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America's water: Agricultural water demands and the response of groundwater

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Key Points:

- Relationship between groundwater levels and a Demand-Sensitive Drought Index is examined
- Depletion of groundwater continues even when agricultural demands are reduced
- Storage of winter precipitation critical to supplying agricultural water demands

Supporting Information:

- Supporting Information S1

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Abstract Agricultural, industrial, and urban water use in the conterminous United States (CONUS) is highly dependent on groundwater that is largely drawn from nonsurficial wells (>30 m). We use a Demand-Sensitive Drought Index to examine the impacts of agricultural water needs, driven by low precipitation, high agricultural water demand, or a combination of both, on the temporal variability of depth to groundwater across the CONUS. We characterize the relationship between changes in groundwater levels, agricultural water deficits relative to precipitation during the growing season, and winter precipitation. We find that declines in groundwater levels in the High Plains aquifer and around the Mississippi River Valley are driven by groundwater withdrawals used to supplement agricultural water demands. Reductions in agricultural water demands for crops do not, however, lead to immediate recovery of groundwater levels due to the demand for groundwater in other sectors in regions such as Utah, Maryland, and Texas.

1. Introduction

Over a third of global freshwater withdrawals are sourced from aquifers [*Stolp and Brooks*, 2009; *Siebert et al.*, 2010]. In the conterminous United States (CONUS) over 40% of water consumed for irrigation, livestock, and domestic water is sourced from groundwater [*Maupin et al.*, 2014], and it is almost exclusively drawn from wells that are deeper than 30 m [e.g., *Nolan and Hitt*, 2006]. Many water withdrawals from deep aquifers are largely nonrenewable due to slow recharge rates [*Gorelick and Zheng*, 2015] with some withdrawals taken from fossil groundwater sources [*Scanlon et al.*, 2012]. In some cases, groundwater extraction leads to the collapse or compaction of the aquifer resulting in land subsidence and associated impacts [*Amelung et al.*, 1999; *Faunt*, 2009]. The impacts of groundwater withdrawals propagate through the groundwater system [*Alley et al.*, 2002], and effects include reversals of ground to surface water recharge [*Huang et al.*, 2012] and saltwater intrusion [*Ferguson and Gleeson*, 2012].

The late 20th century and 21st century saw an expansion in irrigated agriculture across the globe [*Foley et al.*, 2005]. The expansion of irrigated agriculture in the CONUS was accompanied by increased pumping of groundwater and associated depletion [*Famiglietti et al.*, 2011; *Scanlon et al.*, 2012]. These activities were facilitated by improvements in technologies [*Konikow*, 2015] in parallel with inadequate groundwater governance controls [*Srinivasan et al.*, 2012].

Groundwater is typically used to mitigate impacts of drought on surface water supplies enabling water demands to be met as well as to augment sparse surface water resources in arid regions or where surface water availability is highly variable temporally and/or spatially [*Giordano*, 2009; *Leblanc et al.*, 2009; *Famiglietti and Rodell*, 2013]. The association between groundwater-level variability and climate has previously been investigated [*Gurdak et al.*, 2007; *Green et al.*, 2011; *Kuss and Gurdak*, 2014] with *Scanlon et al.* [2012] observing episodic depletions in groundwater primarily restricted to periods of drought with partial recovery during wetter periods, which are more likely driven by changes in groundwater pumping rates rather than recharge rates. In the agricultural sector, hydrological drought conditions often lead to higher levels of irrigation [*Wada et al.*, 2013], which have been shown to have a significant influence on groundwater conditions [*Loáiciga*, 2003; *Ferguson and Maxwell*, 2012] resulting in depletion of groundwater [*Castle et al.*, 2014].

Here we seek to determine whether changes in groundwater levels across the CONUS can be related to a Demand-Sensitive Drought Index that accounts for potential agricultural water use and to regional precipitation anomalies. Our investigation will identify regions in the CONUS where annual groundwater depletion was likely caused by agricultural water demands that exceeded the amount of water supplied from precipitation over the growing season.

2. Materials and Methods

2.1. The Demand-Sensitive Drought Index

Many of the standardized drought indices, such as the Palmer drought severity index, crop moisture index, surface water supply index, and standardized precipitation index [e.g., *Mishra and Singh*, 2010, 2011; *Heim*, 2002], are essentially water-supply-based measures of deficiency in rainfall or streamflow compared to their long-term averages. However, drought impacts manifest as imbalances between supply and demand, which vary by location and by sector of use. Recently, *Etienne et al*. [2016] introduced a new drought index that explicitly considers both water supply and demand and can be applied to aggregated demands over a geographical region or for disaggregated demand related to a specific crop's water demand or sector's water use. This volumetric Demand-Sensitive Drought Index (vDSDI), expressed in volumetric units, accounts for the variability in water supply and demand, while incorporating information specific to the crops of interest. vDSDI is derived by accumulating differences in supply (rainfall) and demand (crop water requirement measured through regional reference crop evapotranspiration) over time to assess the maximum cumulative deficit that is likely to occur. This cumulative deficit index is a primary determinant of the water stress faced by the crop and hence of the dependence of the crop yield on water availability. Significant surface water deficits can adversely impact agricultural production and groundwater reserves and lead to increased energy costs for pumping groundwater for irrigation to maintain yield. vDSDI can hence be interpreted as the volume of water that is required in addition to that supplied by rainfall in order to meet the current agricultural water demand [*Devineni et al*., 2013; *Chen et al*., 2014; *Devineni et al*., 2015; *Etienne et al*., 2016].

In this application, a volumetric measure of agricultural water deficit per county is calculated. Given an *n*-year record of data, vDSDI calculates the day-by-day accumulation of deficit in the water supply in each of the *n* years. The cumulative deficit is reset to zero if the daily rainfall exceeds the cumulative deficit to that point. The maximum of each of the daily cumulative deficit sequences for the year is then taken to be the value of the index for the year. This provides a measure of the seasonal water stress on the crops. Considering daily resolution time series of supply and demand for a geographic unit *j* (e.g., a county in the CONUS), the water deficit and vDSDI are calculated as follows:

$$\text{deficit}_{j,t} = \max\left(\text{deficit}_{j,t-1} + D_{j,t} - S_{j,\,t}\,,\ 0\right)\ldots\text{where deficit}_{j,\,t=0} = 0 \quad (1)$$

$$\text{vDSDI}_{j,y} = \max_t\left(\text{deficit}_{j,\,t(y)};\ t = 1:365;\ y = 1:n\right)\ldots\text{where deficit}_{j,\,t(y)=0} = 0,\ y = 1:n \quad (2)$$

$\text{deficit}_{j,t}$ refers to the accumulated daily deficit, $D_{j,t}$ to total agricultural water requirement, $S_{j,\,t}$ to the total water daily supply volume for geographical location *j*, and day *t*; *y* to a calendar or cropping year. *n* is the total number of years in the analysis. For an *n*-year record, intraannual drought stress is evaluated as the maximum cumulative deficit each year, defined here as $\text{vDSDI}_{j,y}$ (volumetric Demand-Sensitive Drought Index). The vDSDI provides insights on the time-evolving vulnerability to drought arising from changes in climatic and nonclimatic conditions (e.g., cropping area, crop type, and subsequent agricultural water demand). In this study, we derive vDSDI for agriculture covering eight major crops (corn, soybeans, hay, wheat, barley, sorghum, rice, and cotton). These crops contribute to nearly 95% of the national crop revenue each year [*epa.gov*, 2014]. We refer the readers to *Etienne et al*. [2016] for a detailed description of the model along with the assumptions and applications. The following data sets were used to estimate the water supply and crop water demand for each county:

1. Gridded daily rainfall data from 1949 to 2010 (62 years) available at 12.5 km × 12.5 km spatial resolution developed by *Maurer et al*. [2002] were aggregated to 3111 CONUS counties and used to estimate the water supply in each county.
2. Daily air temperature and wind speed from *Maurer et al*. [2002] available at the same spatial and temporal resolutions were used to estimate the potential evapotranspiration for each grid (and then aggregated to county level) based on the Penman-Monteith method [*Zotarelli et al*., 2010].

