ANALYSIS AND ADAPTATION OF THE EFFECTS OF CLIMATE CHANGE AND GROUNDWATER DEPLETION ON CROP PRODUCTION AND WATER AVAILABILITY ACROSS THE HIGH PLAINS AQUIFER

By

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ABSTRACT

ANALYSIS AND ADAPTATION OF THE EFFECTS OF CLIMATE CHANGE AND GROUNDWATER DEPLETION ON CROP PRODUCTION AND WATER AVAILABILITY ACROSS THE HIGH PLAINS AQUIFER

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Crop production in the Central High Plains is at an all-time high due to increased demand for biofuels, food, and animal products. Despite the need to produce more food by mid-century to meet expected population growth, crop production is likely to plateau or even decline in the Central High Plains due to excessive groundwater withdrawal. The Central High Plains has experienced a consistent decline in groundwater due to groundwater withdrawal for irrigation greatly exceeding natural recharge. In this heavily irrigated region, water is essential for maintaining yields and economic stability. Here we evaluate how groundwater depletion impacts total irrigation water demand, and quantify the impacts of these changes on crop yield and production through to 2099 using the well-established SALUS crop model. Additionally, different adaptation methods were examined to explore ways to preserve yields with different future climates and water availability.

This thesis is dedicated to my husband, Trevor, and my parents, Ron and Kathy.
Thanks for always believing in me and supporting my dreams.

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KEY TO ABBREVIATIONS

HPA	High Plains Aquifer
CHP	Central High Plains
SALUS	System Approach to Land Use Sustainability
USDA	United States Department of Agriculture
NASS	National Agriculture Statistics Service
NLDAS	National Land Data Assimilation Systems
RCP	Representative Concentration Pathways

Chapter 1: Groundwater Depletion and Climate Change: Crop Production Declines over the Ogallala Aquifer

1.1 Introduction

Crop production and food security are amongst the top international concerns due to the impacts of climate change (Tilman et al. 2011; Basso et al. 2015; Pei et al. 2015). Global food demand is expected to roughly double from 2005-2050 (Pei et al. 2015), yet projected changes in climate are likely to reduce crop yields given current crop management (Bassu et al. 2014; Asseng et al. 2015). Agriculture's susceptibility to climate change will depend on the biophysical effects of climate change coupled with capabilities for production to adapt (Marshall et al. 2015). To maintain or increase yields in heavily groundwater irrigated areas, farmers will need to adapt to both climate change and declining water resources (Fischer et al. 2007).

Current literature on the combined effects of climate change and reduced water availability for irrigation remains limited or it is considered at global scale with many uncertainties (Elliott et al. 2014). Such an analysis is critical for regions like the High Plains Aquifer (HPA) that rely heavily on groundwater for irrigation to supplement insufficient growing season rainfall. In the most severe drawdown areas, groundwater levels in the HPA have declined by more than 30 meters, impeding its use (Scanlon et al. 2012). Other aquifers across the globe that support irrigated agriculture such as North Arabian, North China Plain, Upper Ganges, Persian, and Western Mexico are similarly experiencing widespread stress on groundwater resources (Gleeson et al. 2012).

Crop modelers have examined numerous aspects of crop growth and development to help understand the implications of reduced water and climate change on crop production. Specifically, modeling studies have examined crop yield and season length (Basso et al. 2006,

2015) and impacts of projected future climate changes on yield (Reilly et al. 2003; Schlenker and Roberts 2009; Basso et al. 2015). Many modeling experiments have analyzed water usage and implications for crops, for example by examining water use efficiency of corn (Al-Kaisi and Yin 2003), sensitivity of recharge due to rainfall variations between irrigated and dryland agriculture (Crosbie et al. 2013), and impacts of crop yield and groundwater depletion by switching from irrigated to dryland agriculture (Colaizzi et al. 2009; Scanlon et al. 2012).

With irrigated agriculture representing 20% of cropland and 40% of food production globally, (Scanlon et al. 2012) it is one of the most vital resources on the planet. Within the United States, 22.9 million hectares of cropland are irrigated with 67% of the water used to irrigate coming from groundwater (Brown and Pervez 2014). Over 6 million hectares of irrigated cropland are fed by the HPA, making it the most extensively used aquifer in the United States (Qi et al. 2002; Harding and Snyder 2012). As farmers have expanded irrigation, stored water in some parts of the HPA have been quickly depleted due to relatively small recharge rates in this semi-arid region (Rosenberg et al. 1999). Historically, Texas, Kansas, and Nebraska have been the primary consumers of groundwater from the HPA, using as much as 88% of the water withdrawn from the aquifer, with nearly all of those withdrawals going to irrigated agriculture (Maupin and Barber 2005; Brown and Pervez 2014). The largest declines of the aquifer have occurred in southwest Kansas along with the panhandle of Texas, within the Southern and Central High Plains (SHP and CHP) (McGuire 2011).

Compounding water availability challenges, the CHP is projected to have both warmer and more drought prone conditions (Rosenberg et al. 1999), with a possible 2 to 5°C increase in average temperature through the end of the century (Intergovernmental Panel on Climate Change (IPCC) 2007; Stocker et al. 2013; Crosbie et al. 2013). Ensemble climate projections indicate that somewhat more precipitation may fall in the north and slightly less in the south (Intergovernmental Panel on Climate Change (IPCC) 2007; Crosbie et al. 2013), with drought events becoming more extensive and frequent (Harding and Snyder 2012). With these trends, along with associated longer growing seasons, water demand for irrigation will increase, further intensifying water availability limitations due to declining aquifer levels (Döll 2002; Harding and Snyder 2012).

Here we apply the System Approach to Land Use Sustainability (SALUS) model, driven by statistically-downscaled climate simulations, to simulate the likely impacts of climate change scenarios on crop yields and irrigation demand for two of the most important global crops: corn (maize) and winter wheat. Historical simulated yields were validated relative to observed annual county yield data from the USDA National Agriculture Statistics Service (NASS), and the bi-decadal USDA Agricultural Census (Smidt et al. 2016). We then created a projection of water resource limitations due to declining groundwater levels across the CHP, which dictates where farmers will be forced to switch from irrigated to dryland production in the future. Regional agricultural production of corn and wheat across the CHP, along with total irrigation water demand, are then quantified.

1.2 Methods

1.2.1 The Central High Plains

The CHP, which covers ~127,000 km^2 of Colorado, Kansas, Oklahoma, Texas, and New Mexico (Stanton et al. 2011), is ideal to examine the combined impacts of climate change and limited water resources because it has experienced significant declines in groundwater levels for decades, and due to upstream diversions has no significant surface water resources. Overall, the CHP terrain consists of varied rolling hills and is predominantly flat. Erosion from the Missouri, Arkansas, Platte, and Pecos rivers formed the western border of the HPA and similarly erosion from several small streams formed the eastern border (Gutentag et al. 1984). Prior to being dominated by agriculture, the HPA consisted of short-grass prairie and few trees (Qi et al. 2002; Hornbeck and Keskin 2011). The climate of the HPA is semi-arid with abundant sunshine, strong winds, and an average of less than 50 centimeters of rain annually, ranging from approximately 40 centimeters in the west to 70 centimeters in the east (Gutentag et al. 1984; Qi et al. 2002; Hornbeck and Keskin 2011). These climate conditions increase the need to irrigate to maintain yields, especially for crops highly dependent on water.

Approximately 20-25% of the HPA already has insufficient groundwater storage to irrigate; by the end of the century this is expected to grow to 40% (Haacker et al. 2015). Once the saturated thickness of the aquifer drops below approximately 9 meters, the aquifer cannot sustain a high enough well yield for typical high volume irrigation systems (Haacker et al. 2015). Based on decades of declining water levels, portions of the HPA that have been heavily used for irrigation will likely continue to decline by 10-20% per decade without widespread conservation of water (Haacker et al. 2015); the region is clearly on an unsustainable path due to high rates of groundwater withdrawal along with minimal annual recharge (Gutentag et al. 1984).

Irrigation is applied to crops to avoid water stress during critical periods of growth, occurring predominantly from June through August for most crops across the CHP. Winter wheat is an exception as it is irrigated in October (after planting) and from March through May; it typically requires 450-650 mm of water to maintain high yields (FAO 2015). Corn demands more water with 550-750 mm of water required annually to maintain acceptable yields (Basso and Ritchie 2014). Since 1970 the amount of corn acreage on the CHP has increased from approximately 0.5 to 2 million acres annually with 75% of those acres being irrigated (National Agricultural Statistics Services database 2015; Smidt et al. 2016). Wheat acreage has slowly declined from its maximum of 7 million acres in 1970 to ~4 million acres today, of which ~20% are irrigated (National Agricultural Statistics Services database 2015; Smidt et al. 2016).

1.2.2 SALUS crop model

The System Approach to Land Use Sustainability Model (SALUS) simulates continuous changes in water, soil, and crop conditions under a range of management options over multiple years (Basso et al. 2006; Senthilkumar et al. 2009; Hoang et al. 2014; Dzotsi et al. 2015). Different management options SALUS simulates include crop rotations, plant populations, planting dates, irrigation, fertilizer, and tillage (Basso et al. 2006; Hoang et al. 2014). The modules for crop growth are based on the CERES (Ritchie et al. 1988; Ritchie et al. 1989) and IBSNAT group of crop production models (Jones and Ritchie 1990) that were designed for annual monoculture simulations (Basso et al. 2006; Hoang et al. 2014). The different management strategies can run simultaneously, allowing comparison of crops and soils under the same weather conditions (Basso et al. 2006; Hoang et al. 2014). The model simulates crop growth and soil using crop-soil-water interactions (Basso et al. 2006) including fallow periods and growing seasons (Hoang et al. 2014). SALUS requires input data on climate, soil, genotype and management, which were obtained from different public sources. Simulated yields were validated with annual average crop yield from 1985-2014 county data from the USDA National Agricultural Statistics Service (NASS) using a combination of Agricultural Census and Agricultural Survey data (National Agricultural Statistics Services database 2015) from all counties across the region.

In order to accurately represent the advancement of corn hybrids, we used three hybrids to represent the historic corn simulations used in the validation. Corn was represented by a low-medium yielding hybrid from 1985-1996, a medium yielding hybrid from 1997-2009, and a medium-high yielding hybrid from 2010-2014 and for all climate projection simulations. A medium-high yielding winter wheat hybrid was used for both the historic validation and climate projection simulations. Identical cultivars were used for both irrigated and dryland scenarios for both corn and wheat.

Weather data was derived from the NLDAS-2 (North American Land Data Assimilation System), (Ek et al. 2011). A 5 by 8 fishnet polygon grid was created that spanned the CHP (Fig. A.1) and was used to find the daily mean of the NLDAS weather attribute for each 93.5 by 68.3 km grid cell. Weather attributes include precipitation (mm), daily maximum temperature (˚C), daily minimum temperature (˚C), and solar radiation (MJ/m^2).

Soil type variability was determined at the scale of the weather grid cells. Within each grid cell, the predominant SSURGO soil textural class upon which corn and wheat were grown according to the 2014 Cropland Data Layer was selected to represent the entire grid. Default soil parameters within SALUS were then chosen for each textural class.

Corn was managed identically for all irrigated and dryland cultivars except for the irrigation component. Every year corn was planted on the 120th day of the year (April 30th) (Shroyer et al. 1996), and was harvested when the crop reached maturity determined by the model. Farmers in the CHP typically irrigate corn every 3-4 days to keep the crop from becoming water stressed, due to its high dependence on water for growth. Therefore, we assumed that irrigation was applied whenever the soil profile from the surface to 25 cm reached

75% of plant available water during the growing season. Irrigation was then applied via sprinkler until the soil reached the drained upper limit, or field capacity.

Winter wheat was also managed identically for both irrigated and dryland wheat except for irrigation. Wheat was planted on the 285th day of the year (Oct 12th, nominally) (Shroyer et al. 1996). Harvest occurred on the 180th day of the year (June 29th) allowing time for the wheat to grow and mature throughout the winter. Automatic irrigation was also used for wheat; however, the soil was allowed to dry significantly more than for corn. Once the surface 25 cm of soil reached 30% plant available water during the growing season, irrigation was added until the soil achieved 75% of plant available water.

To simulate annual crop yield and irrigation application for each of the 40 fishnet polygon cells, SALUS simulations used the predominant soil texture, weather from the three climate scenarios, crop type including both corn and wheat, and management decisions including irrigated or dryland for each cell totaling 480 different simulation combinations for each year from 1985-2099. The median value across all cells was used to represent annual crop yield and irrigation application to reduce the influence of any high and low outliers on the simulated yield and irrigation application values.

1.2.3 Climate Projections

To account for projected climate changes, a change factor downscaling approach (Basso et al. 2015) was used based on historical weather observations from NLDAS-2 (Ek et al. 2011) and future projections from an ensemble of one run of each model in the Coupled Model Intercomparison Project-5 (CMIP-5) database (Taylor et al. 2012). First, a bias-adjusted historical climate change trend was calculated from an ensemble of GCM (General Circulation

Model) simulations for the historic period (1980-2014), which was then used to create detrended 35-year climate series by removing the climate change signal from historical observations. This detrended 35-year time series was then replicated to create a continuous future climate dataset through 2099, by applying time-varying monthly change factors calculated from the ensemble of future projections for each of the RCP 4.5, 6.0, and 8.5 scenarios. These future climate projections were then combined with the observations from 1980 – 2014 to create continuous 120 year daily climate series. CO_2 concentrations were incorporated into the simulations yearly from 1985-2014 using data from Mauna Loa (Tans and Keeling 2016) and once per decade from 2015-2099 based on projections from RCP 4.5 (Smith and Wigley 2006; Clarke et al. 2007; Wise et al. 2009), RCP 6.0 (Fujino et al. 2006; Hijioka et al. 2008), and RCP 8.5 (Riahi et al. 2007).

