

Impacts of Climate Change on Irrigated Agriculture in Northwest Kansas

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Introduction

Scientists that study the dynamics of the atmosphere normally agree that increasing atmospheric concentrations of carbon dioxide (CO₂) and other gases increase the earth's natural greenhouse effect and result in global warming. The gradual warming of the earth's surface may alter precipitation patterns and elevate mean temperatures which may in turn impact crop yields and cropping patterns across the High Plains. Most researchers agree that agriculture may be the most important sector in the economy that is dependent on the climate, but that agriculture may also have the ability to adapt to these changes without major impacts to the profitability of agricultural enterprises (Antle, 2008). However, the general consensus is that the adaptation process will require a greater reliance on irrigation technologies and place a greater burden on water resources (Adams and Peck, 2008; Antle, 2008; Carter et al., 2007; EPA, 1998).

The issue of potential impacts of climate change on groundwater resources is highly relevant to western Kansas. In this area the majority of economic output is dependent on irrigated agriculture that in turn is dependent on the Ogallala aquifer. The current decline of the aquifer has serious implications for the crop, dairy, livestock, and meat processing industries. These industries are vertically integrated so that changes in one industry will impact the others, having a ripple effect on the local economy.

Due to the relative importance of irrigated agriculture, the State of Kansas has been very proactive in implementing and financing water conservation policies to slow aquifer decline rates and achieve sustainability goals. Currently, Kansas is focusing on voluntary and incentive based programs to purchase or lease water rights. These programs are relatively expensive and rely on taxpayer funds. Over 40 sub-basins are seeking policy solutions to declining aquifer levels. Typically, these policies are implemented only after the water savings, hydrological impacts, regional economic impacts, and program costs of the policy have been evaluated, relative to a status quo, or do-nothing scenario by economists, hydrologist, and other regional scientists. Unfortunately, the potential impacts of future climate change currently are not being incorporated into water conservation policy analysis.

The literature suggests that as the climate warms, production patterns in Kansas could shift northward, less soil moisture due to increased evaporation may increase the need for irrigation, and summer nonirrigated crops could experience a 15% yield decline. If the predictions of increased crop water requirements become a reality then irrigation water-use from the Ogallala aquifer may increase. The increase in water-use due to global warming could outweigh the current decreases in water-use resulting from conservation measures.

In this research we evaluate the impacts of future climate changes on the groundwater resources in the Ogallala aquifer, and describe the resulting economic implications. To realize our research objectives, a dynamic economic/hydrological model is developed and applied to project future hydrologic changes, cropping practices and farm income based on climate change predictions.

Dynamic Simulation Model

A dynamic simulation model combines economic models of producer choice which predicts land and water allocations, with a hydrological model, which predicts well capacity and declines in saturated thickness, to investigate the dynamic interaction between the two. The model generates a time-series representation of water-use, aquifer levels, irrigated acreage, and measures of economic productivity. Dynamic simulation models are often used to evaluate the temporal impacts of policy options. Typically, a status-quo scenario is constructed that represents a baseline and assumes unconstrained producer behavior. A second scenario is constructed that represents the exogenous impact of a policy option which imposes a constraint on producer behavior. The time series results of the two dynamic simulation models are then compared to assess the impact of the exogenous shock. For this research the status-quo scenario will mimic producer behavior and water-use assuming that climate change does not occur and the alternate, climate change scenario will assume a gradual increase in mean temperature and decrease in precipitation.