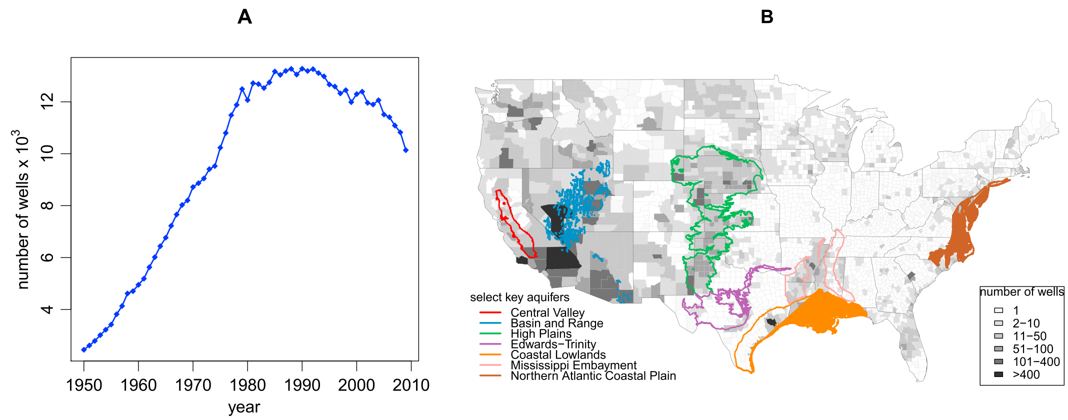

Figure 1. (a) The number of well depth observations through time and (b) total number of wells in each county.

3. Annual time series of the crop area planted for each crop in each county is obtained from the U.S. Department of Agriculture National Agriculture Statistics Service [*Quickstats.nass.usda.gov*, 2014].

The vDSDI record spans from 1949 to 2009. Of the 3111 counties in the CONUS, 390 counties have a vDSDI value of zero in all years (indicating no cumulated deficit based on the selected crops due to either sufficient precipitation, small/no crop areas, or a combination of both), and these include all counties in the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont and over half of the counties in Arkansas and Florida.

2.2. County-Scale Winter Precipitation

Precipitation from *Maurer et al*. [2002], previously used to calculate the vDSDI, was aggregated at a county scale over the boreal winter months of December, January, and February. The winter year was defined as the year corresponding to January and February. An updated version of the precipitation data covering the period up to 2009 was obtained from http://www.engr.scu.edu/~emaurer/data.shtml.

2.3. Groundwater Data

Depth-to-groundwater-level records were obtained from the U.S. Geological Survey (USGS) for wells that were deeper than 30 m with a minimum of 20 years of observations between 1949 and 2009. This collection of well data includes groundwater-level measurements from USGS monitoring wells, agency- or state-operated wells, and domestic wells [*U.S. Geological Survey*, 2015]. Depth to groundwater measurements were made at irregular times and were rarely continuous over the entire study period. The number of well records increased from 1949 until the early 1990s and decreased over the last two decades of the study period (Figure 1a). The minimum number of well records per year was 2275 in 1949; the maximum number of well records per year was 13,269 in 1990. The number of well records decreases exponentially with increasing well depth, with well depths ranging between 30 and 3150 m. The locations of wells are unevenly distributed in space, where some counties have more than 400 wells while others have no groundwater records available through the USGS site (Figure 1b). A total of 13,651 wells in the CONUS region were included in the analysis.

2.4. Method

The relationship between changes in groundwater levels and water demands was investigated using a multilinear regression analysis to identify covariates that influence the depth to groundwater. The following multivariate linear regression model was fitted:

$$D_t = f\left(\mathrm{vDSDI}_{t-1},\ P_{\mathrm{DJF}(t)},\ D_{t-1}\right) \tag{3}$$

Equation (3) includes the previous year's depth to groundwater level (D_{t-1}) along with the previous year's vDSDI value (vDSDI_{t-1}) and precipitation from the preceding winter ($P_{\mathrm{DJF}(t)}$), where January and February correspond to year t and December corresponds to year $t-1$. The depth to groundwater from the previous year was used as a covariate to account for trends in groundwater levels. Pairwise parametric and nonparametric correlations between vDSDI and the depth to groundwater lagged by between 0 and 5 years showed

that the vDSDI value was most strongly related to the depth to groundwater in the following year; hence, vDSDI_{t-1} was selected as a covariate. Winter precipitation was also included in equation (3) to account for precipitation that is not captured by the vDSDI due to the growing seasons of the various crops (see Figures S1 and S2 in the supporting information). In regions where winter precipitation is stored and released in the growing season or where winter snowpack thaws in spring and summer, deficits in agricultural water supplied by precipitation coinciding with crop water demands may be supplemented by the preceding winter's stored precipitation.

3. Groundwater Depletion, Changing Agricultural Practices, and Water Imports

3.1. Multivariate Model Results

The results of the multivariate regression model built using covariates of winter precipitation in addition to the previous year's vDSDI and depth to groundwater level are presented in this section. The significance of the three covariates on depth to groundwater, and whether the relationship to groundwater is positive or negative, is shown in Figure 2.

The depths to groundwater were positively autocorrelated at almost all well locations (Figure 2a). Winter precipitation was significantly negatively related to groundwater levels (Figure 2b), indicating that increases in winter precipitation result in decreases in the depth to groundwater (i.e., accumulation of groundwater) or smaller depletions. These results suggest that storage of winter precipitation either in soil moisture, reservoirs, or in winter snowpack is used to mitigate surface agricultural water deficits during the growing season. The winter precipitation is particularly important in the western U.S., where water demands are largely sourced from water stored in large reservoirs [*Graf*, 1999] that store runoff predominantly associated with major winter storm events [*Redmond and Koch*, 1991; *Woodhouse and Meko*, 1997; *Steinschneider et al*., 2016] or natural storage in the form of seasonal snowpack that accumulates over winter, releasing water as the snowpack thaws [*Serreze et al*., 1999]. The multivariate regression results suggest that reserves of surface water accumulated during winter are used across the CONUS to mitigate agricultural water deficits.

vDSDI was also a significant covariate (Figure 2c) with the significance and sign of the relationship being largely positive across the country, suggesting that the increases in surface water deficits through either increased agricultural demands and/or insufficient growing season precipitation result in increases in the depth to groundwater in the following year (i.e., groundwater depletions likely caused by withdrawals to meet agricultural demands). Positive relationships between vDSDI and depth to groundwater are most distinct in the northern Great Plains region (North Dakota), the northern High Plains aquifer (Nebraska), southern High Plains aquifer (Texas, Oklahoma, and Kansas), and the lower Mississippi River Valley.

Agricultural water demands that exceed the amount of water supplied by precipitation are often supplemented by groundwater resources. Over the past century, changes in agricultural extent, practices, and incentives have driven an increased reliance on groundwater resources, and this is discussed in section 3.2. Agriculture is typically the largest user of water across the CONUS; however, we discuss in section 3.3 a number of regions where water demands have shifted from agriculture to other sectors possibly explaining the negative relationship between agricultural water deficits and depth to groundwater. We also discuss in section 3.4 regions where agricultural water deficits have been met using neither precipitation nor groundwater resulting in the negative relationship between vDSDI and depth to groundwater in Figure 2c.

3.2. Agricultural Expansion in the CONUS

The positive relationships between water deficits and depth to groundwater are likely due to the 20th and 21st century increases in both agricultural productivity and intensification of agricultural activities, in particular, the expansion of irrigation practices using groundwater [*Conway*, 1998; *Tilman*, 1999; *Evenson and Gollin*, 2003]. Agricultural land use expanded in the U.S. Corn Belt region (around Iowa, Illinois, and Indiana) and the Mississippi Delta with slight increases in the Great Plains (region between the Rocky Mountains and the Mississippi River) and was accompanied by rapid increases in irrigated areas [*Hicke et al*., 2004]. The intensification of agriculture in these regions and expansion into high-risk farming areas have also been attributed to incentives administered through reforms in federal crop insurance and disaster relief programs since the 1970s [*Gardner and Kramer*, 1986; *Glauber*, 2013]. The adoption of irrigation technologies was facilitated by a combination of public policy (Reclamation Act) and improvements in irrigation technology resulting in

