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The impact of land cover on groundwater recharge in the High Plains: An application to the Conservation Reserve Program

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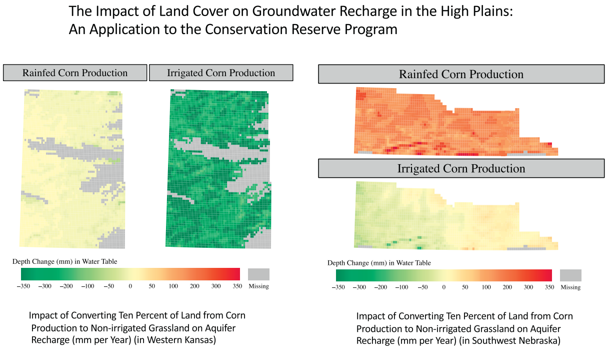
HIGHLIGHTS

- A change in land cover from cropland to grassland reduces aquifer storage in portions of the High Plains Aquifer.
- Magnitude of the difference varies spatially across the High Plains Aquifer.
- Findings reduce the environmental benefit of land retirement programs such as the Conservation Reserve Program.

GRAPHICAL ABSTRACT



1. Introduction

Worldwide, population growth and climate change are putting stress on the available water resources needed for agricultural production, other economic activity, domestic consumption, and ecosystem services. Areas like the High Plains Aquifer (HPA) region of the United States are heavily dependent on groundwater for irrigated agriculture, and about 90% of all water used in the HPA region is from groundwater (Dennehy, 2000). The HPA covers parts of eight states (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming), with the greatest use in any single state in Nebraska. In 2012, Nebraska had more irrigated land than any other state (3.36 million hectares), and almost 92% of the irrigation water used in the state was from groundwater (estimated at 9.1 billion cubic meter from groundwater).[1] Kansas, by comparison, had 1.15 million irrigated hectares in 2012, with about 98% of irrigation coming from groundwater (estimated at 4.2 billion cubic meter from groundwater). However, many parts of the HPA region are facing declining water-table levels, putting the long-term economic viability of the region in peril. The region is estimated to have reduced recoverable groundwater by 337 billion cubic meter since predevelopment (around 1950) to 2015 with

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[1] See the 2013 U.S. Department of Agriculture Farm and Ranch Irrigation Survey (USDA-FRIS) at https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/ for more information.

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2013 to 2015 accounting for a decline of 13.2 billion cubic meter (McGuire, 2017). In addition, groundwater levels in several areas are hydrologically connected to surface water flows. In areas like the Republican River Basin (RRB) of Nebraska, water managers are mandated with ensuring that hydrologically connected rivers have enough streamflow to fulfill Nebraska's surface water obligations for the Republican River interstate compact with Colorado and Kansas.

Therefore, there exists a strong interest in finding and using policies that will maintain or increase groundwater levels, or in redirecting policies that may be harmful to that objective. Assessing the impact of current government programs, such as the USDA Conservation Reserve Program (CRP), is an important step in that process. The CRP is a voluntary conservation program that pays farmers to take environmentally susceptible cropland out of production for 10 to 15 years to achieve environmental benefits. This involves putting the land into a new land cover, such as grassland, woodland, or wetlands. The CRP was established in the 1985 U.S. Farm Bill as a program to reduce soil erosion, and it has been shown to have erosion reduction, surface water quality, and wildlife habitat benefits (Ribaudo et al., 1990; Hansen, 2007). However, CRP can affect water-table levels, as it pays farmers to shift land from crop production to conservation land covers, mainly grassland, which might alter infiltration of precipitation and subsequent groundwater recharge. CRP rental payments are based on non-irrigated rental rates, so irrigation reduction through enrollment of irrigated fields is not expected. Some land retirement programs, such as the Conservation Reserve Enhancement Program (CREP) as practiced in some HPA states, do target irrigated fields. While CRP is known to have several positive environmental benefits, such as reduced soil erosion, the connection between CRP and groundwater recharge is less known. The hydrology literature suggests that differences in groundwater recharge between grassland (expected CRP land cover) and cropland exist in the HPA, with grassland leading to a lower groundwater recharge rate (Dugan and Zelt, 2000). Additional studies in other parts of the world have also looked at the recharge impacts of grassland and cropland (O'Connor, 1985; Le Maitre et al., 1999; Leduc et al., 2001; Favreau et al., 2002; Leaney and Herczeg, 1995; Kendy et al., 2003; Pan et al., 2011). In general, the literature finds greater recharge for cropland compared to grassland. However, this result is not unanimous. Daniel (1999) did find greater recharge with native grasses compared to winter wheat under different tillage methods for a shallow aquifer in Fort Reno, Oklahoma (in years with average or greater rainfall). Any unintended effect of CRP is especially important because of recent changes in the amount of land enrolled in the program. Largely due to reductions in the CRP area cap, total enrolled area in CRP has declined from 14.89 million hectares in 2007 to 9.67 million hectares in 2016. CRP area in the HPA states decreased from 5.95 million hectares in 2007 to 4.09 million hectares in 2016.[2] This reduction in enrolled area could have measurable effects on water-table levels if the land coming out of CRP is put into crop production.

The goal of this paper is to estimate the impact of different types of land cover on water-table levels and aquifer recharge. The analysis uses USGS groundwater monitoring wells and other spatial data from the RRB in Nebraska and the Ogallala Aquifer Region (OAR) in Kansas for the 2007 to 2015 period. These regions were chosen due to the ongoing groundwater quantity concerns and availability of data. We use a spatial buffer to determine annual local land cover, weather, and groundwater extraction around each observation well. The change in depth to the aquifer measured from observation wells is related to the local data using a fixed-effects model. Grassland is used as a proxy for CRP-induced land cover changes.

This article makes several contributions to the existing literature. The first contribution is to the economics literature by considering the impact of CRP-induced land cover changes on aquifer recharge. Previous research on CRP has examined the environmental and economic benefits (Ribaudo et al., 1989, 1990; Hansen et al., 1999; Hansen, 2007), methods of targeting enrollment to attain environmental goals or greater economic benefits (Ribaudo et al., 1989; Szentandrasi et al., 1995; Babcock et al., 1996; Feather et al., 1999; Wu et al., 2001; Feng et al., 2004), what happens to land exiting CRP (Skaggs et al., 1994; Johnson et al., 1997; Roberts and Lubowski, 2007; Secchi et al., 2011; Hellwinckel et al., 2016), and possible slippage issues (Wu, 2000; Wu et al., 2001; Roberts and Bucholtz, 2005; Wu, 2005; Roberts and Bucholz, 2006). This paper adds to the literature by considering a particular type of unintended impact of CRP, specifically the impact on groundwater availability. Ribaudo et al. (1989) and Ribaudo et al. (1990) do consider irrigation reduction impacts on water-table levels through possible enrollment of marginal irrigated fields into CRP. However, widespread enrollment of irrigated fields into CRP is not expected, since CRP payments are based on non-irrigated rental rates. Similar programs (e.g. CREP) that target irrigated fields might achieve notable irrigation reduction, at a higher cost than CRP. CRP-induced land cover change, and any related recharge change, is a more widespread factor for aquifer impacts that needs to be considered.

The paper makes an additional contribution through its method of estimating aquifer recharge, which differs from methods generally used in hydrology by combining statistical analysis with measurements of the change in the aquifer elevation. Scanlon et al. (2002) provide a good overview of standard hydrological methods for estimating recharge. Table 1 provides a summary of methods (and associated limitations) relevant to previous research in the study area. The Water Table Fluctuation (WTF) method is the most comparable to this paper's method. WTF uses changes in the groundwater elevation to estimate recharge, where recharge is estimated as the product of the increase in water table and the specific yield (the drainable volume of an unconfined aquifer). However, it does not incorporate extraction and other exogenous factors (Scanlon et al., 2002, 2005). Tracer methods (e.g., Chloride Mass Balance, Tracer Front Displacement) require a knowledge of historical land use and expensive field-level measurements. Thus, tracer methods are typically used for a small number of sites. They can also perform poorly with non-precipitation based recharge, such as with irrigation inputs. Darcy's Law is an equation for the movement of fluids through porous mediums. In hydrology, it can calculate recharge over small areas, but is difficult to properly apply over large areas given its variability. It also cannot be applied in irrigated areas (Scanlon et al., 2002).

This paper combines a modified version of the WTF method with statistical regression analysis to estimate expected regional impacts of land cover, weather, and groundwater extraction on the amount of groundwater stored in the aquifer, and uses the regression results to make inferences about the effect of policy on recharge. It calculates the annual change in groundwater storage, and uses a statistical regression analysis to relate that change to land cover, extraction, weather, and time-invariant characteristics like soil. It uses a large enough sample to provide robust statistical estimates of the relationship between the explanatory variables and changes in groundwater storage, which are used to estimate recharge. There are several advantages of our method compared to the other techniques described. First, it uses publicly available data, which allows us to use a large enough sample to have statistical power in our results, and to incorporate factors that are constant over time. The method could be applied to any location where land cover, weather, and groundwater extraction data are available. It also incorporates extraction for irrigation in a straightforward manner. Finally, it uses the results to analyze the relationship between existing policies and groundwater elevation. The method has some disadvantages compared to the typical hydrological methods. In contrast to long-term hydrological studies of a single location, it cannot fully capture the dynamics of recharge over time. It also cannot fully capture the site-level and historical details of a single location as well as a study with a small number of observations can.

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[2] This information is available on the USDA-Farm Service Agency website at https://wwwfsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index.

Table 1
Summary of reviewed hydrological methods.

Model	Summary	Used by	Limitations
Water table fluctuation	Measures recharge from rises in the water table	Scanlon et al. (2005)	Not useful with depletion; ignores extraction
Chloride mass balance	Equates Chloride Mass entering and exiting a system	Scanlon et al. (2005), McMahon et al. (2006), Nolan et al. (2007), Scanlon et al. (2012)	Only valid when chloride in a steady state
Tracer front displacement	Tracks movement of a tracer pulse through the soil	McMahon et al. (2003), McMahon et al. (2006), Scanlon et al. (2005)	Requires good knowledge of historical land use; Unusable if tracer has not moved past root zone
Water balance/budget	Equates water entering and exiting a system	Dugan and Zelt (2000), Szilagyi et al. (2003), Szilagyi et al. (2005)	Recharge estimated as error term
Darcy's Law	Calculates recharge from hydrologic conductivity and gradients	Nolan et al. (2007)	Performs poorly over large areas

2. The conservation reserve program

The CRP is a voluntary conservation program run by the USDA-Farm Service Agency (USDAFSA). The program involves enrolling previously active cropland into a conservation land cover, such as grasslands, forest, or wetlands. This is done to primarily to achieve reduced soil erosion, and improved surface water quality and wildlife habitat. Land is enrolled for a 10 to 15 year contract, which generates yearly rental payments based upon local non-irrigated farmland rental rates. The CRP may also provide cost share payments to achieve the contracted land use practices.

