Research Paper

Complex water management in modern agriculture: Trends in the water-energy-food nexus over the High Plains Aquifer

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Abstract

In modern agriculture, the interplay between complex physical, agricultural, and socioeconomic water use drivers must be fully understood to successfully manage water supplies on extended timescales. This is particularly evident across large portions of the High Plains Aquifer where groundwater levels have declined at unsustainable rates despite improvements in both the efficiency of water use and water productivity in agricultural practices. Improved technology and land use practices have not mitigated groundwater level declines, thus water management strategies must adapt accordingly or risk further resource loss. In this study, we analyze the water-energy-food nexus over the High Plains Aquifer as a framework to isolate the major drivers that have shaped the history, and will direct the future, of water use in modern agriculture. Based on this analysis, we conclude that future water management strategies can benefit from: (1) prioritizing farmer profit to encourage decision-making that aligns with strategic objectives, (2) management of water as both an input into the water-energy-food nexus and a key incentive for farmers, (3) adaptive frameworks that allow for short-term objectives within long-term goals, (4) innovative strategies that fit within restrictive political frameworks, (5) reduced production risks to aid farmer decision-making, and (6) increasing the political desire to conserve valuable water resources. This research sets the foundation to address water management as a function of complex decision-making trends linked to the water-energy-food nexus. Water management strategy recommendations are made based on the objective of balancing farmer profit and conserving water resources to ensure future agricultural production.

Keywords: High Plains Aquifer, water management, irrigation, agriculture, economics, policy

1. Introduction

Crop production across the High Plains Aquifer region (High Plains) in the central United States has an annual market value greater than $20 billion—approximately 10 percent of the entire U.S. crop value (NASS-USDA, 2012). Irrigation is essential to much of this crop production. Irrigated agriculture across the High Plains accounts for 30 percent of all irrigated acreage in the U.S. (Dennehy et al., 2002), and 97 percent of High Plains irrigation water is extracted from the High Plains Aquifer (HPA; Maupin and Barber, 2005). Due to extensive irrigation, groundwater levels across large sections of the HPA have been declining for decades, particularly in the southern section where the aquifer is thin and irrigation demand is high (Haacker et al., 2015; McGuire, 2009; Scanlon et al., 2012). Future decades are forecast to bring more widespread groundwater declines, effectively depleting broad regions of the HPA if current practices continue (Haacker et al., 2015). Major reductions in water availability would result in enormous consequences for food and energy production.

At the core of agricultural water management challenges is the water-energy-food nexus. Acting within this nexus across the HPA are the individuals and institutions that adapt to address the realities of groundwater depletion. These include creating and adopting new technologies, developing and planting different cultivars, shifting cropping patterns, implementing new policies, expanding monitoring, and pushing toward more efficient use of limited resources. These strategies have been designed around the objectives of increasing crop yields, decreasing production costs, improving or maintaining soil fertility, and reducing environmental impacts (Edwards, 1989; Stuart et al., 2015). They can be generalized into two broad focus areas: (1) water conservation to both use less water and be more efficient in application, and (2) water productivity to maximize the return on water use. Water conservation research has focused on strategies such as deficit irrigation (Fereres et al., 2007; Geerts and Raes, 2009), irrigation technologies (Colaizzi et al., 2009; Howell, 2001), rainfed agriculture (Rockström et al., 2010; Rosegrant et al., 2002), and land management practices (Bossio et al., 2008; 2010). Water productivity research has focused on improved seed genetics (Hu and Xiong, 2014; Passioura, 2004), variable rate irrigation (Basso et al., 2013; Evans et al., 2013), and intraseason water management through irrigation scheduling and soil moisture monitoring (Aguilar et al., 2015), vegetation indices (Basso et al., 2004), and tillage practices (Derpsch et al., 2010). Despite this increased emphasis toward groundwater conservation among researchers, and new technologies and strategies that can greatly improve water productivity, groundwater supplies across the HPA continue to decline at unsustainable rates (Haacker et al., 2015; Scanlon et al., 2012).

Historically, water management strategies have targeted water use drivers within three major domains: (1) physical (e.g., climate, geology), (2) agricultural (e.g., crop type, tillage practices), and (3) socioeconomic (e.g., groundwater doctrines, market values) (Pimental et al., 1997). However, water use drivers in modern agriculture are too complicated to be regulated individually within these separate domains. For example, changes in precipitation patterns have direct implications on irrigation scheduling and applications (Lorite et al., 2015), improved technologies allow for innovative and heterogeneous farming practices (Steven and Clark, 2013; Zhang and Kovacs, 2012), and crop prices respond to changes in global market demands (Rosegrant, 2008). Furthermore, drivers within these domains each influence short- and long-term water use decisions in ways that have not been addressed in static water management strategies (e.g., climate variability, government incentives, and annual crop insurance plans). Moreover, water use drivers across these domains are inherently linked, making it impossible to implement temporally relevant water management strategies in one domain without impacting another.

There are clear gaps in current water management strategies across the High Plains, as evidenced by the increase in both crop production and water use despite the reality of groundwater depletion (NASS-USDA). Nowhere is agricultural water management more prevalent than in the water-energy-food nexus of the HPA, making the region ideal to learn how complex management domains influence water use and decision-making. This study provides a comprehensive overview of the major drivers of water use across the HPA through a novel synthesis of data and an in-depth review of the relevant literature. We examine drivers in the physical, agricultural, and socioeconomic domains in contrast to the historical approach. Furthermore, within each domain, we analyze water use trends and examine how these drivers interact to influence water use decisions. We then synthesize across domains to present a framework for maintaining long-term aquifer supplies through improved agricultural water management strategies across the water-energy-food nexus.

2. Methods

This study synthesizes extensive agricultural databases along with the relevant water management literature across the HPA. When used, specific processing techniques are discussed within corresponding sections. Sections 3, 4, and 5 compile individual water use drivers or driver categories into major domains, where each subsection represents a major driver set or focus area. Subsections are selected according to the most significant topics for water supply or water use across the region, as a complete synthesis of these drivers is necessary to formulate water management suggestions and highlight areas where water resources are exploited. All drivers at every spatial and temporal scale may not be included, as our subsection lists are representative of and relevant to large scale management schemes. We derive our conclusions based on the trends found within and across each domain, and we make management suggestions based on the goals of maintaining farmer profit and achieving long-term aquifer sustainability.

3. The Physical Domain

The physical domain defines the limits of the water-energy-food nexus. For example, food production requires both energy and water. If water is limited, so will be the ability to increase crop yields. Thus, balancing components within the nexus to find the combination where production is highest and resource expenditures are lowest over time is critical for sustainable agriculture. A required step to reach this ideal nexus status is to assess total water availability and supply through time. Here, we analyze the major physical drivers that impact water availability and supply, and we highlight the trends that have the most influence on long-term sustainability goals.

3.1 Geology, Soil, and Land Cover

The HPA (450,000 km^2; Qi, 2010) is located in the west-central United States and spans portions of eight states: South Dakota, Wyoming, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas (Figure 1A). Given its size, the HPA is often divided into three geographical areas, each with unique physical characteristics: the Northern High Plains (NHP; 249,509 km^2, Central High Plains (CHP; 127,168 km^2), and Southern High Plains (SHP; 75,921 km^2). At 3,750 km^3 of total water volume in 2012 (Haacker et al., 2015), slightly larger than the volume of Lake Huron, the HPA remains one of the largest known freshwater aquifers in the world. The total volume of water estimated within the NHP is ~2,940 km^3, the CHP is ~635 km^3, and the

SHP is ~171 km^3. However, groundwater is being recharged at rates far below annual withdrawals in the south and central portions of the aquifer.

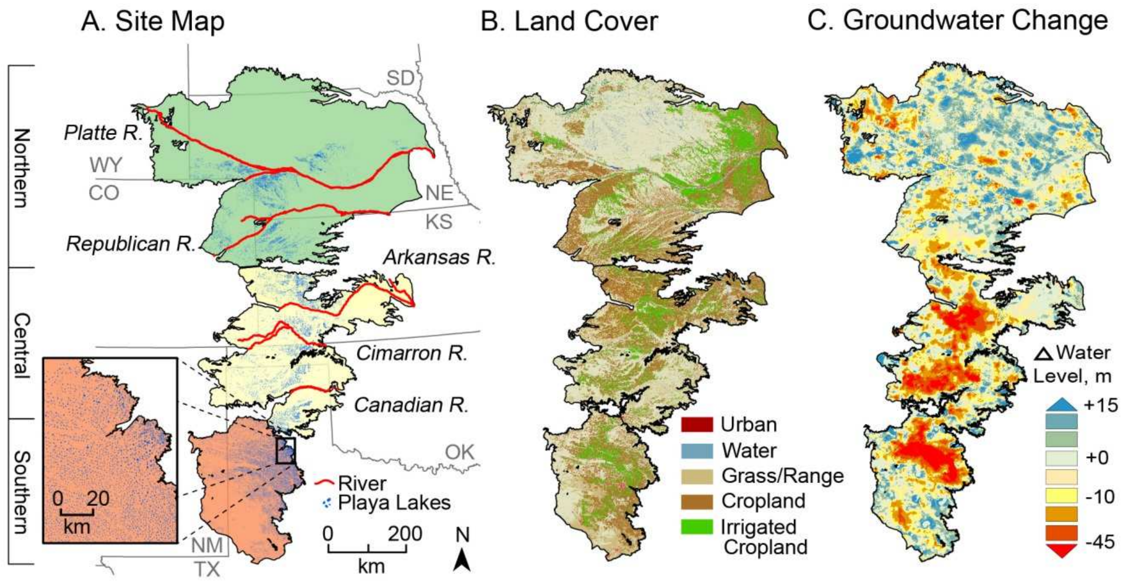


Figure 1. The High Plains and aquifer decline. **A)** Site map of the HPA and its three main regions. **B)** Land cover across the HPA region, dominated by range and cropland (NLCD, 2011). **C)** Interpolated groundwater level declines compared to predevelopment levels (modified from Haacker et al., 2015).