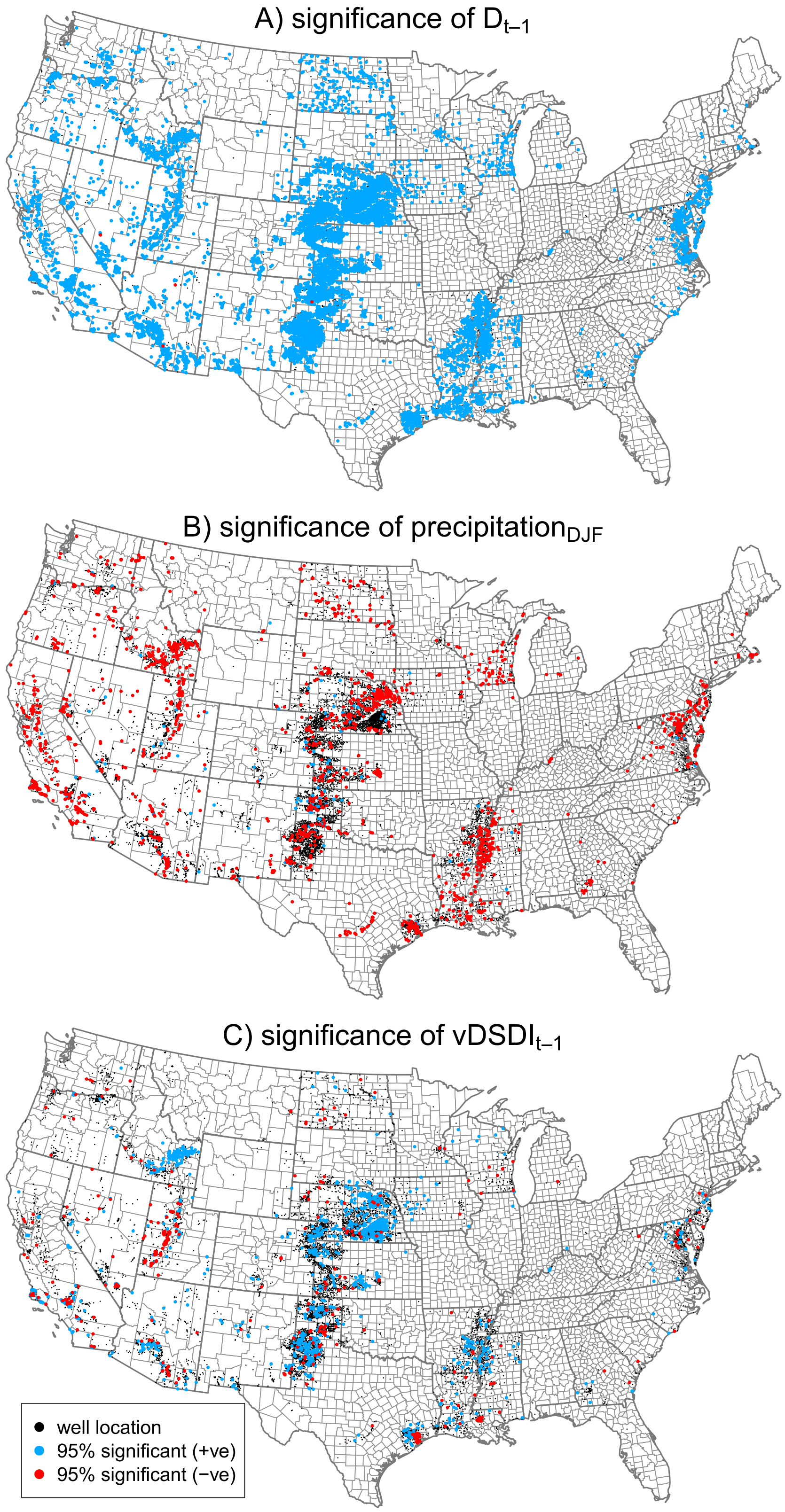

Figure 2. Locations where (a) groundwater depth in the previous year, (b) winter precipitation, and (c) vDSDI of the previous year are significant predictors of the depth to groundwater level in a multivariate regression model.

irrigated agricultural expansions during this period, most notable in the high plains of Kansas [*Brown et al*., 2005] and Texas with irrigation water largely sourced from groundwater [*Ward et al*., 2001]. Similarly, agricultural practices have also been observed to have intensified throughout the Atlantic Coastal Plains region [*Brown et al*., 2005].

3.3. Shifts in Agricultural Water Demands

The regions in the CONUS that have experienced agricultural expansion, described above, are, however, in contrast to the remainder of the CONUS, where croplands have largely declined over this study period through abandonment of marginal lands largely in the Deep South [*Brown et al*., 2005]. This is exemplified in the cropping areas over time for the eight major crops in Texas, where the areas of land used to plant all crops, with the exception of corn and hay, have contracted since 1980 onward (Figure 3). Groundwater accounts for over 80% of irrigation water in Texas [*Ward et al*., 2001]; however, irrigated areas in Texas shrunk by around 30% after the mid-1970s before stabilizing in the late 1980s. In addition, the adoption of improved irrigation technology (e.g., sprinkler systems account for 60% of all irrigated areas in Texas) resulted in a reduction of groundwater withdrawals relative to agricultural production levels. The reduction in agricultural areas in Texas coincides with slight declines in vDSDI values. A corresponding reduction in groundwater depletion would be expected, given reduced agricultural extents and improvements in irrigation practices requiring less water to meet agricultural water deficits. However, the reductions in agricultural water demands are still accompanied by declining groundwater levels as indicated by some negative relationships between vDSDI and depth to groundwater around the southern High Plains aquifer (in north-west Texas) and Edwards-Trinity aquifer (south-central Texas) (red points in Figure 2). The continued depletion of groundwater in the Edwards-Trinity aquifer is likely due to significant municipal and industrial uses [*Chen et al*., 2001; *Georgakakos et al*., 2014], and this shift in groundwater use from agriculture to other sectors is also seen in other regions.

The negative relationship between vDSDI and depth to groundwater in Texas is likewise seen in Maryland, where farming areas have also contracted. Maryland exhibits a similar pattern of declining areas of land used for planting the eight major crops. While grain, corn, and soybeans still comprise a significant portion of Maryland's agricultural output [*U.S. Department of Agriculture National Agricultural Statistics Service*, 2016], there has been a steady move toward diversifying farming practices with expanding poultry, greenhouse and nursery, dairy, and fruit industries [*Schmid*, 2011]. The expansion of these industries and associated water demands are not captured by the vDSDI. However, agricultural water demands only comprise approximately 20% of groundwater withdrawals in Maryland (Figures S3 and S5) [*Maupin et al*., 2014], and therefore, despite the contraction of cropped areas in Maryland, the use of groundwater for municipal, public, and industrial uses is likely the strongest driver of declining groundwater levels in the region [*Konikow*, 2013; *Georgakakos et al*., 2014]. The declines of groundwater in Maryland due to nonagricultural water demands in conjunctions with contracting agricultural cropping areas likely result in the negative relationship seen between vDSDI and depths to groundwater (Figure 2c).

The depths to groundwater in wells located in western Utah also show distinct negative relationships to vDSDI. This region is heavily reliant on water sourced from winter snowfall that is stored as snowpack, and agricultural water demands at some of these locations are significantly related to winter precipitation (Figure 2b). However, the negative relationship between vDSDI and depths to groundwater at a number of these wells could not be explained by winter precipitation supplying the surface water deficit. The majority of water used in agriculture in Utah is, however, sourced from surface water (see Figure S4).

We found that the vDSDI at well locations in Utah showed a sharp spike in water deficits around 1980, followed by a rapid decline. The rapid increase in agricultural water demands appears to reflect a mismatch between the timing of growing season precipitation and crop water demands as summer precipitation around this time was anomalously low. The following decline in vDSDI coincides with a sharp decrease in depths to groundwater levels in the middle to late 1980s, likely due to anomalously high precipitation during this period. Increased precipitation would reduce agricultural demands for groundwater resulting in the decline in vDSDI. Anomalously high precipitation likely contributed to the sharp decrease in depth to groundwater as the aquifer in this region, the Basin and Range aquifer, is significantly impacted by interbasin flows and underflows [*Robson and Banta*, 1999]. However, depths to groundwater levels increase in the years after the mid-1980s, while vDSDI values decline, resulting in the negative relationship seen in Figure 2c.