The CRP was first established in the 1985 U.S. Farm Bill, and has been reauthorized in every Farm Bill since then. The most recent version (the 2014 Farm Bill) reduced the national area cap from the 12.95 million hectare cap in the 2008 Farm Bill to 9.71 million hectares by 2017. This continued a trend of reduced area, since the 2008 Farm Bill had already reduced the cap from 15.78 million hectares. Actual enrollment in CRP has decreased from an all-time high of 14.89 million enrolled hectares in 2007 to 9.67 million enrolled hectares in 2016, but total payments have remained around 1.6 to 1.8 billion US dollars a year. This means the average rental payment per hectare has been increasing. Nationwide, average payments have increased from US\$122.91 in 2007 to US\$179.35 per hectare in 2016. In Kansas, enrolled area decreased from 1.34 million hectares to 0.85 million hectares between 2007 and 2016, and average rental payments increased from US\$96.97 to US\$104.83 per hectare. Nebraska's enrolled area decreased from 0.53 million hectares to 0.32 million hectares between 2007 and 2016, and rental rates increased from \$57.02 to \$79.82. Higher rental rates are generally observed in eastern states (e.g., Corn Belt states like Iowa and Illinois), where greater rainfall increases the value of non-irrigated agriculture.[3]

A landowner who wants to enroll a parcel into CRP needs to submit an offer, which is evaluated based on an Environmental Benefits Index (EBI). The six criteria that are used in the EBI to evaluate offers in the most recent sign-up period include wildlife habitat benefits, water quality benefits through reduced erosion, on-farm benefits of reduced erosion, enduring benefits, air quality benefits, and cost.[4] Impacts on water quantity are not one of the primary criteria. A submitted offer must outline the practices that a landowner will implement on the parcel and the per-hectare payment rate the producer will accept. The maximum payment rates are based on average county-level non-irrigated rental rates. While there are obvious changes in water availability if land is shifted from irrigated crop production to grassland, it is unlikely that much of the CRP enrollment is from irrigated land since the maximum payment is based on the average value of non-irrigated land. If there are significant impacts of land cover on aquifer recharge, the EBI formula could be adjusted to incorporate water quantity impacts where relevant. This would involve higher scores if CRP has a positive effect on groundwater levels or lower scores if CRP has a negative impact on groundwater levels.

Another relevant policy is the USDA-Conservation Reserve Enhancement Program (CREP). While CRP is unlikely to lead to a significant change in irrigated fields since payments are based on non-irrigated rates, the same is not true for CREP. CREP environmental priorities are determined by individual states and involve a partnership between the USDA and the state. The Nebraska CREP has a goal to retire 40,469 ha from irrigated production in the Republican and Platte river basins. Kansas also has a CREP program, with a goal of retiring 11,716 irrigated hectares around the Upper Arkansas River. Additional funding from the state allows CREP payments to be higher than standard CRP rates, making the program competitive with irrigated agricultural production. Any reduction in irrigated production will have a direct benefit on groundwater levels, but that benefit comes at a higher financial cost. Thus, an alternative to modifying the EBI criteria for CRP is to reallocate federal financial resources from CRP to CREP, although this reallocation will lead to less area enrolled overall without a corresponding increase in overall funding.

3. Study region

Our analysis uses data from the OAR in Kansas, and the RRB of Nebraska over the Ogallala aquifer, which are both part of the larger HPA region. We define the OAR of Kansas as land west of the 99.55 line of longitude. Economic activity in these areas is highly dependent on agricultural production. The HPA is a significant source of irrigation water for the overlying states (largely Nebraska, Kansas, and Texas). Groundwater levels in most of the HPA are declining due to groundwater extraction for irrigation. For the larger HPA the water level decline is an average of 4.8 m from predevelopment (around 1950) to 2015 that account for about a 337 billion cubic meter loss of recoverable stored water (McGuire, 2017). The average water level decline in Kansas (Nebraska) from predevelopment to 2015 is 8.0 (0.3) meters, with an associated loss of 85.5 (7.4) billion cubic meters in recoverable water (McGuire, 2017). The two states differ both in their level of depletion, and in the potential for groundwater recharge to occur. More recently (2013 to 2015) Kansas has had a water level decline of 0.4 m and recoverable water decline of 3.9 billion cubic meters while Nebraska had near zero decline in water levels, but still lost about 0.4 billion cubic meters in recoverable water (McGuire, 2017). More regionally in the two states, some parts of the Ogallala in Kansas have had declines >45.7 m from predevelopment to 2015 and declines of up to 6.1 m from 2013 to 2015 (McGuire, 2017). Some areas in the RRB in Nebraska have also seen water level declines of between 15.2 and 30.5 m since predevelopment, and up to a 1.8 m decline from 2013 to 2015 (McGuire, 2017).

Despite the lower decline of groundwater levels in Nebraska, both states make a strong use of groundwater. Data from the USDA-Farm and Ranch Irrigation Survey (FRIS) shows that in 2012 Nebraska had 3.12 million hectares irrigated by an estimated 9.1 billion cubic meters

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[3] Data on past and current enrollment and rental rates by state are available at https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index.

[4] Details about the criteria considered for acceptance into CRP are available at https://www.fsa.usda.gov/programs-and-services/conservation-programs/conservation-reserve-program/.

of groundwater applied, while Kansas had 1.13 million hectares irrigated by 4.2 billion cubic meters of groundwater applied. Nebraska has a greater overall use of groundwater, in part thanks to a greater extent of aquifers in Nebraska than Kansas, but Kansas has a greater application per hectare. The difference in decline of water-table levels is most attributable to the much higher rates of recharge in Nebraska than Kansas (Scanlon et al., 2012; Dugan and Zelt, 2000).

The variable decline of groundwater caused by irrigation has led to a variety of groundwater regulations and local groundwater regulatory bodies aimed at balancing irrigation current needs with future ones. Kansas, for example, requires groundwater well permitting for all large-scale extraction (irrigation, municipal and industrial uses), and in times of shortage the law favors provision of water to those with older permits (first in time first right doctrine). Kansas also requires that all permitted wells be metered and with extraction reported each year. Additional restrictions or services may come from the Groundwater Management Districts (GMDs), Intensive Groundwater Use Control Areas (IGUCAs), Groundwater Conservation Areas (GCAs) and Local Enhanced Management Areas (LEMAs). The different regulation frameworks across Kansas allow for more localized policy decisions based on local aquifer conditions and local management desires. The OAR of Kansas still faces a long-term decline, in part due to low groundwater recharge rates, resulting in management goals to keep the aquifer economically viable for a 50-year horizon.

Nebraska overall has more stable or increasing groundwater levels, in part due to higher recharge rates, and thus has a goal of sustaining irrigated production indefinitely. However, Nebraska still needs to limit groundwater use, especially due to the hydrological connectivity between rivers and aquifers. Extraction of groundwater from aquifers hydrologically connected to local rivers can lead to decreased streamflow. This has been an immediate concern in the RRB where Nebraska needs to provide enough streamflow to meet interstate compact requirements.

Nebraska's water rights system aims to give more equitable groundwater access but requires beneficial use of water on the overlying land (a mix of correlative rights doctrine and reasonable use doctrine). Nebraska's groundwater allocations are managed through a network of Natural Resource Districts (NRD). Each NRD is governed by a locally elected board of directors with some state oversight. The local nature of NRD governance allows regulations to differ to meet local conditions and requirements. The four NRDs in the RRB (the Tri-Basin, Upper Republican, Middle Republican, and Lower Republican) have some of the strongest groundwater regulations in the state in order to meet the requirements of the Republican River Compact. These regulations include required irrigation metering, official meter inspections, and groundwater use limits.

4. Data

4.1. Data sources

The dependent variable of the econometric estimation is annual change in actual water stored in the aquifer measured in height, which is obtained by multiplying changes in the depth to water table (DWT) by specific yield. The DWT data in the study area uses groundwater field measurements from the National Water Information System (NWIS) maintained by the United States Geological Service (USGS). All of the wells used in the analysis are in the Ogallala aquifer, which is an unconfined aquifer. NWIS contains data from wells maintained by the USGS as well as state and local agencies. The NWIS data provides measurements of DWT, the date of measurement, and the geographic coordinates of the measurement wells. Fig. 1 shows the distribution of observations wells in the study area. We use the specific yield data for the study region provided by USGS. Fig. 2 depicts the spatial variation of specific yield in the study region.

While the USGS-NWIS data includes DWT measurements from dates throughout the year, we only use values in non-irrigation months, where non-irrigation refers to the period without active irrigation. For Nebraska we use March and April values, while in Kansas we use January values; these were the non-irrigation months with the most observations in the respective states. For example, for the 2014 cropping season in Kansas, we calculate the change in DWT, and the associated change in groundwater storage, based on the difference in DWT in January 2014 and January 2015. We use non-irrigation period DWT

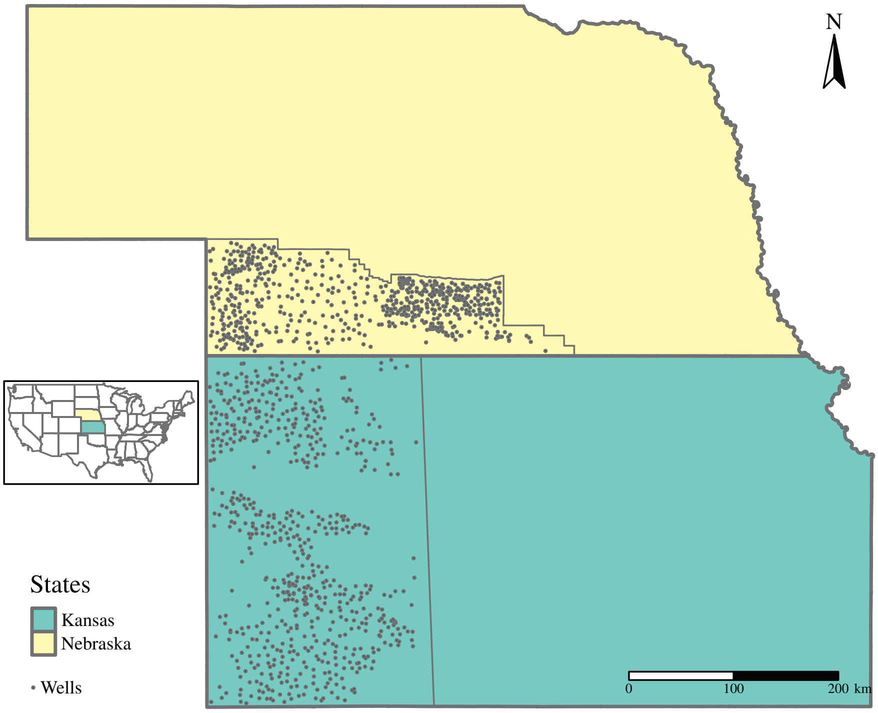

Fig. 1. Study area and observations. Note: The study area includes the southwestern portion of Nebraska and the western portion of Kansas, United States.

