region by calculating annual depth applied by crop type from WIMAS data on well-specific irrigation volume, irrigated area, and crop type, focusing on the four dominant crops (corn, soybeans, sorghum, and winter wheat). Because WIMAS

Table 1. Causal impact of the Sheridan-6 LEMA program on irrigation depth by crop.

Crop	Region	Effect (ϵ, cm)	95% CI	Relative effect	p value
Corn	LEMA	−8.6	[−12, −5.4]	−25%	*0.001
	Control	0.66	[−3.1, 4.1]	1.8%	0.36
Soybeans	LEMA	−5.8	[−13, −0.3]	−20%	*0.016
	Control	7.3	[2.8, 11]	29%	*0.005
Wheat	LEMA	−8.7	[−23, 1.1]	−43%	*0.036
	Control	5.8	[−3.85, 15]	39%	0.103
Sorghum	LEMA	−2.4	[−48, 38]	−12%	0.358
	Control	1.8	[−7.9, 16]	5.8%	0.405

* indicates significance at the alpha = 0.05 level. CI = confidence interval.

does not explicitly break down irrigated area among crops for reported mixed-crop fields, we restricted this analysis to single-cropped fields from 1996 to 2017. We again applied causal impact analysis with the same covariates described in section 2.3 for each of the four crop types, treating irrigation depth as the response variable. This enabled us to estimate changes in crop-specific irrigation depth due to the LEMA while controlling for external climate conditions. We also compared the pre-LEMA and LEMA periods to describe overall changes in irrigation depths. Third, we used AIM-CDL to evaluate changes in crop-specific irrigated area by region between both 5 year periods.

Finally, we calculated the contribution of each of these three conservation strategies to overall water use reductions in the SD-6 LEMA based on differences between the pre-LEMA and LEMA periods. Water savings from reductions in total irrigated area (change in volume pumped due to changes in irrigated area, ΔP_{Area}) were calculated for both WIMAS- and AIM-specified areas using the following equation:

$$\Delta P_{\mathrm{Area}} = 5 \times \bar{d}_{\mathrm{LEMA}}(\bar{A}_0 - \bar{A}_{\mathrm{LEMA}}), \quad (1)$$

where $\bar{d}_{\mathrm{LEMA}}$ is mean annual irrigation depth in the 5 year LEMA period based on annual pumping volume and annual irrigated area for 2013–2017, $\bar{A}_0$ is pre-LEMA mean irrigated area, and $\bar{A}_{\mathrm{LEMA}}$ is LEMA mean irrigated area. We used average applied irrigation depth during the LEMA period ($\bar{d}_{\mathrm{LEMA}}$) in equation (1) to avoid double counting savings from change in irrigations depths between the pre-LEMA and LEMA periods (strategy 2, below). Mean annual water savings are then multiplied by 5 to estimate ΔP_{Area} for the full LEMA period. We then averaged estimates for WIMAS and AIM to obtain a final estimate.

Water savings due to reduced irrigation depths on existing crops ($\Delta P_{\mathrm{Depth}}$) were calculated based on annual crop-specific irrigated area obtained from fused AIM-CDL maps for 2013–2017 and irrigation depth reductions found via causal impact analysis:

$$\Delta P_{\mathrm{Depth}} = \sum_{i}^{\mathrm{years}} \sum_{j}^{\mathrm{crop\ types}} a_{\mathrm{LEMA},ij} \times \epsilon_{\mathrm{LEMA},j}, \quad (2)$$

where $a_{\mathrm{LEMA},ij}$ is the year-specific irrigated area for each crop type and $\epsilon_{\mathrm{LEMA},j}$ is the crop-specific LEMA effect on irrigation depths based on the posterior distribution mean of the causal impact models (see ϵ estimates in table 1). Sorghum was not included here because there was no significant reduction in sorghum irrigation depths (table 1), thus equation (2) is applied to corn, soybeans, and wheat. Because results showed that wheat area increased in SD-6 during the LEMA period, we used pre-LEMA wheat area in equation (2) to avoid double counting water savings with changes in crop choice (strategy 3, below).