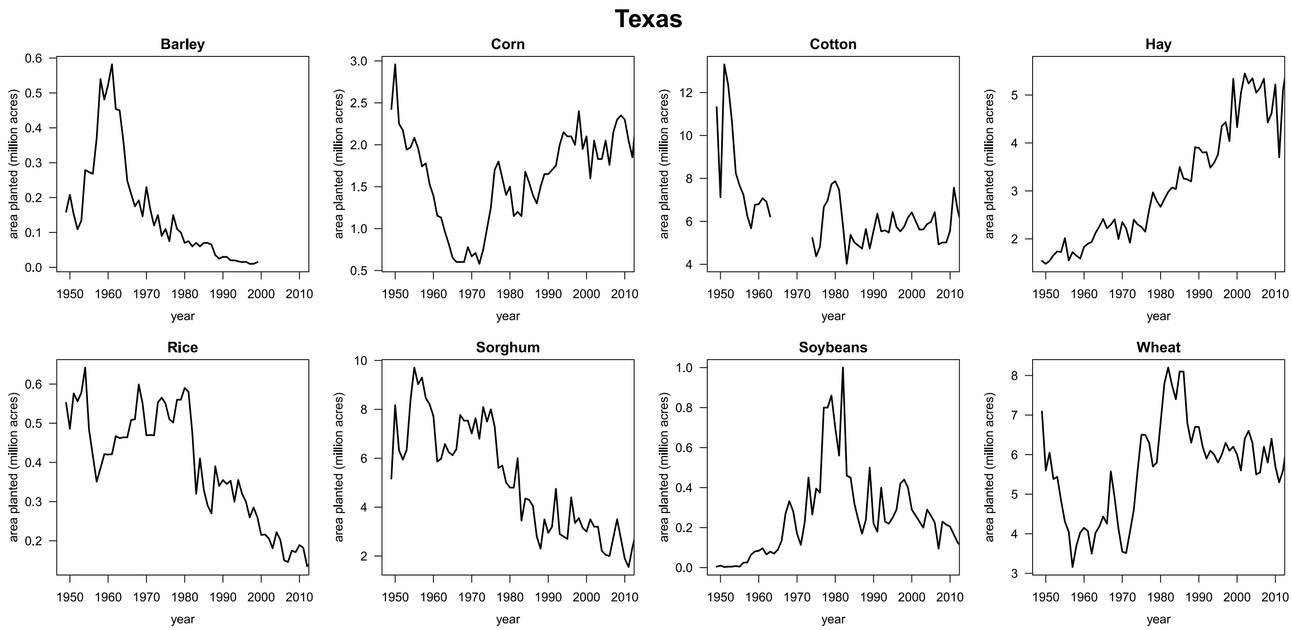

Figure 3. Areas used for planting the eight major crops in Texas. Areas are in million acres.

A significant portion of groundwater in Utah is used for public supply [*Maupin et al*., 2014], with counties, such as Tooele County, undergoing changes in groundwater use and experiencing a systematic decrease in groundwater recharge through improved irrigation efficiencies and diversions of streams that previously contributed to recharge. Declines in agricultural water demands were occurring in conjunction with increased demands in other sectors and mechanisms reducing the recharge of groundwater resulting in the significant negative coefficients.

3.4. Imported Water Resources

Negative relationships between vDSDI and depth to groundwater occur elsewhere in the CONUS in regions where either groundwater resources are largely used to supply municipal, public, and industrial water demands or surface water is largely used for agricultural water supply, or a combination of both scenarios. Another notable location is the San Joaquin Valley in south-central California. Large volumes of water are transferred to the region that is not reflected in the vDSDI, which only considers the occurrence of spatially and temporally local precipitation to supply agricultural water demands. Importation of water into the San Joaquin Valley has been enabled through arrangements such as the Central Valley [*Taylor*, 1949] and California State Water Projects [*California Government Department of Water Resources*, 2016], which transport water from northern to central and southern California. The importation of surface water from the late 1960s onward resulted in a decline in the reliance on groundwater for irrigation, with the exception of a period of drought in the mid-1970s, where surface water imports were reduced [*Bertoldi et al*., 1991]. The projects delivering water to the Central Valley, CA, reduced the regions' reliance on groundwater [*Galloway and Riley*, 1999] despite the expansion of agricultural cropping areas over this time [*Etienne et al*., 2016, Figure 3]. The mid-1970s drought also coincided with a decision by the California Supreme Court to limit the occurrence of over pumping of groundwater in addition to prioritizing municipality access to groundwater over that of private irrigators [*Smith*, 2013]. Groundwater levels in the San Joaquin aquifer largely recovered in response to decreased pumping of groundwater for irrigation. However, large increases in groundwater recharge rates during this period were primarily due to irrigation practices, where the overapplication of imported surface water resulted in irrigation water percolating into the aquifer, resulting in recharge rates exceeding natural recharge rates [*Bertoldi et al*., 1991]. Despite the reduction in reliance on groundwater, the Central Valley still recorded a net depletion in groundwater reserves over the 20th century largely due to intensive groundwater pumping practices earlier in the century [*Ireland et al*., 1984], in addition to ongoing demands for groundwater in municipal sectors [*Konikow*, 2013] and continued pumping for irrigation [*Faunt*, 2009].

4. Conclusions

Konikow [2015] observed that the monitoring and management of groundwater is challenging due to the slow moving nature of the resource and subsequently, groundwater problems are slow to spread, slow to detect, and thus slow to rectify. The difficulties in sustainably managing groundwater resources are underscored by depletions in groundwater levels despite regulated groundwater replenishment activities (e.g., in the lower Colorado Basin [*Castle et al*., 2014]). The depletion of groundwater reserves is of key concern to the irrigated agricultural industry in the CONUS. Steady declines in groundwater levels will increase the costs of pumping groundwater and subsequently increase the costs of agricultural produce.

Our analysis reveals that changes in surface water deficits are related to groundwater withdrawals in many key areas of irrigated agriculture in the CONUS. While we show that surface water deficits appear to be compensated through the use of groundwater in several key irrigated agricultural regions in the CONUS, long-term trends in groundwater levels appear to reflect prolonged periods of surface water deficits, resulting from land use and associated unsustainable water demands and subsequent inability to recover from drought states (e.g., north-west Texas and the Corn Belt region including areas of Nebraska, Iowa, and Minnesota [*Etienne et al*., 2016]).

Recent calls have been made to establish or reform groundwater policies to provide a holistic groundwater management strategy that considers the human demands on both surface water and groundwater [*Castle et al*., 2014; *Grantham and Viers*, 2014; *Young*, 2014]. Such considerations are critical given observed prolonged drought conditions [*Etienne et al*., 2016], the use of groundwater to augment water resources, in addition to the changing demands for groundwater with the emergence of new sectors such as hydraulic fracturing [*Freyman*, 2014]. The intersection of demands by different sectors could provide opportunities for efficient water trading and reuse [*Gaudet et al*., 2006; *Kuwayama et al*., 2013], provided that such trades are feasible [*Scanlon et al*., 2014]. There is a need for relevant groundwater policies to ensure that water demands are adequately managed across sectors without unsustainably depleting groundwater resources and to ensure that economic activities are not restrained by legal limitations to accessing regionally abundant water resources.

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References

Alley, W. M., R. W. Healy, J. W. LaBaugh, and T. E. Reilly (2002), Flow and storage in groundwater systems, *Science*, *296*(5575), 1985–1990, doi:10.1126/science.1067123.

Amelung, F., D. L. Galloway, J. W. Bell, H. A. Zebker, and R. J. Laczniak (1999), Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation, *Geology*, *27*(6), 483–486, doi:10.1130/0091-7613(1999)027<0483:stuado>2.3.co;2.

Bertoldi, G. L., R. H. Johnston, and K. D. Evenson (1991), Ground water in the Central Valley, California—A summary report, U.S. Geol. Surv. Prof. Pap., 44 pp.

Brown, D. G., K. M. Johnson, T. R. Loveland, and D. M. Theobald (2005), Rural land-use trends in the conterminous United States, 1950-2000, *Ecol. Appl.*, *15*(6), 1851–1863, doi:10.1890/03-5220.

California Government Department of Water Resources (2016), California State Water Project overview, viewed 28 January 2016. [Available at http://www.water.ca.gov/swp.]

Castle, S. L., B. F. Thomas, J. T. Reager, M. Rodell, S. C. Swenson, and J. S. Famiglietti (2014), Groundwater depletion during drought threatens future water security of the Colorado River Basin, *Geophys. Res. Lett.*, *41*, 1–18, doi:10.1002/2014GL061055.

Chen, C.-C., D. Gillig, and B. A. McCarl (2001), Effects of climatic change on a water dependent regional economy: A study of the Texas Edwards aquifer, *Clim. Change*, *49*(4), 397–409, doi:10.1023/a:1010617531401.

Chen, X., D. Naresh, L. Upmanu, Z. Hao, L. Dong, Q. Ju, J. Wang, and S. Wang (2014), China's water sustainability in the 21st century: A climate-informed water risk assessment covering multi-sector water demands, *Hydrol. Earth Syst. Sci.*, *18*(5), 1653–1662, doi:10.5194/hess-18-1653-2014.

