Economic and Groundwater Use Implications of Climate Change and Bioenergy Feedstock Production in the Ogallala Aquifer Region

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Introduction

The Ogallala or High Plains aquifer underlies about 450,000 km^2 of the states of South Dakota, Wyoming, Colorado, Nebraska, Kansas, Oklahoma, Texas and New Mexico. The High Plains is one of the most intensively irrigated areas in the US and about 30% of all groundwater withdrawn for irrigation in the United States comes from the Ogallala aquifer. The aquifer also provides drinking water to 82% of the people who live within its boundaries, totally 2.3 million according to the 2000 census (USGS, 2009). The High Plains crops, livestock, and meat processing sectors as well as oil and gas production literally run on water from the Ogallala Aquifer. However, the excessive depletion of the Ogallala Aquifer is treating the rural economy of this region. Substantial pumping over at least the past 50 years caused water tables fall up to 60 m locally and saturated thickness declines greater than 50% in parts of the aquifer. In general, recharge has not compensated for withdrawals since major irrigation development in this region in the 1940s. Growing populations throughout the Ogallala Aquifer region are demanding more water from the only available aquifer source. Climate change is looming over these new demands for the finite water supply. Projections of a warmer future for this region threaten the agricultural activities, primarily through the depletion of already overtaxed water resources. The resulting increase in irrigation water and chemical inputs under these predicted conditions are not sustainable economically or environmentally. The current expanded biofuels policy contributes to additional pressures on water resources. Therefore, better understanding of sustainability of water pumping and associated economic consequence has significant implications not only for the rural communities on High Plains, but also for the future and continued assurance of the competitiveness of the agricultural in that region and nationally.

Literature Review

With the increasing reliance and importance of Ogallala Aquifer, intensive researches have been carried out to understand its hydrological character and economic impacts since last century. The report by Grubb (1966) summarized the importance of irrigation water to the economy of the High Plains. However, with the continuing decline of water level, the economic focus has shifted from development and expansion of irrigation in the 1960s to the implications of the sustainable management in the 2000s. Guru et al. (2000) examined the impacts of increasing mining of the Ogallala with specific focus on the regions in Oklahoma and Texas. The results suggested

ensuring future availability of the Ogallala waters by implementing conserving soil and water policies and promoting diversity of crops. The reports on the water availability in eight states that overlie the aquifer concluded that the volume of water in storage in year 2000 was about 6 percent less than the total water in storage prior to expensive irrigation (Mcguire et al. 2000). Their evaluation by states also indicated the heterogeneity of the aquifer—the change in water storage ranged from an overall rise of 4 million acre-feet in Nebraska to an overall decline of 124 million acre-feet in Texas.

The current state of underground water utilization availability in the High Plains is a reflection of the combined result of economic, social and political factors. Considering the heterogeneity in water table, the researches intend to sub-divide the aquifer into regions where more specialized and accurate information can be analyzed. Das and Willis (2005) tested the effectiveness of two water conservation policies— extraction tax and extraction quotas in the Texas High Plains. Their integrated hydrological and economic optimization model was able to capture spatial variability of water table elevation, but subjective to further improvement with detailed county level data. Almas (2008) projected income and hydrological changes in Texas Panhandle region by applying economic optimization models. The results from the 60-year analysis indicated a significant decline in water use and transition from irrigated agriculture to dryland farming. The same model was employed to analyze different water management strategies and conservation programs in Oklahoma Panhandle (Almas and Colette 2008). The study of water policy alternatives for the southern Ogallala aquifer by Wheeler et al. (2006) indicated that blanket water conservation policies for the region as a whole are likely to be inefficient given that the significant differences in hydrological characteristics and current irrigation levels across the region. These quantitative estimates of water pumping associated with the optimal cropping pattern over the long-run planning provide more information to policy makers concerning water conservation for future irrigation and regional economic development. However, because of the rough modeling of crop production activity and land use change, their optimization model applied to agriculture often yield "unrealistic" results that diverge from farmers' observed behavior (Almas et al. 2006). Moreover, few of these studies take into account of climate change impacts which causes projections regarding possible future cropping activities and water depletion far from reliable.

With regard to the significant socio-economic impacts of the Ogallala Aquifer, a more comprehensive and accurate characterization of the economic and groundwater implications of allocating limited agricultural land and water between crops and biomass production is needed. The application of economic theory and hydrological knowledge to the solution of agricultural management is timely and essential to the survival of agricultural producers facing the declining water supply. The main development can be pursued in two aspects—methodology and policy implications.

The aggregation of hydrological and agronomical parameters to an average level in modeling often leads to inaccurate estimation of both baseline agricultural returns, and land/water use over a next 50 year planning horizon. To our knowledge, neither of the existing models applied for Ogallala Aquifer regions contains detailed county-level studies in optimal land use and associated water pumping management. An integrated dynamic land allocation model with the following features may perform a better projection:

- Addressing the spatial heterogeneity of aquifer depletion and crop system basing on county-level data.
- Incorporating climatic data and climate change factors to project the dynamic adaptation options in agricultural productions.
- Taking "historical crop-mix approach" (McCarl 1982) in programming supply responses, which can characterize the feasible decision space of the aggregate producer.

Objective

Our primary objective is to investigate economic and environmental issues regarding current and future groundwater resources capabilities for the Ogallala Aquifer, and the interrelationships with future climates forecasts, cropping patterns and groundwater use policies and regulations. More specifically, this study is to

- Develop a dynamic economic optimization model for the Ogallala Aquifer Region with a goal of maximizing the net present benefit of groundwater use
- Apply the model to estimate the economic impacts of groundwater depletion on the regional economy over the 2010-2050 planning horizon

- Examine what climate change and alternative bioenergy expansion policies impacts on agriculture economics, land use and groundwater use.