1.2.4 Calculations of Yield, Water Use, and Production Decline

We calculated the year when high volume irrigation will no longer be possible due to the saturated aquifer thickness dropping below 9 meters, which is commonly used as a minimum saturated thickness threshold for maintaining high volume irrigation. The depletion year was determined using a linear fit of water level data within 250 meter grid cells from 1993-2012 to determine a depletion trend (Haacker et al. 2015) (Fig. 1). Irrigated crop production was calculated by multiplying irrigable area within each cell for that crop by simulated yield for that cell and summing across all 40 grid cells; dryland production was calculated in a similar manner. Projected irrigation withdrawals were calculated by multiplying irrigable area within each cell by annual simulated irrigation demand for that cell, which was then summed across all cells. Decline percentages for yield, production, and acreage were calculated based on a linear fit of annual values from 2015-2099. Groundwater depletion impact on regional production was calculated by taking the difference of production change due climate change alone, keeping irrigable area constant at the 2015 values into the future, and subtracting the production change due to both change in irrigable area and future yields.

1.3 Results

Estimated aquifer depletion timeframe across the CHP (Fig. 1a) shows that although most of the eastern portion of the CHP is likely to support irrigation beyond 2099, most of the western CHP and parts of the central portion will lose the ability to irrigate from groundwater by 2050. Once a region loses the ability to pump groundwater for irrigation, farmers will have to move to dryland farming if they do not have access to surface water—largely unavailable in this region. Groundwater levels in such depleted regions will require decades or centuries to recover, making it nearly impossible for farmers return to irrigation once they switch to dryland agriculture.

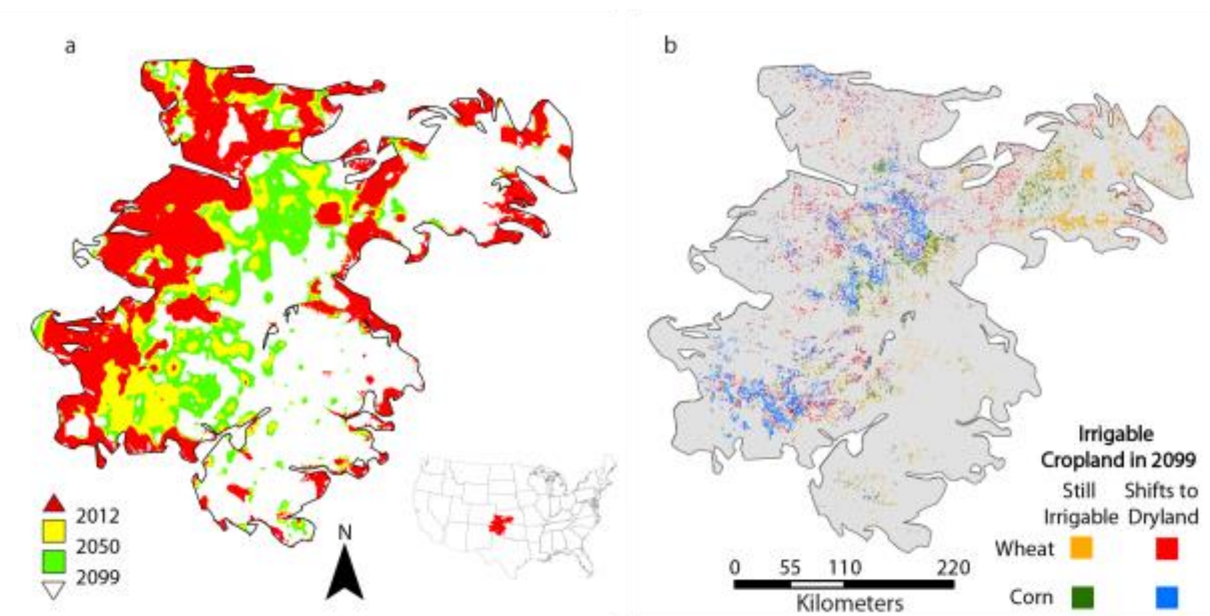

Figure 1: Projected year irrigation become unavailable
a) Projected decline in irrigable area, and b) map of irrigation availability for corn and wheat in 2099. A CHP location map is included in the lower center; note a simplified boundary is shown for easier visualization (Qi et al. 2002)

We forecast the likely influence of saturated thickness decline across the CHP on corn and wheat irrigation availability (Fig. 1b), using a spatially explicit map of crop occurrence from the Crop Frequency Data Layers (Boryan et al. 2014) and remotely sensed irrigation estimates (Brown and Pervez 2014). Areas that were irrigated in 2012 and can still irrigate in 2099 are shown in gold and green in Fig. 1b; these are predominantly in the eastern portion of the CHP that receives more rainfall and groundwater recharge naturally. Areas in red and blue in Fig. 1b were irrigated in 2012 but are projected to have insufficient water to irrigate by 2099 and will be forced to switch to dryland agriculture. Approximately 70% of currently irrigated areas of corn and wheat will likely need to switch to dryland management by 2099.

All four irrigated and dryland corn and wheat simulations reproduced thirty years of yield observations (Fig. 2) with given inputs representative of the area studied. For each year evaluated, the observations fell within ±25% of the median yield predictions for the region, lending confidence that SALUS is capable of effectively projecting crop yield for the region in response to variable climate. On average, irrigated corn historically yields 2-3 times more than dryland, and irrigated wheat yields about 1.5 times more than dryland. Standard deviations (Table A.1) were calculated through time for both irrigated and dryland, corn and wheat. Irrigated and dryland corn had larger standard deviations due to higher yields than wheat and therefore higher range of variability. Irrigated corn and wheat have lower standard deviations relative to dryland corn and wheat indicating that there is less variability in irrigated yields, largely due to farmers adding irrigation to help preserve yields.

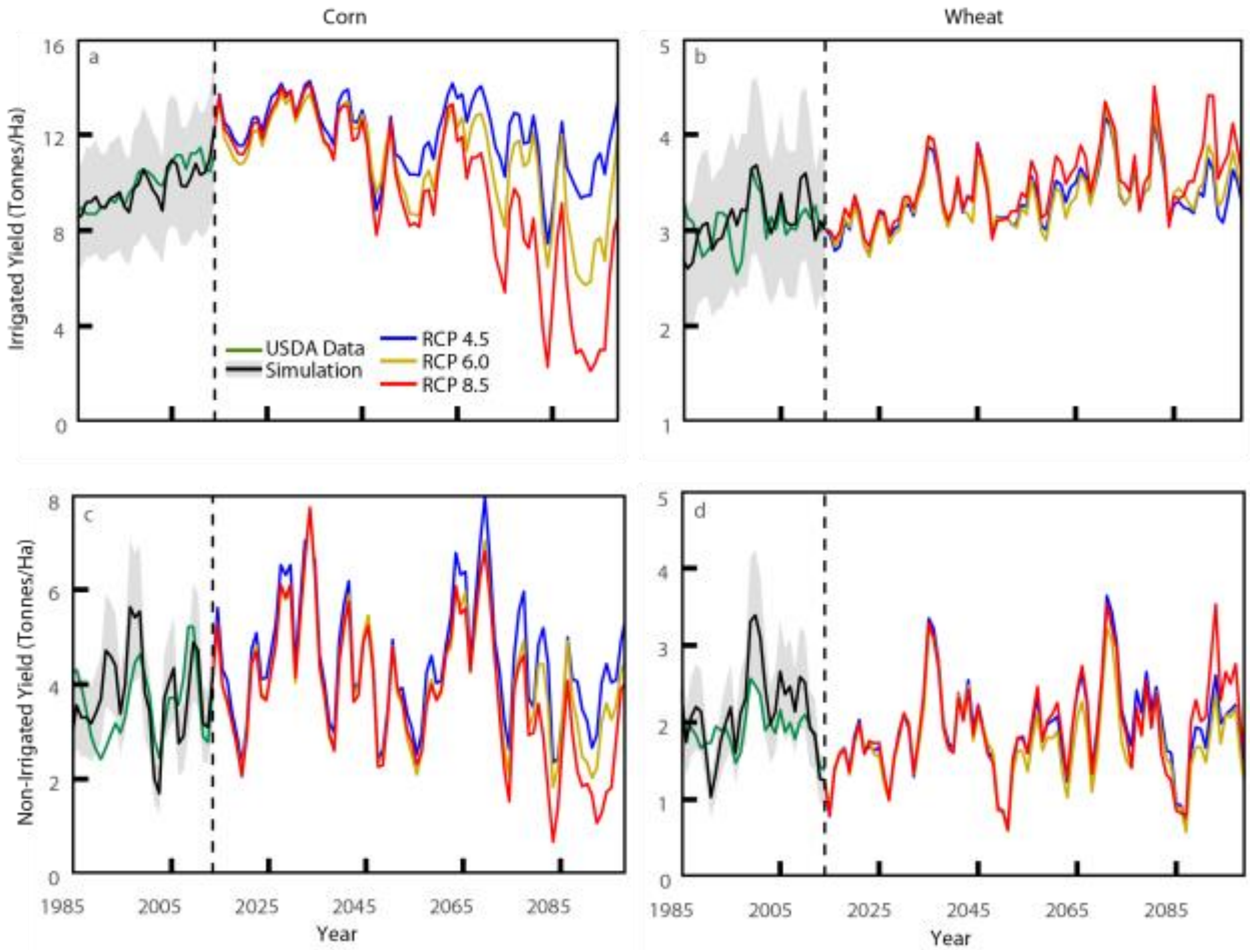

Figure 2: SALUS historic and simulated future yields
SALUS-simulated yields for all four crop treatments and forecast scenarios, along with observed historic values. Median historic simulated SALUS yields (black) overlay gray shading, which depicts simulated cells ±25% from the median. Data and models are both shown with a three year moving average

Simulated irrigated corn yields (Fig. 2a) appear to be relatively insensitive to the differences in projected climate scenarios for the first half of the century (through 2050). However, scenarios diverge significantly towards the end of the century where simulated yields under RCP 4.5 conditions have nearly 4 times the yield of RCP 8.5; all irrigated corn simulations show a loss in yield in the future (Fig. 2a). In contrast to irrigated corn, irrigated wheat yield shows an increase in yield through the end of the century (Fig. 2b).

Future dryland corn yields are projected to decline through the end of the century. Yields of dryland corn (Fig. 2c) show slight declines due to heat stress, especially towards the end of the century with the RCP 8.5 having a 45% reduction; however, RCP 6.0 and RCP 4.5 are not as affected, showing a decrease in yield 17% and 10%, respectively. Projected dryland wheat yields (Fig. 2d) remain fairly consistent for RCP 6.0 showing only a 3% increase whereas RCP 8.5 shows a 40% increase and RCP 4.5 a 20% increase. However, the difference between low yield and high yield years are greater in the future, especially for RCP 8.5.

From 1985 to 2014 (National Agricultural Statistics Services database 2015) there were significant increases in irrigated corn acreage, mostly offset by reductions in irrigated wheat area (Fig. 3a). These changes have been largely driven by water availability and the economics of the two crops (Smidt et al. 2016). Assuming that the 2014 relative proportions of irrigated acreage between these two crops remains the same in the future, our analysis shows that irrigated corn acreage is projected to decrease by 60% through the end of the century; irrigated wheat acreages may decrease by about 50% driven simply by the progressive depletion of water levels beneath the CHP region. As a result of this switch out of irrigated production, acreage planted in dryland corn is projected to increase 125% by 2099, surpassing irrigated corn acreage in the 2050s (Fig 3a). Due to its significantly greater acreage in 2014, dryland wheat acreage is projected to increase by just 10% due to fields switching away from irrigated wheat.