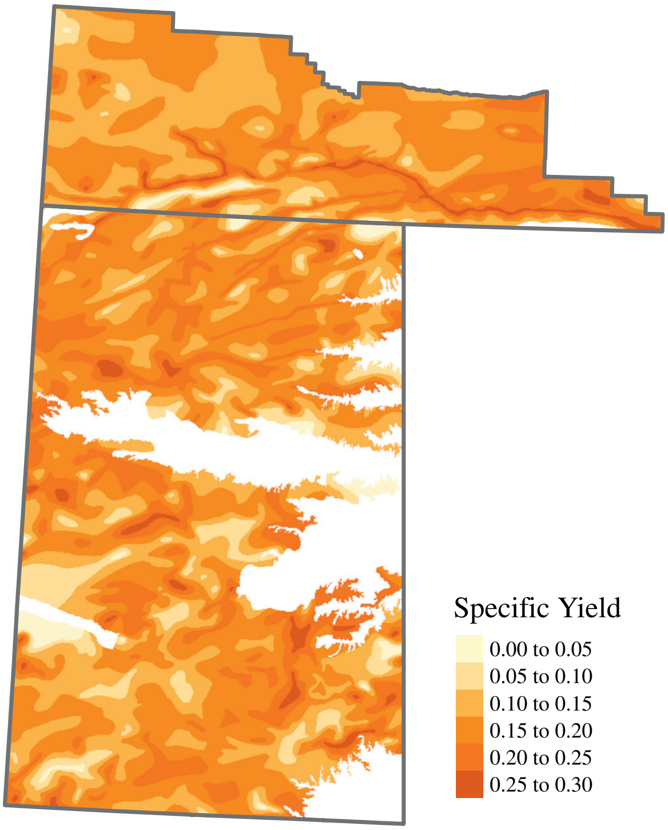

Fig. 2. Spatial variation of specific yield in the study area.

measurements because we only observe groundwater extraction on an annual basis, and we want the change in DWT values to reflect conditions where water-table levels have recovered from the dynamic impacts of intra-annual pumping for irrigation as much as possible. Fig. 3 shows an example of the intra-annual depth changes using daily measurements from a single well. In Fig. 3, it is clear that the depth to water table increases and is highly variable in the summer months (July through October), when groundwater is extracted to irrigate crops. However, much of the variability is due to the immediate drawdown of the aquifer that occurs when groundwater pump is operating. Our goal is not to measure these short-term intra-seasonal changes in aquifer height, but to measure the long-term impacts on the aquifer. During the fall and winter months (October through April), the depth to water table slowly recovers, and then the cycle repeats. The use of DWT observations in the non-irrigation season ensure that the long-term impact of groundwater extraction for agricultural irrigation and recharge is captured in changes in DWT. When multiple measurements are reported in a single year, we take the average of the monthly measurements. Table 4 shows the period used to measure the DWT as the measurement period.

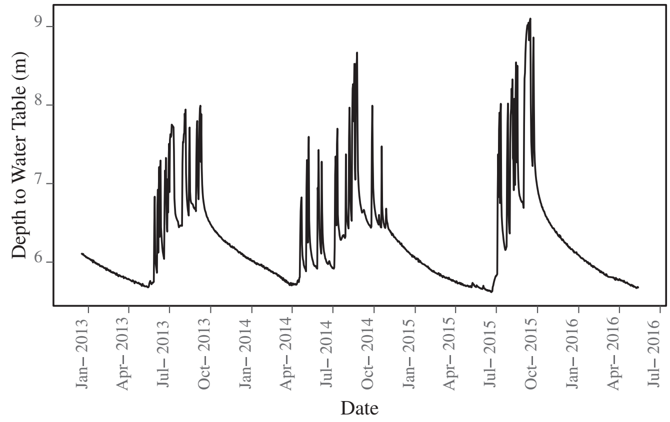

Fig. 3. Example of intra-annual groundwater level fluctuation. Note: This example of groundwater level fluctuation shows the highly variable groundwater level during the irrigation season (typically June to October) and the relatively smooth level during the non-irrigation season.

Land cover data is from the National Agricultural Statistics Service (NASS) CropScape. It a spatial data layer of land cover types denoted in grids, such as corn, soy, and grassland. CropScape maps prior to 2010 use 56-meter grids, CropScape maps from 2010 on use 30-meter grids. One of the limitations of CropScape is that potentially different types of grass surface covers are categorized into a single grass/pasture category in CropScape. Consequently, our grassland category may not necessarily represent the type of grassland used with CRP enrollment. Weather data is from the PRISM climate data group at the Oregon State University, which provides daily precipitation, minimum temperature, and maximum temperature with the spatial resolution of 4 by 4 (kilometer). Finally, annual groundwater extraction and related coordinate data is obtained from the Republican River Compact Administration (RRCA) for Nebraska and from the Water Information Management and Analysis System (WIMAS) for Kansas. Based upon the availability of groundwater extraction data, Nebraska is covered from the years 2007 to 2015 and Kansas is cover from 2007 to 2014. Notably, the Nebraska groundwater extraction data comes from meter inspections by agency personnel, while the Kansas groundwater data is self-reported.

4.2. Data processing

In order to find the local conditions of land cover, weather, and groundwater extraction around the observation wells, we draw a buffer with a 3.2 km (two mile) radius around each of the observation wells, and then summarize the information within the buffers. Because some data is limited to the geographic extent of the study region, observation wells that are within 3.2 km of the RRB border in Nebraska or the state line in Kansas are removed to avoid using observations with incomplete data in the regression analysis. Fig. 4 shows an example of a 3.2 km radius buffer used on a portion of the CropScape map.

To identify the share of each land cover type in each buffer, we overlay the buffer onto the CropScape layer. Similarly, for the weather data, we overlay the buffer on the PRISM grids to identify which grids intersect or are contained in the buffer, and calculate the grid area-weighted weather variables for each buffer and time period. For groundwater extraction, we identify all irrigation wells within a 6.4 km buffer, sum their individual groundwater extractions, and then divide that by the number of hectares in the buffer (3254 ha) to get the average cubic meters per hectare of groundwater extracted in the buffer. For example, one cubic meter extracted per hectare over the entire buffer corresponds to about 826.4 thousand cubic meters of water. We used 6.4 km buffers because groundwater pumping (direct discharge) is likely to affect DWT from further away than precipitation does. Our choice of 6.4 km as a buffer radius is also supported by

Table 4
The in-season definition for included crops.

State	Crop	Measurement period	In-season
Nebraska	Corn	Mar(t)-Feb(t + 1)	May-Oct (t)
	Soy	Mar(t)-Feb(t + 1)	May-Sep (t)
Kansas	Corn	Jan(t)-Dec(t)	Apr-Sep (t)
	Winter wheat	Jan(t)-Dec(t)	Jan-Jun (t) and Oct-Dec (t)

Notes: t and $t + 1$ in parentheses indicate the same year and next year, respectively. For example, for DWT observed between 2012 and 2013, t and $t + 1$ mean 2012 and 2013, respectively. We use this definition so the DWT change reflects the 2012 growing season.

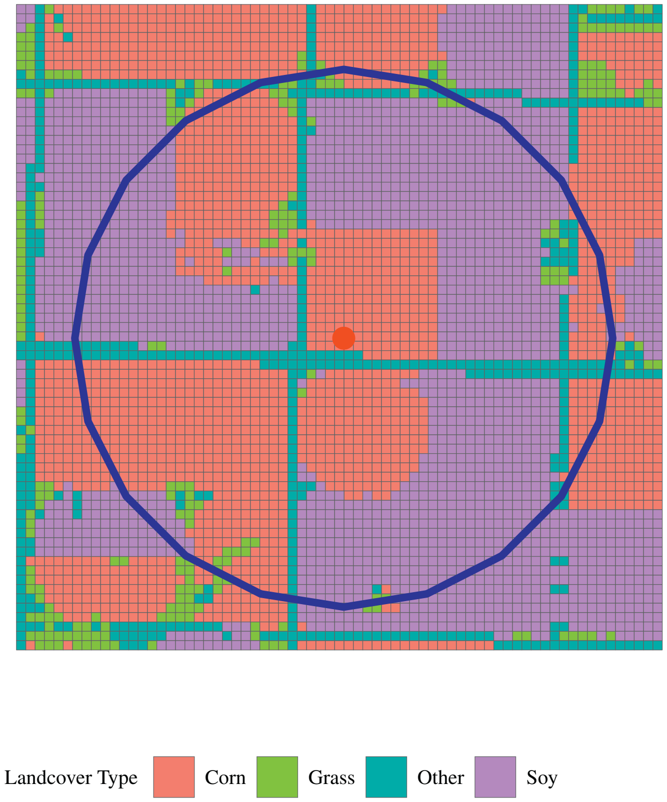

Fig. 4. Example 2-mile radius buffer around a sample well (CropScape data).

Pfeiffer and Lin (2012), which showed that groundwater pumping that occurred as far as 6.4 km (4 miles) affects depth to water table.

4.3. Summary statistics

Summary statistics for the wells in Nebraska and Kansas are presented in Tables 2 and 3, respectively. On average, depth to water table is a little higher in Kansas (46.58 m) compared to Nebraska (34.45 m). A striking difference between the two states is the rate of groundwater depletion. While the average annual increase for Nebraska wells in DWT is 19 mm, Kansas experienced an average annual increase of 494 mm in DWT. This contrast is consistent with McGuire (2017) which found an average of no decline for Nebraska overall from 2013 to 2015 and a 366 mm average decline for Kansas overall for the same period. This contrast is also consistent with the annual recharge differences seen in Scanlon et al. (2012) for the study areas of Kansas (up to 25 mm) versus Nebraska (up to 76 mm).