Methodology

To assess the impacts of climate change and bioenergy expansion policy on land use change with regard to groundwater sustainability in the Ogallala Aquifer Region, we develop an integrated dynamic land allocation model to simulate the optimal inter-temporal land use change at county-level. The model is based on assumptions that farmers make rational decisions to maximize their net income when facing scarce resources constraints including land, water, and production inputs. A dynamic standard linear-programming (LP) model is constructed for each county. To account for the possible heterogeneous land allocation caused by nonuniform hydrological characteristics of Ogallala Aquifer, the study is conducted on subregions (zones) of each county instead of a whole county. The division principle is based on different initial saturated thickness levels while all other conditions are assumed to be the same among these zones. The objective function is to maximize the net present value from agricultural production over a forty-year planning period for a given county:

$$Max\ NPV = \sum_{t=1}^{40} (1+r)^{-(t-1)} NR_t \tag{1}$$

$$NR_t = \sum_z \sum_i \sum_l [P_{it} Y_{ilt} ACR_{zilt} - C_{zilt}] + \sum_z NB_t (PASTLAND_{zt}) \tag{2}$$

where, NPV is the net present value of net returns, r is the discount rate, and NR_t is the net revenue at time t. NR_t is defined as the difference between total benefit and cost of agricultural production. z represents zones in a given county, i represents crop grown, l is the landtype which is categorized as irrigated land, dryland and pastureland. P_{it} is the exogenous price of the crop i at time t, Y_{zilt} is the yield which is related to water use and landtype, ACR_{zilt} is acreage of crop i in landtype l zone z at time t, C_{zilt} is the corresponding variable and fixed cost of production which includes energy cost of water pumping, depreciation cost for irrigation system, harvest cost, maintenance cost and labor cost), NB_t is net benefit of livestock grazing on pastureland which is depending on how many pastureland available at zone z time t ($PASTLAND_{zt}$). The model starts with a baseline crop price, and the prices in future periods are taken from FASOM (Forest and Agricultural Sector Optimization Model) model simulation results. In this price-endogenous

model, the social equilibrium occurs where marketing prices and productions maximize total social welfare. The pumping cost is calculated from widely applied engineering formulas that relate pumping costs to pumping lift, operating system pressure, and the price of energy (Amosson et al., 2001).

A series of constraints are implemented by integrating three sectors: agriculture, hydrology and climate.

Agriculture

$$Y_{ilt} = f(WUS_{zit}), \quad l = irrigated\ land \qquad (3)$$

where WUS_{zit} is the water use per acre of crop i at zone z time t. Crop production function (f) describing crop yield response to applied water for given soil types and climate condition is estimated by statistic method. Continuous nonlinear crop yield response is incorporated. Deficit irrigation is allowed for major irrigated crops such as corn, wheat and sorghum.

$$ACR_{zilt} = \sum_j CROPMIX_{zljt} * hiscrop_{zilj} \qquad (4)$$

$$\sum_i \sum_l ACR_{zilt} \leq CROPLAND_{zt} \qquad (5)$$

where j is the index for historical year from 1990-2010, $CROPMIX_{zljt}$ is the acreage share of historical crop land use of last 20 years ($hiscrop_{zilj}$) for each crop in each landtype, $CROPLAND_{zt}$ is total available crop land at time t. Instead of assigning an upper bound to land annual transition rate as most previous literatures did, risk associated with climatic and other exogenous effects is avoided by requiring the crops in a region to fall within the mix of crops observed in historical (past 20 years) observations of farmers' aggregate response.

$$PASTLAND_{zt+1} \leq PASTLAND_{zt} + \sum_i \sum_l ACR_{zilt} - \sum_i \sum_l ACR_{zilt+1} \qquad (6)$$

Pastureland at time t+1 ($PASTLAND_{zt+1}$) is no more than pastureland at time t ($PASTLAND_{zt}$) plus the land transferred from crop land. For simplicity, we assume that benefit of livestock production is mainly from pastureland availability and consequent inventory of cattle.

Hydrology

$$ST_{zt} = ST_{zt-1} - (TWUS_{zt} - \text{rech}_z)/(overall_z * s_z) \qquad (7)$$

$$WUS_{zit} \leq WUS_{zi0} * (ST_{zt} / IST_z)^2 \qquad (8)$$

$$TWUS_{zt} = \sum_i ACR_{zilt} * WUS_{zit} \leq ST_{zt} * overall_z * s_z \qquad (9)$$

where ST_t is the saturated thickness at zone z time t, $TWUS_{zt}$ is total water pumping, $rech_z$ represents the annual recharge rate, $overall_z$ is the area of Ogallala Aquifer underlying zone z, s_z is specific yield, WUS_{zi0} is assumed to be water use per acre of crop i at baseline year, IST is the initial saturated thickness at zone z. Equation (7) indicates the dynamic relationship between saturated thickness and total water pumping. Equation (8) is based on the assessment of well yield decreasing rate that is the square ratio between current saturated thickness and initial saturated thickness (Kunkel et al., 1969). Equation (9) restricts that total water pumping at time t is no more than actual volume of groundwater which equals to saturated thickness times area and specific yield.

Climate

To conduct climate change effects analysis and adapt crop systems to such change, it is important to know how climate change affects agricultural production and water use efficiency. We used existing data on simulated changes in future temperatures, precipitation, and CO_2 concentrations generated by Global Circulation Models (GCMs) as part of the IPCC (Intergovernmental Panel on Climate Change) AR4 process. These GCMs are run under different Special Report on Emission Scenarios (SREs) describing major alternative futures in terms of climate change driving forces — population growth, economic well being, energy use, greenhouse gas, and aerosol emissions and their evolution during the 21st century (IPCC, 2007). For this study, the scenario A1B was selected which is characterized by a moderate/high rate of CO_2 emissions and most closely reproduces the actual emission trajectories during the period since year 2000-2008 (van Vuuren and Riahi, 2008). Because assumptions and procedures vary substantially across different GCMs, multiple scenarios are being applied to generate a range of results characterizing some of the uncertainty with climate change. The four primary GCMs being analyzed in this study are as follows:

- Coupled Global Climate Model (CGCM3.1) developed by the Canadian Centre for Climate Modeling and Analysis, Canada;

- GFDL-CM2.0 and GFDL-CM2.1 models developed by the Geophysical Fluid Dynamics Laboratory (GFDL), USA;

- Meteorological Research Institute (MRI) coupled atmosphere-ocean General Circulation Model (CGCM) 2.2 developed by the Meteorological Research Institute, Japan Meteorological Agency, Japan.

