Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110

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Groundwater provides a reliable tap to sustain agricultural production, yet persistent aquifer depletion threatens future sustainability. The High Plains Aquifer supplies 30% of the nation's irrigated groundwater, and the Kansas portion supports the congressional district with the highest market value for agriculture in the nation. We project groundwater declines to assess when the study area might run out of water, and comprehensively forecast the impacts of reduced pumping on corn and cattle production. So far, 30% of the groundwater has been pumped and another 39% will be depleted over the next 50 y given existing trends. Recharge supplies 15% of current pumping and would take an average of 500–1,300 y to completely refill a depleted aquifer. Significant declines in the region's pumping rates will occur over the next 15–20 y given current trends, yet irrigated agricultural production might increase through 2040 because of projected increases in water use efficiencies in corn production. Water use reductions of 20% today would cut agricultural production to the levels of 15–20 y ago, the time of peak agricultural production would extend to the 2070s, and production beyond 2070 would significantly exceed that projected without reduced pumping. Scenarios evaluate incremental reductions of current pumping by 20–80%, the latter rate approaching natural recharge. Findings substantiate that saving more water today would result in increased net production due to projected future increases in crop water use efficiencies. Society has an opportunity now to make changes with tremendous implications for future sustainability and livability.

food security | Ogallala Aquifer | sustainability challenges | resilience | ecosystem services

Groundwater provides a reliable water supply that has contributed to the intensification of agriculture and increased food production occurring over the past 50 y (1). Large increases in crop and livestock production commonly co-occur with associated aquifer depletion throughout the semiarid grasslands of the world (2, 3). Yet, the gains in agricultural productivity achieved through tapping groundwater beyond the rate of replenishment threaten its long-term prospects (4). Water is a precious, unique resource that is important for life and a commodity for which no substitute exists (5).

Humanity faces the challenge of balancing the water needs of the present with the long-term needs of the future (6, 7). The consequences of our actions and responses to dealing with the water demands of today and those associated with future changes in population and economic development will overshadow the impacts of changes in climate on future water supplies (8). Although consumption of freshwater supplies has not yet crossed a potentially dangerous planetary threshold (9), crop yields have begun to fall in many regions because of water scarcity, and global food security remains a worldwide concern (10). There is a clear need for society to become prepared for the consequences of reductions in groundwater use that shall occur in the foreseeable future.

The wise management of groundwater resources requires a more comprehensive understanding of the relationships between aquifer pumping and the capacity of the terrestrial environment to provide ecosystem goods and services upon which society depends (6, 11). Informed decision making of processes involving the controls and feedbacks between society and ecosystems is founded on increased understanding of the relevant interdisciplinary linkages (3, 12). Human activity has a significant impact on the structure and function of the earth (13), and changes driven by economic development and population growth are occurring faster than our understanding (14). We developed integrated methods to forecast groundwater depletion into the future, to relate the impacts of pumping on the crop and livestock sectors, and to study the impacts of changes in water use on agricultural production. We show that water limitations will begin to have a significant impact on food production over the next few decades; yet, the changes we might implement today could significantly alter future possibilities.

An Integrated System with Groundwater Depletion Supplying Irrigated Corn and Cattle Production

The consequences of aquifer depletion are studied in a region of national and international importance for agricultural production. The High Plains Aquifer in western Kansas lies in the arid region of the central plains of the United States, which was

foretold by John Wesley Powell (15) to need irrigation for successful agriculture. The region is experiencing the worldwide tragedy of the commons, with aquifer depletion from a common pool resource used to support irrigated agriculture (16), and is one of four "critical areas" for "annual renewable water" in the western hemisphere and one of 22 worldwide (17). Irrigation began in the late 1800s and intensified through the 1980s (18, 19). As a result, the western Kansas congressional district has the highest total market value of agriculture products in the nation (20). Corn-fed cattle revenues far overshadow those from other agricultural sectors (21), and the important region supports the second highest state inventory for cattle on feed (22).

The study region lies near the geographical center of the contiguous United States in the central plains of Kansas, and its data sources are illustrated in Fig. S1. Mean annual precipitation varies from less than 0.5 m/y in western Kansas to over 1.5 m/y toward the southeast, and land elevation decreases from over 1,200 m above mean sea level (m.s.l.) in the west to 250–300 m in eastern Kansas. Groundwater is readily tapped in the drier west where the High Plains Aquifer resides, and the pattern of irrigated corn production follows that of groundwater use. Cattle production is focused near irrigated corn and within the west's higher elevations, where cool nights and lower humidity help cattle dissipate heat and maintain high growth potential within the summer and warmer, drier conditions help maintain production in the winter. Although many data sources are reported annually for Kansas's 105 counties, results are aggregated in this study to the nine agricultural districts (shown in Fig. S1 with 2009 data).

Projections of aquifer depletion are illustrated in Fig. 1. Our methods are articulated in *Appendix A* along with a description of how they compare with previous studies. Briefly, measurements of groundwater level in observation wells are fit to a logistic curve for each well to approximate water level change over time, these projected values are kriged across all wells at fixed times to provide a set of groundwater level surfaces, and the volume of water between surfaces gives change in storage. The saturated thickness in Fig. 1*A* exhibits a persistent declining trend that began before 1960 and continues for the foreseeable future. Groundwater measurements are plotted in Fig. 1*B* using dimensionless variables that enable all data to be plotted on one graph; the logistic function very accurately reproduced the observations. (The average absolute difference between the observed and approximated levels is 1.522 m across all measurements in all wells, from Eq. 3 in *Appendix A*.) These methods also result in estimates of the computed volume of groundwater use in Fig. 1*C* that very accurately reproduce previous studies of aquifer depletion (in Table S1). Although 97% of predevelopment groundwater storage was untapped in 1960, only 70% remained in 2010, and the declining trend continues through 2110 and beyond. Three distinct stores exist: the west central district has experienced a larger fraction of depletion and subsequent decreases in well yields, whereas larger predevelopment stores in the southwest and northwest will begin to experience regional limitations in the capacity to pump over the next two decades given current trends. Future pumping approaches a long-term asymptotic limit equal to the rate of recharge (23), which is 0.61×10^9 m³/y, and 15% of current pumping. If existing trends continue to total depletion, then, depending on the district, projected replenishment times would average between 500–1,300 y (obtained from the volume of predevelopment groundwater storage, S, divided by the annual volume of recharge, R). Although refilling generally is recognized as being a long-term proposition, this method provides holistic estimates as to how long it actually might take, although spatial and temporal heterogeneities would result in some areas recovering more quickly and others more slowly.
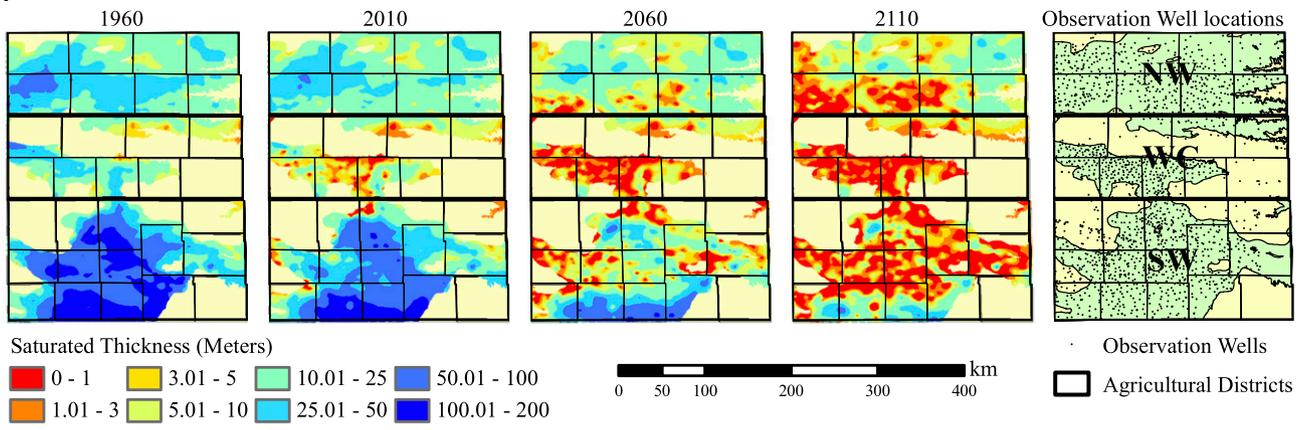
Groundwater-supported agriculture has led to vertically integrated regional industries, in which economic forces drive irrigated corn production to support a concentration of cattle feedlots that provide a continuous flow of supply for slaughterhouses (24). Recent increases in cattle production (Fig. S3) reflect a national redistribution to this region with proximity to slaughterhouses, ideal climate for cattle production, and abundant feed (Fig. S1). Although North America supplies over 40% of the global supply of corn (25), variability in precipitation has a significant impact on dryland production (Fig. S2). This is observed in Fig. 2, in which irrigated and dryland corn production are plotted along with the corn consumed by cattle on feed. Cattle consumption far exceeds dryland production, and its volatility makes it an unreliable source for feedlots. The increases observed in irrigated corn production are the result of both increased crop water use efficiencies and farming practices in which a larger fraction of irrigated land is being used to grow corn (Fig. S4). We incorporate both drivers of change in our model relating groundwater pumping and irrigated corn production in Eq. 11 to quantify the impacts of groundwater limitations on the region's agricultural production.