To quantify water saved by changes in crop choice (ΔP_{Crop}), we compared water use for the mean crop mix in the pre-LEMA and LEMA periods based on crop specific changes in irrigated area between periods and irrigation depths during the LEMA periods as follows:

$$\Delta P_{\mathrm{Crop}} = 5 \times \sum_{i}^{\mathrm{croptypes}} (\bar{a}_{0,i} - \bar{a}_{\mathrm{LEMA},i}) \times \bar{d}_{\mathrm{LEMA},i}, \quad (3)$$

where $\bar{a}_{0,i}$ is crop-specific mean area in the pre-LEMA period, $\bar{a}_{\mathrm{LEMA},i}$ is crop-specific mean area in the LEMA period, and $\bar{d}_{\mathrm{LEMA},i}$ is crop-specific mean irrigation depth during the LEMA period. Water savings were then compared among management responses.

All raw data used in this study are publicly available online. Derived data along with Earth Engine and R processing scripts can be found at https://doi.org/10.5281/zenodo.2542229.

3. Results and discussion

3.1. LEMA impacts on groundwater use and water table elevations

We found that irrigators in the SD-6 LEMA significantly decreased groundwater use. Although some reduction was expected given the program's targeted 20% pumping reduction from 2002 to 2012 levels, analysis of WIMAS pumping data indicated mean annual pumping declined by 39%, from 36.4 million m^3 to 22.1 million m^3. However, mean growing season precipitation derived from GRIDMET was 27% higher during the LEMA period (figure 1(b)), suggesting that at least part of the

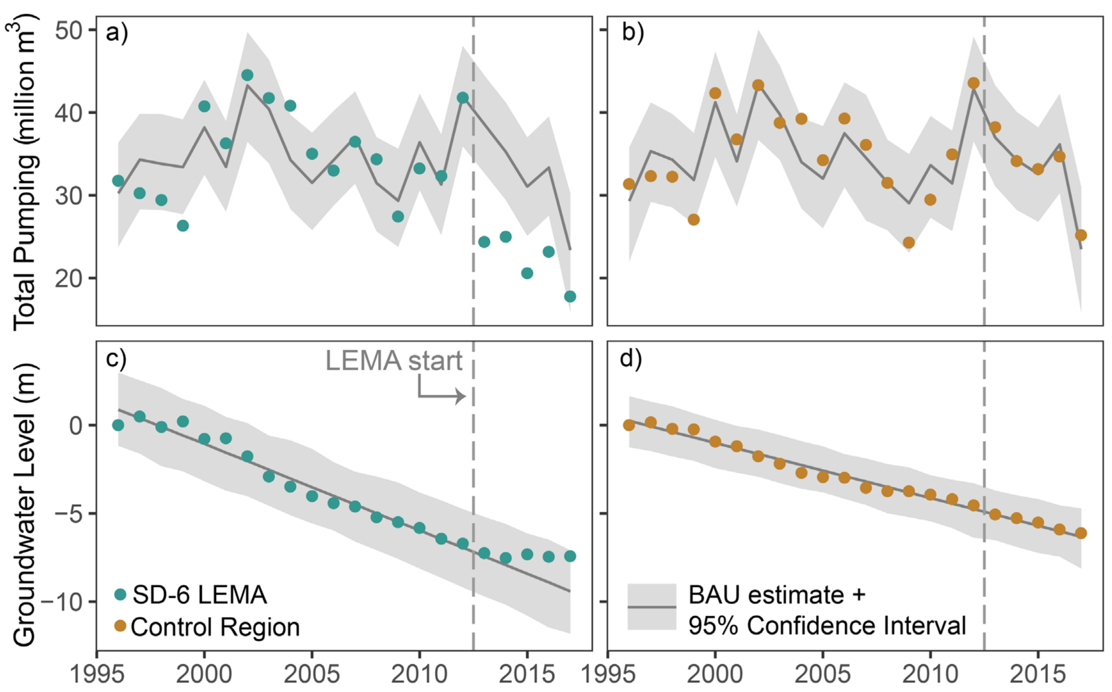

Figure 2. Causal impact analyses on groundwater pumping and water table elevations in Sheridan 6 (SD-6) compared to the control region. (a) The Local Enhanced Management Area (LEMA) significantly reduced groundwater pumping in SD-6 compared to the modeled business-as-usual (BAU) scenario. (b) No pumping change occurred in the control region, where data observations tracked modeled estimates. (c) The LEMA resulted in a non-significant increase in groundwater levels compared to BAU expectations. (d) Groundwater levels continued to decline in line with BAU estimates in the control region. Groundwater levels in (c) and (d) are relative to water-table position in 1996.

decreased pumping may be related to reduced water deficits.