Disaggregated climate change projection data for each county of Ogallala Aquifer region were downloaded from http://www.ipcc-data.org/ar4/scenario-SRA1B.html

These data were incorporated into the EPIC (Environmental Policy Integrated Climate) model to estimate impacts of alternative climate change scenarios on crop yields and water use efficiency for major crops. The EPIC model is a single-farm biophysical process model that composes of several simulation components for weather, hydrology, nutrient cycling, pesticide fate, tillage, soil erosion, crop and soil management and economics. Thus EPIC can account for the effects of climate-induced changes in temperature, precipitation, and other variables, including episodic events affecting agriculture on potential yields (Beach et al, 2010). Yields are simulated by keeping all parameters as constants except for climate conditions to generate values under both baseline climate and alternative climate scenario conditions.

To assess the effects of expansion of biofuel feedstock production on land and water use change, three bioenergy scenarios are defined in the model:

Base— Baseline scenario without implementing the renewable fuel standard (RFS2) program

RFS_30BGY_C0— Scenario under RFS2_36BGY (Energy Independence and Security Act renewable fuel targets) with about 30BGY from starch-based and sugar-based ethanol and cellulosic ethanol production (excluding energy sorghum)

EnergySorghum_07_C0— Scenario with RFS2_36BGY targets and allowing the production of energy sorghum with 0.7% yield progress rate

This integrated dynamic economic model is able to simulate crop irrigation status switch, movements between cropland and pasture land in response to groundwater depletion, changing relative prices, and climate change and energy scenarios.

Results

Our model has been applied to counties in Texas Panhandle Region. Panhandle region of high plains is a major concern in this research, as is the most critical groundwater depletion area (Almas 2009). The central region includes 26 counties in the Texas Panhandle, three counties from Oklahoma Panhandle and one county from Eastern New Mexico. Such region has a semi-arid climate and average low rainfalls which results in little surface water being available year-round for agriculture. Therefore, better understanding of sustainability of water pumping and associated economic consequence has significant implications not only for the rural communities on the Panhandle region, but also for the future and continued assurance of the competitiveness of the American agricultural sector (Almas 2008).

The results of Dallam County (which represents the largest irrigated water use counties in the region) are presented in detail in this paper instead of presenting results for all 26 counties. The initial irrigated land acres for the baseline year 2010 in Dallam County is 215,689 which accounts for 68% of total cropland with 11% less than that in year 2000. Irrigated corn uses about 35% of the total cropland and irrigated wheat and dryland wheat follows with 16% and 11%, respectively. To further account for the heterogeneous land allocation in response to the nonuniform hydrological characteristics of Ogallala Aquifer even in an individual county, we conduct case study by dividing Dallam County into three zones with different level of saturated thickness –120 ft (Zone 1), 100 ft (Zone 2) and 70 ft (Zone 3). All other conditions are assumed to be the same. The next discussions except the heterogeneous analysis are based on Zone 1 with 120 ft saturated thickness.

Our simulation results show that the acreage of total cropland in Zone 1 decreases by 22.7% till year 2050 and pastureland will increase by 16.2% (Figure 1). The total irrigated land diminishes by more than 95% while total dryland crop acres increase by about 375 percent. Figure 2 shows the change of consequent saturated thickness throughout 40 years planning horizon. It began at 120 feet and will decrease to 72 feet by year 2050 with about 45% depletion rate in the first period (before year 2020) and about less than 1% in the later period.

The detailed change of irrigated crop land among different crop patterns is more complex because of the application of deficit irrigation strategy. Traditional irrigation development paradigm aims at applying sufficient water to crops to avoid water deficits at all stages, so as to achieve maximum yields (Lorite et al., 2007). Our results indicate that in the semiarid area like

Texas Panhandle Region which faces more sever water stress, adoption of multiple stages deficit irrigation is more beneficial to regional economy and sustainable water use than traditional strategy. Reduced corn yields as the result of deficit irrigation are compensated by increased production from the additional irrigated land. As shown in Figure 3, the acreage of irrigated corn increases by 35% with 80~90% water deficit in the first 10 years. After that, the acreage decreases annually with higher deficit rate due to less and less saturated thickness and total water availability. Moreover, implementing deficit irrigation promotes diversity of crop mixing patterns which can compensate the reduced corn yield. As indicated in Figure 4-6, the saved water can be distributed to other more drought-tolerant crops such as wheat, grain sorghum and cotton, which leads to increasing production of these crops. During 2011-2020, the acreages for these crops show a flat increase with fully irrigated strategy. After that, land use for all irrigated crops decreases in response to declining of actual water volume.

Figure 7 indicates percentage changes in land allocation between irrigated land and dryland over time. Besides deficit irrigation, dryland farming is an alternative strategy particularly in later period (after 2020). Among four major crops, dryland grain sorghum shows the largest increasing rate compared to its historical acreage records in the past twenty years. But, there is little dryland corn to be adopted over the next forty years due to its very limited record in historical crop mixing in Dallam County. In our model, pastureland is the land with vegetation cover used for grazing of livestock (mainly cattle). Alfalfa hay is a regional marketed perennial and drought resistant forage crop. Increasing trend of total pastureland plus alfalfa hay acreage implies that in addition to dryland, developing pasture land is also an effective strategy for regional economic growth (Figure 1)[1].

Climate Change Effects
Table 1 summarizes average changes in temperature as well as precipitation under each of four GCMs for both spring and summer seasons in Dallam County during 2046-2065. Mean temperatures are simulated to rise under all four of the GCMs modeled in this study for both

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[1] Water consumed by livestock and other processes within whole livestock industry is not counted in the model.

spring seasons (March/April/May) and summer seasons (June/July/August). Generally, GFDL-CM2.0 and GFDL-CM2.1 simulate higher temperature than CGCM 3.1 and MRI-CGCM2.2 do. Changes in precipitation patterns differ by season and climate model. It tends to show drying in Dallam County during the summer growing season in the GFDL-2.0 and GFDL-2.1 model whereas CGCM 3.1 and MRI-CGCM2.2 project the increasing precipitation in both seasons. GFDL-2.1 has a precipitation increase in spring, but a most sever decrease in summer months. As mentioned before, these GCMs cover a range of the different temperature and precipitation outcomes presented in the IPCC.