Average annual precipitation is higher in Nebraska (631 mm) compared to Kansas (481 mm). However, the average groundwater extraction within the 6.4 km (4-mile) buffer of the chosen USGS observation wells is higher in Nebraska (77 mm) than in Kansas (43 mm). Extraction is calculated as the average uniform extraction volume for the full buffer. For example, an extraction value of 100 mm is the amount of water necessary to cover the entire buffer by 100 mm of water. One possible explanation for the differences between states in extraction is that greater precipitation and recharge allow irrigation on a larger proportion of total land. The difference may also be due to variation in land cover patterns. There are notable differences in land cover types between Nebraska and Kansas. In Nebraska, corn (33%) and grass (41%) are the most dominant land cover types, followed by soybean (9%). All the other categories have very small individual shares and are lumped into a single category called "Other," which include sorghum (0.64%), alfalfa (0.97%), development (2.68%), woods (0.19%), wetlands (1.20%) among other land cover types. Corn (33%) and grass (41%) are also important in Kansas. However, the share of soybean is negligibly small (0.75%) in the Kansas study area unlike Nebraska, and winter wheat is more prominent (22%) instead. For Kansas, soy and the remaining land covers are grouped into "Other".

Table 2
Summary statistics (Nebraska).

Statistic	N	Mean	St. dev.	Min	Max
Depth to groundwater (m)	4199	34.45	19.46	0.96	93.13
Annual depth change (mm)	4199	19	524	−4267	4069
Groundwater extraction (mm)	4199	77	49	0.0	369
Precipitation (mm)	4199	631	151	257	1021
Average daily max temp (Celsius)	4199	8.94	0.65	7.39	10.96
Corn share (%)	4199	0.33	0.18	0.00	0.80
Soybean share (%)	4199	0.09	0.11	0	0
Grass share (%)	4199	0.41	0.24	0.01	0.97
Other share (%)	4199	0.17	0.11	0.02	0.80

Notes: These are the summary statistics of the Nebraska data. The temporal coverage of the data is 2007 through 2015. *N* indicates the number of observations.

Table 3
Summary statistics (Kansas).

Statistic	N	Mean	St. dev.	Min	Max
Depth to groundwater (m)	4497	46.58	23.19	1.49	124.88
Annual depth change (mm)	4497	494	961	−5834	6050
Groundwater extraction (mm)	4497	43	65	0.0	371
Precipitation (mm)	4497	481	120	194	924
Average daily max temp (Celsius)	4497	20.14	1.34	17.14	23.90
Corn share (%)	4497	0.18	0.13	0.00	0.73
Winter wheat share (%)	4497	0.22	0.10	0.001	0.57
Grass share (%)	4497	0.29	0.19	0.01	0.95
Other share (%)	4497	0.31	0.11	0.03	0.85

Notes: These are the summary statistics of the Kansas data. The temporal coverage of the data is 2007 through 2014. *N* indicates the number of observations.

Fig. 5 presents the recent history of yearly groundwater depth changes, groundwater extraction, and precipitation in Nebraska. As seen in the summary statistics, the Nebraska wells exhibit a general decline in DWT. However, in 2012 and 2013 Nebraska had unusually severe droughts, higher groundwater extraction, and noticeable increases in DWT compared to other years. Fig. 6 presents the recent history of yearly groundwater depth changes, groundwater extraction, and precipitation for Kansas. Unlike the Nebraska wells, the Kansas wells had consistent increases in the DWT with the largest median increase observed in 2012, a year with severe drought.

5. Econometric method

This study uses a variant of water-table fluctuation method (e.g., Crosbie et al., 2005; Delin et al., 2007; Healy and Cook, 2002). Before we describe our statistical model in detail, we first describe the underlying concept of our method using a stylized model. First, the following equation generally holds:

$$-\Delta DWT \times \text{Specific Yield} = \Delta WS \tag{1}$$

where ΔWS is the change in water stored in the aquifer. Note that a negative change in depth to water table means an increase in groundwater stored in the aquifer, thus $\Delta DWT \times$ Specific Yield needs to be multiplied by -1 to get the correct sign of ΔWS.

It would be erroneous to multiply observed changes in depth to water table by specific yield ($-\Delta DWT \times$ Specific Yield), and consider the results as recharge from precipitation. This is because observed changes in water stored in the aquifer (ΔWS) are affected not only by recharge from precipitation, but also groundwater pumping (discharge) for agricultural production and its return flow, and lateral water movement inside the aquifer. We break down ΔWS into these parts:

$$\Delta WS = -\text{Pumping} + \alpha \times \text{Pumping} + \beta \times \text{Precipitation} + \gamma \times \text{Lateral Movement} \tag{2}$$

The first term is the direct impact of groundwater pumping out of aquifer. Since 1 mm of groundwater removes 1 mm of water stored in aquifer, the pumping variable has the coefficient of -1. However, some of the groundwater pumped for irrigation is not effectively used by the plant, and returns to the aquifer. We use α to represent the proportion of the applied irrigation that returns to the aquifer as return flow. We then have recharge from precipitation, which is represented by $\beta \times$ Precipitation, where β is the proportion of precipitation that reaches the groundwater table. Finally, water can move laterally within the aquifer, and this recharge is represented by $\gamma \times$ Lateral Movement. Regression analysis allows us to estimate the individual impact of these components on changes in water stored in the aquifer.

Our regression approaches is an extension of this stylized model, where the impact of precipitation on water storage in the aquifer is allowed to vary based on the surface landcover type. We now provide a detailed account of how we model heterogeneous impact of precipitation on various landcover types.

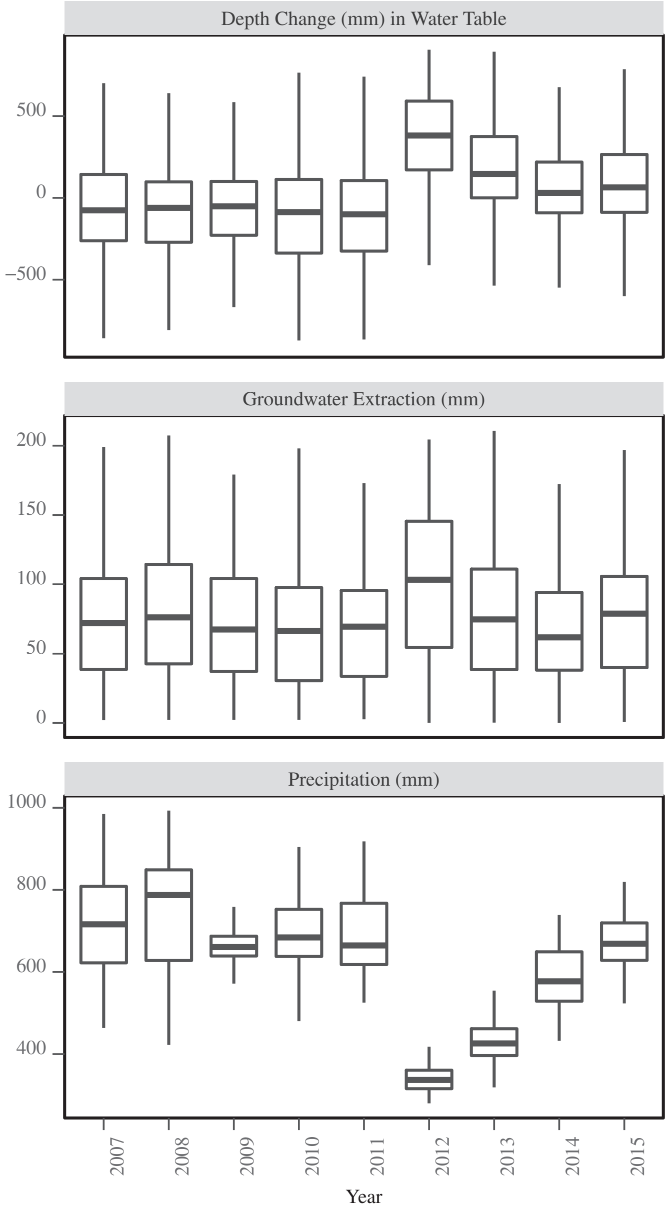

Fig. 5. Distribution of depth change, groundwater extraction, and precipitation by year (Nebraska).

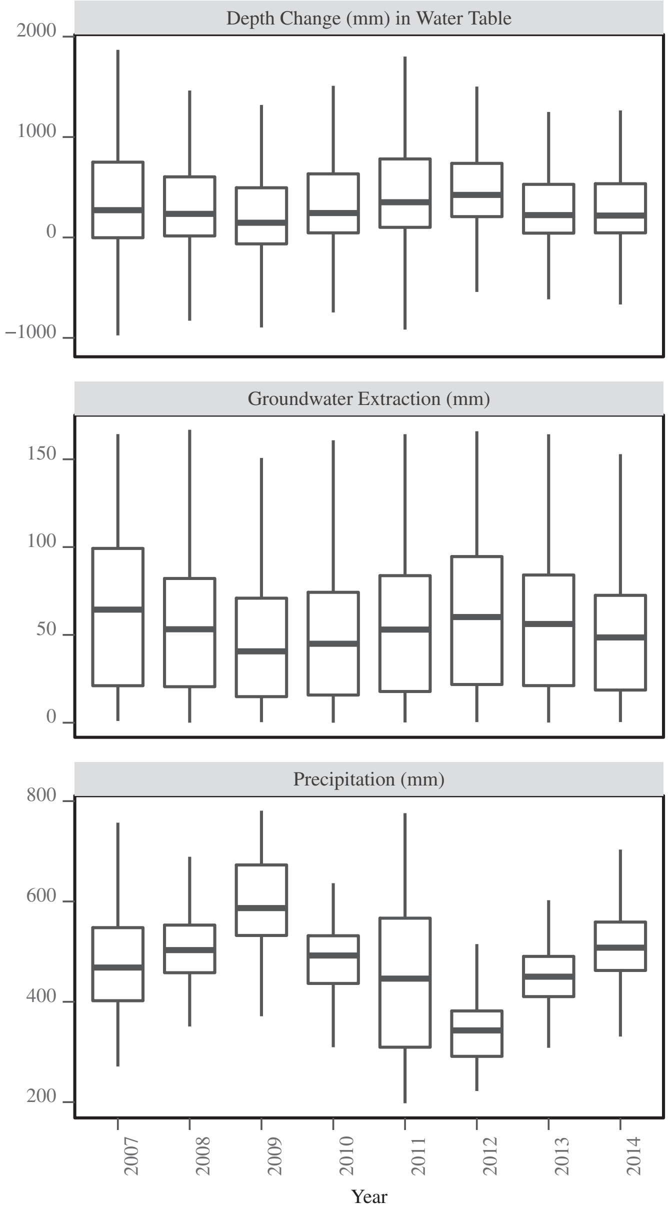

Fig. 6. Distribution of depth change, groundwater extraction, and precipitation by year (Kansas).