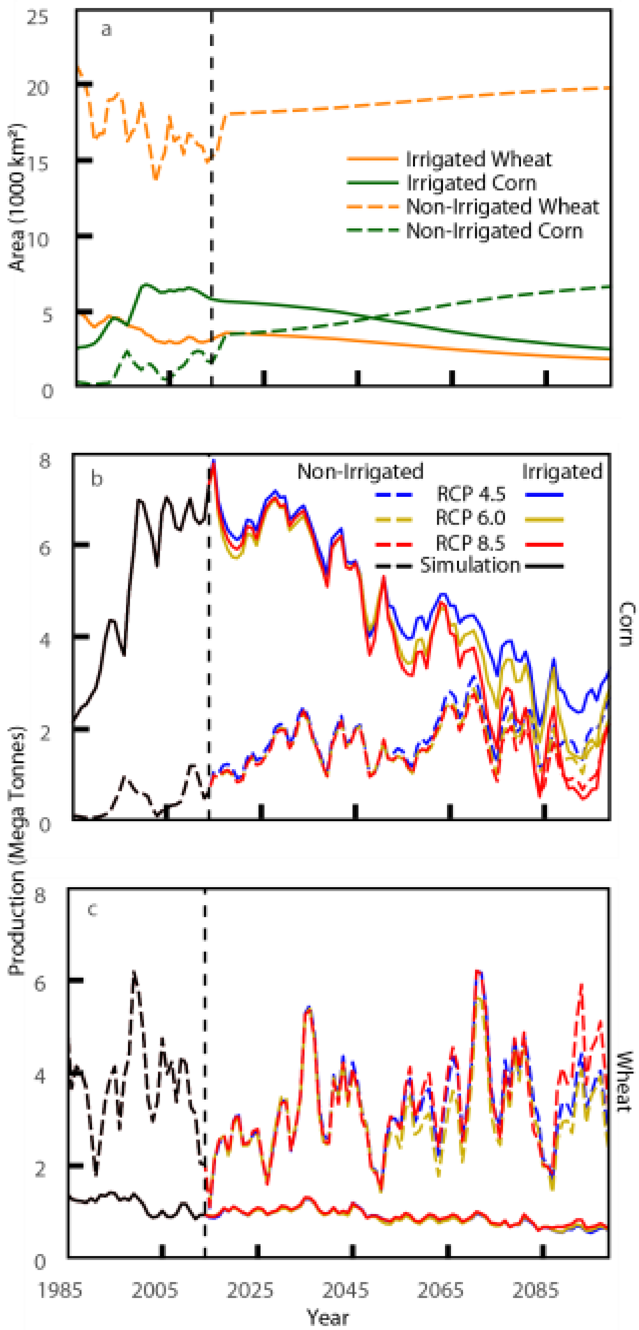

Figure 3: Change in irrigable area and crop production
a) Change in irrigable and dryland area of corn and wheat; production of both irrigated and dryland b) corn and c) wheat

Declines in irrigated acreage dramatically impact total regional grain production. By 2099, irrigated corn production is projected to decline dramatically compared to the production in 2015 (Fig. 3b) with RCP 8.5 having the highest reduction of about 90% (Table 1). Dryland corn production is projected to increase over time, but not enough to compensate for projected decreases in irrigated corn production. Projected total corn production decreases as much as 75% relative to current levels (Table 1). Dryland wheat production is projected to remain fairly steady to the end of the century (Fig. 3c), while irrigated wheat production shows a steady decrease into the future. Total regional wheat production increase ranges from 2% for RCP 6.0 up to 30% for RCP 8.5 by the end of the century (Table 1).

	Corn	Wheat	Corn	Wheat
	Irrigated Yield % Change		Dryland Yield % Change	
RCP 4.5	-16.6	13.7	-11.9	17.4
RCP 6.0	-33.0	18.0	-22.7	3.3
RCP 8.5	-64.1	24.1	-43.1	30.4
	Irrigated Production % Change		Dryland Production % Change	
RCP 4.5	-67.0	-43.6	47.1	36.6
RCP 6.0	-75.6	-41.8	32.0	20.1
RCP 8.5	-90.1	-37.6	-1.2	60.3

Table 1: Percent change of yield and production for corn and wheat
Linearly-fit percent change between 2099 and 2015 of yield and production for both irrigated and dryland corn and wheat

As the aquifer depletes and irrigation becomes unfeasible, total CHP irrigation withdrawals decline. Both wheat and corn irrigation withdrawals are projected to decrease over time for the three climate scenarios (Fig. 4). While total irrigation withdrawals related to wheat production show a decrease of about 50%, the decrease in the total irrigation withdrawal attributed to corn is around 65% (Fig. 4).

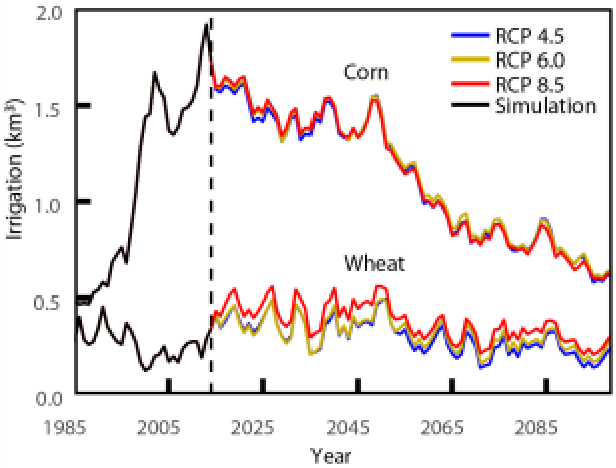

Figure 4: Total irrigation withdrawal across the CHP for corn and wheat
Total irrigation withdrawal for the CHP, including historical simulations (1985-2014) and forecast scenarios (2015-2099)

1.4 Discussion and Conclusions

This study quantifies the combined impacts of climate change and groundwater availability on future crop yields and production. The impact of climate change on crops in the region is mixed, with corn yields declining under higher temperature scenarios, while wheat yields benefit from the projected increase in atmospheric CO_2. In particular, irrigated corn yields are projected to decrease as much as 65% through the end of the century due to rising temperatures and the effects of aquifer depletion on regional production. As the climate scenarios diverge substantially towards the end of the century, there are larger declines in yield under the higher temperature scenarios as heat stress begins to impact plant growth. Dryland corn yields are less sensitive to climate change than irrigated yields because they already experience significant water stress, which limits yields far short of potential during most years. Enhanced CO_2 fertilization, which enhances growth of C_3 plants (Deryng et al. 2016), increase wheat yields for the RCP 8.5 scenario enough to compensate for the increased heat stress, which decreases the yield under the RCP 6.0 scenario.

In semi-arid regions, crop production is a function of both crop yields and water resource availability. Our simulations show that corn production on the CHP will decline regardless of the impact of climate change on yields due to decreases in irrigable corn area of 60%, and despite increased per-acre yields wheat production will only increase slightly due to irrigable wheat area declining by 50% relative to recent levels. Projected reductions in saturated thickness of the underlying aquifer indicate that by 2099 most of the western CHP will no longer be able to irrigate. These decreases in irrigated acreage have a direct impact on total regional grain production. The decline in total regional grain production between 2015 and 2099 is largely due to the reduction in the area that can support corn irrigation (Fig. 3a) forcing farmers to switch to dryland agriculture that has yields 2-3 times lower than irrigated corn yield compounded by decreasing yields due to warmer temperatures (Fig. 2a). Reduction of irrigation availability causes a decrease in total corn production 20-30% and wheat total production about 10%. Fortunately, for wheat, CO_2 fertilization helps to mitigate the negative impacts of climate change. However, projected declines in available groundwater for irrigation causes irrigated wheat production to have a steady decrease into the future. These changes in irrigation availability would greatly reduce yields in a large portion of the central CHP that has extensive irrigation, causing significant declines in regional production. This would devastate the regional economy and reduce grain production for the U.S.A.

Taken together, the paired impacts of aquifer depletion and climate change represent a significant threat to economic and food security in the CHP. For RCP 6.0, the mid-range temperature scenario, we project a decrease in production of about 75% for irrigated corn and decrease of 40% for irrigated wheat. Dryland production would increase on the formerly irrigated land with dryland corn increasing about 30% and wheat about 20%, partially compensating for the loss in irrigated production. However, total regional production will decline as much as 60% for corn and increase only 2% for wheat for RCP 6.0. Assuming 2014 prices, this translates to an annual net economic loss ranging from $260 million to $1.1 billion of corn by the end of the century in current dollar terms.

Our aquifer depletion scenario assumes that declines will continue at the same rate into the future; however, climate change is likely to amplify water resource demands. Irrigation demand for corn is expected to increase 5-15% due to increased ET and evaporative demand causing the crop to become more water stressed and require more irrigation (Figure A.2). Increased irrigation demand would tend to increase the rate of aquifer decline, indicating that the decline scenario presented here is conservative, and actual impacts will likely be higher. While corn is highly dependent upon water for growth and development, wheat is less dependent and will be affected less by decreased water availability. Wheat is planted in the fall and harvested late spring, thereby avoiding the hot, dry summer that can damage plants. Wheat irrigation demand is projected to decrease in the future with about a 5-10% decrease in RCP 6.0 and RCP 8.5, and RCP 4.5 decreasing about 35%. As the aquifer depletes and irrigation becomes unfeasible, total CHP irrigation withdrawals decline. Both wheat and corn total irrigation withdrawals are projected to decrease over time for the three climate scenarios (Fig. 4), largely due to a decrease in the amount of irrigable area (Fig. 3a).

Preserving the food production and economic security of the CHP necessitates both mitigation and adaptation strategies. Mitigation strategies are needed to reduce the rate of aquifer decline, including reducing groundwater withdrawals in some or all years, or artificially supplementing natural recharge. Further strategies are needed to reduce the impacts of higher temperatures on corn yields, including developing new drought resistant cultivars, or those with maturity rates better suited to the shifting regional climate conditions. Adaptation strategies might include changing planting dates, altering plant population density (Basso et al. 2015), or planting different crops. Similarly, irrigation decisions are necessary to prolong the life of the aquifer and be more efficient with available water. These include identifying the optimal time for irrigation along with altering application amounts, implementing deficit irrigation, and continuing to develop and deploy more efficient irrigation technologies such as LEPA (Low Energy Precise Application). Adaptation and mitigation strategies can have a positive long-term impact on both HPA water resources and crop production.

Chapter 2: Quantifying the influence of potential agricultural adaptation to address projected changes in climate and reduced groundwater availability, High Plains Aquifer, USA

2.1 Introduction

One of the dire challenges facing today's society is the projected impact of climate change on water and food sustainability. The Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Reports in 2007 and 2013 respectively, found that the average global temperature has risen approximately 0.7 ° C from 1906-2005, with the warming trend for the 50 most recent years being twice the rate of the previous 50 years (Bernstein et al. 2007). During this same time period, several regions, including eastern parts of North America, had a significant increase in precipitation (Bernstein et al. 2007). These changes in temperature and precipitation, along with increasing levels of atmospheric carbon dioxide, will have strong implications for agriculture.

The High Plains Aquifer (HPA), located in the western/central United States, which is dominated by agriculture, will have to adapt to help mitigate the negative consequences of future climate changes on agricultural productivity. The mean annual temperatures across the Central High Plains (CHP) are predicted to increase by 2 to 5 ºC (Intergovernmental Panel on Climate Change (IPCC) 2007; Stocker et al. 2013; Crosbie et al. 2013), creating warmer and drier conditions (Rosenberg et al. 1999). Future climate predictions show more precipitation in the north and less in the south (Crosbie et al. 2013) with increased frequency and severity of drought events (Harding and Snyder 2012), (Walthall et al. 2012). Such changes in precipitation and temperature will affect crop growth and development which are directly correlated to crop production. To help alleviate the projected yield declines, farmers must alter or modify their crop management decisions to help mitigate climate change impacts (Basso et al. 2015). Reductions in crop productivity in areas such as the HPA will likely be exacerbated due to widespread reliance on withdrawing groundwater for irrigation at unsustainable rates. Since irrigated yields in the region are 2 to 4 times higher than non-irrigated yields (National Agricultural Statistics Services database 2015; Smidt et al. 2016) it is imperative that farmers rapidly move to more sustainable withdrawal rates from the HPA.

Crop growth and development in an agricultural system are affected by a range of environmental factors such as temperature, water, CO_2, nutrients, and agronomic management (Ko et al. 2011). Temperature increases could substantially change plant phenology due to the influence of temperature on the timing of growth and development of crops (Anandhi 2016). During the next century, projected increases in temperatures could cause shifts in crop production areas due to temperatures shifting out of the appropriate ranges for particular crops, or during the crucial time period necessary for peak crop growth and yield (Walthall et al. 2012). While an increase in ambient CO_2 enhances growth in C_3 plants (Deryng et al. 2016), the negative effects of increased temperatures may reduce or exceed the positive impacts of an increase in atmospheric CO_2 in dryland cropping systems for future climate scenarios (Ko et al. 2011).

Along with declining water levels in the HPA due to the excessive irrigation, a longer future growing season will demand improvements in water management (Anandhi et al. 2013). Moisture stress within a week after silking can result in significant declines in corn yield. For example, one day of stress can cause yield losses of up to 8%, whereas severe moisture stress of 3-4 days can reduce yields by 30% or more (Anandhi 2016). Understanding the duration and dates of crop growth stages can be used to estimate crop water requirements based on the duration of each stage and potential evapotranspiration estimates (Anandhi 2016).

Several studies have examined adaptation strategies for crop yield and production to help reduce climate change impacts. Irrigation typically increases crop yields two to four times compared to dryland-based production systems (Colaizzi et al. 2009, Smidt et al. 2016). Irrigated crops could be converted to rainfed crops; however this would decrease yields accordingly while saving on pumping and reducing aquifer depletion rates (Scanlon et al. 2012). Switching crop types and switching to dryland-based systems could cause severe economic consequences due to the semi-arid climate and high reliance on irrigation (Almas et al. 2006), unless alternative economic applications could be developed that did not rely on intense irrigation (Almas et al. 2004; Colaizzi et al. 2009).

Conservation agriculture involves management practices used to maintain or increase crop yields while reducing the degradation of the soil, and to withstand stresses due to weather, including those associated with climate change and variability (Powlson et al. 2016). Conservation agriculture has three main principles: 1) minimizing soil disturbance relative to conventional tillage by no-till or reduced tillage, 2) retaining crop residues to help maintain soil cover, and 3) using crop rotations rather than common monoculture practices (Powlson et al. 2016). In a crop model based study over a 121 year period, conventional tillage produced higher yields than no-till for the first part of the simulation; however after 20 years of soil C accumulation, no-till yields surpassed conventional tillage yields in most years (Basso et al. 2015). A similar study found a no till-based system maintained higher yields than conventional tillage in a wheat fallow rotation for future climate conditions through 2075 (Ko et al. 2011). These studies support the assessment that no-till may be a good adaptation strategy to maintain yields under future climate conditions, which is also the recommended practice under current climate.