Table 2 shows simulated crop yields for both irrigated and dryland crop production. Irrigated crops tend to be less affected than dryland crops under the climate scenarios in the simulation primarily because they are assumed not subjected to water scarce in EPIC model. Irrigated corn and cotton yields are predicted to decrease in each scenario except MRI-CGCM2.2 which projects least temperature increase. Yields of irrigated grain sorghum increase in MRI-CGCM2.2 and GFDL-2.0, but fall in other two scenarios. Simulated irrigated wheat yields show a different pattern than any of the other crops in EPIC. For wheat, yields tend to be increasing in all four scenarios. Dryland yields show consistent simulation results across all major crops. They are projected to increase in each scenario except GFD-2.1 in which there is the largest precipitation decrease in summer growing seasons. In general, there are varying effects on crop yields under different climate change scenarios, both positive and negative. However, dryland yields usually increase due to greater water availability while non-water limited irrigated crop yields decrease due to the net impacts of higher temperatures. The simulated water demand for each crop by EPIC model indicates that climate change usually has positive effects in irrigation water use efficiency. As indicated in Table 3, water demand of irrigated corn, wheat and grain sorghum averagely reduce about 34.91mm, 36.65mm and 31.46mm per acre respectively relative to baseline across all the climate change scenarios. The efficiency enhancement rate is lower for cotton in comparison to other major crops. Even though this county is projected to be warmer, it is reasonable to expect an improvement in water use because elevated CO_2 concentration is better off for water use efficiencies of crops in a certain degrees.

By incorporating the simulated changes in mean yields for each of crops with EPIC-simulated values into our integrated model, we generated climate changes effects on optimal land and water allocation. Figure 8 shows the temporal changes in irrigated land under each climate

scenario. Because of simulated less crop yields, there is a reduction in total irrigated land use under each climate change scenario other than MRI-CGCM2.2 in the first period compared to no-climate-change condition (defined as No CC in the figures). After year 2020, irrigated land allocation shows the decreasing trends under all scenarios. The decreasing rates relative to the no-climate-change scenario are different due to the different compound impacts of crop yields and water use efficiency changes simulated by alternative climate change scenarios. MRI-CGCM2.2 leads to the least decreasing rate since it projects the highest positive effect on irrigated crop yields among all four scenarios as well as moderate water use efficiency enhancement. In 2035-2050, the acreages under all climate scenarios are closing to the one under baseline scenario since the enrichment of water use efficiency can no longer compensate the much less profitable irrigated crop production.

Figure 9 shows the changes of dryland allocation in different climate change scenarios. The simulated positive effects on major dryland crop yields under CGCM 3.1, MRI-CGCM2.2 and GFDL-2.0 result in more movement from irrigated land to dryland after year 2025 because of water limitation. The pastureland acreage is adjusted in such a way that pastureland demand for cattle decreases with increasing grass yields. As a result, before year 2020, the annual increase of total pastureland is very slight; after that, there is more cropland converting to pastureland. The annual amount of pastureland is 10-20% less under CGCM 3.1, MRI-CGCM2.2 and GFDL-2.0 than baseline scenario, since per acre production of grass on pastureland is simulated as 10%-25% increase under these scenarios relative to no-climate-change scenario.

Bioenergy Feedstock Production

Availability of extractable groundwater restricts the expanding of irrigated corn acreage, even though there is increasing demand of corn as biofuel feedstock under RFS2 targets. In the "RFS-30BGY-c0" scenario which mandates 36 billion gallons of renewable fuel by year 2022 and 21 billion gallons to be obtained from cellulosic and other advanced biofuels, switchgrass production shows increasing trend, since switchgrass-based ethanol would account for the majority of cellulosic ethanol with its advantage in water conservation and marginal land use. However, as energy sorghum becomes available (under "EnergySorghum-07-c0"scenario) it is reasonable to observe diminished switchgrass acreage and this is the case. In particular, there are increased acres (more than 24,000 acres) of energy sorghum with averagely 95% acreage

reductions in swithchgrass under the RFS2 without allowing energy sorghum scenario. This implies that there is a significant land use tradeoff between major advanced bioenergy feedstock— swithgrass and energy sorghum.

Heterogeneity Analysis (case study)

The case study conducted on sub-regions in Dallam County illustrates the hydrological heterogeneity effects on regional land and water use. Our results indicate that optimal crop mix and land allocation strategy should take into account of compound factors of hydrological characteristic and geographical locations. Uniform planning over a whole county will cause net revenue loss and inefficient water use in comparison to inconsistent management. The analysis of optimal land use change is conducted on each of three zones. For simplicity, we assume that the initial land allocation in cropland and pastureland are equal over all three zones in baseline year (2010).

Figure 10 shows that irrigated land use changing rates throughout three zones are quite different. In Zone 1 with higher initial saturated thickness, irrigated land use decreases slower, whereas in Zone 3 with the relative lowest initial saturated thickness, irrigated land production reduces at a much higher rate and will be out of business after 2035.

Our simulation results also show that climate change has heterogeneous impacts on optimal land allocation over different zones. As indicated in Figure 11, climate change induced total net present value percentage changes relative to baseline scenario (no climate change) are different in three zones. Under the scenario in which climate change has positive effects on dryland crop yields and water use efficiency, there will be more enhancement of net present value in the zone with less saturated thickness. However, if climate change has negative effect on dryland yields, the zone with less initial saturated thickness will be more vulnerable.

Conclusion

In summary, by developing and applying integrated dynamic land allocation optimization model, we are able to investigate the optimal land and water use strategy in Ogallala Aquifer Region with and without climate change effects. The results show that availability of extractable groundwater has a direct impact on the value of different types of agricultural land. When water supply is enough, dryland and pastureland are not best choices because of their relatively low profitability compared to irrigated land. Deficit irrigation is an effective short-run strategy in

dressing limited water resource. However, with continuing depletion, the model shows the reduction of total irrigated land as producers switch to dryland and pastureland farming. The simulation results under alternative climate change and bioenergy scenarios indicate that changing climate and bioenergy feedstock production have significant effects on water conservation strategy and rural economy. Climate change has more impacts on areas facing more sever water stress. This model can also serve as a policy tool in evaluating the economic impacts of alternative water-use and agricultural policies, which will be pursued in the future.