5.1. Impact of precipitation on depth to groundwater

Here, we explain how we model specification of the impacts of landcover type on groundwater recharge from precipitation. We let i, j, t, and m indicate observation well, CropScape grid cell within the 3.2 km radius of the well, year, and month, respectively. We let $P_{j,\,m,\,t}$ indicate the total precipitation that fell on grid j in month m of year t, and and $c_{j,\,t}$ denotes the predominant crop type at grid cell j in year t, where $c = 1, \ldots, C$. Further, we let $\Omega(c_{j,\,t})$ denote the growing months (the period within a year during which the land is covered with some vegetation), which varies based on the crop type at grid j ($c_{j,\,t}$). The growing seasons for crops are defined by USDA planting and harvesting dates.[5] The in-

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[5] See the 2010 USDA planting and harvesting dates at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1251 for more information.

season period is defined by the most active planting and harvesting dates for each crop and state, except for the last month of most active harvesting. The off-season period is defined by the remaining months between the DWT measurement from current year to next year. Table 4 has the crop season definitions for the crops that we use in the study. Grass and the other remaining land covers are treated as always being in-season. For grass, this is because we do not know its use (e.g. range or wild) or type (e.g. annual or perennial). For the Other category, it includes multiple crops with differing cropping seasons and other things like roads, which have no cropping season.

For each well, we have a fixed number of grid cells within its 3.2 km buffer, denoted by J. The impact of precipitation that falls on grid cell j on the actual water stored in height (WS) for well i between year t and $t+1$ (denoted as $WS^p_{i,j,t}$) can be written as follows:

$$\Delta WS^p_{i,j,t} = \sum_{m\in\Omega\left(c_{j,t}\right)} \beta_c \cdot P_{j,m,t} + \sum_{m\notin\Omega\left(c_{j,t}\right)} \alpha \cdot P_{j,m,t} \tag{3}$$

The parameter β_c is the proportion of precipitation that reaches aquifer as recharge when crop c is present (in-season), while α is the proportion of precipitation that reaches the aquifer when the crop is not present (off-season). Since the parameters measure the proportion of precipitation that reaches the water table from a single grid cell at observation well i, we expect that the values of β_c and α are extremely small, and significantly less than one. The total change in water stored in the aquifer at well i in year t is the sum of water storage change contributions from all the grids surrounding the well:

$$\Delta WS^p_{i,t} = \sum_{j}^{J} \Delta WS^p_{i,j,t} \tag{4}$$

Now, we let N^c_t denote the number of grids where crop c is grown within the 3.2 km radius of well i. Then,

$$\Delta WS^p_{i,t} = \sum_{c=1}^{C} N^c_t \cdot \left(\sum_{m\in\Omega\left(c_{j,t}\right)} \beta_c \cdot P_{j,m,t} + \sum_{m\notin\Omega\left(c_{j,t}\right)} \alpha \cdot P_{j,m,t} \right) \tag{5}$$

Collecting terms by coefficients ($\beta_1, \ldots, \beta_C$ and α),

$$\Delta WS^p_{i,t} = \sum_{c=1}^{C} \beta_c \left(N^c_t \sum_{m\in\Omega\left(C_{j,t}\right)} P_{j,m,t} \right) + \alpha \left(\sum_{c=1}^{C} \left[N^c_t \sum_{m\notin\Omega\left(c_{j,t}\right)} P_{j,m,t} \right] \right) \tag{6}$$

Finally, by dividing and multiplying the right hand side for each land cover type by the number of total grids (J),

$$\Delta DWT^p_{i,t} = \sum_{c=1}^{C} J\beta_c \left(S^c_t \sum_{m\in\Omega\left(C_{j,t}\right)} P_{j,m,t} \right) + J\alpha \left(\sum_{c=1}^{C} \left[S^c_t \sum_{m\notin\Omega\left(c_{j,t}\right)} P_{j,m,t} \right] \right), \tag{7}$$

where $S^c_t = (N^c_t/J)$ is the share of land cover type c in the 3.2 km radius buffer. By including $S^c_t \sum_{m\in\Omega(C_{j,t})} P_{j,m,t}$ $(c = 1, \ldots, C)$ as a covariate, we can recover the coefficient $J\beta_c$, which measures the impact of precipitation during the respective growing season if all the grid cells have land cover type c. Similarly, by including $\sum_{c=1}^{C} [S^c_t \sum_{m\notin\Omega(c_{j,t})} P_{j,m,t}]$, we can recover $J\alpha$, which measures the impact of all off-season precipitation (i.e., when there is no surface vegetation).

Denoting $J\beta_c$ and $J\alpha$ by γ_c and λ, respectively,

$$\Delta WS^p_{i,t} = \sum_{c=1}^{C} \gamma_c \left(S^c_t \sum_{m\in\Omega\left(C_{j,t}\right)} P_{j,m,t} \right) + \lambda \left(\sum_{c=1}^{C} \left[S^c_t \sum_{m\notin\Omega\left(c_{j,t}\right)} P_{j,m,t} \right] \right) \tag{8}$$

Under this specification, for example, if corn covers the 10% of the area within the 3.2 km buffer of well i (located in Nebraska), then the change in WS due to precipitation on grids with corn (and no vegetation after harvesting) is shown in 9. In this example, the months 5 through 10 refer to May through October (the growing season for corn). Since the DWT measurement occurs in March, precipitation from months 3 and 4 (1 and 2) of year t ($t+1$) reflect the off-season for corn production in year t.

$$\Delta WS^p_{i,t} = 0.1 \times \left[\gamma_{Corn} \left(\sum_{m=5}^{10} P_{i,m,t} \right) + \lambda \left(\sum_{m=3}^{4} P_{i,m,t} + \sum_{m=11}^{12} P_{i,m,t} + \sum_{m=1}^{2} P_{i,m,t+1} \right) \right] \tag{9}$$

5.2. Estimating equation

Using the notation established above, the estimating equation is,

$$\begin{aligned} \Delta WS_{i,t} = \; & \beta_0 + \sum_{c=1}^{C} \gamma_c \left[S^c_t \sum_{m\in\Omega\left(C_{j,t}\right)} P_{j,m,t} \right] + \lambda \sum_{c=1}^{C} \left[S^c_t \sum_{m\notin\Omega\left(c_{j,t}\right)} P_{j,m,t} \right], \\ & + \beta_E E_{i,t} + \beta_T T_{i,t} + \alpha_i + \phi_t + \varepsilon_{i,t} \end{aligned} \tag{10}$$

where i denotes the USGS observation well and t the year. The dependent variable is the change in actual water stored in the aquifer in height ($\Delta WS_{i,\,t}$). The variables of the most interest are the amount of precipitation that fell on various land cover types. Groundwater extraction ($E_{i,\,t}$) is also an important variable as it has a significant effect on the amount of water stored in the aquifer. Explicitly modeling it allows us to estimate the impact of converting irrigated cropland into grassland. Groundwater extraction has a direct impact on water stored in the aquifer irrespective of the land cover type, and unlike precipitation, no differentiation is made across various crop types in terms of the marginal impact of groundwater extraction. Further, note that the coefficient on groundwater extraction represents the combined impacts of extraction and return flow ($-1 + \alpha$ in Eq. (2)). For example, if the coefficient on groundwater extraction is -0.7 ($\alpha = 0.3$), then it means that 30% of groundwater pumped returns to the aquifer. We include maximum temperature ($T_{i,\,t}$), measured as the average of the daily maximum temperature values, as a control as it affects evaporation. The higher the temperature, the greater the evaporation, which means more precipitation would be lost to the air, reducing recharge. Additionally, individual well fixed effects (α_i) and year fixed effects (ϕ_t) are included as controls. Individual fixed effects control the impact of variables that are constant over time, such as unobserved soil characteristics that may impact the movement of water through the unsaturated zone to the water table. Using fixed effects in this manner represents a trade-off, as it controls for deeper soil characteristics for which there is limited data, but does not allow us to identify the effect of surface level soil characteristics. Finally, the error term is represented by $\varepsilon_{i,\,t}$. We do not explicitly model the impact of lateral water flow within the aquifer, which means that it is part of the error term. However, this does not cause bias on the coefficient estimates of precipitation variables. This is because omitting a variable (here, lateral water movement in the aquifer) that is not correlated with the variable of interest (here, precipitation variables) does not cause any bias on the coefficient estimation of the variable of interest, which is a well-known econometric theory (Wooldridge, 2015). Since surface landcover type should not affect groundwater movement within the aquifer, the above theory applies to our case as well. Finally, it is important to use the standard error estimation method that is robust to heteroskedasticity, autocorrelation, and spatial correlation when panel data is used (Bertrand et al., 2004; Schlenker et al., 2006). In this study, standard errors are clustered by PLSS (Public Land Survey System) township, which allows for unspecified form of heteroskedasticity, autocorrelation, and spatial correlation within township (Cameron and Miller, 2015). We confirmed that if we cluster by individual well, which allows for heteroskedasticity and autocorrelation, but ignores spatial correlation of the error term, standard errors are substantially underestimated.