The historical trends in groundwater pumping and agricultural production are projected into the future in Fig. 3. The existing trends in groundwater use for each agricultural district are plotted using the same curves as those in Fig. 1*C* from 1980 to 2110. Future pumping rates reflect reductions in the capacity to extract large discharges of groundwater that have begun in west central Kansas and must occur throughout the region as the aquifer water levels decline and pumping eventually approaches, at most, the rate of recharge. A set of water reduction scenarios limit current water use by factors r of 20%, 40%, 60%, and 80%. Reducing pumping rates in 2010, Q_{2010}, by these percentages leads to greater future groundwater availability, which is quantified using a coefficient $D = (rQ_{2010} - R)/(Q_{2010} - R)$ for each scenario that equals the reduction in groundwater removed from storage. Note that an 80% reduction represents pumping at close to, but slightly more than, the recharge rate, R, in each district. For each scenario, the pumping rate in each 5-y interval is reduced to the recharge rate plus D times the groundwater removed from storage ($Q_{2010} - R$) and the time period is extended by $1/D$. These factors conserve mass balance because the same volume of aquifer is just dewatered over a longer time, and each curve reduces future well pumping to eventually approach recharge. The dewatered volume is computed for each scenario through 2110, and the remaining groundwater in storage is reported in Fig. 3 for each scenario.

The corn produced from irrigation is computed by multiplying the groundwater use Q in Fig. 3 by the water use efficiency W from Fig. S4C using Eq. 12. Note that this calculation ignores surface water sources occurring along the Republican, Solomon, and Arkansas rivers in wet years that are only a small fraction of total irrigation (26). The median agricultural production resulting from current trends in groundwater use is shown in Fig. 3*A*, along with the 95% confidence intervals. Although our methods are described fully in *Appendix B*, briefly, bootstrapping with nonlinear regression gives a crop water use efficiency function that is multiplied by groundwater use to give corn produced by irrigation, which then is multiplied by a corn consumption factor to give cattle production. Data points are plotted for the irrigated corn production in each agricultural district minus the dryland yield times the area of irrigation. Results illustrate that the median lines pass through the data and the 95% confidence interval largely contains the data. Note that these data points were not used to fit these lines; they resulted from bootstrapping W in Fig. S4C and give confidence of the functional form in Eq. 11. The good fit of these curves to data also supports the recharge rates in Fig. 1*C*, as changes in R would result in shifting the confidence interval higher or lower along the y axis. The net median corn produced by irrigation from 2010 to 2110 is tabulated

A Saturated thickness of the High Plains Aquifer in Kansas from early development through recent to future projections

1960 | 2010 | 2060 | 2110 | Observation Well locations

Saturated Thickness (Meters)

- 0 - 1
- 1.01 - 3
- 3.01 - 5
- 5.01 - 10
- 10.01 - 25
- 25.01 - 50
- 50.01 - 100
- 100.01 - 200

km 0 50 100 200 300 400

• Observation Wells
▢ Agricultural Districts

B Dimensionless saturated thickness at observation wells from $\mathcal{H}=1$ (predevelopment) to $\mathcal{H}=0$ (depleted) vs. dimensionless time $\mathcal{T}$, using variables in equation [1]
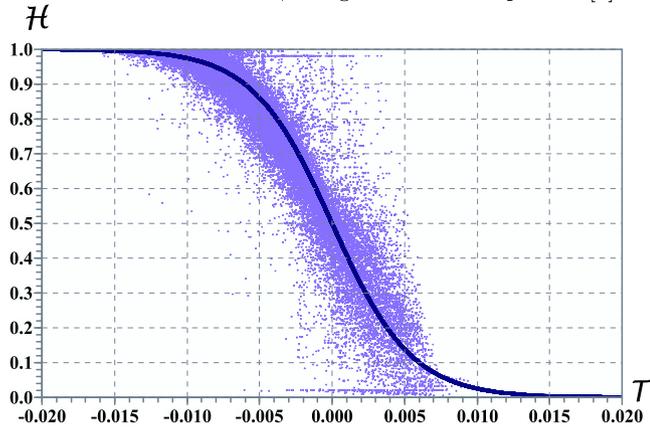
C Recharge plus groundwater depletion from storage over the time period of early development through 2110