The High Plains have a semi-arid, temperate climate, with surface elevations that follow a west-east gradient from ~2,400-m in the west to ~350-m in the east (Dennehy et al., 2002); local relief is generally very low. Soil characteristics follow a general gradient of high permeability in the NHP (Dennehy et al., 2002; Gutentag et al., 1984) to low permeability in the SHP (Dennehy et al., 2002; Reeves Jr., 1970). Native land cover includes short and medium grass prairies, though large sections of modern land cover have transitioned to cropland (Figure 1B) with the major crop choices of corn, sorghum, winter wheat, soybeans, alfalfa, and cotton (Dennehy et al., 2002). Crop selections follow a general gradient of water-intensive crops in the north (e.g., corn, soybeans) to less water-intensive crops in the south (e.g., cotton, winter wheat). The other major land use type across the region is livestock rangeland (primarily cattle; Dennehy et al., 2002). Collectively between cropland and rangeland, 94% of the High Plains is considered agricultural land (Figure 1B).

3.2 Hydrology and Hydrogeology

Several hydraulically-connected permeable units collectively form the HPA complex (Gutentag et al., 1984; Knowles et al., 1984); the largest of which is the Ogallala Formation, or Ogallala Aquifer, a name often used interchangeably with HPA. The Ogallala Aquifer underlies nearly 77 percent of the HPA area, with most of the remaining area composed of the Brule, Arikaree, Great Bend Prairie, and Equus Beds aquifers. Hydraulic conductivity and specific yield across the HPA vary from 1 to 105 m/day and 3 to 35 percent, respectively (Gutentag et al., 1984), resulting in highly variable groundwater yields across the aquifer. Saturated thickness ranges from 0 to 300-m but has drastically declined since predevelopment; average saturated thickness is approximately 60-m. Depth to water is generally from a few to 150-m, and average depth to water in 2012 was 30-m for the NHP, 44-m for the CHP, and 41-m for the SHP.

While groundwater supply in the NHP has been fairly stable since predevelopment, the CHP and SHP have experienced extensive groundwater depletion due to extensive groundwater pumping (McGuire, 2009). Peak groundwater level declines have reached more than 45-m in portions of the CHP and SHP (Figure 1C), while average declines by state for portions of the HPA are: 14-m in Texas, 9-m in Kansas, 6-m in Oklahoma, 5-m in New Mexico and Colorado, and (Haacker et al., 2015). Average groundwater declines in the NHP have been less than 0.5-m in both Nebraska and Wyoming (McGuire, 2009; Scanlon et al., 2012; Haacker et al. 2015), although areas of extensive groundwater withdrawals are common. Collectively, nearly 410 km^3

of water has been depleted from the HPA since predevelopment (Haacker et al., 2015), which is approximately the volume of Lake Erie.

Total annual surface water flow entering the HPA region is ~2.5 km^3 per year (Dennehy et al., 2002), though extensive groundwater depletion has resulted in a net loss in annual streamflow and surface water volume (Nativ, 1992; Scanlon et al., 2012). While major river systems flow from west to east across the NHP and CHP, the SHP has few streams, and none flow consistently. Instead, surface water in the SHP is largely drained and stored in thousands of localized playa lakes that are most concentrated along the eastern margins of the region. These broad, shallow lakes can span up to 1-km in diameter (Osterkamp and Wood, 1987) and drain an estimated 90% of the SHP region (Nativ, 1992). Playa lakes exist across the entire High Plains (~61,000 lakes; Gurdak and Roe, 2010) but are much more prevalent in the SHP (~30,000 lakes; Osterkamp and Wood, 1987; Figure 1A).

Natural recharge in the NHP and CHP occurs primarily as precipitation percolation through permeable soils and leakage from surface water bodies (Weeks et al., 1988; Dennehy et al., 2002). Localized recharge in the SHP region largely occurs as percolation beneath playa lakes where water passes through dissolved or fractured caliche (Osterkamp and Wood, 1987; Scanlon and Goldsmith, 1997; Wood and Osterkamp, 1987). Areal groundwater recharge across the High Plains decreases following a gradient from north to south. Secondary recharge across some portions of the HPA also occurs as irrigation return flow where some of the excess applied water is returned to the aquifer (McMahon et al., 2006; Scanlon et al., 2005; Whittemore et al., 2015).

3.3 Regional Climate

The High Plains are located in a wet-dry climate transition zone (Koster et al., 2004) where soil moisture plays a critical role in modulating the energy and mass transport that impact the regional water cycle (Berg et al., 2014). This is particularly relevant in areas of high irrigation where modified soil moisture significantly impacts the regional hydroclimate through adjusted land-atmosphere interactions (Harding and Snyder 2012a; 2012b; Jódar et al., 2010; Lo and Famiglietti, 2013; Moore and Rojstaczer 2001; 2002; Pei et al., 2016; Qian et al. 2013). One major effect of increased soil moisture is on the Great Plains low-level jet (GPLLJ; Walters et al., 2014; Weaver and Nigam, 2011). The GPLLJ brings moisture into the region from the Gulf of Mexico and provides the main external moisture source for precipitation over the High Plains and central United States (Cook et al., 2008; Higgins et al., 1997; Pei et al., 2014; Tuttle and Davis, 2006; Weaver, 2007). At shorter timescales (event-scale), fluctuations in the GPLLJ prompt nighttime rainfall maxima during warmer seasons, where greater moisture convergence results in heavier precipitation (Carbone and Tuttle 2008; Pu and Dickinson 2014; Zhong et al., 1996).

Climate models project a decrease in warm-season precipitation (Cook et al., 2008; Maloney et al., 2014) and an increase in regional temperatures for the High Plains by the end of this century (Cook et al., 2008; IPCC, 2007). Historically, the High Plains receives ~50-cm of average annual precipitation (Crosbie et al., 2013), with a gradient from ~40-cm along the western border to ~70-cm along the eastern edge (Gutentag et al., 1984). Precipitation is projected to increase for the NHP and decrease for the SHP, and regional temperatures are expected to increase by 2 to 5°C (Crosbie et al., 2013; IPCC, 2007). Increased temperatures would likely favor increased evapotranspiration (Green et al., 2011), and a decrease in precipitation and increase in temperature would both likely exacerbate groundwater supply declines under current water use scenarios (Crosbie et al., 2013).

Extreme drought events have also become more frequent over the past 45 years (NLDAS-2). The average annual HPA precipitation fell below 305-mm five times since 1998, whereas this occurred just once from 1979-1998 (Figure 2). While reductions in annual precipitation are most extreme in the SHP, similar trends have been seen in the NHP and CHP. In particular, SHP precipitation fell below 100-mm during 2012-2013 regional droughts, and for the first time on record, precipitation simultaneously fell below 300-mm for both the CHP and NHP regions during the same drought period.

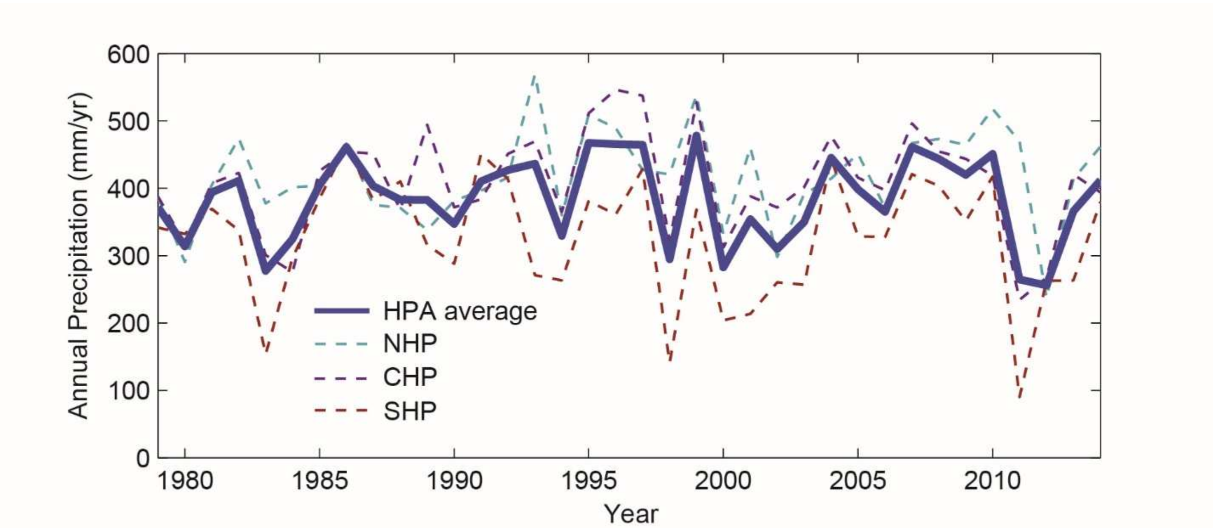


Figure 2. Average annual precipitation for the HPA and its three regions (NLDAS-2 forcing file A).