Gisser and Mercado (1973) were among the first to integrate economic theory and the hydrological theory of groundwater flow into a single model. They conceptualized the single cell aquifer, defined the appropriate equations of motion, and provided the theoretical basis for evaluating the competitive market solution. Within the competitive market framework, a producer maximizes profit by choosing the optimal allocation of land and water on an annual basis. While the producer may realize that the choice of water-use today impacts the aquifer decline and thus the future value of water, this factor is not taken into consideration due to the common property characteristic of the aquifer. Typically, the producer's decisions are simulated on a yearly basis without regard for the future. The producer's annual objective function for the dynamic simulation model can be defined as

$$\begin{aligned}
 & \max_{A,w} \sum_{i=1}^n P_i Y_{i,t}(w_{i,t}) A_{i,t} - C_{i,t}(w_{i,t}) A_{i,t} \\
 (1) \quad & s.t. \quad \sum_{i=1}^n A_{i,t} \leq TA \\
 & \quad \quad \sum_{i=1}^n w_{i,t} A_{i,t} \leq TW_t
 \end{aligned}$$

where $w_{i,t}$ is the water allocation for crop i in time period t , $A_{i,t}$ is the acreage allocation for crop i in time period t , $Y_{i,t}$, a function of $w_{i,t}$, is the per acre yield for crop i in time period t , $C_{i,t}$, a function of $w_{i,t}$, is the per acre cost for crop i in time period t , P_i is the per unit price of crop i , TA is a fixed total acreage constraint, and TW_t is a dynamic total water availability constraint.

In any given time period (t), yields (Y), costs (C), and total water availability (TW) are functions of the applied irrigation water (w). Assuming aquifer recharge (R) is less than the total quantity of water pumped from the aquifer, the aquifer's saturated thickness (ST)

declines over time and the depth to water (DW) increases over time. These changes in ST and DW tend to reduce pumping capacities and limit total water availability (TW). The annual change in saturated thickness can be defined as

$$(2) \quad \Delta ST = ST_{t+1} - ST_t = \frac{R_t}{S} - \frac{TW_t}{S * L},$$

where S is the specific yield of the aquifer, L is the land area overlying the aquifer and recharge (R) has been specified as a function of time. The annual change in the depth to water (DW), or the pumping lift, can be defined as

$$(3) \quad \Delta DW = DW_{t+1} - DW_t = \Delta ST.$$

In order to model the impacts of climate change, the aquifer recharge (R) has been specified as a function of time. The literature suggests that one impact of future climate change may be a reduction in aquifer recharge (EPA, 1998; Rosenberg et al., 1999; Kundzewicz et al., 2007). Assuming α represents the proportional change in recharge over the simulation period (T), for the climate change scenario, the temporal change in recharge (R) can be defined as

$$(4) \quad R_t = R_{t=0} * (1 - \alpha * (t / T)).$$

Several economic studies of groundwater decline have recognized the impact that saturated thickness has on well capacity, and subsequently on crop choice, the decision to cease irrigation production, and production costs (Sloggett and Mapp, 1984; Brill and Burness, 1994; Burness and Brill, 2001; Ding, 2005). In order to place appropriate constraints on total water availability (TW), each of these studies has defined well pumping capacity as a function of saturated thickness (ST). This research relies on a relationship developed by Golden, Peterson, and O'Brien (2008) for western Kansas

$$(5) \quad GPM_t = -488.93 + 3.68 * HC + 8.75 * ST_t + 0.05 * ST_t^2$$

where GPM is the well capacity measured in gallons per minute, HC is the hydraulic conductivity measured in feet per day and ST is the saturated thickness measured in feet.¹ As illustrated in the previous equation, as saturated thickness diminishes, well capacity can be expected to decline and total water availability reduced.

As total water availability declines we can expect crop yields to decrease, acreage allocations to change, and production inputs and resulting costs to change. The dynamic cost function can be defined as

¹ The mathematical function relating well capacity to saturated thickness was derived by Golden, Peterson, and O'Brien (2008) and based on data obtained from Hecox, Macfarland, and Wilson (2002) and the Kansas Geological Survey.

$$(6) \quad C_{i,t}(w_{i,t}) = VE_i + YVE_{i,t}(Y_{i,t}) + IFE(ST_t, w_{i,t}).$$

This cost function has three components: crop specific variable expenses (VE) that are assumed to remain static over time, such as labor, herbicide, and non-irrigation fuel expenses; yield dependent variable expenses (YVE) that dynamically change as yield changes, such as fertilizer, seed, and harvesting expenses; and the irrigation fuel expense (IFE) that is a function of the saturated thickness and crop water allocations.