The BAU scenario generated through causal impact analysis allowed us to quantify the LEMA's effect while accounting for changes in external conditions that can affect irrigation demand, such as increased precipitation. We found that pumping following establishment of the LEMA decreased 31% compared to BAU estimates ($p = 0.001$, 95% confidence interval, CI = [21%, 40%], figure 2(a)). Over the full LEMA period (2013–2017), this amounts to a cumulative reduction of 51 million m^3 (CI = [33, 65]) or 10.2 million m^3 per year, which is substantial relative to pre-LEMA mean annual pumping volumes (36.4 million m^3). Moreover, we found no significant effect in the control region ($p = 0.35$) where observed pumping volumes closely tracked BAU predictions (figure 2(b)). This indicates that the changes observed were unique to SD-6 and were not caused by other regional factors.

For groundwater levels, we found a non-significant 2.0 m increase in SD-6 relative to BAU expectations through 2017 ($p = 0.08$, CI = [−0.52, 4.6], figure 2(c)). This corresponded with a marked decrease in mean annual change from -0.49 m yr^{-1} during the reference 2002–2012 period to -0.04 m yr^{-1} during the 2013–2017 LEMA period. In the control region, we found no evidence of changes in water level trajectory compared with BAU estimates ($p = 0.39$, figure 2(d)). Furthermore, the mean annual change in groundwater level was similar between the 2002–2012 reference period (-0.28 m yr^{-1}) and the LEMA period (-0.26 m yr^{-1}) in the control region. Although we cannot conclusively state that SD-6 groundwater levels deviated from BAU expectations given the large 95% confidence interval in our statistical model (figure 2(c)), the apparent trend towards stabilization in groundwater levels in SD-6 (and not the control region) during the LEMA period suggests the program may be successfully limiting groundwater decline. Similarly, Butler *et al* (2018) used a lumped water balance approach to estimate a 67% reduction in the rate of water level decline based on the reduced pumping through 2016, further indicating a positive effect on groundwater levels. Fully resolving the impact to groundwater levels likely will require detailed hydrologic models to fully account for the influences of subsurface heterogeneity in aquifer characteristics, lateral groundwater flow from adjacent regions, and how reduced irrigation applications affect aquifer recharge through potentially reduced irrigation return flow.

3.2. Land use impacts and farmer adaptation

3.2.1. Changes in total irrigated area

Analysis of annual, satellite-derived land use (CDL & AIM) and reported irrigated area statistics (WIMAS) suggested that farmers made only minor changes in total irrigated area to meet water reduction targets. AIM irrigated area estimates indicated non-significant