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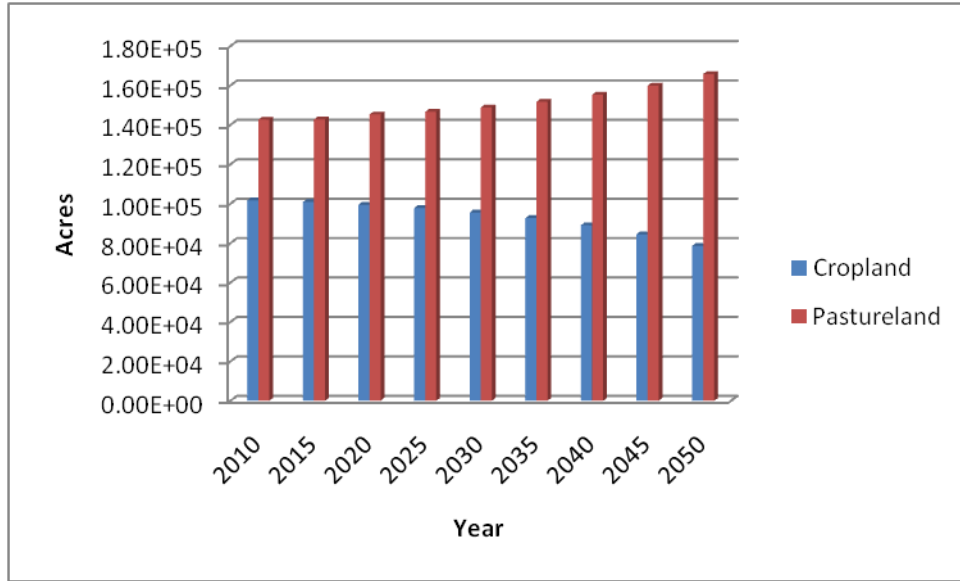
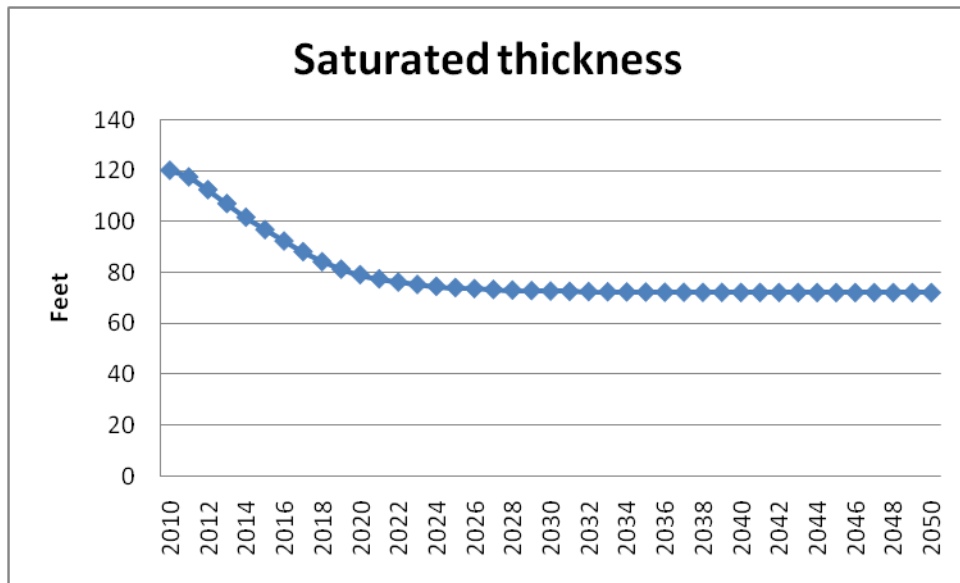**Figure 1. Changes of cropland and pastureland acreages over time**

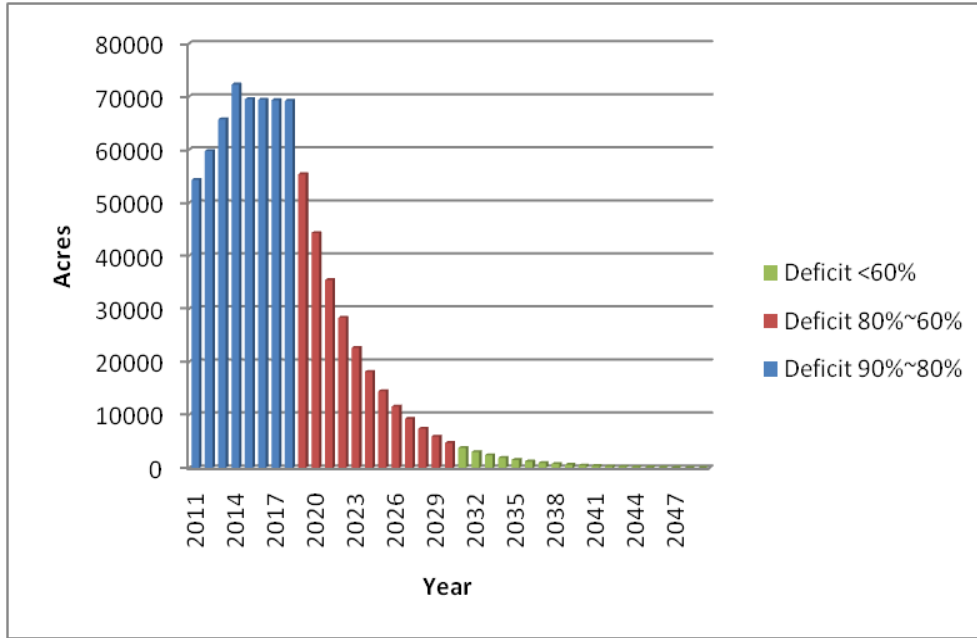**Figure 2. Changes of saturated thickness of Zone 1, Dallam County**