The yield dependent variable expenses (YVE) can be defined as

$$(7) \quad YVE_{i,t}(Y_{i,t}) = \frac{BC_{i,t=0} * Y_{i,t}}{Y_{i,t=0}},$$

where BC is the base cost of the expense category. Essentially, this definition implies that if yields decrease over time yield dependent variable expenses (YVE) also decrease over time.

The irrigation fuel expense (IFE) can be defined as

$$(8) \quad IFE_{i,t} = \frac{(w_{i,t})(0.114)(P_f)(DW_t + PH)}{(E_f)},$$

Where P_f is the price of fuel, E_f is the energy use factor, and PH is the pumping head requirement for the irrigation technology.

The final step in developing the conceptual model defined by equation (1.1) is the development of a dynamic production function that yields $Y_{i,t}$. A production function is a mathematical relationship that relates the quantity of output produced to the quantity of inputs used in the production process. As an example, the production function for irrigated corn would quantify the relationship between the bushels of corn produced per acre to the acre-inches of irrigation water applied. A dynamic production function is a production function that changes over time in response to exogenous impacts. While the literature provides a wide variety of choices relative to the functional form of production functions, for this research it is important that the functional form be adaptable to the dynamics of climate change.

The literature suggests that the major impacts of climate change on crop production will come from 1) changes in temperature, 2) changes in precipitation patterns, and 3) and the impact of elevated levels of atmospheric CO_2 on crop yields. Additionally, Adams and Peck (2008) suggest that the intensity and duration of droughts may increase. If temperature increases more water will be lost to evaporation (Adams and Peck, 2008; EPA, 1998), and the crop specific evapotranspiration (ET) requirements for a fully watered crop may increase. If precipitation decreases we would expect dryland crop yields to decrease and irrigation requirements for a fully watered crop to increase.

Increasing levels of atmospheric CO₂ may generate a fertilization effect. Elevated levels of CO₂ in the atmosphere can lead to an increase in plant photosynthesis which may increase crop yields. It can also lead to a decrease in transpiration (evaporation from plant foliage), which may reduce water stress. While some studies suggested productivity increased by 50% or more (Antle, 2002), there is significant debate about whether CO₂ fertilization effects, which have been observed under laboratory conditions, will be observed under actual field conditions (Rosenzweig and Hillel, 1998; Abler et al., 2002). Long et al. (2006) suggests that field results show that elevated carbon dioxide stimulates crop yields less than previously thought. Specifically, their results imply that elevated levels of CO₂ may generate no yield change in corn. Based on the ambiguous nature of the CO₂ fertilization effect, and since the predominant crop in western Kansas is corn, this research assumes that elevated levels CO₂ associated with future climate change will not impact crop yields. Abler et al., 2002 also reported simulation results in which there were no CO₂ enrichment effects.

Martin, Watts, and Gilley (1984) derive a production function based on well established engineering/agronomic principles. Importantly, this function is based on readily available physically defined parameters and is easily adapted to the dynamic requirements of a climate change model. Based on Martin, Watts, and Gilley (1984), the static production can be defined as

$$(9) \quad Y = DY + [FWY - DY] * \left(1 - \left(1 - \frac{GI}{GIR}\right)^{1/WUE}\right)$$

where Y is crop yield, DY is the dryland yield, FWY is the fully water yield, GI is the gross irrigation, GIR is the gross irrigation requirement for a fully watered yield, and WUE is a measure of season-long water-use efficiency. Implicitly, this production function assumes average rainfall.