6. Regression results

The regression results for Nebraska and Kansas are presented in Table 5. A positive coefficient indicates that an increase in the explanatory variable increases the amount of water stored in the aquifer (net recharge), while a negative coefficient indicates that the opposite. As explained in the econometric method section, the coefficient on the precipitation variables measures the proportion of precipitation (in mm) that reaches to the groundwater table (in mm). This means that an additional mm of precipitation across a buffer fully planted in corn (soybean) during the growing season in Nebraska would increase recharge by about 0.31 (0.29) mm. Precipitation during the off-season has a larger coefficient in magnitude (0.37) than the soybean and corn in-season precipitation coefficient. This is an expected result, because precipitation that falls in the non-growing season often falls on plowed soil with little vegetation. Thus, a higher proportion of the precipitation is expected to percolate into the soil, contributing more to groundwater recharge. Precipitation on grassland does not have a statistically significant impact on groundwater recharge, suggesting little or no recharge from precipitation on grassland. This result is consistent with Scanlon et al. (2005), which uses data from the Texas portion of the High Plains Aquifer and the Mojave Desert, and finds that almost all precipitation that falls on rangeland is used by the vegetation. Thus, overall results from Nebraska suggest that the recharge from precipitation that fell on corn (soybeans) during the growing season is greater than that on grassland. In Kansas, 1 mm of precipitation that fell on a buffer fully planted in corn (wheat) during the growing season decreases DWT by about 0.3 (0.27) mm. The coefficient estimate for corn is similar in magnitude and statistical significance to the estimate in Nebraska. However, unlike Nebraska, the recharge associated with precipitation on grassland is statistically significant, possibly due to differences in the type of grass grown in the two regions. As we discussed in the data section, different types of grassland cover are categorized into a single grassland category in CropScape. Consequently, it is possible that in Kansas, the grassland category includes grassland types that allow greater groundwater recharge compared to Nebraska.

Table 5
Regression results: Determinants of change in stored groundwater change in water stored in the aquifer (in mm).

	Nebraska	Kansas
Groundwater extraction (in mm)	-0.621^{***}	-1.099^{***}
	(0.141)	(0.336)
Precipitation on corn (in mm)	0.312	0.296^{***}
	(0.061)	(0.106)
Precipitation on soybean (in mm)	0.295^{***}	
	(0.108)	
Precipitation on winter wheat (in mm)		0.266^{**}
		(0.120)
Off-season precipitation (in mm)	0.372^{***}	-0.064
	(0.123)	(0.183)
Precipitation on grass (in mm)	-0.034	0.223^{***}
	(0.049)	(0.078)
Precipitation on other (in mm)	0.282^{***}	0.116^{**}
	(0.075)	(0.054)
Maximum temperature (in degrees Celsius)	-10.454	8.811
	(22.074)	(11.462)
Year fixed effects included?	Yes	Yes
Well fixed effects included?	Yes	Yes
Observations	4199	4463
Adjusted R^2	0.201	0.329

Note: This table presents the estimated coefficients of the regression equation described in the method section. Numbers in parentheses are the estimated standard error of the coefficients.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The primary goal of our analysis is to estimate the impact of converting cropland to land covers associated with land retirement programs like CRP, which we measure through the difference in groundwater recharge between cropland and grassland. The difference in the coefficient estimates for precipitation on corn (soybeans) and grassland represent the difference in recharge from 1 mm of precipitation that fell on cropland during the growing season and grassland. Table 6 presents the test of whether the regression coefficients differ for crops and for grassland. In Nebraska, we estimate an average expected impact of −0.35 (−0.33) mm of recharge per mm of precipitation for corn (soybeans) relative to grassland. In Kansas, the impact is −0.07 (−0.04) for corn and wheat, respectively. However, neither estimate for Kansas is statistically different from zero. This is partly due to less accurate estimation for Kansas (the standard errors on the coefficients are higher), as well as the positive recharge associated with grassland in Kansas.

Finally, we look at the impact of groundwater extraction on the amount of groundwater stored in the aquifer, which has important implications in understanding the impact of CREP, which retires irrigated fields. The results (see Table 5) show that groundwater extraction is significant in the expected direction for both regions. For Nebraska (Kansas), increasing groundwater extraction by 1 mm across the entire buffer (an increase of 32,540 cubic meters with the 3.2-km, or 3254 ha, buffer) would reduce the groundwater in storage by an average amount of 0.62 (1.1) mm. The number is much smaller in Nebraska than in Kansas. There are several possible explanations for the difference. First, there may be greater return flows from irrigation in Nebraska than Kansas, possibly due to a lower DWT in Nebraska relative to Kansas (see Tables 2 and 3). Another difference is due to possible measurement error in the data. Most of the extraction data in Kansas is self-reported, while the extraction data in Nebraska is monitored each year by the regulatory authority. Thus, if the self-reported data is more likely to include underestimates of the true extraction level, it could increase the estimated coefficient for extraction in Kansas.

6.1. Consideration on the recharge speed and potential bias

Since water does not move instantaneously through the unsaturated zone, any estimation requires an assumption about how quickly precipitation at the surface reaches the water table. In the main regression of this study, we estimate the regressions using all observation wells. However, as a robustness test, we evaluate the results if we only use shallower wells, as they are more likely to have precipitation from the study year reach the groundwater table during the sample period. Appendix A contains the results when only shallower wells (DWT <15.2 m and DWT <30.5 m) are included. In general, the results are

Table 6
The impact of land conversion on recharge.

Land conversion	Difference in recharge coefficients
Nebraska	
Corn to grassland	-0.35^{***} (-0.07)
Soy to grassland	-0.33^{***} (-0.11)
Kansas	
Corn to grassland	-0.07 (-0.12)
Wheat to grassland	-0.04 (-0.14)

Note: Estimated standard errors of the differences in recharge coefficient are in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

similar, and differ as expected. For example, the absolute value of the coefficients on land cover in Nebraska are generally larger (and still negative), implying a higher recharge value for each mm of precipitation during the sample period on corn or soy. Particularly in Kansas, the reduced sample size results in fewer statistically significant results, even when point estimates are similar.

Regardless of any choice of threshold for the beginning depth, we cannot know the age of the precipitation percolating to the water table with certainty. If one erroneously includes precipitation in the explanatory variable that has not yet reached the aquifer, or omits precipitation that did reach the aquifer in the measure of DWT, it could bias the estimation of the true potential of groundwater recharge from precipitation. We first tested the importance of lagged precipitation by including lagged and current precipitation in the estimation. However, the lagged precipitation was not significant. Now, it seems quite reasonable to assume that the speed at which the water travels through the soil is the same irrespective of the surface land cover once the water gets past the root zone associated with the land cover vegetation. In other words, deep soil properties are likely to be independent of the surface land cover types. Thus, this paper's estimates are likely to suffer from attenuation bias. However, it is important to note that estimated differential is likely to keep the sign of the impact intact.

7. Economic and policy implications

7.1. Economic analysis of CRP and CREP

We now use the regression results to estimate the impact of CRP and CREP-induced land conversions on DWT in Nebraska and Kansas. Our estimates are based on a conversion of 323.75 ha, or 10% of the land within the 3.2-km buffer. We use a value of 10% of the land to illustrate the effect of CRP or CREP. Actual enrollment is typically lower than this at the county or state level, but could be higher than 10% for a single 3.2-km buffer. We evaluate conversions of cropland planted in corn, wheat, or soybeans to grassland. The estimates for CRP and CREP are evaluated based on different counterfactuals. Since CRP rarely retires irrigated land (since the maximum payment is based on rainfed returns), we ignore the impact of extraction when we calculate the estimated impact of CRP. Thus, our estimates of differences in recharge associated with CRP reflect a shift of 325.4 ha from rainfed crop production to a conservation cover. In contrast, since the CREP programs in Kansas and Nebraska are aimed at retiring irrigated fields, we incorporate the estimated reduction in groundwater extraction associated with the conversion of land cover. Given that precipitation is spatially variable, the impact of land conversion is also spatially variable. In order to create a map of the impact of land conversion, we use a PRISM grid as the observation unit and calculate the impact based on the precipitation value for that grid. Let $\hat{\beta}_c$, $\hat{\beta}_{off}$, and $\hat{\beta}_g$ denote the impact of precipitation that fell on the cropland of interest, non-growing season of the cropland, and grassland. Further, let P_c and P_{off} denote the amount of precipitation (in mm) that occurred in the growing and non-growing season of the cropland of interest. Then, the estimated impact of land conversion on depth to water table is as follows:

$$I_{CRP} = \frac{0.1 \times \left[\hat{\beta}_g (P_c + P_{off}) - \left(P_c \cdot \hat{\beta}_c + P_{off} \cdot \hat{\beta}_{off}\right)\right]}{sy} \tag{11}$$

The denominator measures the impact of land conversion in water stored in the aquifer. By dividing it by specific yield (sy), we can translate the water content into height change in groundwater table elevation. For CREP, we consider a decline in pumping. Letting E and $\hat{\beta}_E$ denote the amount of groundwater extraction (in mm) and the coefficient estimate on groundwater extraction, the impact of CREP is as follows:

$$I_{CREP} = I_{CRP} - \frac{\hat{\beta}_E \cdot E}{sy} \tag{12}$$

It has been well established that groundwater extraction (E) depends on precipitation (Allen et al., 1998; Russo and Lall, 2017; Gurdak, 2017), and ignoring this dependence (for example, by simply using the average extraction rate) leads to erratic estimates of the impact of irrigated-land conversion. To determine the relationship between E and precipitation, we use a regression of groundwater extraction on precipitation by crop. The groundwater extraction data for Nebraska does not allow us to estimate the relationship, since it does not have information on which parcels are irrigated. However, the Kansas data (from WIMAS) has information on the crop and irrigation status. Therefore, we estimate the pumping-precipitation relationship for corn, soybeans, and wheat using the WIMAS data. We then apply those estimates for Nebraska, assuming that the pumping-precipitation relationship is similar between Kansas and Nebraska. The regression results of pumping on in-season precipitation are presented in Table 7. For example, the results show that an additional mm of in-season precipitation reduces groundwater pumping by 0.51, 0.49, and 0.34 mm for corn, soybeans, and wheat, respectively. These estimates are somewhat larger, but similar to, other estimates in the literature (Hendricks and Peterson, 2012; Mieno and Brozović, 2016; Li and Zhao, 2018).

The estimated impacts on precipitation-driven recharge of converting cropland to CRP or CREP are presented in Table 8 and in Figs. 7–10. Table 8 includes the average estimated impact for each state at the 10th, 50th, and 90th precipitation percentiles. Column P_{in} and P_{off} indicate the expected total in-season and off-season precipitation (in mm), and *Pumping* indicates the total expected extraction (in mm) for irrigated production by crop, state, and precipitation level. A positive value indicates an increase in net recharge. The CRP estimates are predicted with a rainfed (no irrigation) counterfactual, while the CREP estimates are predicted with expected irrigation usage.