Conway, G. (1998), *The Doubly Green Revolution: Food for All in the Twenty-First Century*, pp. 334, Comstock Publishing Associates, Ithaca, N. Y.

Devineni, N., S. Perveen, and U. Lall (2013), Assessing chronic and climate-induced water risk through spatially distributed cumulative deficit measures: A new picture of water sustainability in India, *Water Resour. Res.*, *49*, 2135–2145, doi:10.1002/wrcr.20184.

Devineni, N., U. Lall, E. Etienne, D. Shi, and C. Xi (2015), America's water risk: Current demand and climate variability, *Geophys. Res. Lett.*, *42*, 2285–2293, doi:10.1002/2015GL063487.

epa.gov (2014), Major crops grown in the United States|Ag 101|Agriculture|US EPA, viewed 23 November 2014. [Available at http://www.epa.gov/agriculture/ag101/cropmajor.html.]

Etienne, E., N. Devineni, R. Khanbilvardi, and U. Lall (2016), Development of a Demand Sensitive Drought Index and its application for agriculture over the conterminous United States, *J. Hydrol.*, *534*, 219–229, doi:10.1016/j.jhydrol.2015.12.060.

Evenson, R. E., and D. Gollin (2003), Assessing the impact of the green revolution, 1960 to 2000, *Science*, *300*(5620), 758–762, doi:10.1126/science.1078710.

Famiglietti, J. S., and M. Rodell (2013), Water in the balance, *Science*, *340*(6138), 1300–1301, doi:10.1126/science.1236460.

Famiglietti, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage, and M. Rodell (2011), Satellites measure recent rates of groundwater depletion in California's Central Valley, *Geophys. Res. Lett.*, *38*, L03403, doi:10.1029/2010GL046442.

Faunt, C. C. (Ed.) (2009), Groundwater availability of the Central Valley aquifer, California, *U.S. Geol. Surv. Prof. Pap., 1766*, 225 pp.

Ferguson, G., and T. Gleeson (2012), Vulnerability of coastal aquifers to groundwater use and climate change, *Nat. Clim. Change*, *2*(5), 342–345, doi:10.1038/nclimate1413.

Ferguson, I. M., and R. M. Maxwell (2012), Human impacts on terrestrial hydrology: Climate change versus pumping and irrigation, *Environ. Res. Lett.*, *7*(4), 044022, doi:10.1088/1748-9326/7/4/044022.

Foley, J. A., et al. (2005), Global consequences of land use, *Science*, *309*(5734), 570–574, doi:10.1126/science.1111772.

Freyman, M. (2014), *Hydraulic Fracturing and Water Stress: Water Demand by the Numbers*, pp. 85, Ceres, Boston, Mass.

Galloway, D. L., and F. S. Riley (1999), San Joaquin Valley, California—Largest human alteration of the Earth's surface, in *Land Subsidence in the United States*, *U.S. Geol. Surv. Circ.*, vol. 1182, edited by D. L. Galloway, D. R. Jones, and S. E. Ingebritsen, pp. 23–34, U.S. Geol. Surv., Reston, Va.

Gardner, B. L., and R. A. Kramer (1986), Experience with crop insurance programs in the United States, in *Crop Insurance for Agricultural Development: Issues and Experience*, edited by P. Hazell, C. Pomareda, and A. Valdés, pp. 195–222, John Hopkins Univ. Press, Baltimore, Md.

Gaudet, G., M. Moreaux, and C. Withagen (2006), The Alberta dilemma: Optimal sharing of a water resource by an agricultural and an oil sector, *J. Environ. Econ. Manage.*, *52*(2), 548–566, doi:10.1016/j.jeem.2006.02.005.

Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, T. C. Richmond, K. Reckhow, K. White, and D. Yates (2014), Water resources, in *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond, and G. W. Yohe, chap. 3, pp. 69–112, U.S. Global Change Research Program, New York.

Giordano, M. (2009), Global groundwater? Issues and solutions, *Annu. Rev. Environ. Resour.*, *34*(1), 153–178, doi:10.1146/annurev.environ.030308.100251.

Glauber, J. W. (2013), The growth of the federal crop insurance program, 1990–2011, *Am. J. Agric. Econ.*, *95*(2), 482–488, doi:10.1093/ajae/aas091.

Gorelick, S. M., and C. Zheng (2015), Global change and the groundwater management challenge, *Water Resour. Res.*, 1–21, doi:10.1002/2014WR016825.

Graf, W. L. (1999), Dam nation: A geographic census of American dams and their large-scale hydrologic impacts, *Water Resour. Res.*, *35*(4), 1305–1311, doi:10.1029/1999WR900016.

Grantham, T. E., and J. H. V. Viers (2014), 100 years of California's water rights system: Patterns, trends and uncertainty, *Environ. Res. Lett.*, *9*(8), 084012, doi:10.1088/1748-9326/9/8/084012.

Green, T. R., M. Taniguchi, H. Kooi, J. J. Gurdak, D. M. Allen, K. M. Hiscock, H. Treidel, and A. Aureli (2011), Beneath the surface of global change: Impacts of climate change on groundwater, *J. Hydrol.*, *405*(3–4), 532–560, doi:10.1016/j.jhydrol.2011.05.002.

Gurdak, J. J., R. T. Hanson, P. B. McMahon, B. W. Bruce, J. E. McCray, G. D. Thyne, and R. C. Reedy (2007), Climate variability controls on unsaturated water and chemical movement, High Plains aquifer, USA. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher, *Vadose Zone J.*, *6*(3), 533–547, doi:10.2136/vzj2006.0087.

Heim, R. R. (2002), A review of twentieth-century drought indices used in the United States, *Bull. Am. Meteorol. Soc.*, *83*(8), 1149–1165, doi:10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2.

Hicke, J. A., D. B. Lobell, and G. P. Asner (2004), Cropland Area and net primary production computed from 30 years of USDA agricultural harvest data, *Earth Interact.*, *8*(10), 1–20, doi:10.1175/1087-3562(2004)008<0001:CAANPP>2.0.CO;2.

Huang, Y., B. Scanlon, J.-P. Nicot, R. Reedy, A. Dutton, V. Kelley, and N. Deeds (2012), Sources of groundwater pumpage in a layered aquifer system in the Upper Gulf Coastal Plain, USA, *Hydrogeol. J.*, *20*(4), 783–796, doi:10.1007/s10040-012-0846-2.

Ireland, R. L., J. F. Poland, and F. S. Riley (1984), Land subsidence in the San Joaquin Valley, California, U.S. Geol. Surv. Prof. Pap., 93 pp.

Konikow, L. F. (2013), Groundwater depletion in the United States (1900–2008), U.S. Geol. Surv. Sci. Invest. Rep., 63 pp.

Konikow, L. F. (2015), Long-term groundwater depletion in the United States, *Groundwater*, *53*(1), 2–9, doi:10.1111/gwat.12306.

Kuss, A. J. M., and J. J. Gurdak (2014), Groundwater level response in U.S. principal aquifers to ENSO, NAO, PDO, and AMO, *J. Hydrol.*, *519*, 1939–1952, doi:10.1016/j.jhydrol.2014.09.069.

Kuwayama, Y., S. M. Olmstead, and A. J. Krupnick (2013), Water resources and unconventional fossil fuel development: Linking physical impacts to social costs, *Resour. Future*, *41*, doi:10.2139/ssrn.2352481.

Leblanc, M. J., P. Tregoning, G. Ramillien, S. O. Tweed, and A. Fakes (2009), Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia, *Water Resour. Res.*, *45*, W04408, doi:10.1029/2008WR007333.

Loáiciga, H. A. (2003), Climate change and ground water, *Ann. Assoc. Am. Geogr.*, *93*(1), 30–41, doi:10.1111/1467-8306.93103.

Maupin, M. A., J. F. Kenny, S. S. Hutson, J. K. Lovelace, N. L. Barber, and K. S. Linsey (2014), Estimated use of water in the United States in 2010, U.S. Geol. Surv. Circ., 56 pp.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002), A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States, *J. Clim.*, *15*(22), 3237–3251, doi:10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2.

Mishra, A. K., and V. P. Singh (2010), A review of drought concepts, *J. Hydrol.*, *391*(1–2), 202–216, doi:10.1016/j.jhydrol.2010.07.012.

Mishra, A. K., and V. P. Singh (2011), Drought modeling—A review, *J. Hydrol.*, *403*(1–2), 157–175, doi:10.1016/j.jhydrol.2011.03.049.