Groundwater use, Q $[10^9 \mathrm{m}^3/\mathrm{yr}]$
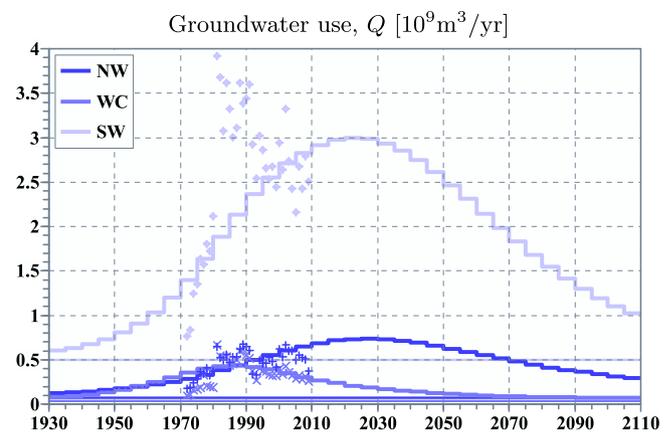
District	Predevelopment storage, S $[10^9\mathrm{m}^3]$	Untapped groundwater in storage $[10^9\mathrm{m}^3]$ through year				Recharge, R $[10^9\mathrm{m}^3/\mathrm{yr}]$	Refill time S/R [yr]
		1960	2010	2060	2110		
NW	93.1	90.6(97%)	73.1(78%)	42.2(45%)	25.3(27%)	0.07	1300
WC	31.1	28.4(91%)	12.3(39%)	5.7(18%)	3.7(12%)	0.04	800
SW	267.4	260.6(97%)	187.0(70%)	73.0(27%)	21.9(8%)	0.50	500
aggregate	391.6	379.6(97%)	272.3(70%)	120.9(31%)	50.9(13%)	0.61	640

Fig. 1. Irrigated agriculture is supported by groundwater pumping that exceeds the rate of recharge in most regions of western Kansas, which led to depletion of the High Plains Aquifer (*A*). The groundwater level is measured across a network of observation wells, and results are individually fitted to a logistic regression model (*B*). This gives approximate values of the saturated thickness at each well at specified times, and these values are interpolated geospatially between wells. Changes in groundwater storage are computed by integrating the volume of groundwater depletion across observation wells at 5-y intervals for the agricultural statistic districts in northwestern, west central, and southwestern Kansas (*C*). Results are plotted along with point data representing the sum of all annual water use reports in each district. Tabular results forecast existing trends of progressive groundwater declines and illustrate that natural recharge rates would take centuries to refill a depleted aquifer completely.

in Fig. 3 for each scenario, along with the corn that could be grown in 2110 using the remaining groundwater in storage.

The cattle production supported by groundwater is computed by multiplying the irrigated corn production by the corn fed per head of cattle, F in Eq. **7**. Results are aggregated to the High Plains region of western Kansas, and the median line and confidence interval are computed from the sum of corn production across the three agricultural districts. Data are plotted for the number of cattle obtained by multiplying the tabulated head of cattle in January by the factor in Eq. **5**. Note that the number of cattle is larger than those supported by irrigation, because the irrigation calculations do not include dryland corn production nor the component of irrigated corn resulting from precipitation. Data also are plotted for the number of cattle minus these dryland corn components times F. Results reflect the trends (Fig. 2)

in which cattle consumed more corn than was produced in Kansas from 1980 to 1995, and more recent cattle consumption is approximately the total corn crop. The net cattle production from irrigation is tabulated in Fig. 3 for each scenario for corn grown from 2010 to 2110 and also for the corn production remaining in 2110 (e.g., current trends give projected median production of 414 million head (Mhead) of cattle through 2110 along with the net production capacity from groundwater stores remaining at the end for an additional 138 Mhead). Results show a net increase in cattle production with increasing water reductions today.

The Challenge of Stemming Groundwater Declines Today to Sustain Agriculture's Future

Adoption of groundwater and agricultural management actions that move toward balancing current and future benefits requires
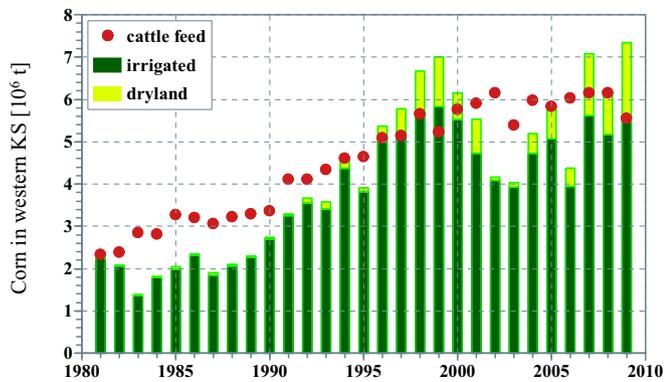
Fig. 2. Cattle production in western Kansas increased over the past few decades. Overall, cattle consumed more corn than was produced in the region throughout the 1980s, and more recently, the herd size has leveled off and regional corn production (irrigated plus dryland) is approximately equal to the net corn consumption by cattle.

a better understanding of the impacts of groundwater depletion and increased interdisciplinary understanding of the consequences of change (27). Irrigation practices in the region are adapting to groundwater depletion and reduced pumping capacity by transitioning from full irrigation to limited irrigation rates on the same land area, by decreasing irrigated acreage, and by applying preseason irrigation to increase the duration of pumping (2). Such adaptive strategies reduce the risk of crop failure and are observed in the west central district, where increased water limitations have promoted higher water use efficiencies than in the other districts (Table S2). Inexpensive water has added value to irrigation of marginal farm land, driven by the proximity of cattle demand and the irrigation needs of an arid grassland biome.

The water laws that affect groundwater pumping practices and data are recorded by Kansas Statutes Annotated (K.S.A.). The Kansas Water Appropriation Act (K.S.A. 82a-701) defines a water right as a real property right to lawfully divert and use water, and annual water use reports have been required for every water right in Kansas since 1981 (K.S.A. 82a-732). These data are available publicly via the Water Rights Information System (WRIS) database at the Kansas Division of Water Resources, and the annual groundwater pumping data points in Fig. 1C were obtained by summing this reported water use for the wells in each agricultural district. A steep increase in reported pumping is observed through 1981 (illustrated in Fig.1C); these non-regulated water use reports do not reflect the consistent levels of corn grain production and acres harvested for several years before and after 1981 observed in US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) data. Groundwater use declined slightly after 1981, and this may the result of wells taken out of production because of depleted groundwater (as has occurred in portions of west central Kansas). However, it also may be a consequence of more accurate water use reports as a result of the increasing use of flowmeters, as irrigators have been found to overreport water use before flowmeter installation (28). The Groundwater Management District Act (K.S.A. 82-1020) created local governance with the jurisdiction to require flowmeters on wells starting in 1987, and these have been in place in much of Kansas for the past 5–20 y (ref. 29, p. 53). All data used in this study are limited to the period of mandatory water use reporting beginning in 1981 (i.e., data shown before 1981 in Fig.1C were not used for model development).