Knowledge of spatial and temporal variations in growing degree days (heat units corn depends on for growth and maturity) can be beneficial to improve management decisions such as timing of planting, harvesting, and efficient timing for application of fertilizer, pesticides, and irrigation (Anandhi 2016). Research is needed to better understand the effects of changes in the quality and yield of crops as well as use of crop models to help sustain agricultural yields under such projected changes (Anandhi 2016). Studies have shown that increased temperatures may reduce yields by shortening the crop growth cycle and reducing the optimal growing season length. One adaptation strategy is to use corn cultivars that have a longer duration and can tolerate higher temperatures (Islam et al. 2012). Future predictions indicate an earlier emergence and maturity of crops, which is important to consider when planning to plant and harvest (Anandhi 2016). By planting 10 days earlier, and at higher planting densities, in addition to choosing a cultivar with higher kernel setting efficiency, yields can be sustained despite the negative effects of projected temperature increases during the critical time period of kernel setting (Basso et al. 2015). Other studies, however, have shown that the adaptive strategy of planting the crops earlier (up to 30 days from the historical dates) did not yield promising results (Ko et al. 2011). Farmers will likely modify their management plans by altering planting dates and choosing cultivars that might benefit from a longer growing season due to earlier possible planting and shorter periods of frost risk under climate change scenarios (Basso et al. 2015).

Other adaptive strategies include changing planting dates, varieties/cultivars, cropping sequences, and irrigation levels (Islam et al. 2012). Earlier crop emergence and physiological maturity can be used in combination with projected available groundwater to help estimate changes in crop water requirements including periods of water stress during crop growth. The stressors could reduce yields, therefore making it imperative in selecting hybrids that produce good yields with the available water (Thorp et al. 2007; Anandhi 2016). Another important agricultural aspect of the CHP is the large number of livestock operations. Much of the corn in the CHP is grown to feed nearby livestock. Therefore, farmers must choose crops and irrigation strategies to maximize agriculture production for crops and livestock while continuing to be sustainable into the future (Geerts and Raes 2009).

Here we examine the impact of crop yields using different adaptation strategies under projected changes in climate that account for changes in growing season and plant phenology. Since future climate in the HPA is projected to be warmer and drier than historical conditions, it is important for farmers to modify their crop management decisions to compensate for these projected changes. This situation is exacerbated in the HPA with farmers using groundwater for irrigation at unsustainable rates, already causing parts of the aquifer to become unusable for large volume irrigation (Haacker et al. 2015). We then compare crop yields with and without adaptation to emphasize the importance of different adaptation strategies.

2.2 Methods

The Central High Plains (CHP) was chosen as our area of study due to its unsustainable reliance on groundwater pumping for agriculture at rates far exceeding natural recharge. The region has a semi-arid climate (Gutentag et al. 1984), which greatly limits crop yields without irrigation. Groundwater availability for irrigation varies across the region. The northern section of HPA has less declines in groundwater levels despite widespread use of groundwater for irrigation because more conductive soils and greater rainfall amounts lead to higher recharge rates. In contrast, a large portion of the southern section of the HPA has already lost the ability to provide irrigation water due to a long history of groundwater depletion along with limited recharge.

2.2.1 SALUS modeling and static inputs

The System Approach to Land Use Sustainability Model (SALUS) simulates daily changes in soil, water, and plant conditions in crop production systems through a variety of management options over numerous years (Basso et al. 2006; Senthilkumar et al. 2009; Hoang et al. 2014; Dzotsi et al. 2015). This model has been used to simulate crop yields and irrigation demand for climate change adaptation strategies including irrigation, tillage, fertilizer application, crop rotations planting dates and density. Different management strategies can be simulated concurrently, allowing for evaluation of soils and crop parameters with the same weather conditions (Basso et al. 2006; Hoang et al. 2014), with crop growth and soil being simulated using crop-soil-water interactions (Basso et al. 2006). SALUS requires four main types of inputs: weather, soil type, plant genotype, and management criteria. These inputs were used to run crop simulations, with simulated yields being validated relative to county level data from USDA National Agriculture Statistics Service (NASS) (Cotterman et al. submitted).

Crop models should be run in a continuous, sequential mode (as opposed to a commonly used annual re-initialization mode) to more accurately predict soil carbon, nutrient and moisture conditions at the start of the season based on recent and long-term soil environmental changes (Basso et al. 2015). Only using a continuous simulation model such as SALUS, can we accurately assess the likely effectiveness of different adaptation strategies for agriculture systems including earlier planting dates, new cultivars, and improved soil management practices (Basso et al. 2015).

For this study, SALUS simulated historic and future scenarios across the CHP. To simulate spatial variability of yields across the CHP, a 5 by 8 fishnet polygon grid was overlain on the CHP to determine soil and weather model inputs (Cotterman et al. submitted). The NLDAS-2 (North American Land Data Assimilation System) climate reanalysis dataset was used for weather data (Ek et al. 2011). Precipitation (mm), maximum and minimum temperatures (˚C), and solar radiation (MJ/m^2) were extracted from the NLDAS-2a forcing dataset and were represented in each grid by finding the daily mean of each variable within the grid resulting a spatial resolution of 93.5 by 68.3 km for each grid cell. Similarly, one average soil texture for each grid cell was determined from corn and wheat locations according to the 2014 cropland data layer (USDA NASS Cropland Data Layer, 2014) overlain on SSURGO soil types (Cotterman et al. submitted).

2.2.2 Modeling experiments

A change factor downscaling approach was used to account for projected changes in climate (Basso et al. 2015) based on historical weather observations from NLDAS-2 (Ek et al. 2011) and projections from the Coupled Model Intercomparison Project-5 (CMIP-5) database (Taylor et al. 2012). A bias-adjusted climate change trend for the historic period (1980-2014) was created for each calendar month using an ensemble of all GCM (General Circulation Model) simulations. Three different future climates were created representing RCP 4.5, 6.0, and 8.5. These monthly trends were normalized by dividing by the historical mean for solar radiation and precipitation while subtracting the mean from the daily minimum and maximum temperature (Basso et al. 2015), thus developing a historical climate series, essentially attempting to eliminate the climate change signal from historical observations. This dataset was then replicated at 35 year intervals into the future to create a continuous dataset of climate through 2099. Once the climate series was developed, a monthly time-varying change factor representing RCP 6.0 was applied to the climate series. The change factor was created from the ensemble of future projections for the RCP 6.0 climate scenario (Fig. A.5). Monthly averages from 2000 to 2009 were compared to monthly averages from 2090 to 2099 demonstrating a change in the climate over the CHP (Fig. A.6). The combination of historical data and future climate projection create a 120-year continuous climate series. Changes in CO_2 concentration were integrated into the simulations with yearly historical concentrations from the Mauna Loa observatory (Tans and Keeling 2016) from 1985-2014 and CO_2 concentrations for each decade from 2015 to 2099 based on the RCP 6.0 projection (Fujino et al. 2006; Hijioka et al. 2008).

This study focuses on potential adaptive strategies for corn and winter wheat to reduce the amount of irrigation water needed (and extracted from the HPA) while helping preserve yields under projected future climate conditions. Two adaptation strategies were evaluated for corn and wheat: changing planting dates and adopting different cultivars. For the historic time period, corn was planted on the 120th day of the year (April 30th) (Shroyer et al. 1996), and was harvested once at crop maturity as was determined by the model. Winter wheat was planted on the 285th day of the year (Oct 12th, nominally) for the historic time period (Shroyer et al. 1996); it was harvested on the 180th day of the year (June 29th). With projected future warmer and drier climate conditions for the CHP region coupled with declining available groundwater for irrigation, simulations were run with the planting date 15 days and 30 days earlier for corn, and later than traditional dates for wheat to assess the potential benefits of compensating changes in projected weather patterns. Changing the planting date will allow plants to grow and develop before the relatively warmer and drier days of summer that could lead to moisture and heat stress, which would reduce yield. Alternate planting dates may also help the crop use less water, as it will be shifting its growth pattern in regards to climate.

Choosing a cultivar appropriate for future climates is important for agricultural success. Both corn and wheat cultivars used in the simulations differ by the time period required for the grain fill growth stage, with the adapted cultivar requiring a longer period. Having a longer grain fill period and maturity time will help the crops use the available water more efficiently within the plant, maturing at a rate more suitable for future climate conditions. This can help preserve the available water in the aquifer. Simulations for winter wheat and corn were assessed under both irrigated and dryland management strategies. All simulations were evaluated using both no tillage and conventional tillage, with conventional tillage executed in early spring for corn and early fall for winter wheat.

Automatic irrigation within SALUS was used to irrigate both corn and winter wheat. With corn, farmers typically irrigate every 3-4 days in the CHP due to corn's high dependency on water. Therefore, irrigation was applied during the growing season when the soil's surface to 25 cm reached 75% plant available water until the drained upper limit, or field capacity, was reached. Since wheat is less dependent on water than corn, during the growing season, once the surface to 25 cm of soil reached 30% plant available water, irrigation occurred until the soil reached 75% of plant available water.

Each SALUS simulation used weather, soil properties, cultivar type, and management decisions for each of the 40 fishnet polygon cells. In total we ran 1,920 simulations per year from 1985-2099. Cells which had no crop growth according to the 2014 Cropland Data Layer were excluded making 29 cells for corn and 32 cells for winter wheat for the analysis. The median of the simulated values across the grid was calculated for annual yield and irrigation application amount; thus reducing the influence of outliers.

2.2.3 Calculating Aquifer Level Decline, Production, and Total Irrigation Withdrawals

The year when irrigation could no longer occur was estimated using a linear fit of measured water levels from 1993-2012 (Haacker et al. 2015). The depletion trend was then linearly projected to find the year when irrigation would likely no longer be available based on the saturated thickness dropping below 9 meters, which is a common threshold for sustaining high volume irrigation. Irrigated production for each irrigated cell was calculated as the irrigated acreage multiplied by the irrigated yield and summed across all cells (Cotterman et al. submitted). Dryland production was calculated using the same method, substituting dryland acreage for irrigated acreage. Total irrigation withdrawal was calculated as the sum of irrigation amount per cell multiplied by the irrigated acreage per cell.

2.3 Results

As shown in Cotterman et al., (submitted), SALUS accurately captures observed yields from county level crop yield data from 1985-2014 from the USDA NASS, giving us confidence in our simulations (Table A.1). Corn yields exhibit complex responses to climate change and simulated adaptation strategies as shown by percent difference between non-adapted and adapted corn cultivars grown at different planting dates (Fig. 5). As time progresses, the difference in irrigated yield becomes more substantial by switching to the corn hybrid that is adapted for future climates (Fig. 5a). This is especially true towards the end of the century when the climate change signature is stronger. Throughout the entire time period, the crops planted earliest consistently had the highest yields. However, there were a few years where the adapted corn cultivar yielded less than the non-adapted cultivar. Dryland corn responds less dramatically over time to the simulated adaptation strategies; similarly, to irrigated corn, the adapted dryland corn cultivar yielded higher than the non-adapted cultivar (Fig. 5b). Over time, however, the difference between the yields of the adapted and non-adapted cultivars remained fairly consistent.

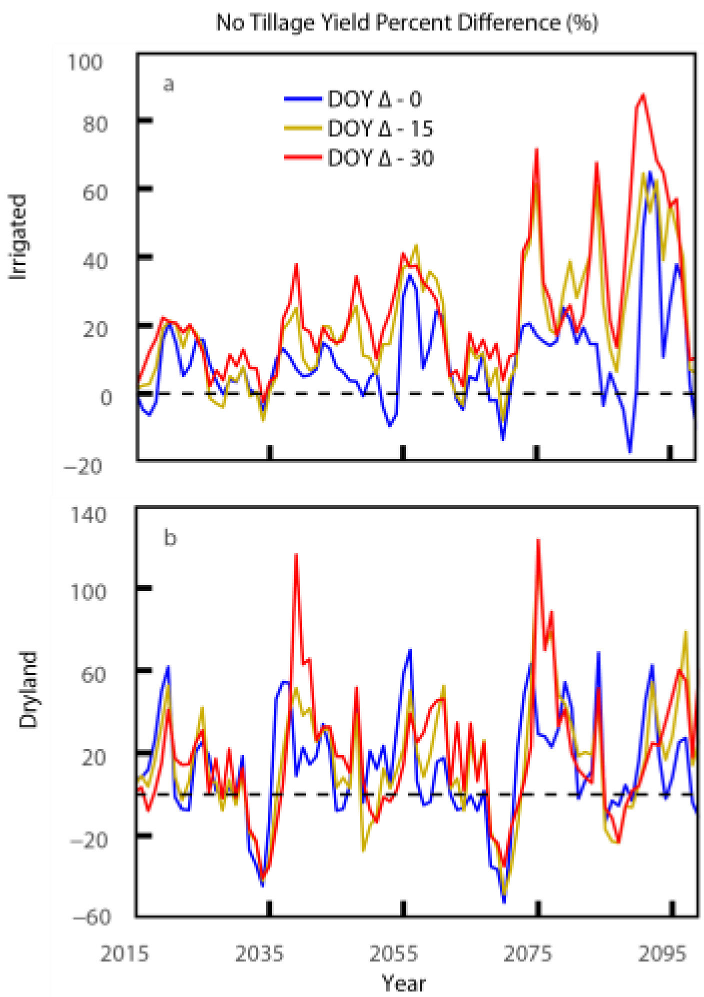

Figure 5: Percent difference of no tillage corn yield
Percent difference of irrigated and dryland corn yields are shown through time with both non-adapted and longer-maturing climate adapted cultivar. For the forecast period (2015 – 2099), colors indicate different days of planting.