Discrepancies in the projected GPLLJ strengthening and subsequent precipitation decreases suggest changes in future climate regimes over the HPA (Maloney et al., 2014). Areas of the HPA that are currently limited by water availability will likely be the most affected by these changes (Ng et al., 2010). However, accurately capturing these patterns remains a challenge for predictive models even with knowledge of the major climate controls (Hoerling et al., 2014). For example, the 2012 severe Great Plains drought was suggested to be independent of these climate patterns and likely a result of atmospheric noise alone (Kumar et al., 2013). Future water management strategies would clearly benefit from improved climate prediction skills.

4. The Agricultural Domain

Crop yield in the agricultural domain is the primary indicator of resource efficiency within the water-energy-food nexus, given its dependence on both growing conditions and agricultural management practices. Generally, increased yields through time indicate improved technologies or agricultural practices that allow physical resources to be used more efficiently. However, improved efficiency is not always an indicator of sustainability. Increased crop yields may be a function of efficient practices, but that does not mean they are always less taxing on resources within the physical domain (e.g., water, soil). Cross-domain impacts must be considered to achieve sustainable management strategies in modern agriculture. In this section, we highlight the major agricultural drivers that impact water use, the primary component limited by availability and supply in the physical domain.

4.1 Soil Management

Soil management strategies focus on maximizing crop yield, maintaining long-term soil fertility, and mitigating environmental impacts such as nitrate leaching and greenhouse gas emissions. Example soil management strategies include conventional tillage versus no-till farming (e.g., Ghimire et al., 2012; Hobbs et al., 2008), crop rotations (e.g., Johnston, 1986; Odell et al., 1984), and off-season cover crops (e.g., Allen et al., 2005; Havlin et al., 1990). Conservation agriculture incorporates these land management strategies to increase soil fertility by preserving surface organic carbon, protecting soil from water runoff, and reducing soil loss by eliminating bare exposure (Basso et al., 2006; 2014; Hobbs et al., 2008). Managing soils to improve fertility reduces the demand for additional water applications. However, the potential for soil management to conserve water does not negate the substantial amount of water used for irrigation.

4.2 Irrigation and Crop Yield

A new synthesis of annual irrigated and non-irrigated yield since 1970 across the HPA was conducted using data from the National Agricultural Statistics Service (NASS-USDA), plotted in Figure 3. This synthesis uses annual county-level surveys of yields for the six major commodities grown across the HPA: corn, soybeans, winter wheat, alfalfa, cotton, and sorghum. The analysis of these data highlight: the considerable benefit of irrigation across the HPA (with little difference across subregions), the large increase in yields of corn, soy, and cotton over time due to improved management and crop genetics, and much larger annual variability in yields from dryland relative to irrigated production. The linear trends fit to this data from 1970-2014 show that non-irrigated and irrigated yields have increased by 133 and 96 percent for corn, 74 and 330 percent for cotton, 69 and 89 percent for soybeans, 17 and 26 percent for alfalfa, 11 and 13 percent for sorghum, and 4 and 27 percent for wheat, respectively. Today, *non-irrigated* corn yields are similar to the *irrigated* corn yields of 1970, and irrigated corn yields today are more than double non-irrigated yields (Figure 3A). Similar trends can be seen in cotton yields, although the gap between irrigated and non-irrigated yields has been increasing in recent years (Figure 3B). Alfalfa, sorghum and wheat yields have not rapidly increased since 1970, though irrigated yields are still approximately double the non-irrigated yields of these crops (Figure 3D-F).

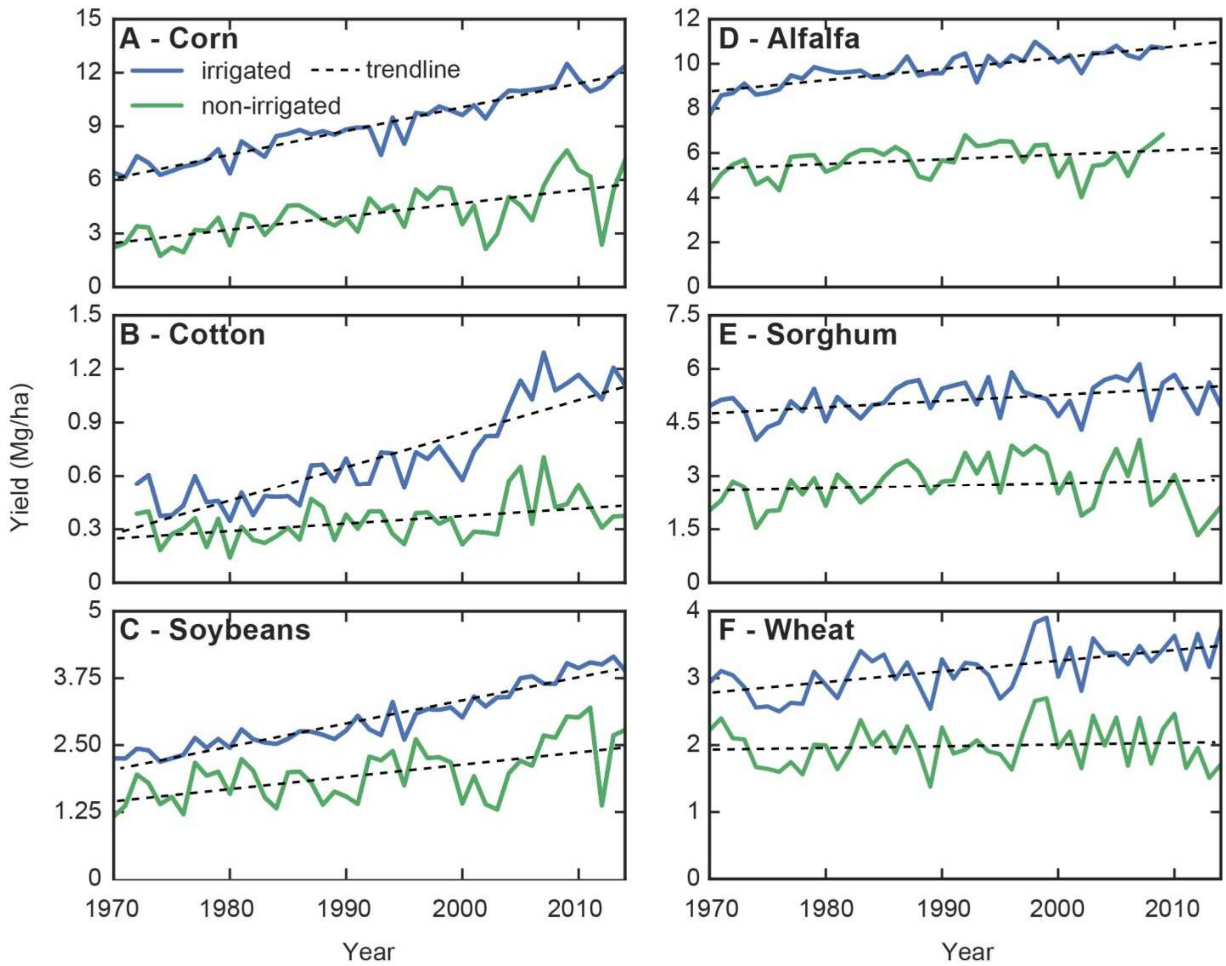


Figure 3. Irrigated and non-irrigated yields for the main commodities grown across the HPA (NASS-USDA). Alfalfa yields were not available after 2009.

In general, we found that irrigation increases yield by a factor of two to four times relative to dryland farming, a significantly larger yield increase than can be generated by other land management strategies (Colaizzi and Gowda, 2009; Colaizzi and Schneider, 2004). This boost in crop yield generates a major economic incentive to irrigate. Today, over 12 million acres of irrigated cropland are fed by the HPA for these six commodities (NASS-USDA). Irrigation over the HPA is so extensive, and high-yield agriculture is such a major component to the regional economy, that widespread transitions to dryland agriculture would cause severe economic consequences for the region (Colaizzi et al., 2009).

4.3 Crop selection

Water demand varies by commodity, and in general, the most water-intensive crops return the greatest short-term profit. For example, cotton demands approximately 69-cm of water for peak yields while corn requires almost 80-cm (Moore and Rojstaczer, 2001). This has resulted in both the widespread selection and the irrigation of more water-intensive crops, such as corn, across the High Plains. To investigate commodity selection trends, we calculated annual irrigated and total acreages from 1970 to 2014 for the six major commodities (NASS-USDA). We used a composite of annual county-level surveys, which may in some years only include a subset of commodities for each county, and the more complete bi-decadal Agricultural Census. Additionally, the noisier annual survey data were bias corrected to match the 5-year Census data. Biases in survey data are calculated for each county relative to the Census values as

$$bias_{year} = (Census_{year} - survey_{year})/survey_{year} \quad \text{(eq. 1)}$$

and linearly interpolated between Census years. This annual bias was then converted to a multiplicative correction factor as

$$correction_{year} = bias_{year} + 1 \quad \text{(eq. 2)}$$

which was then multiplied by the annual survey data for each county. Counties partially within the HPA were multiplied by the fraction of each county that falls within three HPA subregions. Adjusted acreages were then summed across the three HPA subregions (Figure 4).