Trends in irrigated and dryland corn production (Fig. S2) illustrate the importance of irrigation to the study region. Across

the United States, annual increases in yield averaged 1–2% per year over the period 1960–2000 (ref. 30, figure 2). In western Kansas, both dryland yields and annual precipitation exhibit stationary trends over the past 30 y. Although recent no-till dryland farming practices have higher yield potential than conventional cropping systems as the result of more available water and increases in soil organic matter, the actual yields may be lower because of diseases (31). Note that dryland yields do not account for unharvested fields due to failed crops during dry years or for fields that went unplanted because of low subsoil moisture during planting time. Irrigated yields have increased steadily by 1.5% per year in the study area, illustrating the emergence of higher yields with lower irrigation rates. These increases are a result of the adoption of farming practices that increase infiltration and reduce runoff by improvements in soil and residue management (such as no-till), conversion from less efficient flood irrigation to center-pivot low-pressure drip irrigation and some subsurface drop irrigation, which enable better irrigation use efficiency, and the introduction of hybrids with better genetics (25). The assumption of a linearly increasing trend in yields is observed in the agricultural data (32) and may be expected into the future, as evidenced by Monsanto's goal of doubling 2000 yields in the United States by 2030 (33).

Realizing the potential of improved future prospects requires collective action to design solutions that reduce aquifer depletion today while rewarding participation (34, 35). The scenarios in Fig. 3 illustrate the impact of regional reduction in groundwater use on agricultural production. Current pumping rates have peaked (as constrained by both hydrogeology and water law), and withdrawal rates will begin to decrease over the next 15–20 y throughout western Kansas given existing trends in aquifer depletion. Corn and cattle production is projected to increase through the next 30–40 y because of increasing water use efficiencies. Although the west central district, with its larger fraction of aquifer depletion, faces more limited prospects for improvements through water savings, there still is time in the southwest and northwest districts to make changes today with significant implications for the future. The water reduction scenario that reduces pumping by 20% would cut current agricultural production back to the levels of 15–20 y ago; yet, the time of peak agricultural production would extend to the 2070s, and agricultural production significantly improves beyond 2070. Increasing water savings now from 20%, 40%, and 60–80% extends the time to peak production further into the future, and, ultimately, the region produces more corn and cattle because of more available water when increased water use efficiencies are realized. The production levels at 80%, which approach the limitations imposed by regional recharge, can support only 12% of today's cattle population—0.5 Mhead of cattle, rising to 1.4 Mhead in 2110 as the result of increased water use efficiencies (as quantified using Eq. **13** in *Appendix B*). Essentially, we show that value is added by water conservation today through increased future and net agricultural production. The reality of the situation is causing stakeholders to consider conservation options such as the 2012 K.S.A. 82-1041 that established Local Enhanced Management Areas (LEMAs), such as High Priority Area 6 in Sheridan County, where 26% reductions are planned (36).

Our model accurately reproduces historical aquifer declines in Table S1, giving credence to our projections of future water stores. Note that our results are presented for the Ogallala Aquifer portion of the High Plains Aquifer in the three western agricultural districts of Kansas and that the previous studies are presented for the entire High Plains Aquifer, which also includes the eastward Great Bend Prairie and Equus Beds aquifers in south central Kansas. The predevelopment storage of the Ogallala is 392×10^9 m^3 and that for the High Plains is 430×10^9 m^3 (Table S1). The results comparing retrospective studies in Table S1 are presented in terms of the change in storage that has occurred since
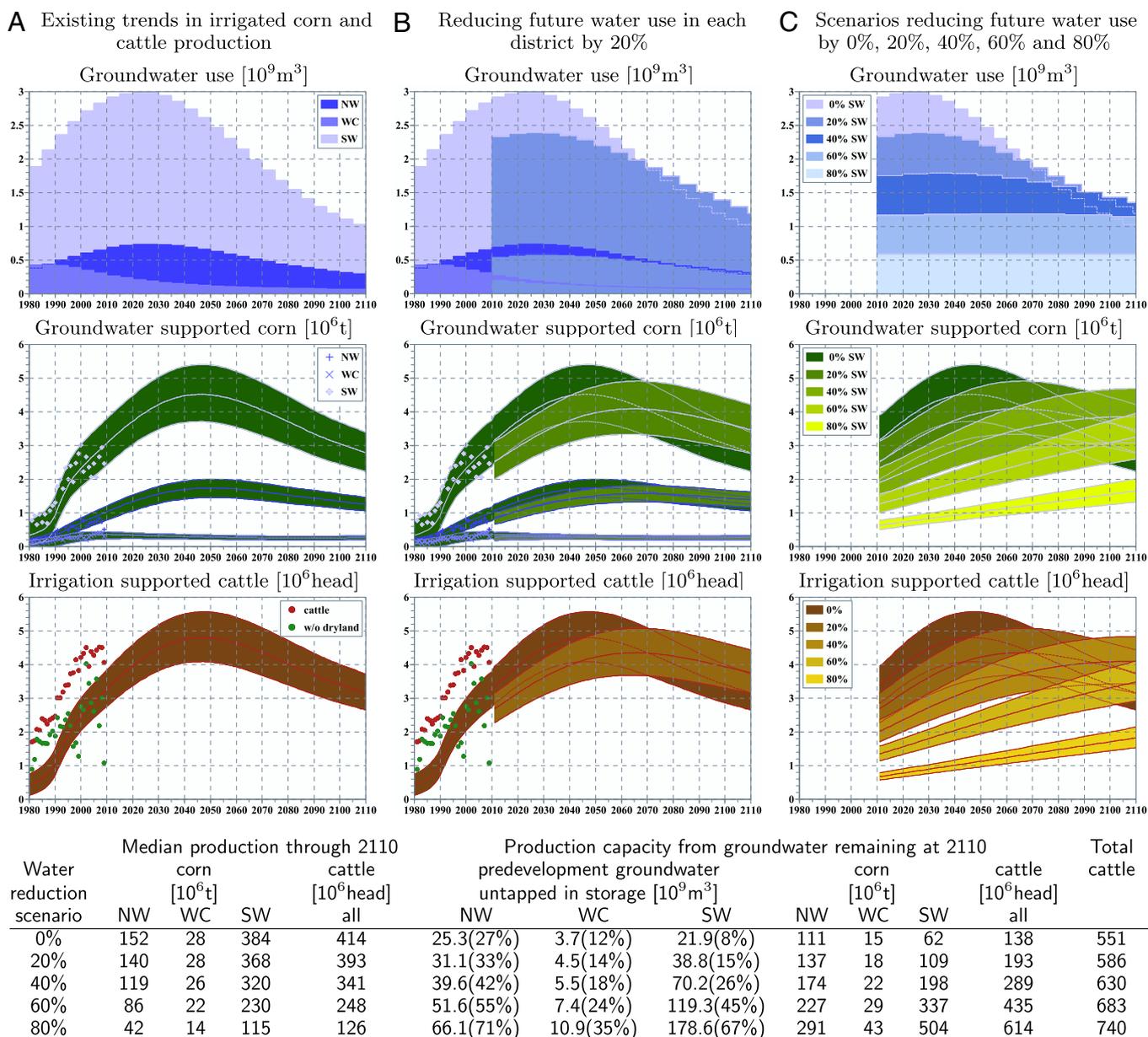
A Existing trends in irrigated corn and cattle production