Overall, the percentage difference of conventional tillage corn (Fig. 6) compared to no-tillage corn had very similar results. When compared to no tillage corn, the irrigated corn produced higher yield with the adapted cultivar than the non-adapted cultivar, especially as time progressed. The times when the non-adapted cultivar produced better yield occurred when simulated with the current planting date, not the projected early planting dates required for future climates. The percentage difference of dryland corn using conventional tillage did not have the extreme high percent differences as shown by the no tillage dryland corn. Once again the percentage difference of dryland corn remains fairly steady throughout the time period and is not as affected by the planting date as the irrigated corn.

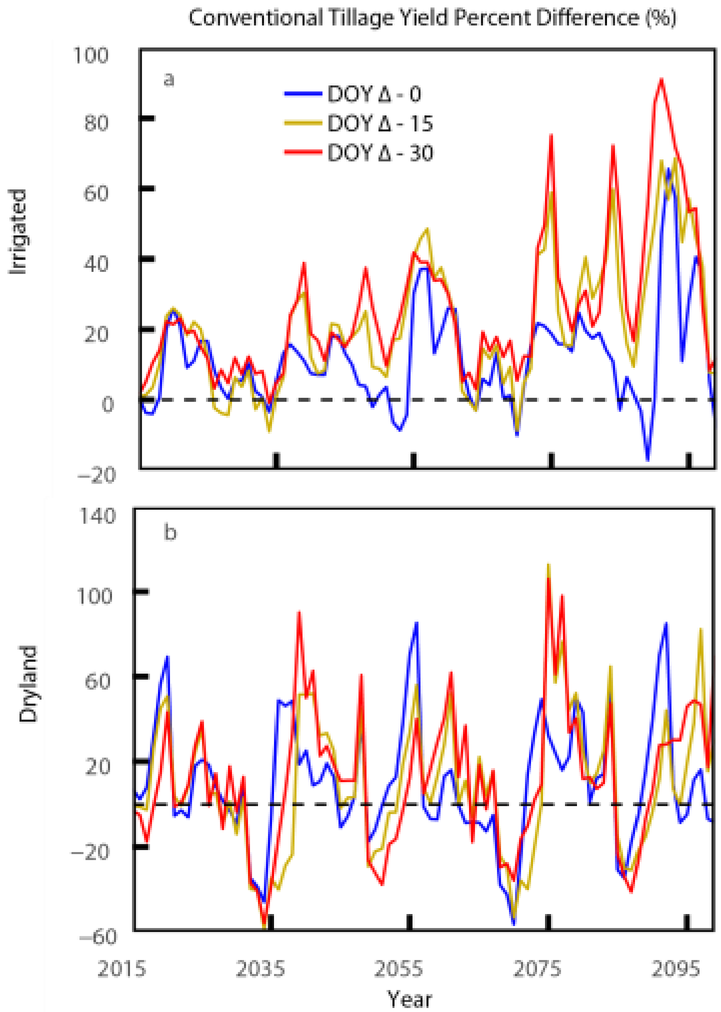

Figure 6: Percent difference of conventional tillage corn
Percent difference of irrigated and dryland corn are shown using conventional tillage instead of no tillage as shown in Figure 5. The different colors for the future simulations represent different planting dates.

Similarly to corn, wheat yields varied across the changes in adaptation strategies in response to climate change (Fig. 7). As expected, irrigated wheat produced yields 1.5 to 2 times that of dryland yields. Like corn, changing the planting date does improve the yields with the as shown by the earliest planted cultivar having a higher yield. The adapted cultivar for both irrigated and dryland produces higher yields than those of the non-adapted cultivar. Dryland wheat is less affected by the adapted cultivar than the irrigated wheat by increasing yields about 40-60% whereas irrigated wheat increased yields about 60% with the climate adapted cultivar.

Throughout the time series, yield differences between the planting dates stay very consistent for all simulations. New wheat cultivars are currently being developed and have shown to yield approximately 10% more annually than previous cultivars (Zhang et al. 2016).

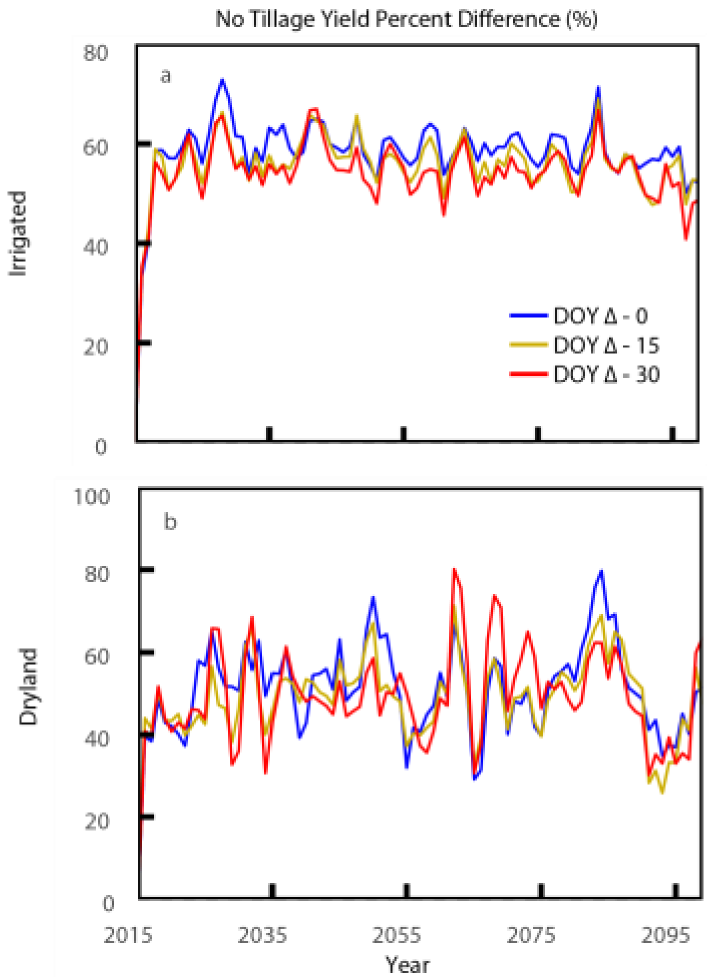

Figure 7: Percent difference of no tillage wheat
Similar to Figure 1, irrigated and dryland wheat percent difference of yields are represented showing the effect of switching to a climate adapted cultivar. Different colors represent different planting days for the forecast period (2015 – 2099).

Conventional tillage and no tillage wheat yield are similar, but not as similar as conventional tillage compared to no tillage corn (Fig. 8). By switching to a climate adapted cultivar irrigated wheat yields under conventional increase about 50-60% which is slightly less than the increase using no tillage. However dryland wheat using conventional tillage did have a higher percent difference switching from a non-adapted to adapted climate cultivar compared to using no tillage.

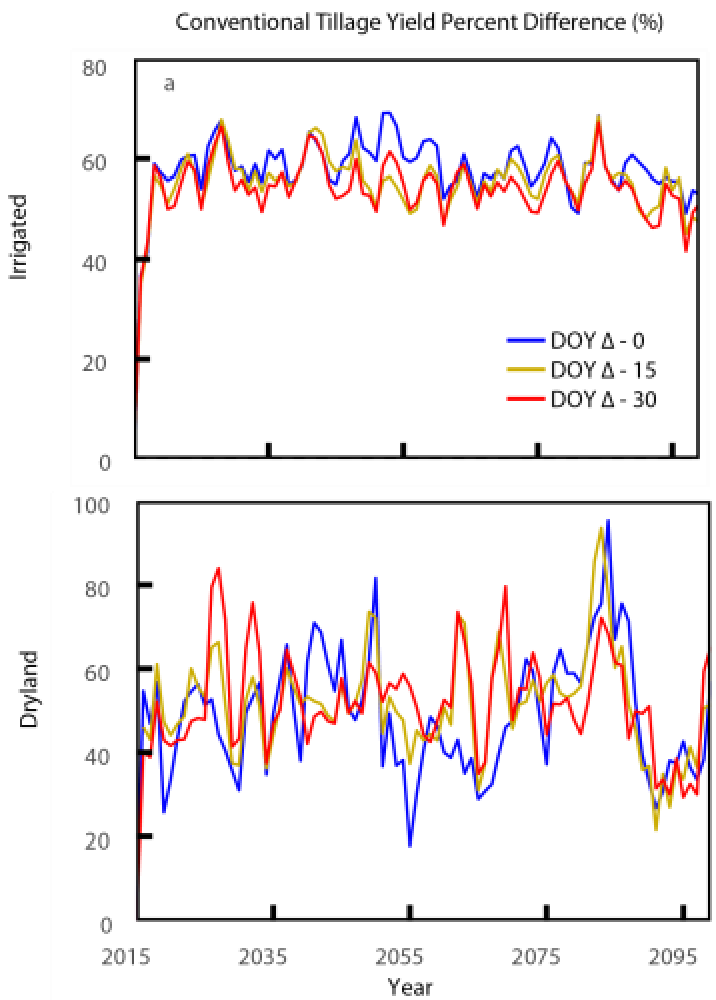

Figure 8: Percent difference of conventional tillage wheat
Percent difference of wheat yield using conventional tillage due to switching from a non-adapted to a climate adapted cultivar. Different planting dates for future climate are shown in different colors.

Irrigation demand for corn (Fig. 9) shows that the irrigation variability between the high and low years decreases as time progresses, however the trend is not significant for any of the simulations. Overall, the non-adapted corn cultivar consistently had higher irrigation application rates than the adapted corn cultivar. Both cultivars, however, show increases in irrigation for the earlier planting days, although the differences among planting dates decreases later in the forecast period. Most prominently, the irrigation water requirements for the non-adapted corn cultivars all exceeded that of the adapted cultivars, regardless of planting date. When comparing corn cultivars for identical planting dates, the non-adapted cultivars required, on average, 10-15% more water than the cultivar adapted counterpart. Wheat irrigation demand (Fig. 9) shows an increase in irrigation as time progresses for all simulations. Throughout the simulation period, the irrigation difference between planting dates remains fairly steady with the earliest planting date requiring the most irrigation. The irrigation water requirements were higher for the adapted wheat cultivar than the non-adapted cultivars for all planting dates, but remained similar over trends. When comparing the wheat cultivars at the same planting date, the adapted cultivar required approximately 5-15% more irrigation than the non-adapted cultivar.

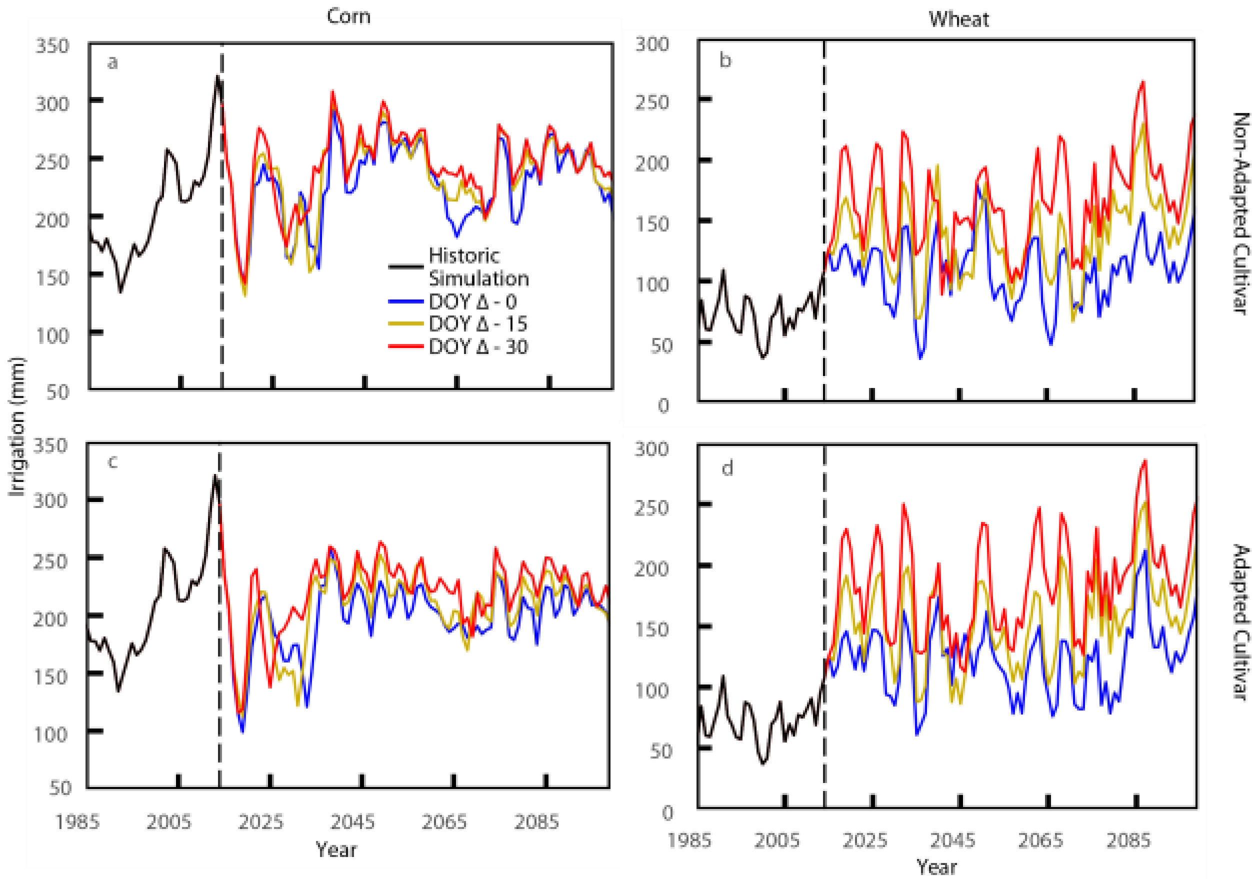

Figure 9: Historic and future simulated irrigation application for corn and wheat
Annual irrigation application for corn a) & c), and wheat b) & d) for both climate adapted and non-adapted cultivars. Black represents the historical time period (1985-2014), and red, gold, and blue represent different planting dates for future simulations (2015-2099), with corn planting earlier and wheat planting later.