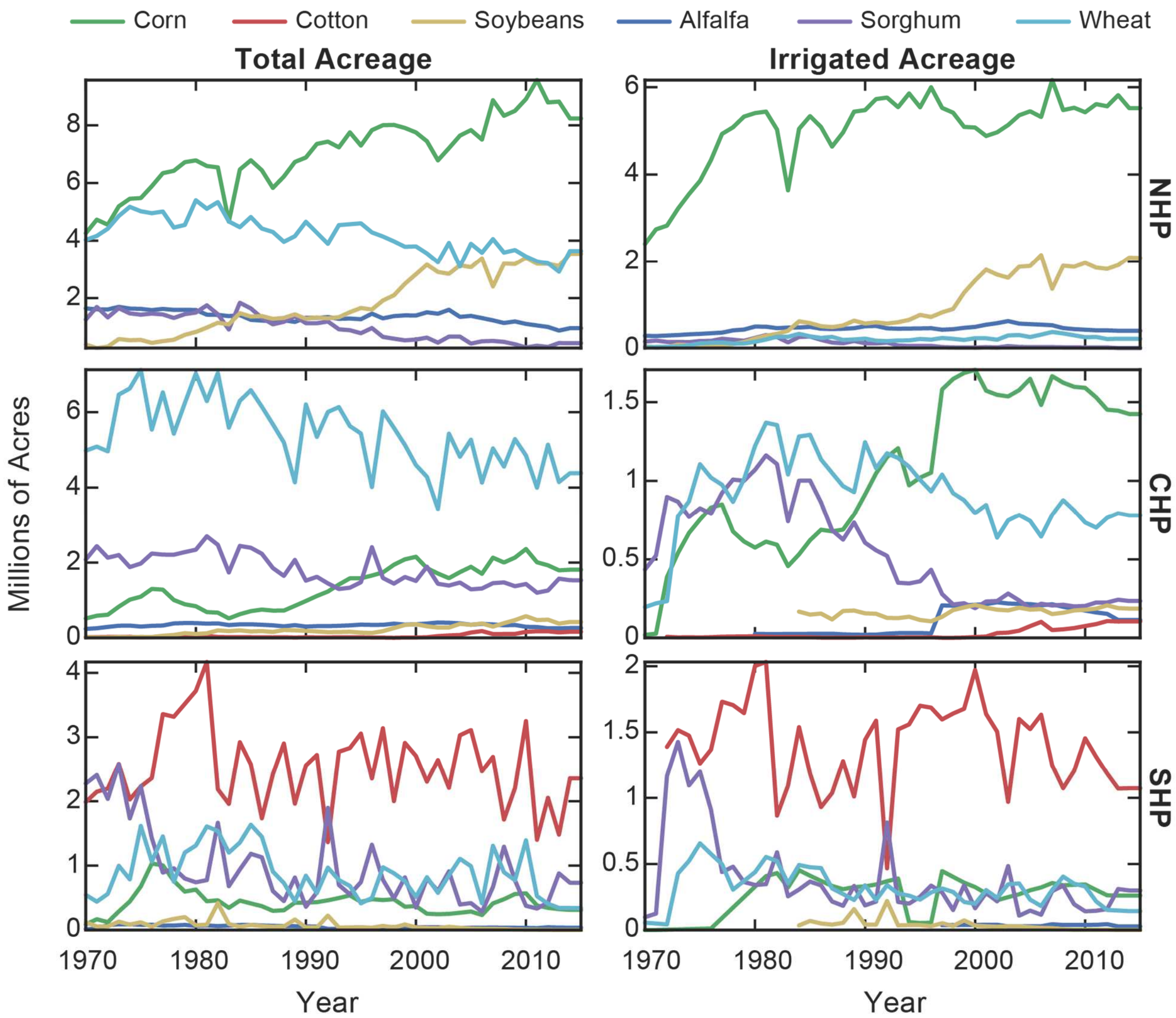


Figure 4. Total commodity acreage (left) and irrigated commodity acreage (right) by region (NASS-USDA).

By the middle of the 1990s, over 7.5 million acres of corn were irrigated across the HPA region compared to just over 2 million acres in 1970. Today, irrigated corn acreage alone is greater than all other major commodities combined for the NHP and CHP regions (Figure 4). While some areas of the HPA have tried shifting from corn to less water-intensive crops in an attempt to conserve water (e.g., Colaizzi et al., 2009), extensively irrigating the crop with the greatest economic return is still widely in practice today. For total acreage, corn is the primary crop in the NHP, wheat is primary in the CHP, and cotton is primary in the SHP. This trend in dominant crop type follows the same gradient of regional water availability, where the most water intensive crop is dominant in the north and the least water intensive crop in the south, further demonstrating how water supply in the physical domain affects decision-making in the agricultural domain. Across the HPA, irrigated corn now accounts for over 50 percent of all irrigation; with approximately 70, 75, and 80 percent of the corn being irrigated in the NHP, CHP, and SHP, respectively.

4.4 Groundwater Pumping

Widespread irrigation is the largest contributor to groundwater decline across the HPA. Steady groundwater level declines across both the CHP and SHP are evidence that irrigation practices in these regions are unsustainable (Figure 5A). Since the late 1930s, saturated volumes of the CHP and SHP aquifers have been reduced by ~30 and ~50 percent, respectively. Our projections based on linear extrapolation of trends in saturated thickness from 1993-2012 (after Haacker et al., 2015) show that irrigable acreage availability (areas with >10-m saturated thickness) will fall below 50 percent of the total SHP and CHP area by the years 2025 and 2065, respectively (Figure 5B). However, irrigation on the NHP has had little impact on the overall decline of groundwater in the region as a whole. This suggests that water in the NHP can generally be treated as a renewable resource (Haacker et al., 2015; Scanlon et al., 2012), except for some portions of the region.

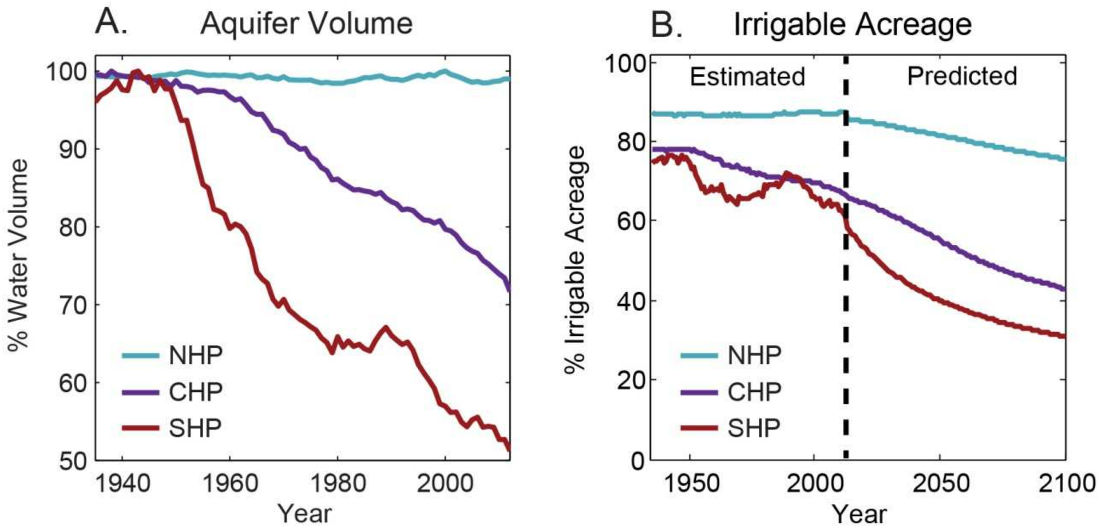


Figure 5. Aquifer decline across the High Plains. **A)** Saturated aquifer volume for each HPA region since predevelopment. **B)** Estimated (left) and predicted (right) irrigable acreage based on saturated thickness interpolations for each region (modified from Haacker et al., 2015).

Saturated thicknesses across the NHP have historically varied nonlinearly in a given location, suggesting that overall irrigable acreage may remain relatively stable into the future. However, saturated thicknesses across the CHP and SHP have not evidenced recovery, thus declining saturated thickness estimates are representative of declining irrigable acreage predictions for these regions. Extending the time frame for trend analysis prior to 1993 would allow for more comprehensive predictions of each region, but this dilutes the role of recent agricultural practices on declining groundwater levels. The average projected usable lifespan of the aquifer based on estimated 2007 storage and depletion rates is around 81-yrs for the SHP and 238-yrs for the CHP, while the NHP is relatively sustainable under current irrigation trends (Scanlon et al., 2012).

4.5 Efficient Water Use

Irrigation has become more expensive due to groundwater declines and the increased costs for the energy sources needed to lift groundwater, further supporting the central role of the water-energy-food nexus in modern agriculture. This increase in cost, in addition to the goal of conserving water resources, has led to the development and adoption of increasingly efficient irrigation technologies (i.e., reduction in the percent of water lost to direct evaporation per amount applied). In theory, improved efficiency of water use increases farmer profit by lowering production costs.

Since the 1980's, a common strategy to improve irrigation efficiency has been to modify pre-existing central pivot systems with lower-pressure spray applicators (Colaizzi et al., 2004; Colaizzi et al., 2009; Lyle and Bordovsky, 1983). Low-pressure spray applicators are classified according to the height of the nozzle, as Low-Elevation Spray Applicators (LESA) or Mid-Elevation Spray Applicators (MESA). Systems using an applicator sock dragged along the soil or a sprayer near the soil are referred to as Low Energy Precision Applicators (LEPA), which is also the common name for this entire low pressure applicator class.