B Reducing future water use in each district by 20%

C Scenarios reducing future water use by 0%, 20%, 40%, 60% and 80%

Water reduction scenario	Median production through 2110				Production capacity from groundwater remaining at 2110							Total cattle
	corn [10^{6}t]			cattle [10^{6}head]	predevelopment groundwater untapped in storage [10^{9}m^3]			corn [10^{6}t]			cattle [10^{6}head]	
	NW	WC	SW	all	NW	WC	SW	NW	WC	SW	all	
0%	152	28	384	414	25.3(27%)	3.7(12%)	21.9(8%)	111	15	62	138	551
20%	140	28	368	393	31.1(33%)	4.5(14%)	38.8(15%)	137	18	109	193	586
40%	119	26	320	341	39.6(42%)	5.5(18%)	70.2(26%)	174	22	198	289	630
60%	86	22	230	248	51.6(55%)	7.4(24%)	119.3(45%)	227	29	337	435	683
80%	42	14	115	126	66.1(71%)	10.9(35%)	178.6(67%)	291	43	504	614	740

Fig. 3. An integrated system with cattle consuming irrigated corn grown with groundwater (*A*). A set of hypothetical yet realistic scenarios are developed to illustrate how changes in water use would affect agricultural production (*B* and *C*). The groundwater pumping follows current trends from Fig. 1, and optional scenarios are developed that scale the current annual water use by a factor and then extend the time of aquifer depletion. Thus, the same volume of water eventually would be extracted from the aquifer for each scenario. The water use efficiencies in Fig. S4 enable prediction of the additional corn produced from irrigation, as well as the number of cattle this value-added corn production would support. The two upper right graphs (*C*) show only the southwestern district for clarity, and the same graphs are repeated in Fig. S5 along with the other two districts. The integral of corn and cattle production through 2110 and the production remaining in 2110 is tabulated. These production capacities are presented in terms of projected 2110 water use efficiencies; production would be higher if further efficiencies were realized beyond 2110. Tradeoffs exist whereby water use reductions today decrease current agricultural production, yet net production forecasts increase as the result of future improvements in water use efficiency.

predevelopment; this is a reasonable comparison across the Ogallala and High Plains aquifers because the Great Bend Prairie and Equus Beds aquifers have smaller volumes of groundwater that are managed for safe yield and have not experienced groundwater level declines as large as that of the Ogallala (37). The changes in groundwater storage in Table S1 compare favorably from predevelopment to 1980 and to 1992, and although differences exist between our results and those published for 2000, 2007, and 2009, a brief interpretation of methods illustrates that our results are consistent with all previous studies. A major difference between previous studies in 1980 and 1992 and those in the 2000s is that

a new surface of predevelopment water level was adopted (ref. 38, p.13) that changed the predevelopment volume of groundwater from 430×10^9 m^3 (ref. 18, pp. 34 and 47) to 395×10^9 m^3 (ref. 29, p. 58). Consequently, although 63×10^9 m^3 had been pumped by 1992 (39) using the original surface, the change in storage from predevelopment to 2000 removes only 58×10^9 m^3 using the new surface (38). Yet, groundwater levels continued to go down between 1992 and 2000, as measured by the spatially averaged decline in saturated thickness of 5.27 m (17.3 ft) in 1992 (ref. 39, p. 34) and 5.55 m (18.2 ft) in 2000 (ref. 38, p. 32). This follows the steadily declining trend in cumulative change in storage oc-

curring from 1980 to 2009 (ref. 40, p. 9). When groundwater storage is subtracted from the earlier estimates of predevelopment storage, the results show a depleted volume of 93×10^9 m^3 in 2000 compared with our results of 90×10^9 m^3, and 112×10^9 m^3 in 2007 compared with our 111×10^9 m^3. Therefore, our results very closely match those from previous studies when they use the predevelopment water level from ref. 18 that we also use.

Our regional estimates of recharge integrate across the spatially and temporally varying local recharge processes. The deeper "fossil water" from recharge over the past 13,000 y (41, 42) is overlaid by more recently recharged water (43) that historically supplied stream flow to perennial rivers and streams (44). Many streams no longer flow because of groundwater depletions that diverted this base flow component to wells, creating dry channels and ephemeral streams that recharge groundwater during runoff events (45). As groundwater stores deplete, the groundwater budget eventually will transition to a new equilibrium in which extractions equal recharge (46). We computed recent recharge rates to preserve conservation of mass, in which the annual pumped volume is equal to the change in storage plus the recharge captured by wells. This gave the recharge volume in Fig. 1, which was used to compute the average recharge rate over each agricultural district by dividing by the surface area in Table S3. Note that the lines of recharge plus storage in Fig. 1C very closely approximate the recent data points of metered groundwater pumping rates. The recharge rates for our study compare well with those for other studies summarized in Table S3, although they are smaller than the estimates used by the Kansas Division of Water Resources in Table S3, obtained by spatially integrating recharge (39, 47) over the extent of the High Plains Aquifer and dividing by surface area. This suggests that the water captured by wells using our mass balance approach may not reflect the entire recharge from the terrestrial ecosystem, some of which may be destined for base flow to the streams and rivers that still flow in the region. Note that our methods do not capture the recent additions to recharge that may occur from excess irrigation that returns to groundwater through the vadose zone (45) or hysteresis effects. Although transit time estimates from the surface to the groundwater table in Kansas are on the order of 50–2,000 y (ref. 48, p. 42), recharge beneath topographical depressions where surficial water concentrates may reach groundwater over periods of months to decades (49). Although artificial recharge projects such as those in central Kansas (37) are being considered to provide more groundwater, it would take time for such systems to infiltrate water and affect groundwater levels.

Our methods of forecasting changes in groundwater stores and agricultural production are applicable to other areas where regional groundwater depletion supports crop and livestock production, although the simplicity of the groundwater system [an aquifer that responds to pumping as an unconfined aquifer (41)] and the socioeconomic system [hyperextraction with vertical integration of regional industries supported by cost-efficient water extraction technology (50)] may limit application. Likewise, our assumption of linearly increasing crop yields already may have tapped out the maximal impacts available through advances in irrigation technology (conversion from flood to central-pivot to LEPA irrigation), and crop function may evolve over time in response to a more dynamic, changing climate. Changes in water use by other industries (dairy, hog, alfalfa, etc.) would influence our projections of irrigated corn and cattle production.

Conclusions

Eventually, the southwest and northwest districts in Kansas will realize the fate emerging in the west central district, where shallower groundwater stores have resulted in decreased well yields, well abandonment, and conversion back to dryland, although a reduced number of ideally situated and constructed wells may continue to capture natural recharge indefinitely. The capacity to pump water will be affected in the 2020s; yet, aggregate corn and cattle production will increase through the 2040s, reflecting current trends of linearly increasing water use efficiencies over time and the ability to grow more corn with less water. The future is bright in the near term but bleak beyond, and increased agricultural production may be realized before imminent reductions occur. Our scenario analysis in Fig. 3 substantiates the impacts of water savings on today's production levels and on future prospects.

Although agricultural practices and technologies have led to advances in crop and cattle production (Fig. 3), water policies have not yet realized significant reductions in the rate of groundwater use (Fig. 1). Instead, pumping decreases as wells go dry. Short-term crop production leads to long-term sustainability challenges due to groundwater depletion, and tradeoffs exist. The excess short-term capacity might be used to support projected increases in the demand for the region's nationally and internationally important livestock sector (51). Alternately, current increases could supply the biofuel industry for a while, although water limitations raise concerns for long-term biofuel production (52), or saving water now could provide a future store that builds resiliency and stability for agricultural ecosystems to weather the future impacts of climate variability and change (53).