Nolan, B. T., and K. J. Hitt (2006), Vulnerability of shallow groundwater and drinking-water wells to nitrate in the United States, *Environ. Sci. Technol.*, *40*(24), 7834–7840, doi:10.1021/es060911u.

Quickstats.nass.usda.gov (2014), USDA/NASS QuickStats Ad-hoc Query Tool, viewed 23 November 2014. [Available at quickstats.nass.usda.gov.]

Redmond, K. T., and R. W. Koch (1991), Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices, *Water Resour. Res.*, *27*(9), 2381–2399, doi:10.1029/91WR00690.

Robson, S. G., and E. R. Banta (1999), Arizona, Colorado, New Mexico, Utah, in *Ground Water Atlas of the United States*, edited by J. A. Miller and C. L. Appel, pp. 248, U.S. Geol. Surv., Reston, Va.

Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon (2012), Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, *Proc. Natl. Acad. Sci. U.S.A.*, *109*(24), 9320–9325, doi:10.1073/pnas.1200311109.

Scanlon, B. R., R. C. Reedy, and J. P. Nicot (2014), Will water scarcity in semiarid regions limit hydraulic fracturing of shale plays?, *Environ. Res. Lett.*, *9*(12), 124011, doi:10.1088/1748-9326/9/12/124011.

Schmid, M. (2011), Understanding and responding to the changing needs of Maryland agriculture, Governor's Intergovernmental Commission for Agriculture, Ed., Maryland Department of Agriculture, 44.

Serreze, M. C., M. P. Clark, R. L. Armstrong, D. A. McGinnis, and R. S. Pulwarty (1999), Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data, *Water Resour. Res.*, *35*(7), 2145–2160, doi:10.1029/1999WR900090.

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann (2010), Groundwater use for irrigation—A global inventory, *Hydrol. Earth Syst. Sci.*, *14*(10), 1863–1880, doi:10.5194/hess-14-1863-2010.

Smith, Z. A. (2013), *Groundwater in the West*, Elsevier Sci., New York.

Srinivasan, V., E. F. Lambin, S. M. Gorelick, B. H. Thompson, and S. Rozelle (2012), The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies, *Water Resour. Res.*, *48*, W10516, doi:10.1029/2011WR011087.

Steinschneider, S., M. Ho, E. R. Cook, and U. Lall (2016), Can PDSI inform extreme precipitation?: An exploration with a 500 year long paleoclimate reconstruction over the U.S, *Water Resour. Res.*, *52*, 3866–3880, doi:10.1002/2016WR018712.

Stolp, B. J., and L. E. Brooks (2009), *Hydrology and Simulation of Ground-Water Flow in the Tooele Valley Ground-Water Basin*, pp. 86, U.S. Geol. Surv. Sci. Invest., Tooele County, Utah.

Taylor, P. S. (1949), Central Valley project: Water and land, *West. Political J.*, *2*(2), 228–253, doi:10.2307/441998.

Tilman, D. (1999), Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices, *Proc. Natl. Acad. Sci. U.S.A.*, *96*(11), 5995–6000, doi:10.1073/pnas.96.11.5995.

U.S. Geological Survey (2015), USGS groundwater levels for the nation, viewed 2015. [Available at http://waterdata.usgs.gov/nwis/gw.]

USDA National Agricultural Statistics Service (2016), 2014 state agriculture overview, viewed 2016/02/24. [Available at http://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=MARYLAND.]

Wada, Y., L. P. H. van Beek, N. Wanders, and M. F. P. Bierkens (2013), Human water consumption intensifies hydrological drought worldwide, *Environ. Res. Lett.*, *8*(3), 034036, doi:10.1088/1748-9326/8/3/034036.

Ward, J. K., W. H. M. J. Madden, W. W. Meadows, D. V. Guerra, J. Hunt, T. W. I. Labatt, and E. G. R. Pittman (2001), Surveys of irrigation in Texas, 102 pp.

Woodhouse, C. A., and D. Meko (1997), Number of winter precipitation days reconstructed from southwestern tree rings, *J. Clim.*, *10*(10), 2663–2669, doi:10.1175/1520-0442(1997)010<2663:NOWPDR>2.0.CO;2.

Young, M. D. (2014), Designing water abstraction regimes for an ever-changing and ever-varying future, *Agric. Water Manage.*, *145*, 32–38, doi:10.1016/j.agwat.2013.12.002.

Zotarelli, L., M. D. Dukes, C. C. Romero, K. W. Migliaccio, and K. T. Morgan (2010), *Step by Step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method)*, pp. 10, Inst. of Food and Agric. Sci., Univ. of Fla., Gainesville.

Water Resources Research

Supporting Information for

America's Water: agricultural water demands and the response of groundwater

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Figure S1-S5.

Introduction:

This supporting information provides additional figures summarizing USGS water use data and USDA crop planting times and growing season durations that support our findings presented in the paper.

The first two figures show details of growing times and seasons of each of the eight crops considered in the analysis. Figures S 4 and 5 show the proportion of groundwater that is used for irrigation in each county and the proportion of groundwater contributing to the total irrigation volume. Figure S 5 identifies the sector in each county that uses the most groundwater.

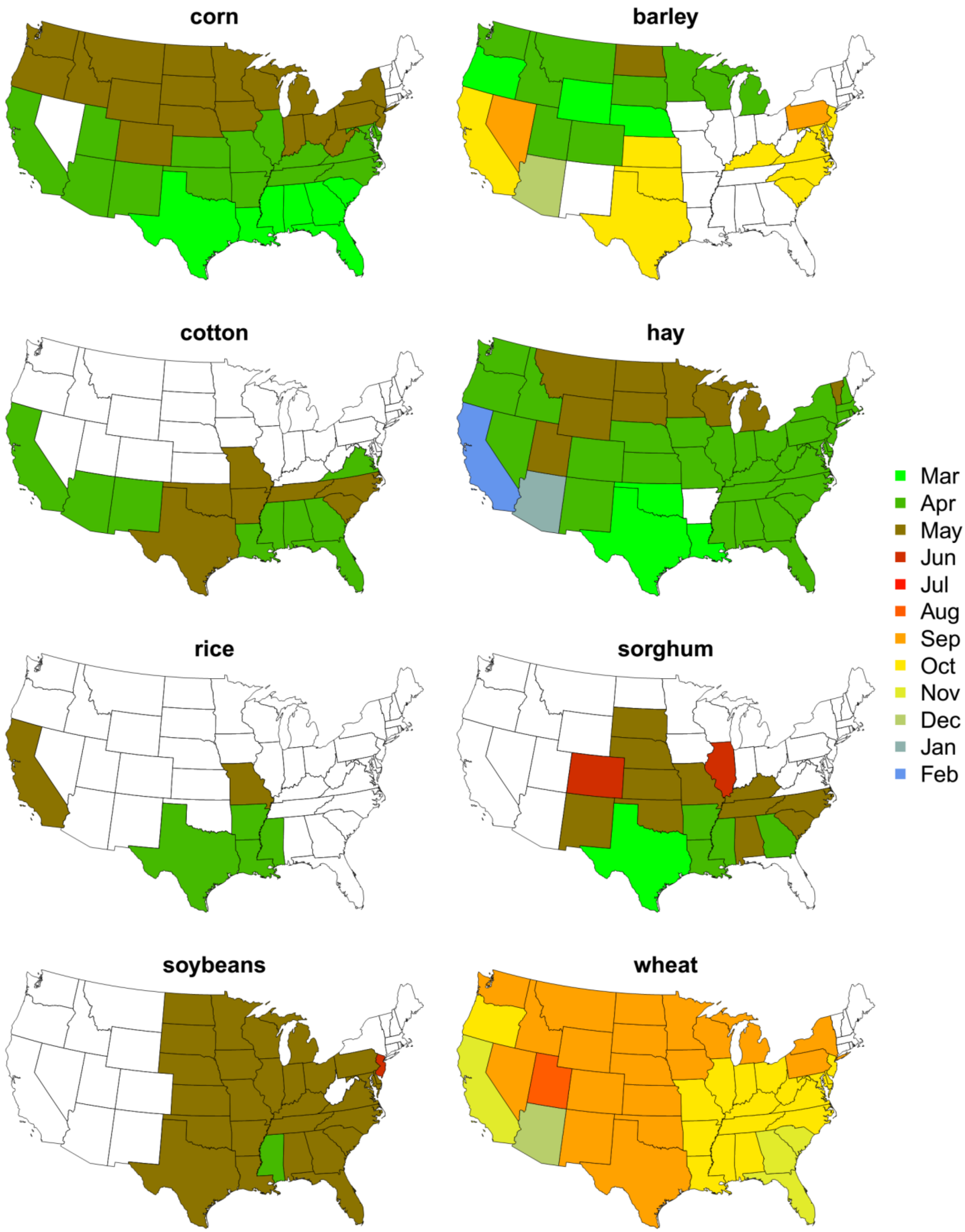

Figure S 1: Typical month that crops are planted in each state (data from USDA National Agricultural Statistics Service (2011))