We quantified the change in irrigation technologies across Kansas since 1990 (Figure 6) using water rights data from the Kansas Water Information Management and Analysis System (WIMAS). Prior to 1990, adoption of LEPA and related technologies was small, remaining below 5%. While the prevalence of flood irrigation systems steadily declined, farmers were transitioning to traditional high-pressure center pivot systems until 1997 when an abrupt inflection in adoption of LEPA-type systems occurred, along with a steady decline in flood and high pressure center pivot systems. By 2010, LEPA-type systems accounted for almost 65% of all irrigation systems across the HPA region of Kansas. Irrigation technology selections in

Kansas demonstrate the widespread adoption of LEPA technology, trends which are mimicked across the rest of the HPA states.

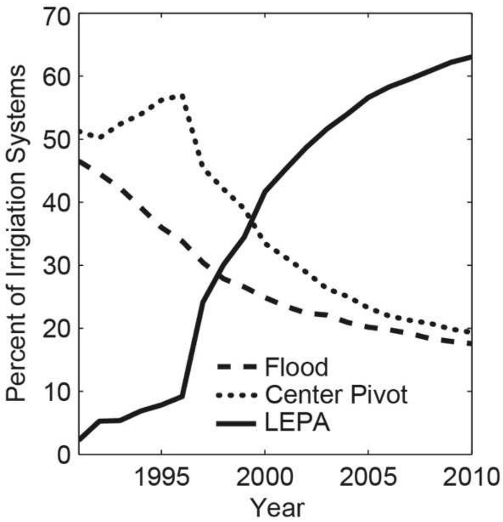


Figure 6. Irrigation technology selections across the HPA in Kansas (Kansas Division of Water Resources).

4.6 Water Use Response to Efficient Technologies

Irrigation technology can have a large effect on water use efficiency (Deng et al., 2006). For example, subsurface drip irrigation can reduce irrigation water use by 35 to 55% (Lamm and Trooien, 2003). However, groundwater level declines have not been mitigated by the widespread conversion to more efficient irrigation technologies; instead, total withdrawals have increased. As improved irrigation efficiency decreases the usage cost for water applications, more acreage can be irrigated at a lower cost, resulting in increased profit margins for farmers and increased incentive to irrigate more acres (Pfeiffer and Lin, 2014; Upendram and Peterson, 2007).

To demonstrate that efficient irrigation technologies have led to increased water use across the HPA, we processed data for total irrigated acreage from 1990-1996, seven years prior to the widespread adoption of LEPA technology, and 1997-2003, seven years directly after

LEPA adoption (NASS-USDA). Total irrigated acreage across the HPA increased by ~11.38 million acres after widespread LEPA adoption; by subregion, the NHP, CHP, and SHP increased by 5.55, 3.63, and 2.22 million acres, respectively (Table 1). Also significant are the trends in irrigated crop choice that directly follow LEPA adoption. For example, NHP farmers focused on irrigating a variety of crops rather than isolating corn expansion, CHP farmers expanded water intensive crops despite regional water level decline, and SHP farmers primarily sought to improve yields on predominant crops like cotton while also capitalizing on the incentive to grow water-intensive corn in the relatively dry region. From 1996 through 2015, there has been an 11 percent increase in irrigated acres on the NHP and CHP; in contrast there has been a 25 percent decrease on the SHP, likely due to the decrease in available irrigable acreage as displayed in Figure 5.

4.7 Other Methods

Past studies have also highlighted how maximizing efficient water use includes more than just improved irrigation technology. For example, efficient water use also includes processes such as fertilizer regimes (Ogola et al., 2002), root zone uptake (Clothier and Green, 1994), pre-existing soil moisture (Panda et al., 2003), and irrigation frequency and intensity (Kang et al., 2002; Nair et al., 2013). Yields have been highest when irrigation applications were frequent with low intensity (Behera and Panda, 2009) and when fertilizer applications integrated with irrigation could offset the additional need for water to maximize yield. Water uptake by plant roots mostly occurs in the uppermost 45-cm of soil, thus irrigation applications that supply water beneath this depth generally add to nutrient and water leaching (Panda et al., 2003). Furthermore, increased irrigation applications, even with efficient technologies, lead directly to increased water loss due to increased evapotranspiration (Howell et al., 2004; Ogola et al., 2002). Improved irrigation regimes are a major focus area for water conservation, and further research is needed that integrates water use with the social drivers behind water management.

4.8 Water Productivity

Improved water use efficiency can both limit the total volume of water applied per area and reduce the total water demanded by the crop system. This movement has been widely linked with "crop per drop" research where the objective is to maximize crop yield for every drop of water applied (Brauman et al., 2013). To quantify the amount of crop returned per water amount of water applied, we conducted a novel synthesis of the benefit of irrigation on yields, irrigated water applications per commodity, and irrigation water use efficiency (Figure 7). The yield benefit of irrigation (Figure 7A), or the difference between irrigated and non-irrigated yields, was calculated for each commodity and averaged across the HPA using the data in Figures 3 and 4. To calculate water applications per commodity, three county-level time series were used: (1) annual irrigated yields per commodity (Figure 3), (2) annual irrigated acreages per commodity (Figure 4), and (3) water use per commodity, which was estimated every five years using Agricultural Census and USGS Water Use data (NASS-USDA, 2012; NWIS-USGS). USGS Water Use data prior to 1985 are at the state level, so we first disaggregated these to county level by assuming that relative county-level water use remained the same from 1985 back to 1970. Second, we used state level data from the 2013 Agricultural Census on water applied per commodity and assumed that relative water applied per commodity remained the same within each state across the analysis years. Third, we multiplied commodity acreages in each county by relative water use to partition total water among commodities. Finally, we divided the commodity water use in each county by county acreages to get water use per commodity. To estimate the “crop-per-drop” of irrigation water across the HPA, and how it varies across commodities, we divided the irrigated yield benefit (Figure 7A) by the water applied (Figure 7B), yielding Irrigation Water Use Efficiency (Figure 7C), or the benefit of irrigation per unit of applied water, across commodities.

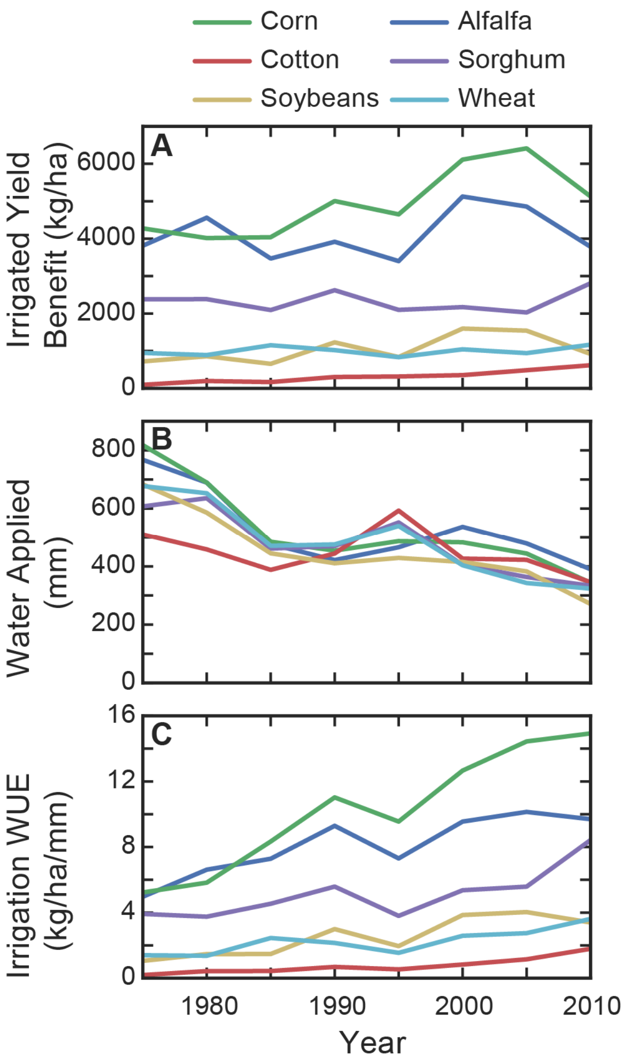


Figure 7. Crop yield, irrigation application data, and water use data (NASS-USDA; NWIS-USGS) were used to quantify crop yield per water spent in 5 year increments since 1970. **A)** Yield benefit is calculated as the difference in yield between irrigated and non-irrigated yield. **B)** The HPA-average annual amount of water applied for each commodity. **C)** Irrigation Water Use Efficiency (WUE), calculated as the irrigated yield benefit divided by applied water.

The incentive to irrigate is obvious based on the irrigated yield benefit. For example, irrigated corn yield is approximately 5,000 kg/ha greater than non-irrigated yield (Figure 7A). However, the productivity of water (i.e., crop yield per drop) has not been well documented across regions. Due to many factors including more efficient irrigation systems, shifts in cropping patterns regionally, and changes in irrigation application practices, the amount of water applied per season has decreased for all common commodities (Figure 7B), and the magnitude of crop yield gained per amount of water applied has steadily increased in recent decades across the HPA (Figure 7C), demonstrating that the productivity of irrigation water has steadily improved. For example, irrigation water use efficiency has nearly tripled in the last 45 years for corn and more than doubled for alfalfa, sorghum, soybeans, and wheat. This boost in regional productivity is directly linked to both the improvement in yield benefit (Figure 7A) as well as reduced water applications. Assuming these positive water productivity trends continue into the future, the incentive to irrigate will continue to increase, further intensifying resource demands in the water-energy-food nexus over the HPA.