Our scenario analysis provides a foundation toward understanding the impacts of changes in groundwater tapping on agricultural production today and into the future. Society has an opportunity now to make changes with tremendous implications for future sustainability and livability. The time to act will soon be past.

Appendix A. Groundwater Methods

Groundwater is studied using a variety of data sources. A network of observation wells exists where the groundwater level is measured over time and made available through the Kansas WIZARD database (54). Contour maps of the elevation of the base of the aquifer and the predevelopment groundwater level (before large-scale pumping) were developed by the US Geological Survey (USGS) (18) for the High Plains Aquifer as part of the Regional Aquifer-System Analysis project. This source has been used extensively to study groundwater in the Kansas region, and digital forms exist (55, 56). Within Kansas, more recent borehole data led to construction of an enhanced contour map of bedrock elevation (57). The values of bedrock elevation and predevelopment water level at the observation wells were obtained by applying the ArcGIS Topo to Raster tool to the contour maps to produce grids and by assigning the value at each well using the raster cells. Likewise, the ground elevation at each well was obtained using the USGS Digital Elevation Model (DEM) data. Together, these data provide the base elevation, B; the land elevation, L; the predevelopment groundwater level, h_0; and a set of M measurements of groundwater levels h_m at times t_m at each observation well.

These data were used in previous studies of groundwater level and stores. Surfaces of groundwater level have been developed by spatially extrapolating measurements at observation wells at specified times, and changes in storage have been obtained from the groundwater volume between surfaces (40). Such surfaces also have been used to linearly extrapolate the rate of change in groundwater level across 10-y periods (58). One issue in such studies involves the temporal changes in water level during pumping (levels commonly drop in wells by tens of meters during seasonal pumping schedules). This problem is dealt with by screening data to use water level measurements only when wells have recovered from the drawdown associated with irrigation; in this study, we use only measurements taken in December and January because irrigation typically ends in late summer and early spring preirrigation of fields has not yet begun (16). Another issue

is related to an ever-changing set of observation wells over time (some wells were measured decades ago whereas others just in recent years). One consequence is that considerable changes in the surfaces of groundwater level emerge as hills and valleys form where observations wells are added and removed across periods of study. One method of dealing with this problem is to develop surfaces over a range of years in which the same observation wells exist at the start and end; this gives 566 wells between predevelopment to 2009 for all of Kansas (40) and fewer than 10 wells per county over most of the High Plains Aquifer (ref. 38, p. 22). Changes in storage also have been computed by adding the results during recent periods using a larger set of wells (39, 40) to regional contour maps of observed changes in groundwater level from predevelopment to 1980 (59), obtained by subtracting maps of groundwater observations from predevelopment (18) and connecting points with equal change.

We developed a functional form that correctly reproduces the trend in groundwater level from predevelopment to depleted conditions for all 3,025 observation wells in the High Plains Aquifer region of Kansas. This is accomplished using a dimensionless saturated thickness (60)

$$\mathcal{H} = \frac{h - B}{h_0 - B} \qquad [1A]$$

that varies between 1 (predevelopment with $h = h_0$) and 0 (depleted with $h = B$). A mathematical function that reproduces these asymptotic limits is given by the logistic function

$$\mathcal{H} = \frac{1}{1 + e^{\mathcal{T}}}, \qquad [1B]$$

where the dimensionless time $\mathcal{T}$ is approximated as a linear function of time:

$$\mathcal{T} = a_0 + a_1 t. \qquad [1C]$$

This gives our well functional used to approximate groundwater level over time:

$$\hat{h}(t) = B + \frac{h_0 - B}{1 + e^{a_0 + a_1 t}}. \qquad [2]$$

The coefficients a_0 and a_1 are obtained using regression over the M measurements of groundwater level h_m at time t_m for each well (60).

A set of criteria was developed to correct discrepancies between data sources:

1. The measured groundwater levels in some observation wells were not between the base elevation and the predevelopment water level. This was rectified by lowering the base elevation and raising the predevelopment level so that all observations fit within this range. This method was chosen because observed water level (surveyed land elevation minus measured depth to water) is more accurate than the kriged surfaces for base and predevelopment levels.
2. Extra measurement data were added to reproduce the long-term declining trends. A point was added for wells not measured recently from a kriged surface of observation wells at 2005, and measurement points were added at 1930 and 2060 from a linear extrapolation of observations while keeping these points within the saturated aquifer. The year 1930 starts the period when technological capabilities began to develop for significant groundwater extraction (19, 45), and 2060 represents the end of the "estimated usable lifetime" for signif-

icant portions of the High Plains Aquifer from a previous study that used linear trends (58).

Wells with inconsistent or incomplete data were excluded because of

1. Predevelopment groundwater level greater than land elevation
2. Predicted well water level at 1930 more than 5 m below predevelopment water level
3. Drop in predicted water level by more than 10 m between 1930 and 1960 (excluding wells with too-large predevelopment water level)
4. Fewer than $M = 10$ measurements

The data used includes 1,601 observation wells with 45,038 measurements. The average of the absolute difference between the approximate function and observations across all measurements is

$$\frac{\sum\limits^{\text{all wells}} \sum\limits_{m=1}^{M} |h_m - \hat{h}(t_m)|}{\sum\limits^{\text{all wells}} M} = 1.522 \text{ m.} \qquad [3]$$

Although the coefficients for each well provide the capacity for changes in storage to occur over different periods of time at different points in the aquifer (as is actually happening across the region), the approximated function and all measurements may be plotted on the same graph using the dimensionless coefficients $\mathcal{H}$ vs. $\mathcal{T}$ in Fig. 1B.

Our well function, Eq. 2, provides the saturated thickness and changes in storage in Fig. 1. The groundwater level was calculated at each observation well by evaluating the function at times 1960, 2010, 2060, and 2110. Surfaces of saturated thickness were obtained by applying the universal kriging algorithm with a second-order trend to these water levels and subtracting from the surface of bedrock elevation (57). The volumes of water in storage at these times and at predevelopment were computed by multiplying this saturated thickness by the specific yield (18, 61) to get the water content, clipping to the extent of the High Plains Aquifer (47) in each agricultural district, and summing using zonal statistics in ArcGIS. The changes in storage over 5-y periods were computed by evaluating the well function at the start and end of each period, kriging the differences to derive a surface across wells, multiplying this by the specific yield, clipping, and summing. The results are reported as the change in storage per year by dividing these results by the 5-y period.