In Nebraska, a conversion from rainfed crop production to CRP reduces groundwater recharge by a range of 109 to 175 mm, depending on crop and precipitation, and results are statistically significant for both crops and all precipitation levels. Thus, while there may be environmental benefits from CRP for habitat, water quality, reduced soil erosion, and other environmental indicators, the results show that the conversion does lead to a reduction in the quantity of water in the aquifer. However, the impact does not vary significantly by crop. These results are slightly higher, but still in line with results from Dugan and Zelt (2000), who estimate deep percolation rates for dryland production in the eastern RRB. They find a range of 15.24 to 36.83 mm for hay and a range of 62.23 to 122.94 mm for high water demand crops such as corn. These results imply a difference in deep percolation between hay and high water demand crops that ranges between 46.99 and 86.11 mm,

Table 7
The impact of precipitation on pumping by crop type (Kansas) groundwater pumping (mm).

	Corn	Soy	Wheat
Precipitation	-0.509^{***}	-0.493^{***}	-0.341^{***}
	(0.003)	(0.006)	(0.014)
Intercept	598.825^{***}	506.517^{***}	351.225^{***}
	(1.546)	(2.975)	(5.728)
Observations	76,203	17,339	6951
Adjusted R^2	0.242	0.282	0.084

Note: This table presents the estimated coefficient of the regression of groundwater pumping on in-season precipitation. Numbers in parentheses are the estimated standard error for the coefficients.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 8
The impact of land conversion on aquifer recharge (in mm) at the 10th, 50th, and 90th levels of precipitation.

Crop	[%: *Pin*, *Poff*]	Pumping	CRP	CREP
Nebraska				
Corn	[10th: 405.0, 129.5]	393	-121^{***} (19.6)	57 (42.5)
Corn	[50th: 493.3, 153.5]	348	-146^{***} (23.8)	11 (42.0)
Corn	[90th: 581.7, 192.4]	303	-175^{***} (28.4)	−38 (42.2)
Soy	[10th: 367.7, 166.5]	325	-109^{***} (26.2)	38 (43.1)
Soy	[50th: 427.3, 221.7]	296	-134^{***} (31.3)	−0.34 (44.6)
Soy	[90th: 497.6, 281.1]	261	-162^{***} (37.3)	−44 (47.3)
Kansas				
Corn	[10th: 285.0, 101.5]	454	−10 (22.9)	323^{***} (106.1)
Corn	[50th: 360.6, 114.7]	416	−15 (28.5)	290^{***} (99.7)
Corn	[90th: 447.4, 166.0]	371	−14 (36.1)	258^{***} (93.9)
Wheat	[10th: 264.1, 111.8]	261	3 (25.6)	195^{***} (63.8)
Wheat	[50th: 338.5, 141.5]	236	4 (32.7)	177^{***} (62.2)
Wheat	[90th: 423.6, 176.2]	207	5 (40.9)	156^{**} (62.0)

Note: Estimated standard errors of the change in aquifer recharge are in parentheses. P_{in} and P_{off} refer to the amount of precipitation (in mm) that occurs during the in-season and off-season for the crop. CRP and CREP show the estimated annual change in recharge (in mm) if 10% of the land is converged from dryland (irrigated) production to CRP (CREP). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

depending on soil type. One possible explanation for the difference is that our results only include changes in recharge due to precipitation and extraction, and not lateral flow. In contrast to rainfed production, enrollment of an irrigated parcel into CREP has no significant impact on the aquifer. This is because there are two components that need to be incorporated into the CREP estimate. First, there is lower recharge due to the conversion from corn or soybeans to grassland, and this effect reduces recharge. Second, there is a reduction in extraction that increases recharge. These effects balance out, with a net effect close to zero.

Results in Kansas differ from Nebraska. In Kansas, a conversion from rainfed crop production to CRP has no measurable impact on net recharge for either crop at any level of precipitation. However, a conversion from irrigated crop production to CREP increases net recharge for both corn and wheat at all precipitation levels. A conversion of irrigated corn increases recharge by 258 to 323 mm, while a conversion of irrigated wheat increases recharge by 156 to 195 mm. In this case, the results differ by crop, with average estimated impact from corn about 50% higher than the impact from wheat. These results suggest that CREP can be an effective program to protect or increase groundwater levels in the Ogallala Aquifer Region of Kansas.

While Table 8 presents average results for each state, heterogeneity in climate conditions imply that results are also heterogeneous across each state. Figs. 7 to 10 translate the change in stored groundwater to a change in DTW, determined at average precipitation levels across space. In Nebraska, the estimated impact of converting rain-fed corn to grassland is presented in Fig. 7. For the RRB, a conversion of 325.4 ha (10% of the land) from corn to CRP would result in an average increase in DWT of about 147 mm. As expected, the impact is spatially variable. In the western portion of the RRB, where precipitation is low, the impact of conversion is small, while the impact is larger on the east side. If 325.4 ha of irrigated corn is converted to grassland under the CREP program in the western portion of the RRB, the benefit of the reduction in groundwater extraction outweighs the impact of land cover change, thus helping to reduce DWT. Our results show a similar pattern for the conversion of soybeans (see Fig. 8).

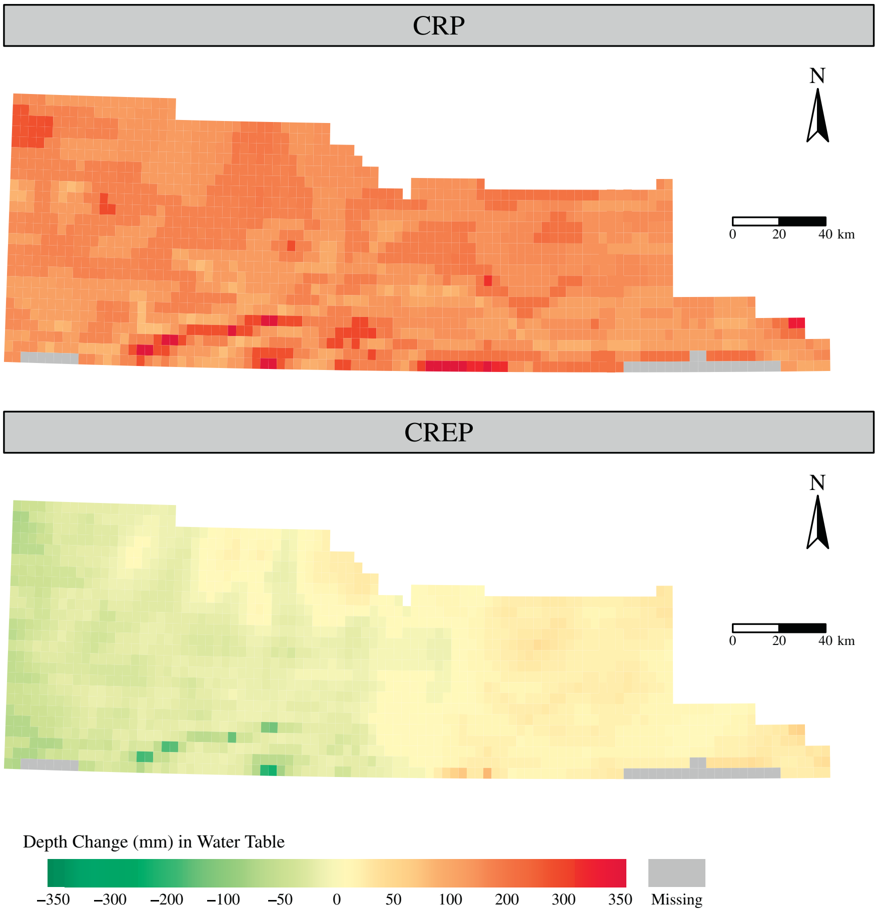

Fig. 7. The impact of converting ten percent of all land from corn production to grassland on depth to water table (in mm) (Republican River Basin). Note: Changes under CRP indicate a change from rainfed corn production to grassland. Changes under CREP indicate a change from irrigated production at expected irrigation application rates to grassland.

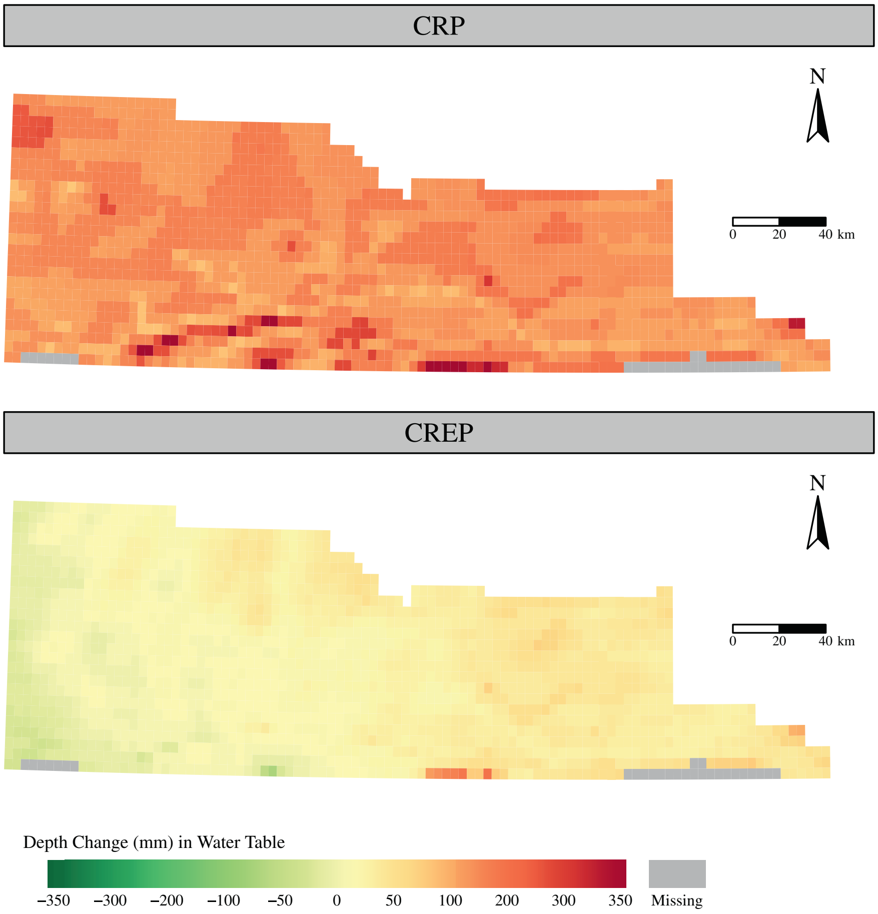

Fig. 8. The impact of converting ten percent of all land from soybean production to grassland on depth to water table (in mm) (Republican River Basin). Note: Changes under CRP indicate a change from rainfed soybean production to grassland. Changes under CREP indicate a change from irrigated production at expected irrigation application rates to grassland.