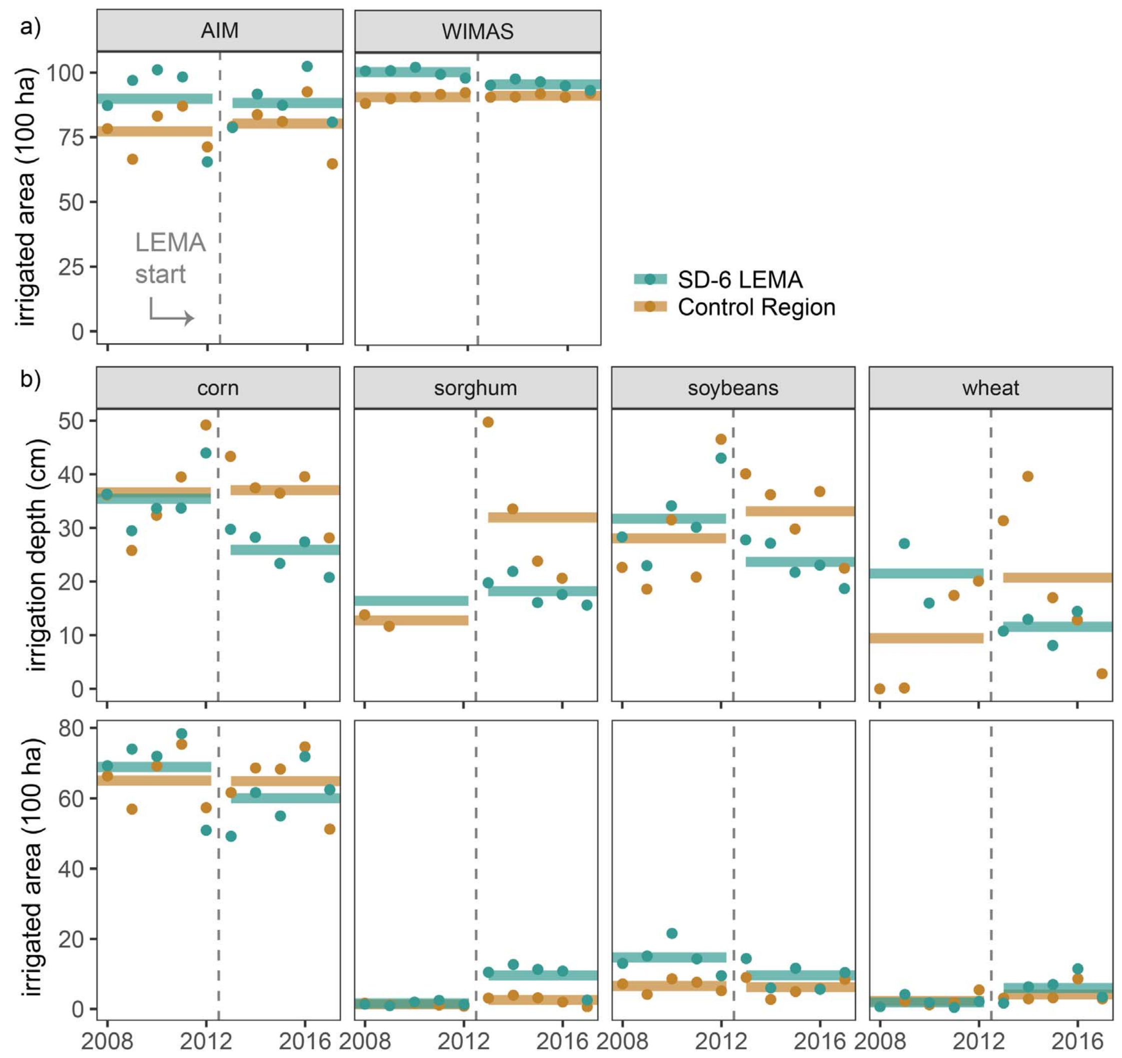

Figure 3. Farmer adaptation to water restrictions. (a) Changes in total irrigated area based on remotely sensed annual irrigation maps (AIM) and WIMAS irrigator-reported data for the Sheridan-6 (SD-6) Local Enhanced Management Area (LEMA) and the control region. (b) Changes in crop-specific irrigation depths derived from WIMAS, and crop-specific irrigated area derived from fusion of USDA Cropland Data Layers and AIM. Colored bars indicate five-year means. Sorghum irrigation depth mean for SD-6 represents 2002–2012 mean due to lack of sorghum fields in the 2008–2012 period.

−1.8% (T-test, $p = 0.84$) and +3.9% (T-test, $p = 0.62$) changes in irrigated area for SD-6 and the control region, respectively (figure 3(a)). WIMAS self-reported irrigated area showed the same directions of change, with a statistically significant 4.7% decrease in SD-6 (T-test, $p = 0.002$), and a non-significant 0.6% increase in the control region (T-test, $p = 0.51$, figure 3(a)). Irrigated area estimates between the two sources generally agreed, although AIM displayed higher variability and tended to underestimate area compared to WIMAS. Overall, our results indicated SD-6 largely was able to sustain nearly the same irrigated cropping area following LEMA establishment. Although irrigated area apparently decreased in SD-6, this 2%–5% reduction is modest given the large reduction in irrigation pumping volumes.

3.2.2. Changes in crop-specific irrigation depths

Farmers did show considerable adaptation in terms of water use and crop choices. Based on causal impact analysis of the 1996–2017 WIMAS data (section 2.4), we found the SD-6 LEMA produced significant decreases in irrigation depths relative to the BAU scenario of 25%, 20%, and 43% for corn, soybeans, and wheat, respectively (table 1). In contrast, within the control region we found no significant changes in irrigation depths for wheat or corn, and a significant increase of 29% for soybeans. We found no significant changes in sorghum irrigation depth for either region, although high uncertainty due to a low number of data points limited inference (table 1), since there were few single-cropped sorghum fields prior to LEMA establishment in the WIMAS data set for either SD-6 or the control region.

In addition to this causal impact analysis, we also visualized changes in irrigation depths for the pre-LEMA and LEMA periods (figure 3(b)). Several features likely enabled the substantial reduction in irrigation depths within SD-6. First, structural changes incorporated in the LEMA framework lowered barriers for deficit irrigation practices, which can generate similar yields while using less water (Chai *et al* 2016). For example, it removed the 'use it or lose it' system that traditionally could void a water right for non-use (Streeter *et al* 2018). Similarly, it resulted in the development of a limited-irrigation crop insurance product that irrigators could use to avoid needing to meet irrigation depth mandates for full irrigated crop insurance (Manning *et al* 2018). However, few producers in SD-6 took advantage of this change due to the more involved enrollment process and an incomplete understanding of the program (R Rockel, Kansas Water Office, personal communication, 27 June 2018).