4.9 Emerging Strategies

Emerging research to improve water productivity has largely focused on precision agriculture, crop choice, and cultivar improvement (Basso et al., 2011; 2013; Ritchie and Basso, 2008). In recent years, the emphasis on cultivar development has increased given the expected cross-domain implications of climate change such as decreased crop yields due to increased water stress (Basso et al., 2015; Basso and Ritchie, 2014). New crop cultivars may result in increased yields despite growth challenges posed by climate change by allowing for some traditionally water-intensive crops to be grown in regions where water is scarce (Hu and Xiong, 2014; Lobell et al., 2014). As more drought-resistant crop cultivars enter the market, growth of these cultivars in water-deficient areas will likely become more profitable (Benson et al., 2011).

Precision agriculture has generated significant interest among researchers and farmers given its potential to improve long-term production even at the small farm scale, although the adoption of precision agricultural practices has only grown moderately since their introduction in the 1990s (Daberkow and McBride, 2003; McBratney et al., 2005). Precision agriculture uses discretized, site-specific information based on factors including crop choice and soil type to develop strategies that are unique to that site, such as only applying irrigation to moisture deficient sections of a field (Basso et al., 2001; Bongiovanni and Lowenberg-Deboer, 2004). One challenge for large scale increases in water productivity using precision agriculture is that variable rate technologies are still under development and have not been widely applied in areas such as the HPA. The implications of precision agriculture on water productivity are likely most beneficial when considering adaptive, full-field irrigation strategies that respond to low soil moisture conditions.

4.10 Natural Viability

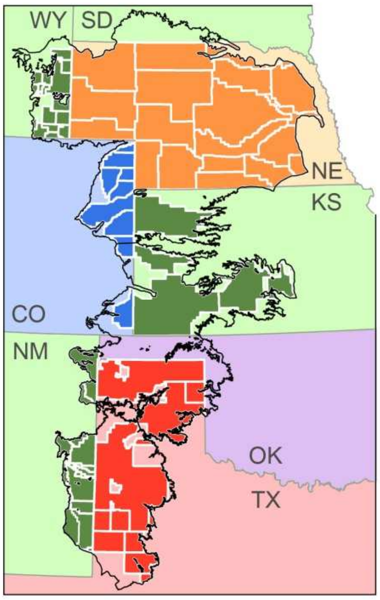
Crop type selection is a natural solution to water conservation. For example, switching from water-intensive corn to a less water-intensive crop mitigates the need for excess irrigation. In the northern Texas region of the SHP, switching half of irrigated corn to irrigated cotton could reduce water withdrawals by 8% (Colaizzi et al., 2009). Growing water-intensive crops in regions that need supplemental irrigation generates the largest demand for water withdrawal from the HPA aquifer. Crop selection based on the natural variability of the regional climate is the most effective method of water conservation. However, natural crop selection generally results in less farmer profit.

5. The Socioeconomic Domain

The socioeconomic domain both motivates and regulates how water is used within the water-energy-food nexus. In other words, this domain defines the incentives and social penalties for water use. Farmers generally aim to maximize profit, meaning the nature and location of economic incentives within the nexus can be useful indicators of potential water use. At the same time, legislation and political actions define to what extent, and sometimes at which locations, water can be used. Understanding how drivers within the socioeconomic domain may impact cross-domain trends in the physical and agricultural domains is a challenging but critical task in modern agriculture. We highlight historical socioeconomic and policy trends that provide key insights into areas where future management strategies can improve within the context of water conservation.

5.1 Historical Water Policy

In the United States, water allocation laws are made at the state level except where subject to federal rules such as interstate commerce (Peck 2007). Among U.S. states, there are four predominant doctrines governing water policy: (1) the absolute ownership doctrine: all water beneath a property owner's land belongs to the landowner, (2) the correlative rights doctrine: landowners must share underlying water with other owners of land over an aquifer, and each owner has equal rights to groundwater, (3) the reasonable use doctrine: the landowner can use underlying water without restriction as long as it is beneficial to the overlying land, and (4) the prior appropriation doctrine: priority belongs to the most senior claim, often phrased "first in time, first in right." The dominant legal doctrines governing water rights across the HPA states are displayed in Figure 8.



State	*Doctrine*	*Control*	*Strategic Plan*
CO	Modified Prior Appropriation[1]	State,[1] Local	Planned depletion[3]
KS	Prior Appropriation[1]	State,[1] Local	Sustainable yield,[2] planned depletion
NE	Reasonable Use/Correlative Rights[1]	Local[2]	Set by NRDs[2]
NM	Prior Appropriation[1]	State[1]	Planned depletion[4]
OK	Reasonable Use[1]	State[1]	Planned depletion[4]
SD	Prior Appropriation[1]	State,[1] Local	Set by state and[4] Indian Reservations
TX	Absolute Ownership[1]	Local[1]	Set by monitoring[2] program
WY	Prior Appropriation[1]	State[1]	Long-term monitoring[5]

[1]McGuire et al., 2003; [2]Peck, 2007; [3]White and Kromm, 1996; [4]Gutentag et al., 1984; [5]Taboga, 2015

Figure 8. Dominant groundwater doctrines, local management boundaries, primary control levels, and prevailing management plans across the HPA in each state.

Most HPA states have developed localized management areas to enact further protection for groundwater after decades of following a state-first control model (Fipps, 1998; Peck, 2007). HPA states have intensified groundwater management strategies by implementing plan requirements, regulating case-specific problems, and establishing critical watershed areas in efforts to address groundwater decline issues not met by pre-existing allocation policies (Ashley and Smith, 1999; Kaiser and Skillern, 2001; Mace et al., 2006). Despite a more localized and defined management approach, allocation policies have failed to adequately protect against groundwater depletion (Kaiser and Skillern, 2001). The control levels of all HPA states are further summarized in Figure 8.

Surface water connections have also become increasingly prominent in modern groundwater policy and legislation. For example, in 1999, Kansas sued Nebraska and Colorado alleging that reduced flow in the Republican River due to large-scale groundwater development violated the Republican River Compact of 1942. Although groundwater was not explicitly addressed in the Compact, the US Supreme Court ruled that groundwater use was restricted if it depleted transboundary streamflow. The resulting restrictions for this region of Nebraska included a suspension on drilling new water wells, mandatory metering of irrigation wells in the watershed and certifying irrigation acreages, restrictions of groundwater pumping volumes, and a framework to use groundwater modeling to assess compliance on five-year running averages (Kuwayama and Brozović, 2013; Peck, 2007). Future water management can capitalize on improved observations and numerical models to formulate strategies that integrate surface water and groundwater as a preemptive step to groundwater conservation.

5.2 Motivation for Policy Changes

Historically, water policies in the High Plains states were created during periods of limited demand on water resources. These initial policies still exist as political frameworks, and policies have been fit within the structure of these outdated philosophies. Most HPA states acknowledge that under current policy, it is more realistic to manage groundwater as a nonrenewable resource or mined commodity, rather than a sustainable and renewable resource (Waskom et al., 2006). As a result, many areas on the High Plains have implemented "manage for depletion" regimes where calculated water withdrawals are permitted based on an extraction formula, rather than targeting aquifer sustainability (McGuire et al., 2003; Peck, 2007; Waskom et al., 2006). Management strategies across the HPA region are summarized in Figure 8.

HPA states have attempted to modify federal, state, or local governance models to fit within the limiting frameworks of historical policy and mitigate groundwater decline, but the limitations of these adjustments are frequently debated as groundwater depletion has continued under both large and small-scale control (Haacker et al., 2015; Kromm and White, 1987; Peck, 2003; Scanlon et al., 2012). A challenge is that large-scale control often overlooks localized needs, but local management bodies can be reluctant to self-impose overwithdrawal sanctions (Peterson, 1991). For example, the absolute ownership doctrine in Texas grants the landowner flexibility in water withdrawals, but little protection exists for neighbors against overwithdrawals. Localized permit systems discourage overwithdrawals, providing greater state and local control, but little flexibility is granted to the landowners and extensive government resources are necessary to administer the complex system of water rights and allocation. Given these challenges, traditional management strategies emerging from past policies are unlikely to meet the water demands of the future (NRCS, 2001; 2004).

5.3 Farmer Profit

Water use across the HPA region is intimately linked to short-term farmer profit. This concept is demonstrated by irrigating corn, the commodity most likely to return the greatest profit, in the water-stressed SHP region, the HPA region least suited for the crop, despite the understood implications of groundwater decline. This suggests that future management strategies focused on water conservation should also take farmer profit into consideration through various economic policies; these policies can be broadly sorted into: (1) ***direct policies***, where direct restrictions are imposed on human behavior (e.g., restrictive water use legislation), and (2) ***indirect policies***, where economic incentives are used to encourage a change in behavior (e.g., subsidies for water-conserving practices). An ideal economic policy should be designed to simultaneously encourage farmer profit protection and water conservation, all while staying within the pre-existing frameworks of direct policies.

Farmer profit is a function of global market demand, production costs, and the variability or risk involved in crop growth. From the perspective of a farmer, risk and variability linked to decreased yields are often the biggest concern for decreased revenues (Barry, 1984). In general, agricultural risk can be divided into: (1) production risk (associated with yield, input costs, and weather variability), (2) market risk (uncertainty about future market value of the harvest), and (3) institutional risk (the potential for change in agricultural policies; Babcock and Shogren, 1995; Barret; 1996; Eakin, 2005). By reducing risk and variability through indirect policies, expected revenue and production costs can be balanced to provide a substantial influence on crop choice.