Appendix B. Agricultural Production Methods

The production and consumption of corn are quantified using recent agricultural data. The irrigated and dryland corn production for western Kansas in Fig. 2 is obtained by aggregating the USDA NASS's annual reports (62). Although these data are reported as volume (bushels), the findings are multiplied by density (56 lb/bushel) and converted to units of metric tons. The USDA data also report the number of cattle in feedlots on January 1 of each year. The following conversion factors document the practices of cattle operations in Kansas and were used to compute feed requirements: calves gain 0.3 t while on feed, the overall dry matter conversion is 5.5 t of feed per 1 t of weight gain, 90% of feed is corn, and corn contains 85% dry matter. Yearling cattle gain 0.2 t while on feed and consume 6 t of feed per 1 t of weight gain. These performance parameters were selected in an attempt to provide median estimates across differences encountered depending on breed, sex, entry weight within age category, and market conditions.

These parameters form a basis for our estimates of corn requirements to feed calves and yearlings to finished weight:

$$\frac{0.3 \text{ t-weight gain}}{\text{calf}} \times \frac{5.5 \text{ t-feed}}{\text{t-weight gain}}$$

$$\times \frac{0.9 \text{ t-dry corn}}{\text{t-feed}} \times \frac{\text{t-corn}}{0.85 \text{ t-dry corn}} = \frac{1.75 \text{ t-corn}}{\text{calf}} \qquad [\textbf{4A}]$$

and

$$\frac{0.2 \text{ t-weight gain}}{\text{yearling}} \times \frac{6 \text{ t-feed}}{\text{t-weight gain}}$$

$$\times \frac{0.9 \text{ t-dry corn}}{\text{t-feed}} \times \frac{\text{t-corn}}{0.85 \text{ t-dry corn}} = \frac{1.25 \text{ t-corn}}{\text{yearling}}. \qquad [\textbf{4B}]$$

Calves typically are fed for 220–240 d, and the potential exists to feed 1.5 calves per year for every calf on feed in January; yearlings are fed for 120–140 d, and there is a potential to feed 2.5 per year for every yearling on feed in January. Of the cattle fed in a given year, we used the estimate that ∼30% are calves and 70% are yearlings at the time of feedlot entry. This gives a relation between the total annual cattle per year vs. the cattle counted during the annual survey in January:

$$\frac{1.5 \text{ cattle}}{\text{calf in Jan.}} \times \frac{0.3 \text{ calf in Jan.}}{\text{cattle in Jan.}}$$

$$+ \frac{2.5 \text{ cattle}}{\text{yearling in Jan.}} \times \frac{0.7 \text{ yearling in Jan.}}{\text{cattle in Jan.}} \qquad [\textbf{5}]$$

$$= \frac{2.2 \text{ cattle}}{\text{cattle in Jan.}}.$$

We validated our estimates by comparing USDA NASS cattle data to our estimate, in which the fed cattle sold in Kansas (ref. 63, p. 434) divided by the cattle on feed on January 1 (63, p. 420) was 2.08 and 2.21 in 2002 and 2007, respectively. The ratios in the last equations combine to give the corn requirement per cattle counted in January:

$$\frac{1.75 \text{ t-corn}}{\text{calf}} \times \frac{1.5 \text{ calf}}{\text{calf in Jan.}} \times \frac{0.3 \text{ calf in Jan.}}{\text{cattle in Jan.}}$$

$$+ \frac{1.25 \text{ t-corn}}{\text{yearling}} \times \frac{2.5 \text{ yearling}}{\text{yearling in Jan.}} \times \frac{0.7 \text{ yearling in Jan.}}{\text{cattle in Jan.}} \qquad [\textbf{6}]$$

$$= \frac{3.0 \text{ t-corn}}{\text{cattle in Jan.}}.$$

The corn consumption by cattle in Fig. 2 was obtained by multiplying this ratio by the aggregated cattle-on-feed data from the USDA (62). Together, the last two ratios give the corn feed needed per head of cattle for feedlot practices in Kansas:

$$F = \frac{2.2 \text{ cattle}}{3.0 \text{ t-corn}} = 0.73 \, \frac{\text{cattle}}{\text{t-corn}}. \qquad [\textbf{7}]$$

Data related to crop production are aggregated to the level of the nine agricultural districts in Kansas. The yields of irrigated corn, Y_I, and dryland corn, Y_D, are reported by the USDA (62), and precipitation data were gathered from the Kansas Weather Data Library (64). These time series are shown in Fig. S2 from 1981 to 2009 along with the annual irrigation, I, which was obtained by dividing the pumping rate of all irrigation wells in each district by the total irrigated area reported on the annual WRIS water use reports (65). These data illustrate that the west's higher irrigation leads to higher irrigated yields, and the east's higher precipitation leads to higher dryland yields. Data for the eastern and central districts are not reported on other figures to aid in visual interpretation. The median level and 95%

confidence intervals also are shown in this figure for the western districts; their construction is detailed next.

We used the bootstrap method (66) to extrapolate and project data trends over time as follows. The data sets for each variable in each district in Fig. S2 contain $n = 29$ data points. The median value and 95% confidence intervals are constructed for each dataset using sampling with replacement for data with linear trends as follows:

1. Develop a set of $n = 10,000$ randomly generated samples that select n data points with replacement.
2. For each sample, calculate the slope and intercept using linear regression with least squares, and calculate the residual difference between each data point and the linear estimate.
3. For every time for which statistics are to be evaluated, project each of the N regression lines to that year, and detrend the data by adding the residuals of the sample set to the value of the regression line at its intercepts.
4. Sort the $n \times N = 290,000$ points for each year, take the median 50% value, and drop the lower and upper 2.5% to get the 95% confidence interval.
5. Repeat the last two steps for each year for which statistics are evaluated, and connect points on the lines for the median and confidence intervals across years.

The probability of an independent trial exceeding a $1-\alpha/2$ confidence limit has a binomial distribution (here, $\alpha = 0.95$). When the number, N, of independent trials is large, the binomial distribution closely approximates a normal distribution with mean Np and variance $Np(1-p)$, where $p = \alpha/2$. When $n = 10,000$, one has a 90% confidence that the realized confidence limits are between 94.64% and 95.36%.

The increase in corn production from recent water use efficiencies is illustrated in Fig. S4A by plotting the difference between irrigated and dryland yields divided by the rate of irrigation, $(Y_I - Y_D)/I$. The bootstrapping procedures are applied to construct median lines and confidence limits for each district and demonstrate the linear trend in data. Corn production also has increased because of changes in land use practices over the past 30 y, where a larger fraction of irrigated fields, f, now is used for corn production. This is illustrated in Fig. S4B, in which the USDA-reported (62) harvested area of irrigated corn in each agricultural district is divided by the total irrigated area in the WRIS annual water use reports (65). These data follow a functional form that transitions from a lower limit, $f_{\min}$, to an upper limit, $f_{\max}$, and it is approximated here using the same logistic equation as for the observation wells:

$$\hat{f}(t) = f_{\min} + \frac{f_{\max} - f_{\min}}{1 + e^{b_0 + b_1(t-t_0)}}. \qquad [\textbf{8}]$$

This trend reflects USDA reports (62) in which irrigated corn has become the primary irrigated crop, but that water also is used for irrigated alfalfa, soybeans, wheat, and sorghum. Only a small fraction of groundwater in western Kansas is used by municipalities, industry, and feed yards. It is likely that current land use practices will continue as long as markets continue to make corn profitable, and other competing uses may limit f from becoming larger in the future.