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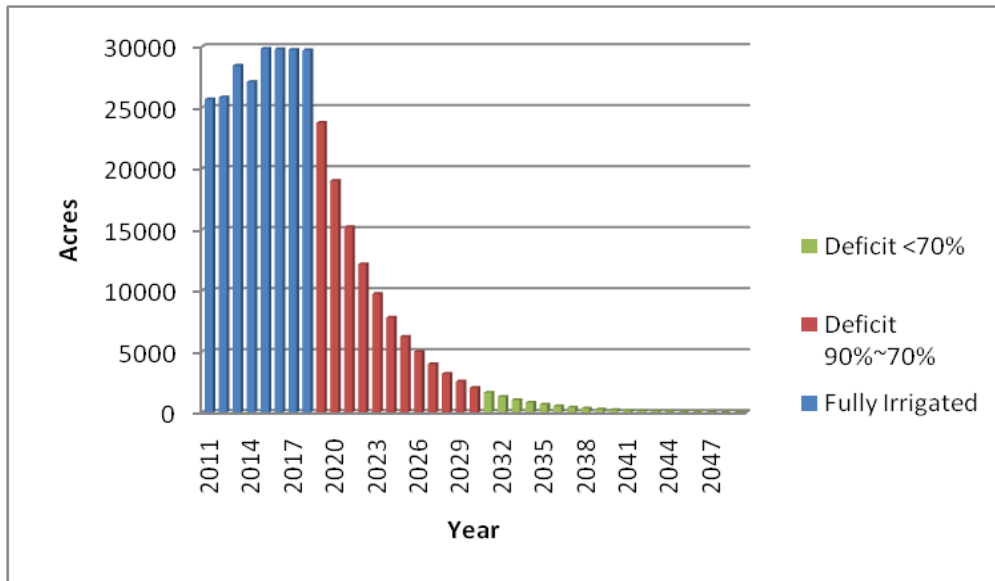**Figure 3. Changes of irrigated corn acreages over time**

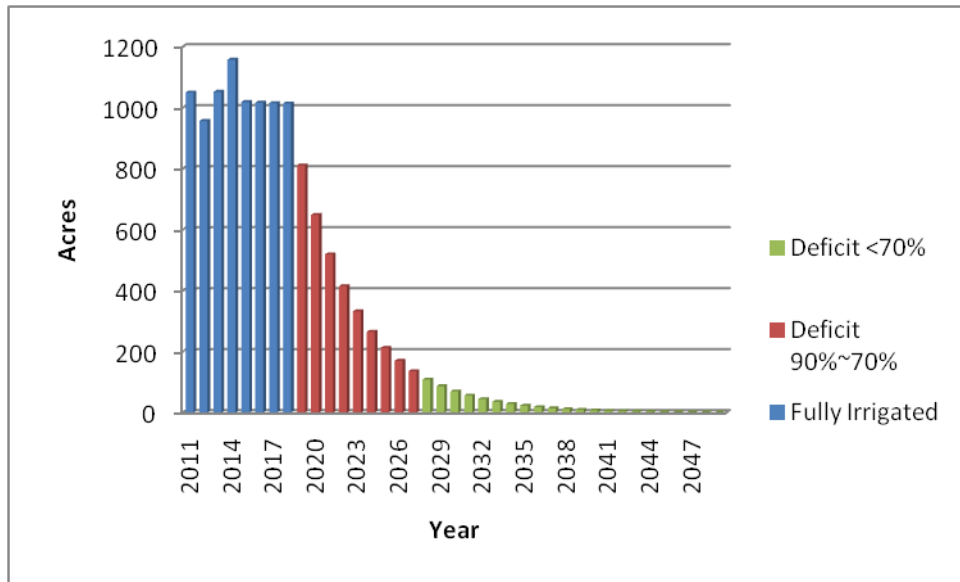**Figure 4. Changes of irrigated wheat acreages over time**

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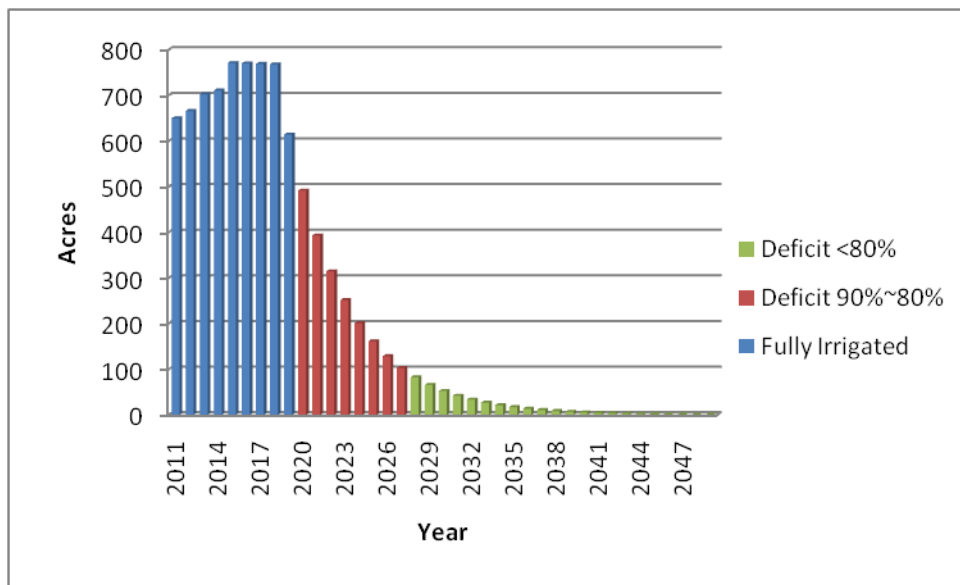**Figure 5. Changes of irrigated grain sorghum acreages over time**