Crop insurance provides one method to mitigate production risk (Hazell et al., 1986), but the long-term success of this strategy is often questioned (Duncan and Myers, 2000; Miranda et al., 1997). Few other risk mitigation methods exist despite the critical link between risk management and best management practices. For the High Plains, many of the active indirect policies and risk management strategies are defined in the U.S. Farm Bill, a comprehensive agricultural bill passed by congress every five years.

The U.S. Farm Bill includes market supports that boost the value of particular commodities, subsidies that provide incentives for best management practices (e.g., switching to high-efficiency irrigation systems), and crop insurance that decreases the risk of profit loss during a variable growing season. For example, the 2014 US Farm Bill includes the Stacked Income Protection Plan (STAX), which allows enrolled cotton farmers to receive payments if regional yields fall below 90% of the expected level, ultimately decreasing the risk for growing cotton. Another example is the Conservation Reserve Program (CRP), which was first introduced in the 1985 Farm Bill and has significantly affected the HPA region by encouraging the retirement of marginal farmland through rental and cost-share payments to farmers (Osborn, 1993). However, despite the long history of the U.S. Farm Bill, only a few studies (e.g., Rao and Yang, 2010) have examined how indirect policies have influenced water availability.

Most indirect policies have done little to protect HPA groundwater, given that the incentive to increase profits is antithetical to water conservation. In fact, current indirect policies may increase the demand for water use across the HPA. For example, the Renewable Fuel Standard (RFS) of 2005 required that 7.5 billion gallons of renewable fuel be blended into gasoline by 2012 (Schnepf and Yacobucci, 2013). This biofuel mandate generated a profitability incentive to farmers, ultimately increasing the planting of water-intensive biofuel crops (e.g., corn). This increased water burden may or may not be reduced in the future as less water-intensive biofuel crops (e.g., sorghum) become more profitable. Indirect policies concentrated on water conservation will be more realistic if factors such as irrigable acreage and total water use are considered (Caswell and Zilberman, 1985). Interdisciplinary research that integrates social and natural sciences will be necessary to help develop successful future water management strategies that incorporate indirect policies and still mitigate groundwater decline.

5.4 Market Prices

Effective groundwater management strategies must capture spatially and temporally dynamic drivers, making it difficult for uniform policies to be effective. Market prices, for example, have strongly fluctuated over the last fifty years (Figure 9). Commodity prices during the 1970s were much higher than the 1990s, but values increased in the early 2000s to those similar to the early 1980s. More recently, record grain production in 2012 and 2013, coupled with unusually high grain prices in 2012, generated substantial bumper crops and subsequently a sharp decline in grain prices prior to the 2014 season, demonstrating that short-term factors can compromise management strategies even at the seasonal scale (USDA, 2014). Value fluctuations have direct implications on irrigation demand through revenue incentives, particularly when water intensive crops have a high market value. These dynamic complexities in management strategies remain challenging to capture for long timescales; this challenge is intensified by the unknowns linked in other domains such as climate variance and irrigation technologies.

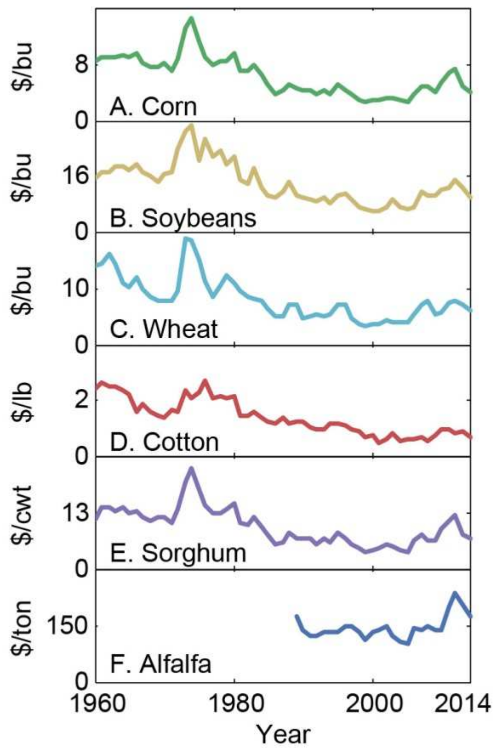


Figure 9. 2014 price adjusted market values for common HPA commodities. Commodity prices are synthesized for HPA states, with the exception of cotton which did not have official state data for the HPA region (NASS-USDA). Cotton prices are derived from national market values. Official alfalfa prices are not available prior to 1989 for the HPA states.

5.5 Irrigation Value

One challenge to cross-commodity analyses is finding an equal metric for comparison. For example, comparing the irrigation water use efficiency for corn and cotton (Figure 7A) would suggest that it is much more efficient to grow corn rather than cotton. But without an economic value for efficiency, it is not an even comparison (i.e., a kilogram of cotton is not equal to a kilogram of corn). To allow for cross-commodity comparisons, we calculated the value of irrigation by multiplying irrigation water use efficiency in kg/ha/mm (Figure 7C) by market value for each commodity converted to $/kg (Figure 9), linearly interpolating the irrigation water use efficiency data annually. The result is a time-series of annual irrigation per commodity (Figure 10). It is no surprise that the irrigation value is high for corn given the large irrigated yield benefit (Figure 7A) and high water use efficiency associated with the crop (Figure 7C), but the irrigation value of cotton is also high despite the relatively low irrigated yield benefit (Figure 7A) and low market value (Figure 9) on a per-mass basis. Thus, quantifying the economic value for irrigation can offer key insights that highlight incentives within the water-energy-food nexus.

Our results indicate that given high irrigation values for both corn and cotton, restructuring a management plan or subsidy program around the production of irrigated cotton instead of water-intensive corn may provide an economic opportunity for farmers in regions like the SHP to switch from corn to the less water-intensive commodity. Another example is the irrigation value of wheat, which has yield benefits and water use metrics similar to those of cotton, but its irrigation value is substantially less (Figure 10). This suggests that economic incentives aligned with the production of irrigated wheat may not be very beneficial to either farmer revenues or water conservation. By understanding the value of drivers like irrigation value, management plans can be designed to promote both farmer profit and the mitigation of groundwater loss by anticipating the most economical decisions for farmers.

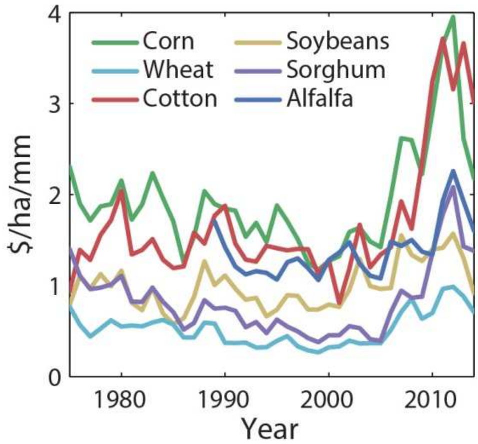


Figure 10. The value of irrigation per commodity across the HPA. Irrigation value is calculated as water use efficiency for each commodity (Figure 7C) multiplied by its corresponding market value in $/kg (Figure 9).

5.6 Adaptive Management and Innovative Strategies

The High Plains would also benefit from adaptive management that is responsive to short-term drivers (e.g., government subsidies, drought) within a long-term framework. Recently, sustainable management approaches have defined long-term goals for desired conditions 50-100 years into the future and used backcasting to inform short-term objectives and water use limits (Gleeson et al., 2012). By adapting short-term regulations to meet long-term goals, water management can be tailored to regional challenges and newly implemented programs. This allows for spatially and temporally relevant adjustments that adapt to the regional needs across the HPA while still maintaining groundwater sustainability as an objective. However, implementation of these strategies is too recent to evaluate the effectiveness of this approach.

Innovative strategies have also been integrated into current policies, but the benefits of these trials have been mixed. Current attempts have included: (1) heterogeneous tax policies, where water during dry years is seen as more valuable than during wet years, thus subsidies are given in exchange for groundwater conservation (e.g., Ashwell and Peterson, 2013), (2) restrictions on new drilling and pumping, and (3) voluntary restrictions to total water use that are self-imposed through personal or local initiatives (Mulligan et al., 2014). However, these strategies have also been shown to increase water use and streamflow depletion because they do not accurately capture changes in practice by users (Ashwell and Peterson, 2013; Scheierling et al., 2006; Ward and Pulido-Velazquez, 2008). Innovative strategies designed to mitigate water use must include the preferences of farmers if groundwater conservation is to be achieved.

When combined with innovative methods and regional markets, adaptive management strategies could significantly alter water use across the High Plains. For example, the Twin Platte Natural Resources District in Nebraska implemented the first groundwater permit trading market in the United States in 2014 to maintain streamflow in the Platte River (Young and Brozović, 2016). Because the marginal cost of water reductions varies across users, permit trading theoretically allows each unit of water pumped out of the system to be used at the lowest overall cost to the system (Brozović and Young, 2014). This contrasts with uniform quotas on groundwater pumping across users, which can force some users to make costly reductions while other low cost solutions are overlooked. Permit markets have the potential to be cost-effective while maximizing flexibility for water users (Palazzo and Brozović, 2014). A longer implementation period is needed for full evaluation, but permit trading highlights a cost-effective groundwater management strategy that promotes farmer profit, includes farmer values, and could be implemented in other regions of the HPA.