Beyond lowering structural barriers, the LEMA framework induced SD-6 producers to emphasize net profits, part of a shifting mindset from targeting 'highest yield' to 'highest return on investment' (Waskom 2017). For example, reduced water use requires less energy to operate groundwater pumps. Energy supplies traditionally accounted for almost 10% of corn growing costs in western Kansas (Pfeiffer and Lin 2014). Similarly, some producers used a lower seed density in irrigated fields as a strategy to maintain a fully irrigated crop under water constraints (R Luhman, Groundwater Management District #4, personal communication, 27 June 2018). Preliminary analyses conducted by Golden and Liebsch (2017) comparing production in SD-6 with irrigated fields just outside the LEMA boundary indicate that despite small yield decreases, the majority of LEMA producers reported higher net profit. For corn, a 1.2% decrease in yield corresponded to 4.3% higher net profits when comparing 20 fields within SD-6 with 11 neighboring fields outside the LEMA. Limited observations for other crops (<5 per class) suggested that LEMA producers improved water productivity and overall net profit for corn, sorghum and wheat, but not soybeans (Golden and Liebsch 2017).

Finally, water use became more efficient through increased awareness and new tools, particularly surrounding irrigation scheduling and soil moisture monitoring (Lauer and Sanderson 2017, NW KS GMD 4 2017). This allows producers to better take advantage of precipitation events and target irrigation during periods of crop need. Precision agriculture practices can help optimize management by specifying needed water, fertilizer, and other inputs in space and time, reducing waste and increasing net profits (Basso *et al* 2013). Analysis of WIMAS data, which also records the irrigation system in operation at each well, suggested that changes in irrigation delivery technology likely was not a large contributor to LEMA water savings. Low Energy Precision Application (LEPA) center pivot systems have dominated both SD-6 and the control region since the late 1990s and continue to increase in area each year. For the 2008–2017 study period, however, the area using LEPA technology increased at a higher rate in the control region.

3.2.3. Changes in crop choice

SD-6 irrigators also reduced water use by switching to crops with lower irrigation demand, namely planting sorghum and wheat rather than corn and soybeans (figure 3(b)). Crop water requirements vary based on plant physiology, management practices, and environmental demands (Assefa *et al* 2014); typical irrigation requirements for these crops in this region can be seen in figure 3(b). When comparing the pre-LEMA and LEMA periods, we found that mean irrigated corn and soybean area decreased 13% and 35%, respectively, in SD-6. In comparison, the control region had decreases of 0.2% and 5% for irrigated corn and soybeans. Both SD-6 and the control region had increases in irrigated sorghum and wheat area, but increases within SD-6 were considerably higher for both crops (sorghum: 493% versus 101%; wheat: 224% versus 82%; figure 3(b)). Crop choice could be a flexible strategy to manage the 5 year water allocation cycle of the LEMA program. Basso *et al* (2013) suggested that there is opportunity across the aquifer to improve sustainability by choosing crops with water requirements that match local availability; combined with strict water restrictions and oversight, these changes have a larger probability of translating into reduced water consumption (Grafton *et al* 2018).

3.2.4. Relative contributions of water conservation strategies

Based on these changes in irrigated area, irrigation depths, and crop types, we estimated the relative contribution of each management response to overall water reductions in SD-6 over the LEMA period using equations (1)–(3). Reductions in irrigation depths accounted for 71.6% of total water savings; reductions in corn irrigation depths accounted for 7/8 of total water saved through this strategy due to irrigated corn's dominance on the landscape (approximately 2/3 of irrigated area in SD-6 during the LEMA period, figure 3(b)). Changes in crop choice further contributed 19.1% of water reductions, based on the difference between mean crop areas from 2008 to 2012 versus 2013 to 2017 using mean crop-specific irrigation depths during the LEMA program (section 2.4). These additional gains are largely due to lower irrigation water requirements for sorghum (Araya *et al* 2018) and wheat, which gained area previously used for more water intensive corn and soybeans (figure 3(b)). Reductions in total irrigated area accounted for the remaining 9.3% of water reductions.