The climate change projections indicate that corn and wheat production (Fig. 10) over the CHP will likely decrease for all irrigated simulations. Non-adapted corn has approximately a 75% decrease in production, whereas the adapted cultivar has a 65-70% decrease. Similarly, irrigated wheat showed a 50-55% decrease of production for both cultivars and all planting dates. Dryland production of corn increases approximately 40-50% for the adapted cultivar and 25-30% for the non-adapted corn cultivar. Dryland production of wheat showed approximately a 10-15% decline in production for both the adapted and non-adapted cultivar for all planting dates.

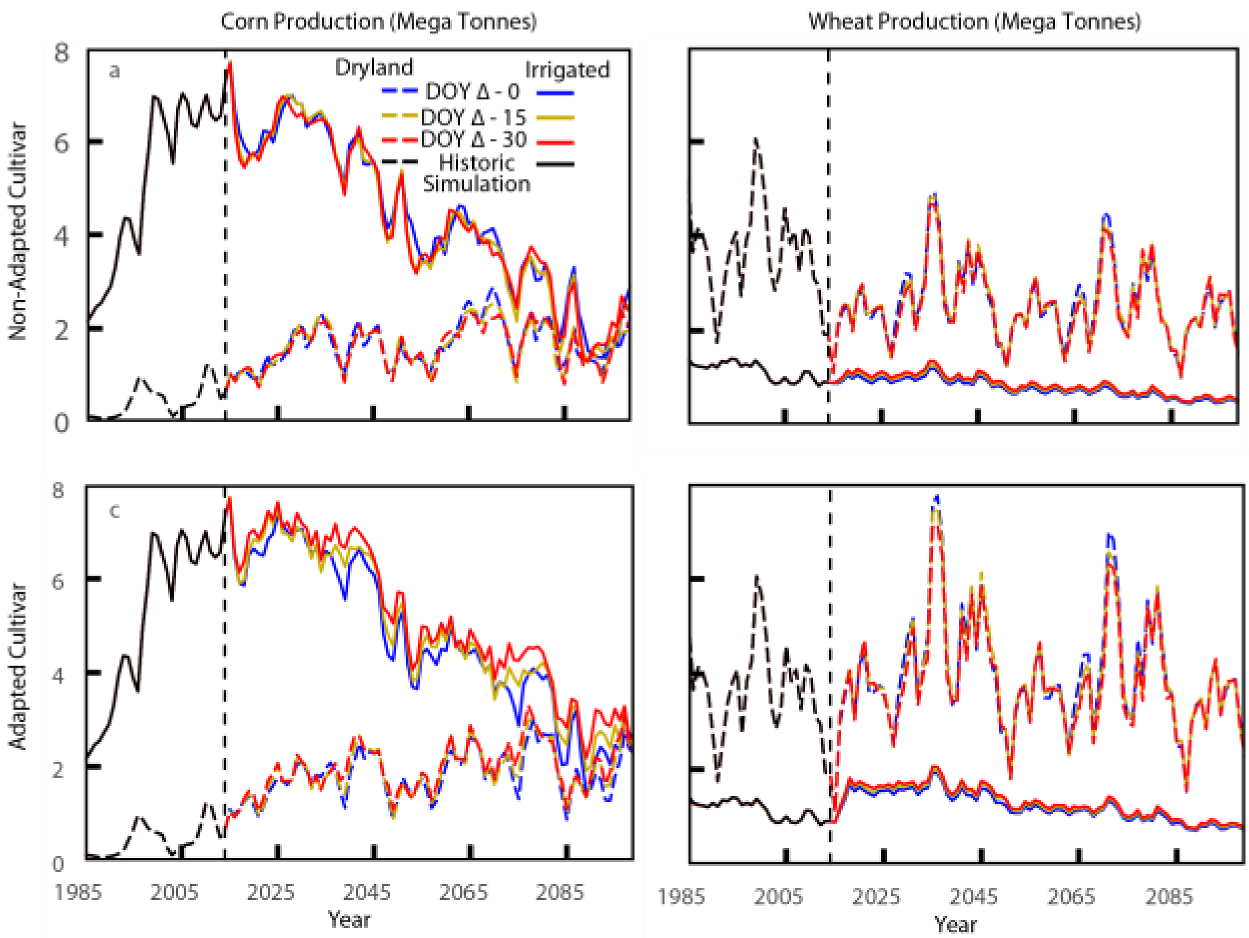

Figure 10: Corn and wheat historic and future production
Irrigated and dryland production for both corn a) & c) and wheat b) & d) are shown through time with different planting dates for both the climate adapted and non-adapted cultivar. The historic period (1985-2014) is represented with black while the forecast period (2015-2099) is represented with different colors based on different planting dates.

As irrigable acreage continues to decline across the region, total irrigation withdrawals a), b) will respond (Fig. 11). Although there are some differences across planting dates, the general decline of irrigable area dominates the overall trend in this plot. In general, corn total irrigation withdrawal decreases at a much steeper rate than wheat. The non-adapted corn cultivar consistently has higher total irrigation withdrawal throughout the time series than the adapted cultivar. Total irrigation withdrawal for wheat was dominated by planting date rather than cultivar with the earliest planting date requiring the most water. Cumulative irrigation c), d) shows a fairly steady increase through the simulation period (Fig. 11). The beginning of the future time period, corn cumulative irrigation varied less than 5% between the cultivars for all planting dates. However, as time progress, the cultivars varied between 5-10% for cumulative irrigation withdrawal with the non-adapted cultivar being higher. Similar to corn, wheat had a small percentage difference of cumulative irrigation between the cultivars in the beginning of the time period with all planting dates having a difference of less than 2%. Towards the end of the simulation, the percent difference of cumulative irrigation increase to 5-10% between the cultivars for each of planting date with the adapted cultivar requiring more irrigation.

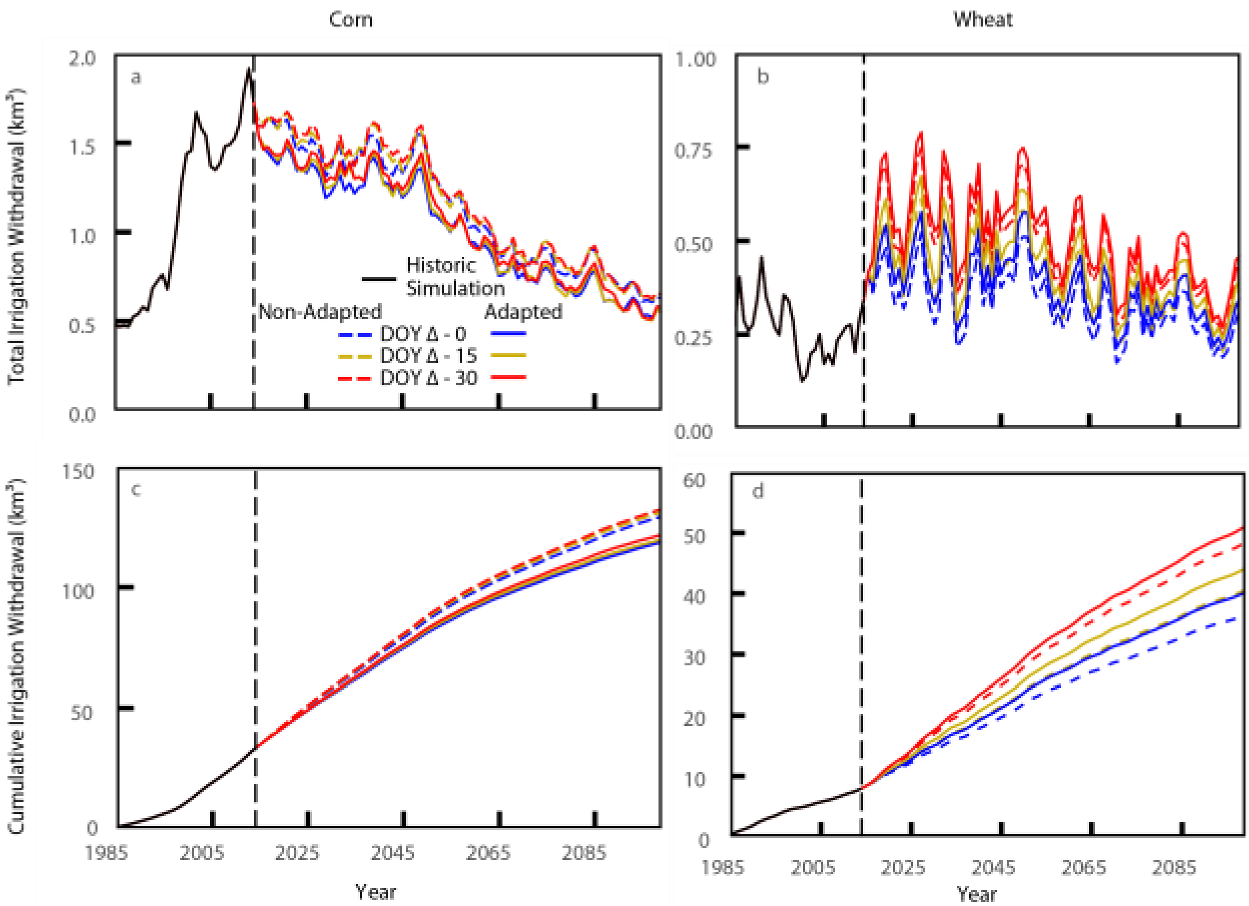

Figure 11: Total irrigation withdrawal across the CHP and cumulative irrigation withdrawal in the CHP

Total irrigation withdrawal a), b) and cumulative irrigation withdrawal c), d) are shown for both non-adapted and adapted for climate change corn and wheat cultivars. The historic (1985-2014) time period is represented with black and the future simulations (2015-2099) are represented with different colors dependent upon the different planting dates.

2.4 Discussion and Conclusions

Due to receiving water during critical growth periods, the adapted corn cultivar had higher yields as the cultivar was planted earlier and matured before the hot, dry summer months associated with different future climates (Fig. A. 6); the separation in yield between the different planting days increases as time progresses and the change in climate becomes more intense. In years of high yield, dryland corn with an adapted cultivar also showed the highest yield. The non-adapted cultivars are less affected by planting dates, except in high yield years where current management for planting date had the highest yield. Unfortunately, the future climate projects overall less precipitation (Fig A. 6). Since corn yield is highly dependent upon water, this projected trend reduces the yields, especially during low yield years. With irrigated corn yield decreasing in the future this shows that high temperatures are affecting the growth and development of corn more than water. Corn cultivars can be adapted to maintain yields under climate change by increasing the time for grain filling. Earlier planting dates can also increase or maintain yields under climate change as the optimal crop growth period moves earlier than under current climate. However, with an earlier planting there are aspects to consider such as a late frost/freeze which can damage a crop or being able to get into the field.

Similar to corn, the adapted wheat cultivar has higher yields than the non-adapted wheat cultivar by having a longer time for the grain to fill. Overall less work has been to develop new wheat cultivars, compared to corn. However, with a changing climate, more research is being done to develop new hybrids for wheat along with new management techniques, such as higher density planting, to help maintain and increase yields (Zhang et al. 2016). Irrigated wheat yields showed a much sharper difference between the different planting dates than the dryland wheat.

Both corn and wheat irrigated yield is higher than dryland yield due the much higher likelihood of water being available during the critical growth period.

Both corn and wheat conventional tillage are very similar to the non-tillage yield. However, there was more variability in the dryland yields than the irrigated yields largely due to irrigated yields having more available water. Different tillage affects the amount of residue and carbon buildup in the soil, and is a key management component in most farms.

Irrigation amounts for the climate adapted corn cultivar were simulated to be higher than for the non-adapted corn. This indicates that by planting a corn hybrid better suited for future climate conditions, farmers can maintain current yields using less irrigation despite projected changes in climate. This can help to sustain the water storage in the aquifer and allow for a longer period of irrigation before the aquifer is depleted, or in combination with other measures could help move the region to sustainable withdrawals of groundwater. The majority of the annual precipitation in the study region occurs during the growing season (April-July) (Table A. 2). By planting during the time of year where the maximum amount of natural rainfall occurs, this increases yield by the crop receiving more water and decreases the amount of groundwater needed for irrigation as the crop is naturally receiving sufficient water for growth. This is especially important for corn, which is grown during the hot, dry summer months. Fortunately for wheat, it is harvested before the warmest summer months therefore helping to reduce the risk of heat and moisture stress. For both cultivars, the wheat planted the earliest required the most water and it also produced the highest yield. This indicates that the plant received the water during the critical growing period, and coupled with the optimal weather conditions produced more yield. While the adapted cultivar does require more water than the non-adapted cultivar, it is less than a 10% difference in water requirements. Fortunately, wheat is less water dependent than corn and as irrigation becomes unavailable and farmers are forced to switch to dryland wheat, the effects of switching from irrigated wheat to dryland wheat will have less of a negative impact compared to switching from irrigated to dryland corn.