6. Discussion and Conclusions

Agricultural water use is depleting the High Plains Aquifer, yet current water management strategies will not prevent future declines. Increased climate variability will likely increase the stress on water resources across the High Plains, specifically through changes in precipitation patterns and drought intensification. We found that irrigation tends to at least double commodity yield when compared to their non-irrigated counterparts, placing a large economic incentive on irrigated water use across the semi-arid High Plains region. Additionally, we found that efficient irrigation technologies can reduce total groundwater conservation, as irrigated acreages substantially increased after the widespread introduction of efficient irrigation technologies and groundwater level declines continued at rates similar to those prior to the efficient systems. Future decades will require significant changes in agricultural practices for the SHP and CHP regions, as irrigable areas are predicted to decline ~30 to 50 percent by 2100 relative to current irrigable areas. We further quantified irrigation water use efficiency and found that the amount of crop per unit irrigation, often called crop per drop, has increased through time for every major commodity. We multiplied these crop per drop values by market prices to quantify the unit value of irrigation water for each commodity. Based on our results, cotton and corn have the highest irrigation value, followed by alfalfa, soybeans, sorghum, and lastly wheat. These new datasets provide a basis to evaluate the influence of major water use drivers across domains and develop key insights into the water-energy-food nexus for modern agriculture.

Based on the trends analyzed in this study, our main conclusion is that future water management strategies would benefit most from: (1) prioritizing farmer profit as an incentive for change in practice, (2) managing water as an input in the water-energy-food nexus, (3) focusing on adaptive frameworks, (4) adopting innovative strategies that function within current policies, (5) reducing production risk, and (6) increasing political desire for resource sustainability.

Short-term farmer profit is the primary driver to water use across the High Plains. As long as there is an economic incentive to irrigate, farmers across the HPA have largely demonstrated that extensive groundwater extraction will continue regardless of the potential risk for resource collapse. While aquifer depletion may be inevitable in some locations, water conservation provides an optimal economic path, giving the region's economy time to diversify and maximize both crop per drop and profit per drop. Introducing restrictive caps and regulations can reduce groundwater use, but these efforts also result in decreased crop yields which pose direct threats of food, fiber, and fuel shortages, as well as local economic hardship. Instead, future strategies should attempt to shift the economic incentive away from immediate groundwater extraction by placing incentives in the growth of less water-intensive crops as a way to encourage sustainable management. This requires development of alternative biofuels, increased demand for the commodities that generate alternative biofuels, and the implementation of government programs or market adjustments to make these alternative crops valuable. Farming practices will follow economic incentives, thus management strategies should incentivize farmers to profitably reduce water use rather than making it more difficult to maintain livelihoods through water use restrictions.

Water is the limiting component to agricultural production within the water-energy-food nexus, and past practices on the HPA demonstrate that overlooked water use incentives will be exploited if not properly accounted for in management strategies. Groundwater sustainability goals can only be met when water use is balanced as an input within the nexus, where food and fuel are functions of water use. In budget terms, groundwater sustainability goals can only be met when annual groundwater use is nearly equal to the annual recharge supplied. Given that the agriculture industry across large portions of the HPA has historically been established using unsustainable practices, future management strategies must compound multiple water conservation methods to offset the extensive reliance on groundwater pumping.

Adaptive frameworks capture temporally dynamic water use drivers (e.g., extended droughts, new government incentives, and market price fluctuations) by granting decision-making freedom in response to changing circumstances. Thus, adaptive management strategies must incorporate short-term objectives that align with long-term goals to remain relevant at extended timescales, and must react to changing physical and social drivers that caused past strategies to become outdated. By allowing for heterogeneous, short-term flexibility in a long-term framework, strategies can be tailored to dynamic drivers even at the seasonal timescale to meet long-term goals.

Widespread groundwater decline is enabled by pre-existing political frameworks that govern water law. These frameworks are outdated and often irrelevant on the High Plains, as evidenced by the shift from regional- to local-scale groundwater management over many areas of the HPA. Management strategies that follow this traditional political framework will also likely fail. Traditional frameworks are too restrictive to capture every critical water use driver, allowing farmers to exploit these overlooked areas and capitalize on the economic incentives they leave unregulated. Instead, innovative and nontraditional strategies should be designed to fit within existing legislation, but designed to capitalize on the decision-making behaviors that follow economic incentives. Innovative strategies do not need to capture every driver; rather, they need to manage for the decisions that follow the key driver: farmer profit. New strategies that align farmer profit with reduced water use may prove more effective within the legislative framework.

Reduced production risk is another way to encourage farmer behavior by placing an economic incentive toward ensured revenue. If the risk associated with a change in practice (e.g., less irrigation) is reduced, then farmers will be more likely to adopt new practices that align with water conservation objectives. Reduced risk can come through mechanisms including the enhanced development of climate resistant cultivars or more effective insurance programs.

There must be the political will to promote groundwater conservation. Past strategies can mitigate groundwater declines to a certain extent, but they cannot fully succeed if there is not the will to implement them. Given that some portions of the HPA are already managing for depletion, there appears to be a conflict between these areas and a regional desire for groundwater sustainability. Management strategies must be constructed with the necessary tools to succeed, but they must also be implemented in a political framework that promotes and advocates for successful implementation.

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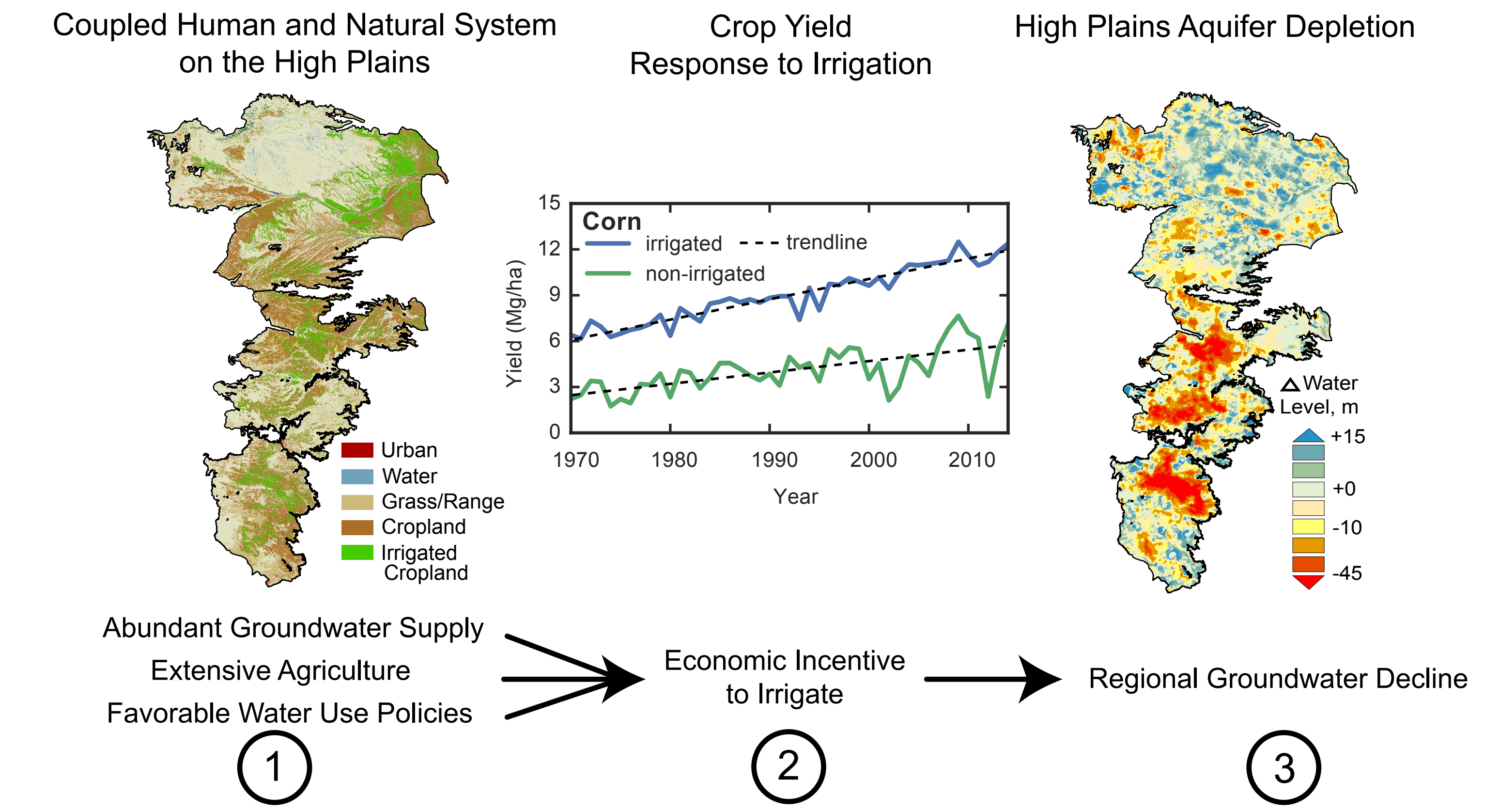

Coupled Human and Natural System on the High Plains
Crop Yield Response to Irrigation
High Plains Aquifer Depletion
Urban
Water
Grass/Range
Cropland
Irrigated Cropland
Corn
irrigated
trendline
non-irrigated
Yield (Mg/ha)
15
12
9
6
3
0
1970
1980
1990
2000
2010
Year
Water Level, m
+15
+0
-10
-45
Abundant Groundwater Supply
Extensive Agriculture
Favorable Water Use Policies
Economic Incentive to Irrigate
Regional Groundwater Decline
1
2
3