4. Conclusions

The combined causal impact and control region approach allowed us to quantify the effects of stakeholder-driven groundwater management while accounting for changes in external conditions that can affect irrigation demand. By leveraging rich publicly available datasets, we found that this pioneering LEMA in the HPA in northwest Kansas surpassed goals for reduced water use, leaving enough water in the aquifer to provide over 1.4 years' worth of historic water needs. Farmers made only minor adjustments to total irrigated area to meet water reductions, instead relying on more efficient water management and less water intensive crops. Preliminary economic analyses suggested that farmers are maintaining net profit despite lower yields due to reduced input and energy costs; the recent stakeholder-voted renewal for another five-year cycle corroborates the economic feasibility of the SD-6 LEMA (Golden and Liebsch 2017).

There remains a need to robustly quantify trade-offs in both crop yield and total water budget impacts, accounting for complexity in the physical system through coupled crop-hydrology models. Because the SD-6 LEMA has unique elements hypothesized to promote self-organization (Ostrom 2009), the generalizability remains to be tested on larger scales, such as the recently approved LEMA over most of the GMD that includes SD-6. Increases in irrigation efficiency are often ineffective at reducing overall water consumption, but enforceable accounting, extraction limits, and improved understanding of irrigator behavior can help ensure efficiency improvements translate into water conservation (Grafton *et al* 2018). In systems more dissimilar from Kansas or lacking strong local leaders and local accountability as in the SD-6 region, programs like the LEMA may be difficult to implement. In particular, Kansas' long record of valuable water use data give the region a head start when implementing sustainability programs. Even in other regions of the HPA, these conditions do not exist.

While groundwater level declines are a global problem, solutions are inherently and necessarily local and site specific. Nevertheless, the strategies observed in SD-6 will likely be part of the solution in other water-stressed aquifers, though specific strategies will depend on what crops are viable in an area, legal frameworks, and community structure. Perhaps the most transferable aspect of the success of SD-6 is the approach that underlies the LEMA program in Kansas—locally-driven and agreed-upon water use reductions, informed by tangible sustainability goals, and backed up with robust state-level enforcement. As aquifer depletion threatens crop production in many parts of the world, the successful water use reduction pathways detailed here can motivate and inform economically and hydrologically sustainable management.

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References

Abatzoglou J T 2013 Development of gridded surface meteorological data for ecological applications and modelling *Int. J. Climatol.* **33** 121–31

Aeschbach-Hertig W and Gleeson T 2012 Regional strategies for the accelerating global problem of groundwater depletion *Nat. Geosci.* **5** 853–61

Araya A, Kisekka I, Gowda P H and Prasad P V V 2018 Grain sorghum production functions under different irrigation capacities *Agric. Water Manage.* **203** 261–71

Ashworth W 2006 *Ogallala Blue: Water and Life on the Great Plains (First)* (New York: Norton)

Assefa Y, Roozeboom K, Thompson C, Schlegel A, Stone L and Lingenfelser J E 2014 Corn and grain sorghum morphology, physiology, and phenology *Corn and Grain Sorghum Comparison* (New York: Academic) pp 3–14

Basso B, Kendall A D and Hyndman D W 2013 The future of agriculture over the Ogallala Aquifer: solutions to grow crops more efficiently with limited water *Earth's Future* **1** 39–41

Bertrand M, Duflo E and Mullainathan S 2004 How much should we trust differences-in-differences estimates? *Q. J. Econ.* **119** 249–75

Brauman K A, Siebert S and Foley J A 2013 Improvements in crop water productivity increase water sustainability and food security—a global analysis *Environ. Res. Lett.* **8** 024030

Brodersen K H, Gallusser F, Koehler J, Remy N and Scott S L 2015 Inferring causal impact using bayesian structural time-series models *Ann. Appl. Stat.* **9** 247–74

Bruhn C A W *et al* 2017 Estimating the population-level impact of vaccines using synthetic controls *Proc. Natl Acad. Sci.* **114** 1524–9

Butler J J, Whittemore D O, Bohling G C and Wilson B B 2018 Sustainability of aquifers supporting irrigated agriculture: a case study of the high plains aquifer in Kansas *Water Int.* accepted **43** 815–28

Butler J J, Whittemore D O, Wilson B B and Bohling G C 2016 A new approach for assessing the future of aquifers supporting irrigated agriculture *Geophys. Res. Lett.* **43** 2004–10

Chai Q, Gan Y, Zhao C, Xu H L, Waskom R M, Niu Y and Siddique K H M 2016 Regulated deficit irrigation for crop production under drought stress. A review *Agronomy Sustain. Dev.* **36** 1–21

Cotterman K A, Kendall A D, Basso B and Hyndman D W 2018 Groundwater depletion and climate change: future prospects of crop production in the central high plains aquifer *Clim. Change* **146** 187–200