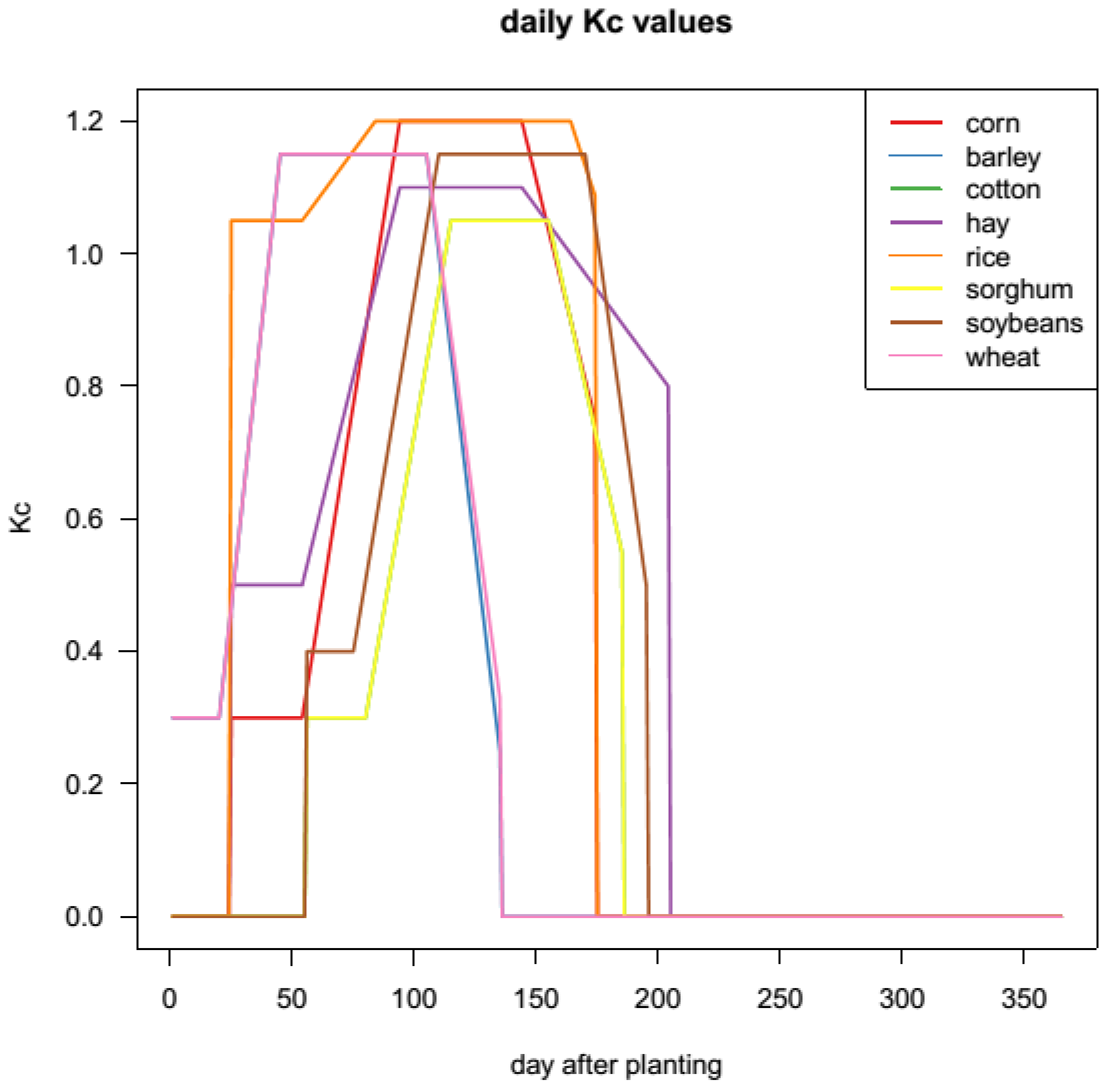

Figure S 2: Typical growing season of crops. Day 0 is the planting date (data from Allen et al. (1998))

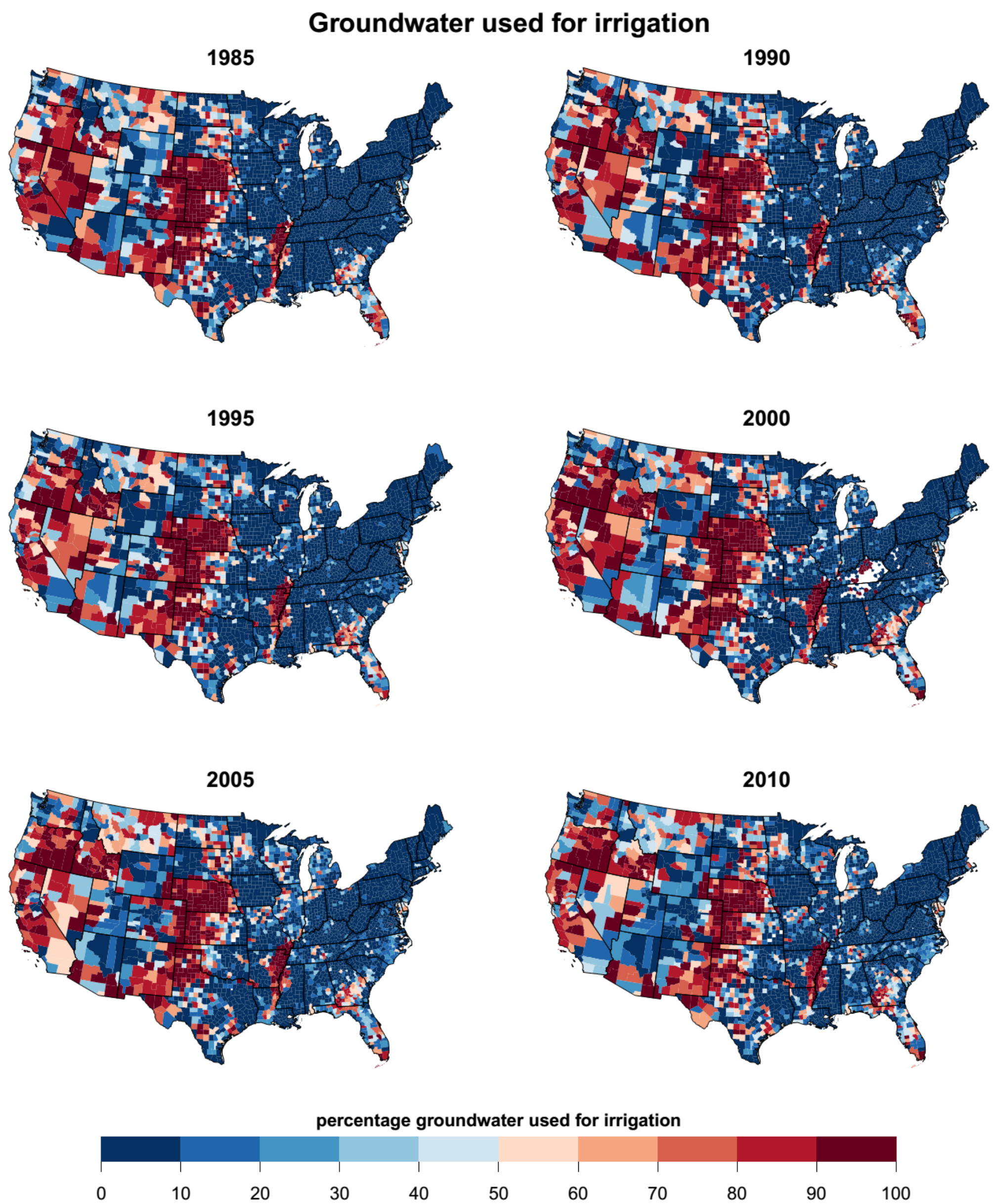

Figure S 3: Percentage of extracted groundwater that is used for irrigation – USGS water use data (U.S. Geological Survey, 2016).