Production is dependent on both yield and acreage. As the amount of irrigated acreage decreases due aquifer depletion, there will be a negative effect on irrigated production for both cultivars for corn and wheat. In addition to loss of acreage, future yields will be negatively impacted by projected increases in temperature and solar radiation, due to less cloud cover, and reductions in precipitation. While dryland production increases due to the increase in dryland acreage, it is not enough to compensate for loss of irrigated production since irrigated corn yields are 2 to 3 times higher than dryland yields, and irrigated wheat yields are 1.5 to 2 times higher than its dryland counterpart. The corn adapted cultivar shows less decrease in production for the irrigated and dryland production due to having higher yields than the non-adapted cultivar. Different planting dates for both corn cultivars are similar throughout the time period; however the earliest planting date consistently had the highest yield. Total corn production decreases approximately 45% to 55% for the adapted cultivar and 55% to 60% for the non-adapted cultivar. Similarly to corn, the adapted wheat cultivar had higher irrigated and dryland production throughout the entire simulation period due to higher yields. The different planting dates have smaller impact on production relative to the effect of different cultivars; however the cultivar that is planted at the earliest consistently had the highest yield. Wheat total production decreases approximately 20-25% for all cultivars and different planting dates. With irrigated production decreasing at a rate faster than dryland production, this creates an overall net loss in total production for both corn and wheat throughout the CHP. This projected decrease in production would have a substantial negative effect on the regional economy.

Total irrigation withdrawal declines for all cultivars and planting dates due to the projected declines of the aquifer storage. Longer maturing varieties may help prolong the life of the aquifer due to plants reaching growth stages at different times throughout the growth and development period therefore causing a change in the water demand of plant compared to current varieties. While this will likely not prevent many areas of the aquifer from becoming unusable for irrigation, it could help increase the longevity of the aquifer. This would allow more time to develop new hybrids that use less water and develop and adopt irrigation systems that more efficiently apply water. Farmers would also be able to irrigate for a longer period, allowing them to maintain their irrigated yields and land values. With yields driving profits it is crucial for farmers to maintain yields not only now, but also in the future. Cumulative irrigation shows a steady increase in both corn and wheat for both cultivars and all different planting dates. As time progresses the different simulations diverge with corn being separated by cultivar and wheat being separated by date of planting.

Adapting to climatic variability and change and to reductions in available groundwater is imperative for farmers. If adaptation does not occur, farmers suffer significant economic losses and cause an intensive economic decline for much the High Plains region. This is shown in the comparison between the climate adapted cultivar yields compared to the non-adapted cultivar yields. Consistently for both corn and wheat, the climate adapted cultivars have higher yields due changes in the plant that are more appropriate for future climates. The change in cultivar could be vital for agriculture success especially in areas like the CHP which is highly dependent upon groundwater for irrigation to maintain yields. With a loss in yield this could have major global implications as many countries rely on the United States for portions of their food supply. Future research can explore a wide range of potential adaptation strategies to maintain yield and irrigation amounts including limited irrigation, crop rotations, and different irrigation applications (such as LEPA). While much has been done to develop corn hybrids that are more drought resistant, more research could look into water use efficiency as future climates in agricultural regions across the world are likely to have less rainfall. This is especially important for the CHP as the region is semi-arid and projections indicate that there will be less annual precipitation throughout the region coupled with an increase in solar radiation (Fig. A.6) creating a higher demand of water for the plant to grow and develop. Relatively less varietal development has occurred for wheat, thus new varieties that mature differently in winter, especially with the likelihood of more frequent milder winters might be advantageous for projected future climate conditions. Since wheat is less dependent upon irrigation to maintain yields, it is possible that farmers will switch from corn to wheat in the future once the aquifer depletion surpasses the irrigation limit. This only increases the need for wheat hybrids better suited for the future as the number of acres planted in wheat could grow substantially. With projected warmer weather, double cropping may become a popular option. The growing season is projected to be significantly longer, which will allow growth of a second crop in some regions; however this would also affect soil nutrients and water availability. These changes in management will show that adaptation is key to preserving both yield and water usages, therefore helping farmers retain their livelihood.

Agriculture is one of the most, if not *the* most, important aspects of today's society; without, we would be unable to feed our ever growing global population. Therefore, we must continue to improve and make necessary changes to ensure successful agriculture regardless of the climate and water availability conditions of the future.

APPENDIX

In order to accurately model the influence of soil and weather conditions for the CHP, a fishnet polygon grid (Figure A.1) was created allowing for one soil and weather variable to represent each grid. These soil and weather conditions were then used for both the historic and future time periods, for both unadapted and adapted simulations. The locator map in the upper right hand corner (Figure A.1) represents the location of the CHP in the United States including parts of the states of Texas, Kansas, Oklahoma, Colorado, and New Mexico.

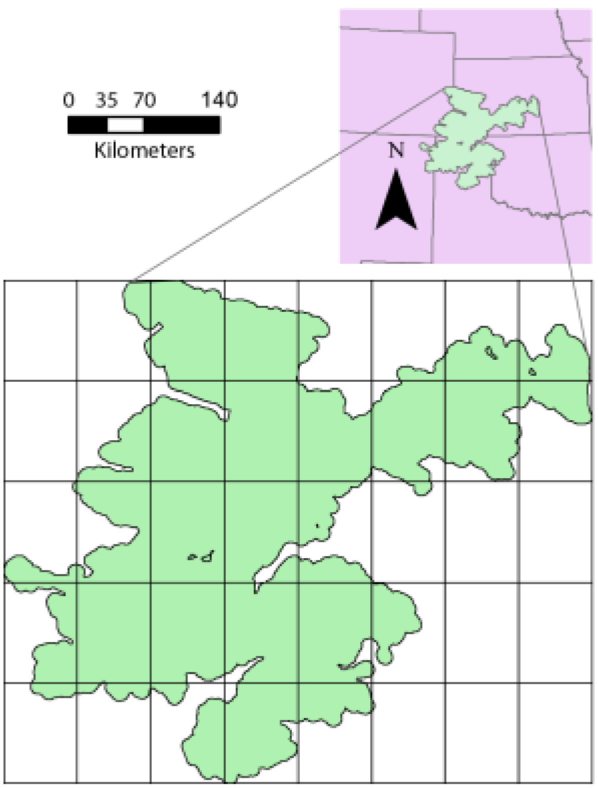

Figure A.1: Fishnet polygon grid of CHP
Each grid represents one set of weather variables and predominant soil texture parameters used for each of the SALUS simulations along with crop and management decisions

Standard deviations were calculated based on the yield amongst all grids were the crop was grown according to the 2014 Cropland Data Layer. This shows the annual variation of yield between different grid cells for corn and wheat under irrigated and dryland management across the Central High Plains.

Year	Irrigated Corn	Dryland Corn	Irrigated Wheat	Dryland Wheat
1985	1401.2	1861.9	366.0	740.2
1986	1610.3	2967.9	345.7	734.3
1987	1599.4	3328.6	239.3	855.9
1988	1451.9	2564.9	413.9	1199.9
1989	1776.1	3057.7	394.2	994.6
1990	1989.1	3261.5	1585.0	1316.7
1991	1741.2	2748.0	557.8	775.0
1992	1707.1	4055.1	368.4	1024.8
1993	1278.2	3336.6	428.9	947.7
1994	1488.9	3044.6	407.1	937.2
1995	1481.3	3084.2	305.7	1004.5
1996	1772.3	3091.5	423.0	640.5
1997	2206.2	4563.0	461.4	1011.8
1998	2921.4	3797.0	541.0	967.7
1999	2533.8	3902.7	387.4	892.9
2000	2083.7	3376.4	298.4	1159.3
2001	2433.4	2611.5	402.4	932.7
2002	1518.9	2266.2	433.4	929.3
2003	1991.8	1806.5	344.9	969.3
2004	2434.0	5000.8	370.7	791.4
2005	1831.7	2549.0	347.7	853.2
2006	2136.2	2071.6	304.8	688.4
2007	1779.6	3222.9	471.1	560.8
2008	1920.8	3047.1	405.6	1431.1
2009	2380.6	3503.3	594.0	993.9
2010	2921.0	3702.5	351.2	751.3
2011	3055.0	2333.0	405.2	607.8
2012	2156.2	1059.8	330.8	752.0
2013	2372.5	4842.6	395.0	1576.1
2014	2513.2	3441.7	396.9	446.7

Table A.1: Historic yield standard deviations
Standard deviations across model cells each year of the historic simulation for all four treatments (kg/ha)

We evaluated likely changes in irrigation water demand for both corn and wheat under three climate change scenarios (Figure A.2). Irrigation water demand for corn in the CHP significantly increased from about 1990-2015 largely due to new, higher yielding cultivars that require more water. Overall, future simulations indicate that irrigation water demand for corn increases under projected climate change, with RCP 8.5 requiring ~5% more water and RCP 6.0 and RCP 4.5 requiring ~15% more water. Wheat irrigation has remained consistent historically;

overall wheat saw a decrease in irrigation in the future with RCP 8.5 and RCP 6.0 decreasing about 5-10% and RCP 4.5 decreasing 35%.

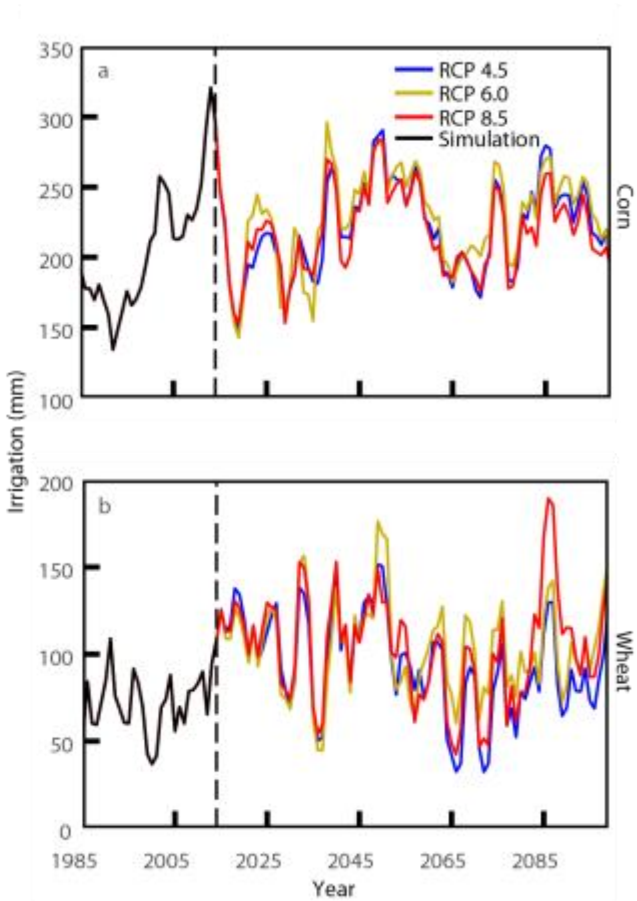

Figure A.2: Annual irrigation application for corn and wheat
The median annual historic irrigation application for a) corn and b) wheat are shown in black. Future climate scenarios are blue, gold, and red representing RCP 4.5, 6.0 and 8.5

Winter wheat is the most common crop grown on the CHP, with approximately 4 million acres cultivated in 2014; corn is the second most common in the region with approximately 2 million acres (National Agricultural Statistics Services database 2015; Smidt et al. 2016) (Figure A.3). While corn is the second most common crop grown on the CHP, it is the most common irrigated crop in the CHP with 1.5 million acres, or ~75% of CHP corn (National Agricultural Statistics Services database 2015; Smidt et al. 2016). Winter wheat is the second most common irrigated crop at approximately 0.75 million acres (National Agricultural Statistics Services database 2015; Smidt et al. 2016).