Deines J M, Kendall A D and Hyndman D W 2017 Annual irrigation dynamics in the U.S. northern high plains derived from landsat satellite data *Geophys. Res. Lett.* **44** 9350–60

Fileccia A 2016 Some simple procedures for the calculation of the influence radius and well head protection areas (theoretical approach and a field case for a water table aquifer in an alluvial plain) *Acque Sotterranee—Ital. J. Groundwater* **4** 7–23

Foster T, Brozović N and Butler A P 2017 Effects of initial aquifer conditions on economic benefits from groundwater conservation *Water Resour. Res.* **53** 744–62

Gleeson T, Wada Y, Bierkens M F P and van Beek L P H 2012 Water balance of global aquifers revealed by groundwater footprint *Nature* **488** 197–200

Golden B and Liebsch K 2017 Monitoring the Impacts of Sheridan County 6 Local Enhanced Management Area *Interim Report for 2013–2016* Kansas State University, Manhattan, KS (https://circleofblue.org/wp-content/uploads/2018/03/Sheridan6LEMAstudy.pdf)

González R and Hosoda E B 2016 Environmental impact of aircraft emissions and aviation fuel tax in Japan *J. Air Transp. Manage.* **57** 234–40

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R 2017 Google earth engine: planetary-scale geospatial analysis for everyone *Remote Sens. Environ.* **202** 18–27

Grafton R Q *et al* 2018 The paradox of irrigation efficiency *Science* **361** 748–50

Gräler B, Pebesma E and Heuvelink G 2016 Spatio-temporal geostatistics using gstat *R J.* **8** 204–18

Haacker E M K, Kendall A D and Hyndman D W 2016 Water level declines in the high plains aquifer: predevelopment to resource senescence *Groundwater* **54** 231–42

Hardin G 1968 The tragedy of the commons *Science* **162** 1243–8

Hendricks N P and Peterson J M 2012 Fixed effects estimation of the intensive and extensive margins of irrigation water demand *J. Agric. Resour. Econ.* **37** 1–19

KDA 2013 Order of designation approving the Sheridan 6 Local Enhanced Management Area within Groundwater Management District No. 4. Kansas Department of Agriculture, Manhattan, KS (http://dwr.kda.ks.gov/LEMAs/SD6/LEMA.SD6.OrderOfDesignation.20130417.pdf)

KDA DWR 2017 Water information management & analysis system (WIMAS). Kansas Department of Agriculture, Division of Water Resources, Manhattan, KS (http://hercules.kgs.ku.edu/geohydro/wimas/query_setup.cfm)

KGS 2018 Water Information Storage and Retrieval Database (WIZARD). Kansas Geological Survey, Lawrence, KS (http://kgs.ku.edu/Magellan/WaterLevels/index.html)

Kiparsky M 2016 Unanswered questions for implementation of the Sustainable Groundwater Management Act *Calif. Agric.* **70** 165–8

KS DWR 2017 Kansas authorized irrigation place of use tracts. Kansas Department of Agriculture, Division of Water Resources, Manhattan, KS

K.S.A. 82a-1041 2012 Local enhanced management areas; establishment procedures; duties of chief engineer; hearing; notice; orders; review, Pub. L. No. 82a–1041. Kansas Statutes Annotated, Topeka, KS (http://ksrevisor.org/statutes/chapters/ch82a/082a_010_0041.html)

Kustu M D, Fan Y and Robock A 2010 Large-scale water cycle perturbation due to irrigation pumping in the US high plains: a synthesis of observed streamflow changes *J. Hydrol.* **390** 222–44

Lauer S and Sanderson M 2017 Managing groundwater together in western Kansas *Colorado Water* 16–7

Lobell D B, Cassman K G and Field C B 2009 Crop yield gaps: their importance, magnitudes, and causes *Ann. Rev. Environ. Resour.* **34** 179–204

Manning D T, Rockel R, Schneekloth J, Stoecker A and Warren J 2018 Crop insurance. *Ogallala Aquifer Summit White Papers, Garden City, KS* (http://ogallalawater.org/ogallala-summit-april-2018-crop-insurance-white-paper/)

NW KS GMD 4 2016 Revised management program. Northwest Kansas Groundwater Management District, Colby, KS No. 4 (http://gmd4.org/Management/GMD4-MgtPro.pdf)

NW KS GMD 4 2017 The Water table. Northwest Kansas Groundwater Management District, Colby, KS No. 4 (http://gmd4.org/Newsletter/2017-Fall.pdf)