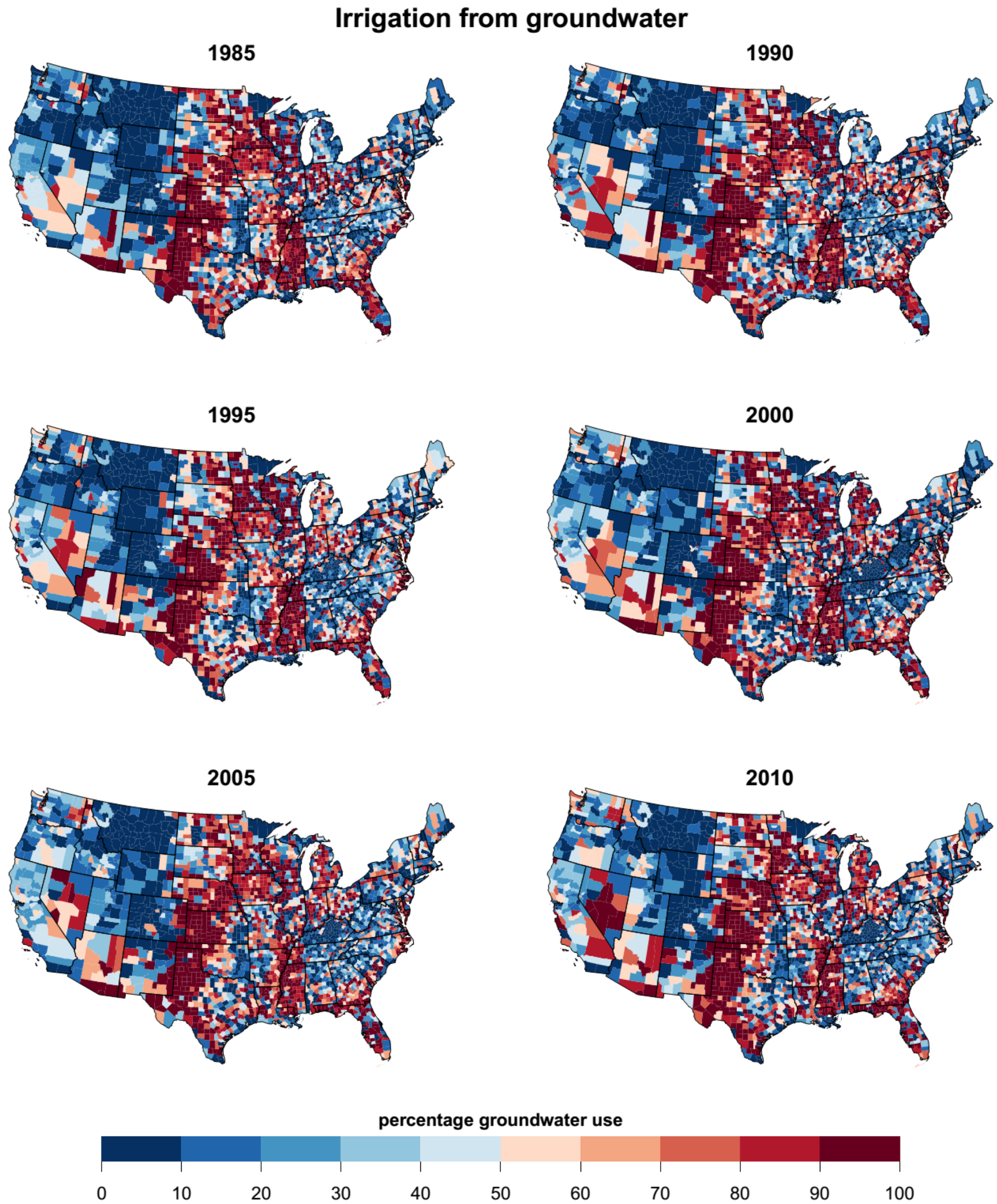

Figure S 4: Percentage of irrigation water that is supplied from groundwater in each county – USGS water use data (U.S. Geological Survey, 2016).

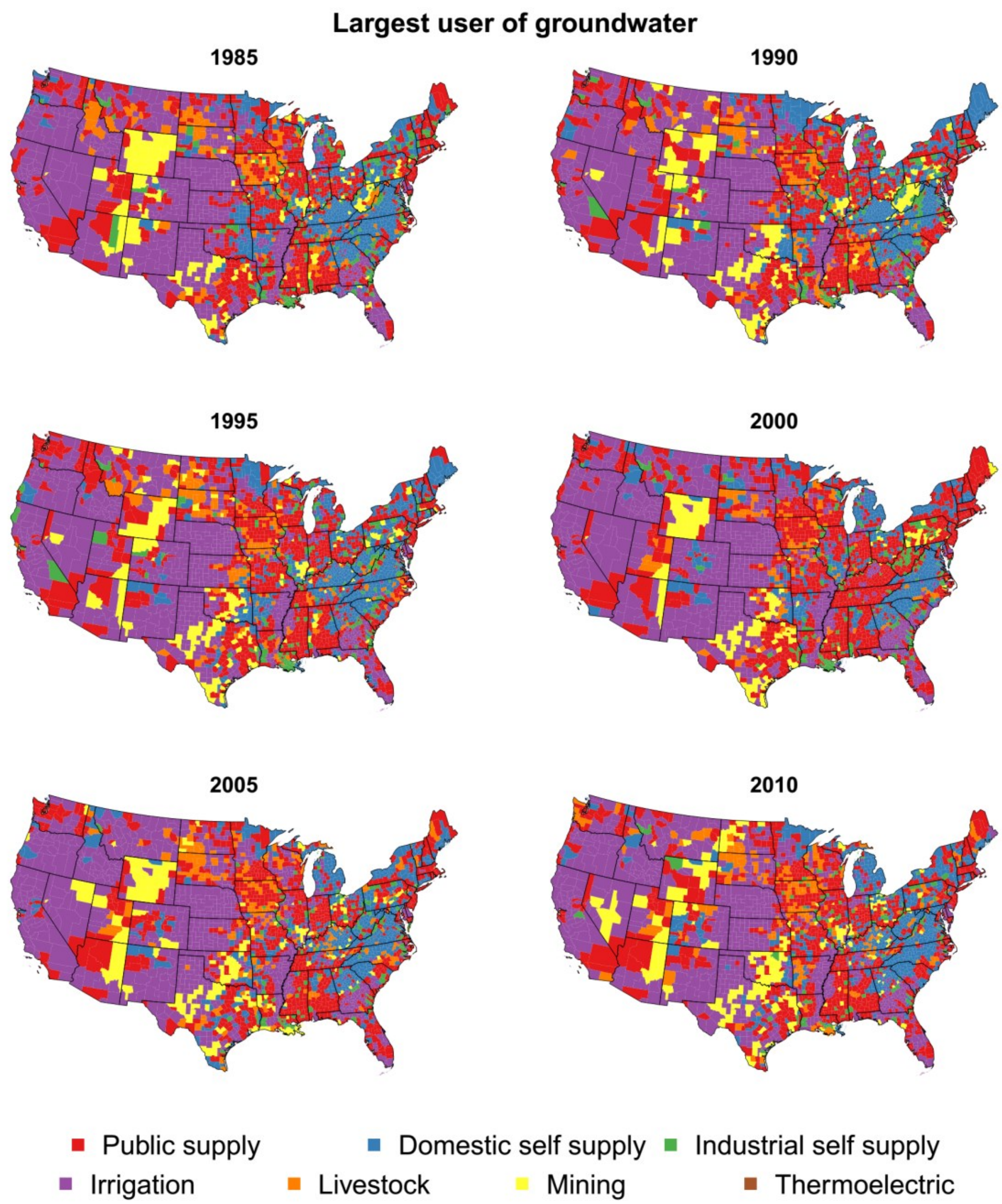

Figure S 5: Sector using the most groundwater (by volume) in each county – USGS water use data (U.S. Geological Survey, 2016).

Additional references

Allen, R. G., L. S. Pereira, D. Raes and M. Smith, 1998: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, *FAO, Rome*, **300** (9), D05109, doi.

U.S. Geological Survey, 2016, Water-use data available from USGS, viewed April 11 2016, <http://water.usgs.gov/watuse/data/>.

USDA National Agricultural Statistics Service, 2011: Usual Planting and Harvesting Dates for US Field Crops, Agricultural Handbook, United States Department of Agriculture, pp. 51.