In contrast to Nebraska, CRP has a very small impact for both corn and wheat in Kansas as shown in Figs. 9 and 10. Indeed, the estimated impacts are all statistically insignificant. This implies that unlike Nebraska, a conversion of rain-fed corn or wheat has a negligible impact on DWT. However, the conversion of an irrigated field under the CREP program has a much larger benefit in reducing DWT, compared to Nebraska. This is because the impact of groundwater pumping on DWT is greater in Kansas, likely due to the smaller rate of return flow in Kansas.

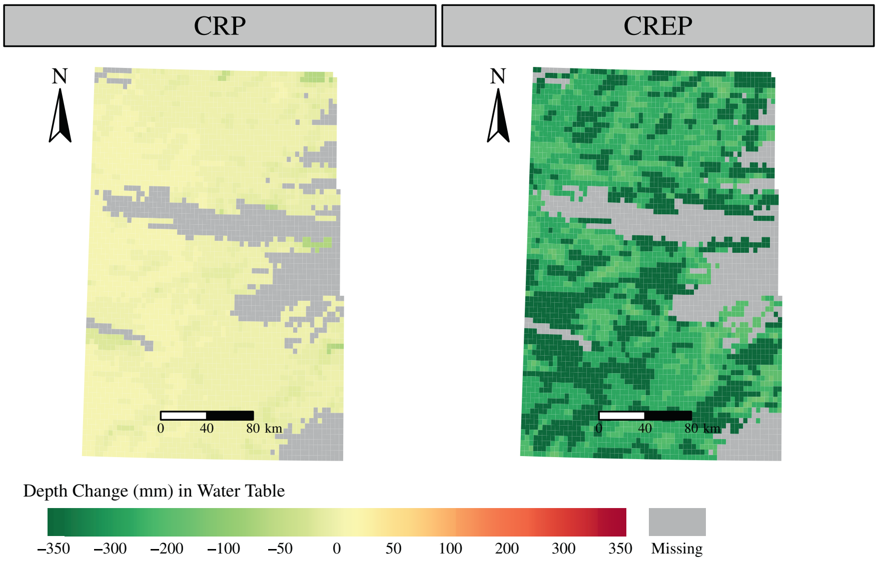

Fig. 9. The impact of converting ten percent of all land from corn production to grassland on depth to water table (in mm) (Western Kansas). Note: Changes under CRP indicate a change from rainfed corn production to grassland. Changes under CREP indicate a change from irrigated production at expected irrigation application rates to grassland.

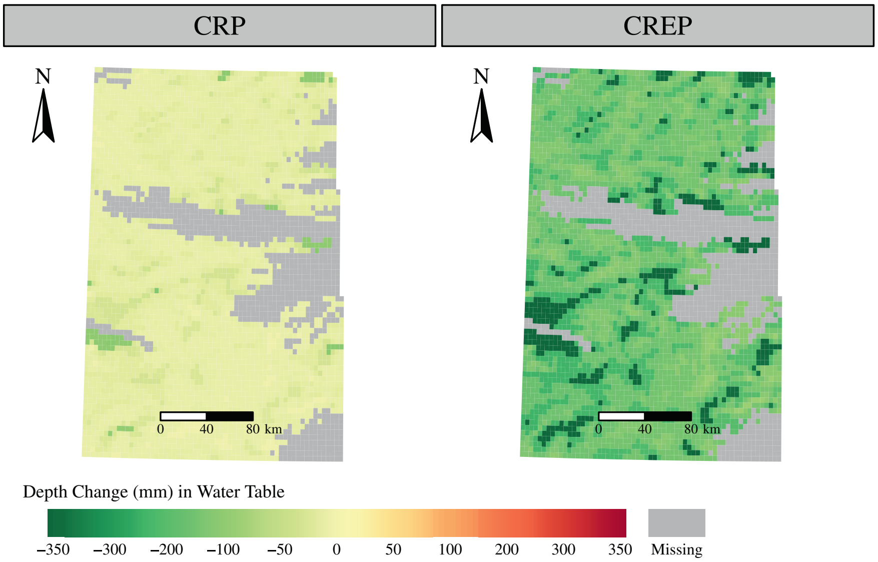

Fig. 10. The impact of converting ten percent of all land from wheat production to grassland on depth to water table (in mm) (Western Kansas). Note: Changes under CRP indicate a change from rainfed soybean production to grassland. Changes under CREP indicate a change from irrigated production at expected irrigation application rates to grassland.

Moreover, land conversion has a very limited impact on DWT in Kansas, as recharge from precipitation is similar (not statistically distinguishable) between corn, wheat, and grassland.

7.2. Discussions and policy implications

The findings suggest that grassland, a major CRP land cover, induces smaller amounts of recharge from precipitation compared to corn, and soy, which are the major land cover types in Nebraska's RRB. In Kansas' OAR however, there seems to be no land cover impact on recharge from precipitation, which is consistent with reports of the region's overall poor recharge (Scanlon et al., 2012; Dugan and Zelt, 2000). This means that policy makers should be aware of and take into account the impact of land cover conversion from cropland to grassland on groundwater recharge in deciding where to place CRP fields, especially in regions where groundwater recharge is significant. However, such consideration is less warranted in areas where groundwater recharge is minimal in the first place, like Kansas.

Decision makers for CRP (or similar programs) that are concerned about the net benefit of enrolling cropland into land retirement programs such as the CRP may find it prudent to reduce targeting (e.g. lower EBI scores) in areas with a strong need for groundwater storage but insufficient recharge, such as near rivers in Nebraska. The need in this area is to keep groundwater levels higher to improve streamflow in the hydrologically connected rivers. Additional CRP fields are expected to reduce recharge to aquifers and therefore reduce streamflow and increase associated environmental impacts. An example of an associated environmental impact is in Nebraska's Platte River region, where streamflow is needed to help provide proper habitat for the Sandhill cranes that migrate through the area and for a range of threatened and endangered species that rely on Platte River habitat. Poor targeting could also increase other costs, such as expenditures on programs to improve streamflow in the Republican River to meet RRCA compact requirements. Fully understanding these costs, and redirecting land retirement programs elsewhere can improve net benefits.

In areas where CRP may reduce needed recharge, another option is to direct funding towards CREP, or a similar irrigation reduction scheme to gain irrigation offsets. Using CREP-like programs could be beneficial in providing the environmental benefits associated with grassland (e.g., habitat, decreased runoff, and water quality improvements) and for increasing groundwater levels. Given the higher costs associated with land retirement under CREP than under CRP, it is particularly important to understand the tradeoffs between irrigation reduction and land cover changes, and the impact on groundwater levels.

Given the large amount of land leaving CRP, there may be a benefit to aquifers if the land exiting CRP is moved into non-irrigated production. However, these benefits are tempered by the loss of other environmental benefits that result from CRP exit. An additional concern would be a higher mobilization of pollutants to the water table that comes with the higher mobilization of water (Scanlon et al., 2007), or losses in wildlife habitat. As such, areas that are more concerned about water quality, soil erosion, or habitat needs (some of the primary benefits of CRP) than groundwater depletion may need to be targeted for protection of current CRP enrollment under declining budgets.

8. Conclusions

Using USGS data on the depth to groundwater table, along with land cover data collected by the USDA, we estimate the impact of land cover conversion on groundwater recharge for a large portion of the Ogallala Aquifer region. The results suggest that grassland, and therefore CRP-induced land cover changes, will lead to decreased recharge compared to the common crops (corn and soy) in the RRB of Nebraska. No difference is detected between grassland and common crops (corn and winter wheat) in the OAR portion of Kansas. The findings suggest a need to balance the known environmental benefits of CRP and associated programs like the USDA Conservation Reserve Enhancement Program (USDA-CREP) with expected regional impacts on groundwater and available funding. The results can inform policymakers and agency personnel to better target CRP enrollment, and to incorporate any positive or negative externalities on groundwater levels associated with changes in land cover.

The conclusions of this study are for the immediate impact of land cover changes. Land cover changes might also have long term impacts that are not yet accounted for, but require additional years of data for this paper's method to be utilized with longer lags. Another important limitation is that the CropScape map used for land cover only considers broad categories of grassland and other categories. Certain varieties of grasses or crops could have different recharge impacts. The previous limitation also extends to not knowing the land use practices from CropScape. This study also does not account for any variable impacts of hydrologically connected groundwater.

Future work should aim to address the previous limitations where possible. Additional extensions of this work could include looking at the groundwater quality impacts of land cover changes, and looking at optimal methods for spatially relating groundwater level changes with local conditions. Ultimately, this study provides a useful first step in considering the trade-offs in environmental programs like CRP that focus on a subset of all possible environmental benefits, and other environmental impacts. It also highlights the need to consider and account for the unintended impacts of policies.

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Appendix A. Additional regression results

Table A.1
The impact of land cover types on groundwater depth change for wells shallower than 15.24 m (50 ft) and 30.48 m (100 ft).

	Change in depth to water table			
	Nebraska (50)	Nebraska (100)	Kansas (50)	Kansas (100)
Groundwater extraction	-0.744^{***}	-0.533^{***}	-0.982	-2.291^{***}
	(0.187)	(0.203)	(0.844)	(0.517)
Precipitation on corn	0.447^{***}	0.426^{***}	0.150	0.150
	(0.112)	(0.071)	(0.350)	(0.232)
Precipitation on soybean	0.483^{***}	0.429^{***}		
	(0.178)	(0.113)		
Precipitation on winter wheat			0.198	0.076
			(0.294)	(0.224)
Off-season precipitation	0.408^{***}	0.291^{**}	0.922	0.492
	(0.143)	(0.136)	(1.314)	(0.421)
Precipitation on grass	-0.075	-0.017	0.291	0.289^{**}
	(0.115)	(0.084)	(0.196)	(0.129)
Precipitation on others	0.355^{***}	0.525^{***}	0.271	0.057
	(0.120)	(0.091)	(0.165)	(0.107)
Maximum temperature	-31.137	21.578	-5.088	4.164
	(48.279)	(37.984)	(28.823)	(20.533)
Year fixed effects included?	Yes	Yes	Yes	Yes
Well fixed effects included?	Yes	Yes	Yes	Yes
Observations	770	1884	461	1046
Adjusted R^2	0.323	0.334	0.358	0.281

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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