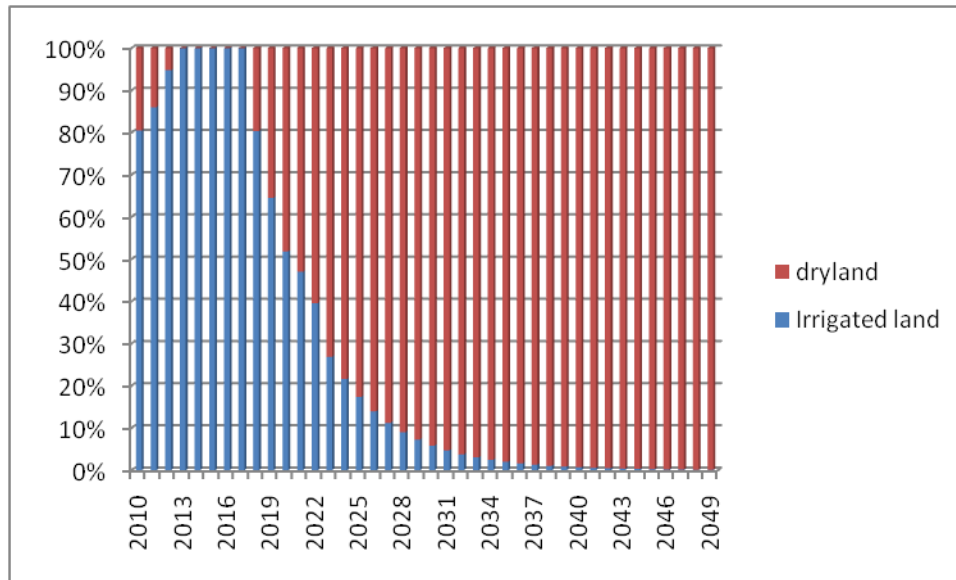**Figure 6. Changes of irrigated cotton acreages over time**

Figure 7. Percentage changes of irrigated land and dryland in total cropland over time

Table 1. . Changes in Temperature and Precipitation under four GCMs Modeled in Dallam County, 2046-2065 relative to 2000 climate baseline

Model	CGCM3.1		MRI-CGCM2.2		GFDL-CM2.0		GFDL-CM2.1	
Season	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
Change in Precipitation(%)	8.06	2.88	13.50	12.00	-4.38	-10.30	10.40	-22.50
Change in Mean Temperature( )	1.17	1.73	1.03	1.10	2.27	2.97	1.53	2.70

Table 2. Crop yields sensitivity to climate change under four GCMs Modeled, 2046-2065 relative to 2000 climate baseline

		CGCM31	MRICGCM	GFDL20	GFDL21
Corn(%)	Irrigated	-2.27	1.57	-5.97	-10.98
	Dryland	19.47	15.25	22.39	-7.35
Cotton(%)	Irrigated	-1.16	7.33	-0.89	-9.66
	Dryland	-1.13	7.64	11.06	-18.81
Wheat (%)	Irrigated	7.74	3.82	1.67	4.83
	Dryland	45.11	15.99	18.32	20.12
Sorghum(%)	Irrigated	-3.85	5.81	0.36	-12.65
	Dryland	17.24	21.68	4.53	-1.88

Table 3. Irrigation water use sensitivity to climate change under four GCMs Modeled, 2046-2065 relative to 2000 climate baseline. (Unit: mm)

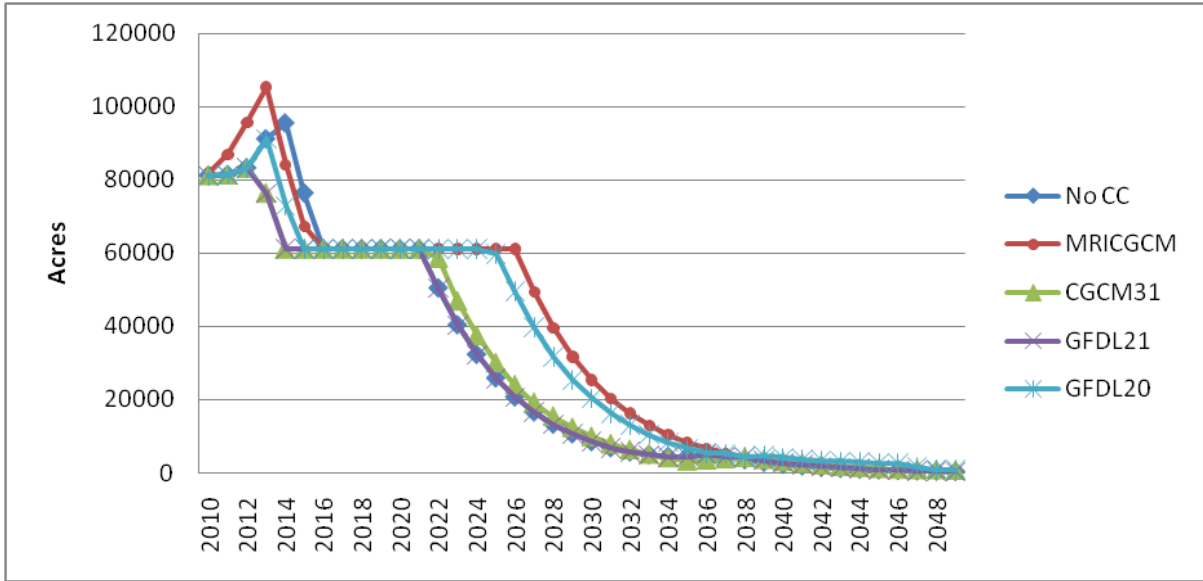|	CGCM31	MRICGCM	GFDL20	GFDL21
Corn	-40.019	-45.336	-44.065	-10.221
Cotton	-9.812	-0.562	-12.779	9.063
Wheat	-41.57	-4.142	-65.434	-36.653
Sorghum	-35.291	-25.916	-45.605	-19.025