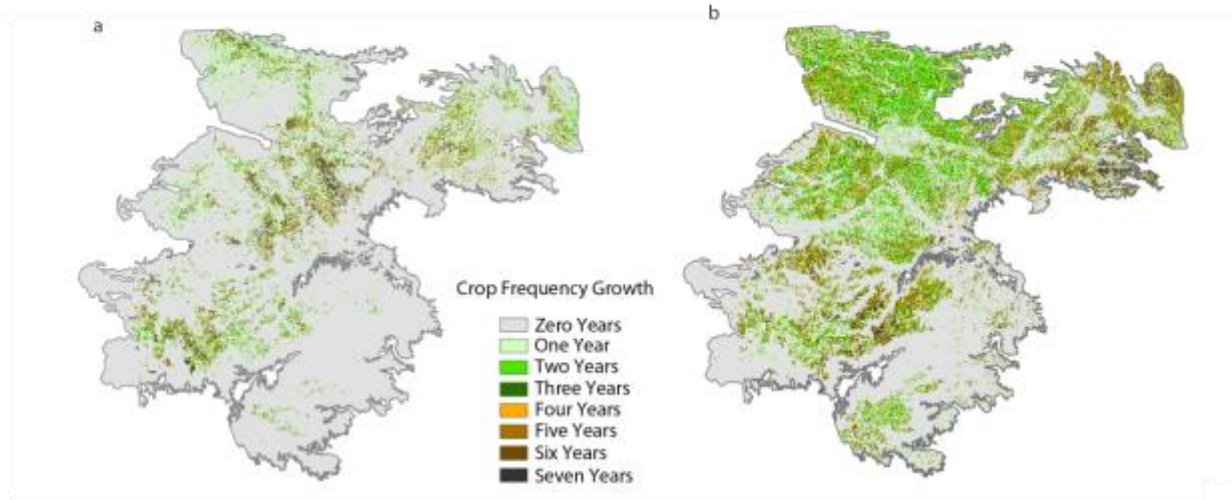

Figure A.3: Crop frequency growth from 2008-2014 for corn and wheat
Corn a) and winter wheat b) are grown throughout the CHP. These maps represent crop type growth frequency from 2008-2014 (Boryan et al. 2014)

Understanding precipitation and temperature trends is vital for agricultural success. Approximately 75% of precipitation occurs from April-September coinciding with the growing season (Gutentag et al. 1984). A large portion of the precipitation occurs with thunderstorms, which have highly variable rainfall both spatially and temporally (Gutentag et al. 1984; Hornbeck and Keskin 2011). During the growing season (May-August), there is a strong precipitation gradient across the CHP from the west to the east with the eastern portion receiving more rainfall (Figure A.4b). This allows these regions to grow more water dependent crops and rely less on irrigation than the western CHP. The central and eastern parts of the CHP have the highest growing season maximum temperatures, which can add stress to crops in hot/dry years (Figure A.4d). The HPA has a strong north-south temperature gradient with seasonal extremes varying by 70°C. Most of the High Plains has low humidity with high evaporation. However, parts of Kansas and Nebraska have high precipitation leading to higher humidity than the dry continental climate across the remainder of the High Plains (Gutentag et al. 1984). Hot temperatures during summer months accompanied with continuous winds cause high evaporation rates ranging from approximately 150 centimeters in Nebraska to 270 centimeters in western Texas and southeastern New Mexico. These rates of evaporation leave little water for groundwater recharge, which averages less than 13 millimeters annually (Gutentag et al. 1984). Crops need heat and sunlight to reach maturity but too much can cause heat stress causing the plant to become water stressed, which reduces yield.

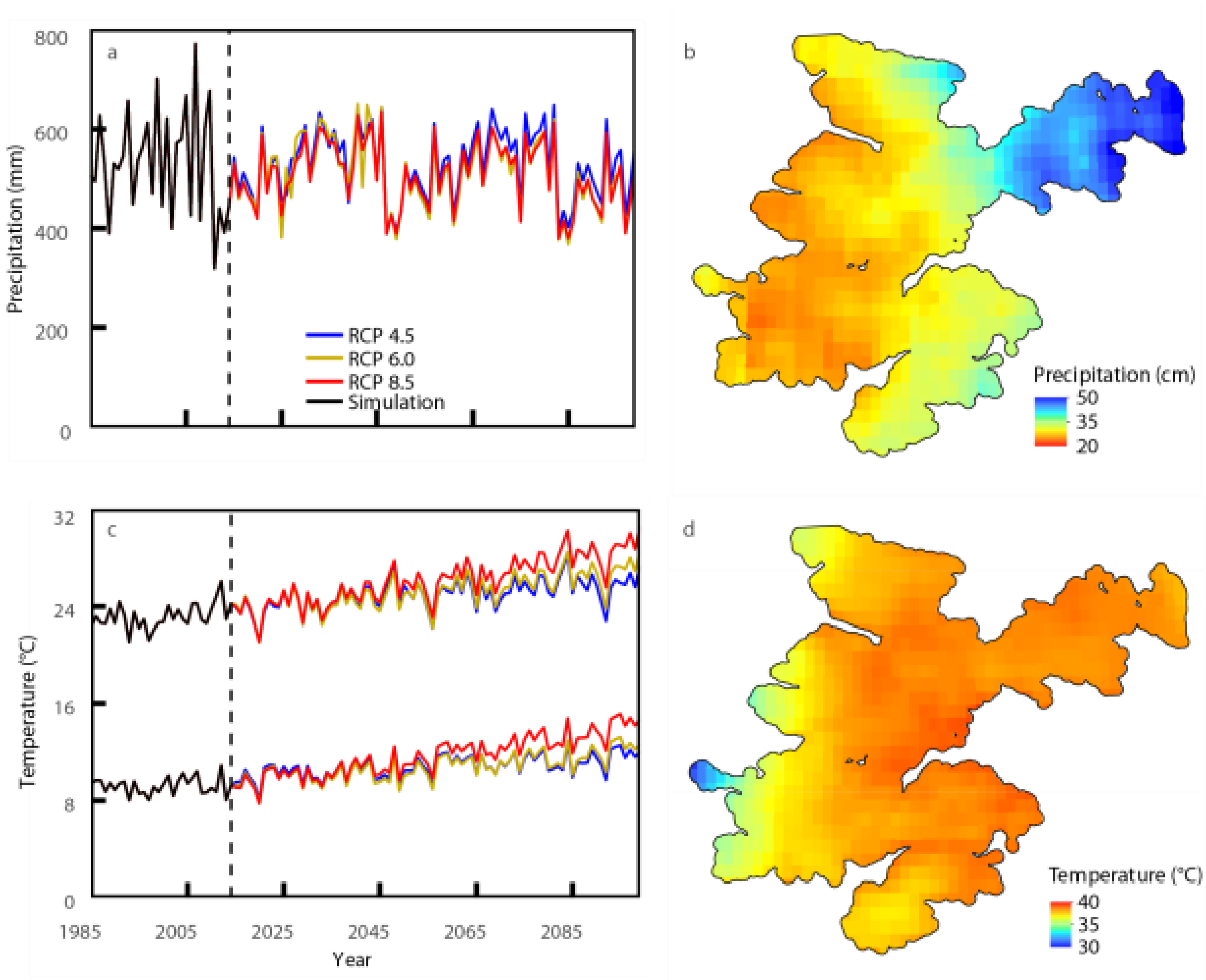

Figure A.4: Historic and future precipitation and temperature with RCP 4.5, 6.0, and 8.5
Precipitation a) and temperature c) are shown through time with the black lines representing historic temperature and precipitation and RCP 4.5 (blue), RCP 6.0 (gold), and RCP 8.5 (red) representing future climate scenarios. Total precipitation b) and maximum temperature d) represent the growing season averages (May-August)

GCMs vary in their predictions of precipitation for the High Plains, as some show an increase in precipitation whereas others show a decrease. Even though there is an increase in precipitation through some GCMs, there is also an increase in evapotranspiration, which removes some water that would otherwise recharge the aquifer (Rosenberg et al. 1999). However, GCMs are consistent and show an increase in temperature throughout the HPA. Thus, with GCMs showing warmer temperatures and drier conditions over the High Plains, less recharge will occur. With much of the irrigated water in the High Plains being evapotranspirated then falling out as enhanced downwind precipitation, this will create a change in the hydrologic cycle (Harding and Snyder 2012; Pei et al. 2015). The future climate scenarios used remain steady with temperature through 2050, and then begin to deviate with RCP 8.5 showing the highest increase in temperature, followed by RCP 6.0 and RCP 4.5 (Figure A.4c). However, annual precipitation remains consistent throughout the CHP for all climate scenarios (Figure A.4a).

Chapter 2 focused on RCP 6.0 , as it is the most likely trajectory for future climate. As shown by Figure A.5, precipitation is projected to slightly decrease into the future. However, both temperature and solar radiation are projected to increase, with solar radiation increasing quickly. The percent difference changes shown in Figure A.6, compare 2000-2009 to 2090-2099, by comparing the difference between 2000 and 2090, then 2001 and 2091, etc. Minimum temperature had the highest percent change due to low temperatures not being as low. Similarly, maximum temperature also increased in the future due to higher temperatures. Precipitation decreases especially towards the end of the century. Solar radiation increased slightly but remained largely the same; this is likely due to a decrease in cloud coverage. These changes in weather patterns will affect crop growth and development likely causing farmers to switch planting dates and develop new management techniques. Table A. 2. shows growing season precipitation which decreases through time.

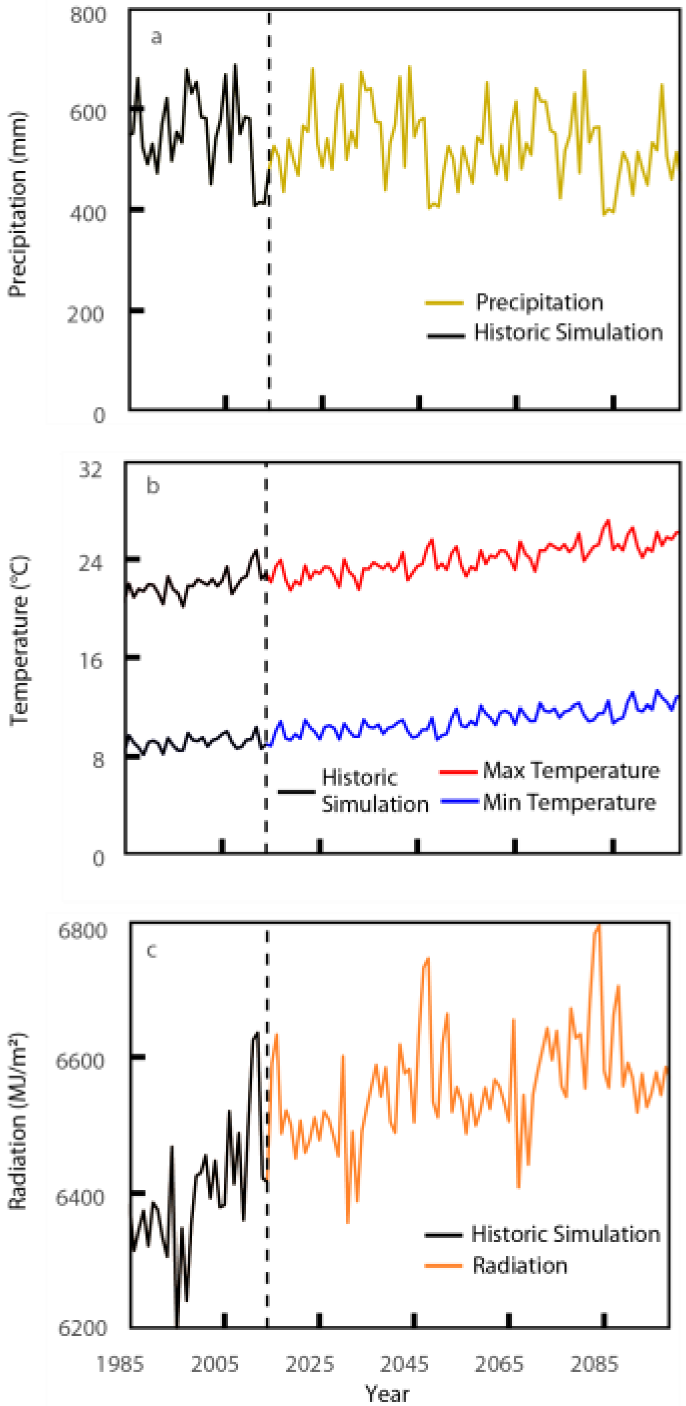

Figure A.5: Historic and future precipitation, temperature, and solar radiation for RCP 6.0 Annual Precipitation a), mean maximum and minimum temperature b), and annual solar radiation c) are shown through time. The black line represents the historic time period in each of the figures.

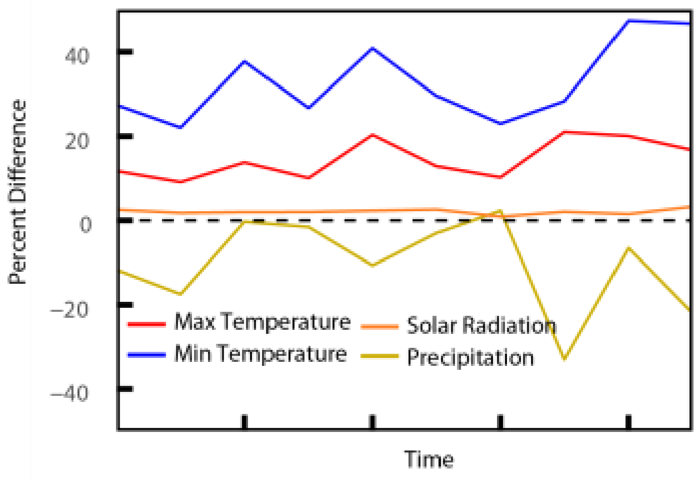

Figure A.6: Percent difference of historic and future temperature, precipitation, and solar radiation
Percent differences between historic (2000-2009) and future (2090-2099) yearly averages of precipitation, maximum and minimum temperature, and solar radiation were contrasted to demonstrate the change in the climate over the CHP in the future.

Decade	Average Precipitation Per Decade
1985-1989	546.66
1990-1999	576.79
2000-2009	569.22
2010-2019	593.09
2020-2029	551.61
2030-2039	570.38
2040-2049	533.71
2050-2059	586.97
2060-2069	515.48
2070-2079	592.24
2080-2089	483.84
2090-2099	569.22

Table A.2: Growing season precipitation for each decade
Average growing season precipitation (mm) was calculated by determining the sum of precipitation from April-July and averaging across cells of the CHP for each year from 1985-2099 then averaging for each decade.

All graphs for this manuscript were made using R for statistical computing (Wickham 2007, 2009, 2011, 2016; Grolemund and Wickham 2011; Wickham and Francois 2015; Ulrich 2016) and maps were created in ArcMap.

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