We used nonlinear regression to determine the coefficients in Eq. **8** that minimize the least-square objective function containing the difference between the $n = 29$ estimate $\hat{f}$ at time t_m and the data points f_m:

$$\mathcal{F} = \sum_{m=1}^{n} \left[\hat{f}(t_m) - f_m \right]^2. \qquad [\textbf{9}]$$

This nonlinear function was minimized using the Levenberg–Marquardt method (67, 68) to obtain the coefficients b_0 and b_1. This may be written as follows:

$$\left(\mathbf{J}^{\mathrm{T}}\mathbf{J}\big|_q + \lambda\mathbf{I}\right)\left(\vec{x}\big|_{q+1} - \vec{x}\big|_q\right) = -\mathbf{J}^{\mathrm{T}}\vec{f}\big|_q \qquad \textbf{[10A]}$$

using the Jacobian matrix $\mathbf{J}$ with

$$\mathbf{J} = \begin{bmatrix} \dfrac{\partial\hat{f}(t_1)}{\partial b_0} & \dfrac{\partial\hat{f}(t_1)}{\partial b_1} \\[2mm] \dfrac{\partial\hat{f}(t_2)}{\partial b_0} & \dfrac{\partial\hat{f}(t_2)}{\partial b_1} \\ \cdots\cdots\cdots\cdots \\ \dfrac{\partial\hat{f}(t_n)}{\partial b_0} & \dfrac{\partial\hat{f}(t_n)}{\partial b_1} \end{bmatrix}, \; \vec{x} = \begin{bmatrix} b_0 \\ b_1 \end{bmatrix}, \; \vec{f} = \begin{bmatrix} \hat{f}(t_1)-f_1 \\ \hat{f}(t_2)-f_2 \\ \vdots \\ \hat{f}(t_n)-f_n \end{bmatrix}, \qquad \textbf{[10B]}$$

where $\mathbf{I}$ is the identity matrix, and λ is adjusted using the values of b_0 and b_1 for the qth iterate as per ref. 69. The bootstrap procedures were applied using this functional form and optimization technique to get the median lines and confidence intervals in Fig. S4B. The coefficients f_{min} and f_{max} were found ad hoc by repeating the bootstrap method with different values and determining those that minimized the objective function. The results for f_{min} and f_{max} are reported in Table S2 for the three western agricultural districts, along with values of b_0 and b_1 for $t_0 = 2010$ that closely approximate the median lines of $\hat{f}$ (within 0.7% for all values in Fig. S4B).

The recent increases in the fraction of irrigated land used for corn production reflect increases in demand for corn in cattle production. The number of head of cattle on feed in January is shown in Fig. S3. The median lines and confidence intervals were constructed for each agricultural district using bootstrap with the logistic equation in Eq. 8. These trends reflect a redistribution of cattle feed locations over the last 30 y as operations in the Midwest focused on the large feedlots of western Kansas with ideal weather for cattle production, local irrigated corn, and proximity to major slaughterhouses. Thus, the use of the logistic function to redistribute irrigated corn production in Eq. 8 follows the trends observed in the cattle production that consumes corn.

We developed a function to relate groundwater pumping to corn production. Data measurements for the fraction of irrigated area in corn times the increase in yield divided by the irrigation rate, $f(Y_I - Y_D)/I$, are plotted in Fig. S4C. We expect the functional relation between corn production from irrigation and groundwater pumping of the following form:

$$\hat{W}(t) = \hat{f}(t)[c_0 + c_1(t - t_0)]. \qquad \textbf{[11]}$$

This reflects both the recent redistribution of land use in the logistic curve and the long-term linear trend of increasing crop water use efficiencies (70). The coefficients in $\hat{f}$ were constrained to match existing redistribution trends of the median line in Fig. S4B and Table S2. The median lines and confidence intervals for the corn water requirements in Fig. S4C were obtained using the bootstrap procedures with coefficients c_0 and c_1 obtained using least-squares regression. The values of c_0 and c_1 that closely approximate the median lines (within 0.11 t/ha·m of the lines in Fig. S4C) are reported in Table S2. The variable c_0 represents the corn production per irrigation, and the median values of 23.6–25.6 t/ha·m compare well with the Kansas State Research and Extension (71) estimates of 23 t/ha·m (3,000 gallons of water per bushel of corn yield). The ratio c_1/c_0 represents the median increase in water use efficiency, and the values of 1.7–2.1% per year reflect recent national increases in yield of 1–2% per year (30). Eq. 11 takes on a simpler form at future times when $\hat{f} = f_{max}$ and the expressions and coefficients for $\hat{W}$ for these asymptotic forms are found in Table S2.

Our estimates of the corn water requirement W in Eq. 11 represent the fraction of irrigation used for corn times the increase in yield per irrigation. If we write f as the area of irrigation, A_I, divided by the area of groundwater pumping, A_Q,

$$W = f\frac{Y_I - Y_D}{I} = \frac{A_I(Y_I - Y_D)}{A_Q I} = \frac{C_I - A_I Y_D}{Q}, \qquad \textbf{[12]}$$

then the irrigated corn production is $C_I = A_I Y_I$, and the annual pumped volume of groundwater is $Q = A_Q I$. Thus, the corn produced by irrigation may be obtained by multiplying W in Fig. S4C by the pumped groundwater Q. Note that this gives the corn resulting from irrigation; the corn production resulting from precipitation alone, $A_I Y_D$, must be added to this value to get the net irrigated corn production.

A simplified projection may be computed for the number of cattle produced from recharge alone. The sum across agricultural districts of the annual volume of recharge, R in Fig. 1, times the long-term estimates of corn production from irrigation, $\hat{W}$ in Eq. 11, with coefficients from Table S2, times the feed requirements for cattle, F in Eq. 7, gives

$$\begin{aligned}
B &= \sum^{3\,districts} R\hat{W}F \\
&= \frac{0.07\times10^9\,\mathrm{m}^3}{\mathrm{y}} \times \frac{[15.576 + 0.2838(t - t_0)]\mathrm{t}}{10^4\,\mathrm{m}^3} \times \frac{0.73\,\mathrm{cattle}}{\mathrm{t}} \\
&\quad + \frac{0.04\times10^9\,\mathrm{m}^3}{\mathrm{y}} \times \frac{[12.544 + 0.2695(t - t_0)]\mathrm{t}}{10^4\,\mathrm{m}^3} \times \frac{0.73\,\mathrm{cattle}}{\mathrm{t}} \\
&\quad + \frac{0.50\times10^9\,\mathrm{m}^3}{\mathrm{y}} \times \frac{[10.584 + 0.1764(t - t_0)]\mathrm{t}}{10^4\,\mathrm{m}^3} \times \frac{0.73\,\mathrm{cattle}}{\mathrm{t}} \\
&= \frac{[0.50 + 0.0087(t - 2010)]\times10^6\,\mathrm{cattle}}{\mathrm{y}}. \qquad \textbf{[13]}
\end{aligned}$$

Thus, the annual corn production from recharge can support 0.5 Mhead of cattle today and could support 1.4 Mhead/y in 2110 if existing production trends continue.

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