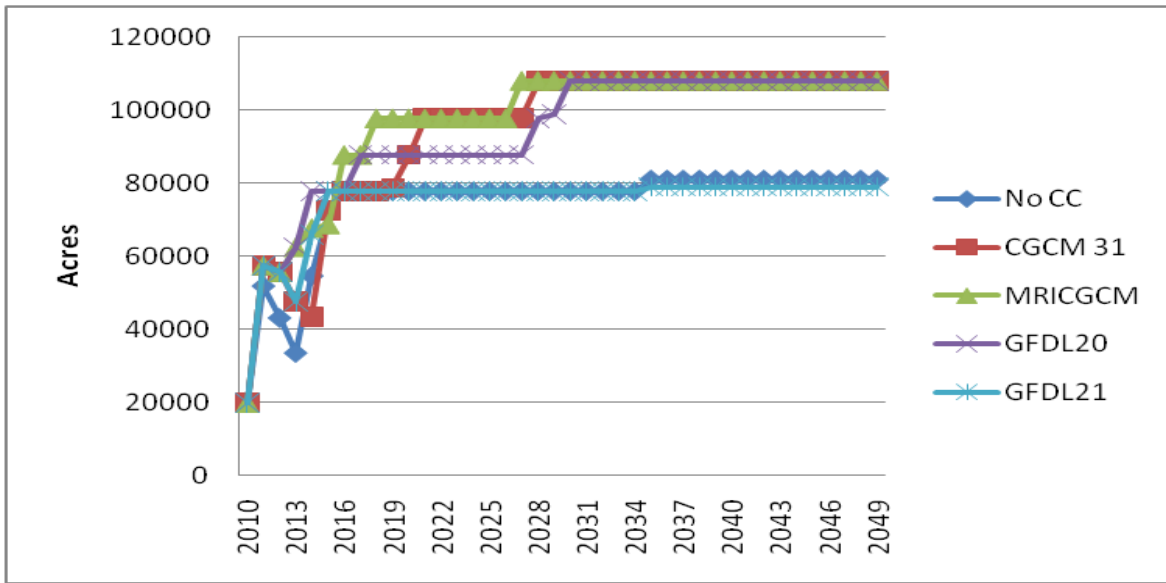**Figure 8. Total acreage of irrigated land under four GCMs and no climate change scenario**

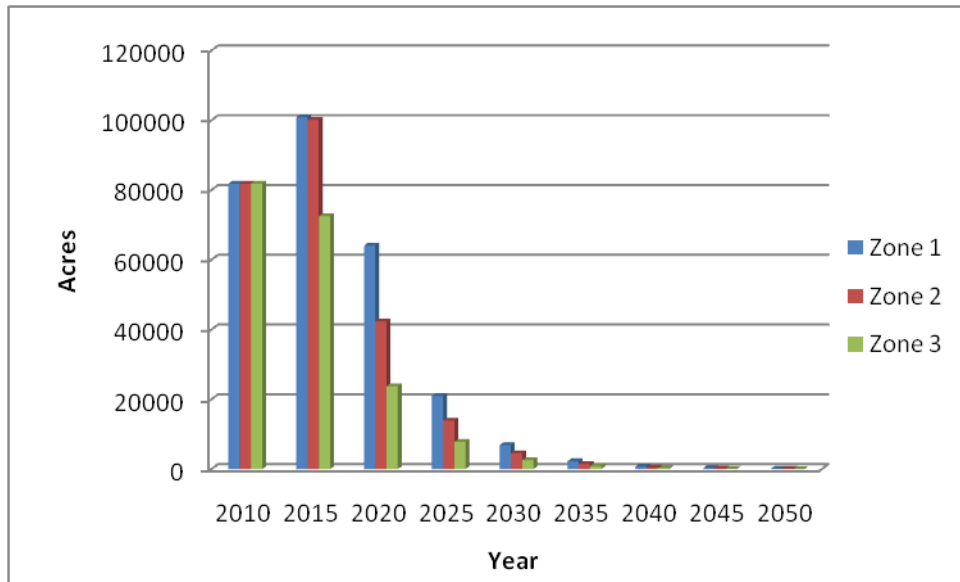**Figure 9. Changes of dryland allocation under different climate change scenarios**

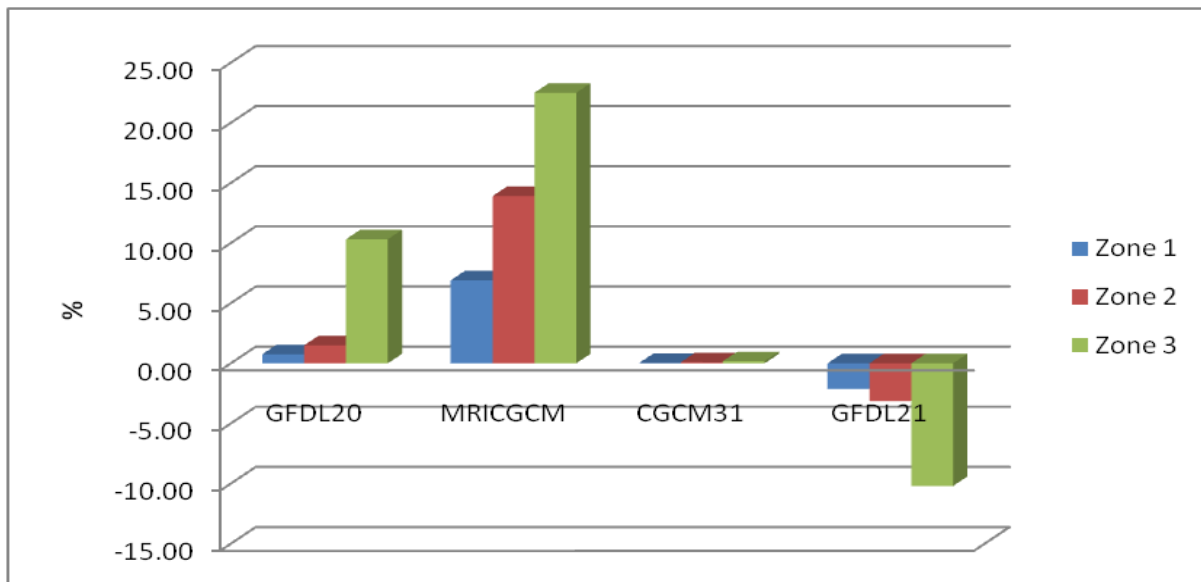**Figure 10. Changes of irrigated land over different zones**

Figure 11. Percentage changes of net present value over different zones and climate change scenarios