Ostrom E 2009 A general framework for analyzing sustainability of social-ecological systems *Science* **325** 419–22

Ostrom E, Gardner R and Walker J 1994 *Rules, Games, and Common-Pool Resources* (Ann Arbor: University of Michigan) (https://doi.org/10.3998/mpub.9739)

Pebesma E J 2004 Multivariable geostatistics in S: the gstat package *Comput. Geosci.* **30** 683–91

Pfeiffer L and Lin C Y C 2014 The effects of energy prices on agricultural groundwater extraction fromthe high plains aquifer *Am. J. Agric. Econ.* **96** 1349–62

Quintana Ashwell N E, Peterson J M and Hendricks N P 2018 Optimal groundwater management under climate change and technical progress *Resour. Energy Econ.* **51** 67–83

R Core Team 2014 *R: A Language and Environment for Statistical Computing* (Vienna: R Foundation for Statistical Computing) (http://r-project.org/)

Rattalino Edreira J I, Guilpart N, Sadras V, Cassman K G, van Ittersum M K, Schils R L M and Grassini P 2018 Water productivity of rainfed maize and wheat: a local to global perspective *Agric. Forest Meteorol.* **259** 364–73

Rodell M, Famiglietti J S, Wiese D N, Reager J T, Beaudoing H K, Landerer F W and Lo M-H 2018 Emerging trends in global freshwater availability *Nature* (https://doi.org/10.1038/s41586-018-0123-1)

Rufin P, Levers C, Baumann M, Jägermeyr J, Krueger T, Kuemmerle T and Hostert P 2018 Global-scale patterns and determinants of cropping frequency in irrigation dam command areas *Glob. Environ. Change* **50** 110–22

Scanlon B R, Faunt C C, Longuevergne L, Reedy R C, Alley W M, Mcguire V L and Mcmahon P B 2012 Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley (https://doi.org/10.1073/pnas.1200311109)

Siebert S, Burke J, Faures J M, Frenken K, Hoogeveen J, Döll P and Portmann F T 2010 Groundwater use for irrigation—a global inventory *Hydrol. Earth Syst. Sci.* **14** 1863–80

Smidt S J *et al* 2016 Complex water management in modern agriculture: trends in the water energy-food nexus over the high plains aquifer *Sci. Total Environ.* **566–567** 988–1001

Streeter T, Metzger S, Beightel C, Stover S, Aguilar J and Golden B B 2018 Kansas. *Ogallala Aquifer Summit White Papers* (http://ogallalawater.org/ogallala-summit-april-2018-kansas-white-paper/)

Tringali C, Re V, Siciliano G, Chkir N, Tuci C and Zouari K 2017 Insights and participatory actions driven by a socio-hydrogeological approach for groundwater management: the Grombalia Basin case study (Tunisia) *Hydrogeol. J.* **25** 1241–55

Troy T J, Kipgen C and Pal I 2015 The impact of climate extremes and irrigation on US crop yields *Environ. Res. Lett.* **10** 054013

USDA-NASS 2017 *USDA National Agricultural Statistics Service Cropland Data Layers* (Washington, DC: USDA-NASS)

USGCRP 2018 *Impacts, Risks, and Adaptation in the United States: Fourth National Assessment* ed D R Reidmiller, C W Avery, D R Easterling, K E Kunkel, K L M Lewis, T K Maycock and B C Stewart (Washington, DC: U.S. Global Change Research Program) Vol II, p 1515

Wada Y, Van Beek L P H, Van Kempen C M, Reckman J W T M, Vasak S and Bierkens M F P 2010 Global depletion of groundwater resources *Geophys. Res. Lett.* **37** 1–5

Wang T, Park S C and Jin H 2015 Will farmers save water? A theoretical analysis of groundwater conservation policies *Water Resour. Econ.* **12** 27–39

Waskom R 2017 The Ogallala aquifer: director's Letter *Colorado Water* 1 (https://wsnet2.colostate.edu/cwis31/ColoradoWater/Images/Newsletters/2017/CW_34_6.pdf)

Whittemore D O, Butler J J and Wilson B B 2016 Assessing the major drivers of water-level declines: new insights into the future of heavily stressed aquifers *Hydrol. Sci. J.* **61** 134–45

Zipper S C, Qiu J and Kucharik C J 2016 Drought effects on US maize and soybean production: spatiotemporal patterns and historical changes *Environ. Res. Lett.* **11** 094021