In order to define the dynamics of the gross irrigation requirement (GIR) we start with developing the information necessary to estimate the net irrigation requirement (NIR) for a fully watered crop. The net irrigation requirement (NIR) is the amount of irrigation water required, at 100% season-long application efficiency, necessary to achieve the maximum or fully watered yield. The relationship between GIR and NIR can be defined as

$$(10) \quad NIR = GIR * WUE$$

To a large extent NIR for a given crop is dependent on the evapotranspiration requirements for a fully water crop (ET_{FWY}). Evapotranspiration (ET) is the water removed from the soil by a plant through transpiration of water through the plant leaves and evaporation of water from the plant and soil surface. Evapotranspiration is determined by the crop type, growth stage of the plant, weather conditions, and cultural practices. Evapotranspiration is important because crop yield relates more-or-less directly to this measure. It is generally believed that the relationship between evapotranspiration and yield is linear (i.e., a straight line). The yield- ET relationship can be defined as

$$(11) \quad Y = b_0 + b_1 * ET$$

where b_0 is a constant and b_1 is the slope of the yield- ET function. The slope parameter can be viewed as a measure of a plant's water-use efficiency in converting ET (water) into crop yield.

Because yield increases with evapotranspiration, the maximum yield cannot be reached until the maximum evapotranspiration level is also reached. For our purposes, define ET_{FWY} as the evapotranspiration requirement of a fully water crop. ET_{FWY} can be considered as the net water requirement needed to achieve the maximum crop yield. The ET_{FWY} requirement can come from water stored in the soil, rainfall, and/or irrigation. Based on the conventional crop water balance equation, ET_{FWY} can be defined as

$$(12) \quad ET_{FWY} = GSP - RU - DR + NIR + \Delta SM ,$$

where GSP is the growing season precipitation, RU is runoff, DR is drainage, and ΔSM is the difference in soil moisture between planting and harvesting. Growing season precipitation (GSP) can be defined as the precipitation that occurs during the growing season that can be of beneficial use to crop production. The change in soil moisture (ΔSM) can be defined as the total amount of water that was stored in the soil at planting time and used during the growing season.

In the event of high precipitation rates, water may run off the field to a stream or percolate past the root zone and be ineffective at meeting the crop's evapotranspiration requirement. Also, evaporation might greatly reduce the benefit of low rainfall events. Part 623 of the National Engineering Handbook defines effective precipitation (EP) as the part of rainfall that can be used to meet the evapotranspiration of growing crops. Factors that influence effective precipitation are soil slope, soil texture and structure, plant cover or crop residue, and storm intensity and duration. Assuming the effectiveness of the growing season precipitation (EP) captures the effect of runoff and drainage, NIR can be redefined as

$$(13) \quad NIR = ET_{FWY} - GSP * EP - \Delta SM .$$

Assume that λ quantifies the impact that a total change in temperature ($\Delta Temp$), resulting from climate change, will have on ET_{FWY} . Also assume that ΔGSP represents the total change in growing season precipitation resulting from climate change, over the modeling horizon. The dynamic net irrigation requirement can be defined as

$$NIR_{i,t} = (ET_{FWY_i} + \lambda_i * \Delta Temp * \frac{t}{T}) - (GSP_{t=0} + \Delta GSP * \frac{t}{T}) * EP - \Delta SM$$

(14) *and*

$$GIR_{i,t} = \frac{NIR_{i,t}}{WUE}$$

Assuming that there is no CO₂ fertilization effect implies that b_0 , b_1 , and FWY remain constant over time. Based on the yield- ET relationship, for an individual crop, the dynamic dryland yield (DY_i), as a function of the static fully watered yield (FWY_i) can be calculated as

$$DY_{i,t} = b_0 + b_1 * ET_{DY_{i,t}}$$

$$FWY_i = b_0 + b_1 * ET_{FWY_i}$$

(15) $DY_{i,t} = FWY_i - b_1 * (ET_{FWY_i} - ET_{DY_{i,t}})$

$$NIR_i = ET_{FWY_i} - ET_{DY_{i,t}}$$

$$DY_{i,t} = FWY_i - b_1 * NIR_{i,t}$$

The dynamic production function can now be defined as

$$(16) \quad Y_{i,t} = DY_{i,t} + [FWY_i - DY_{i,t}] * (1 - (1 - \frac{GI_{i,t}}{GIR_{i,t}})^{1/WUE}),$$

where equation (15) defines $DY_{i,t}$ and equation (14) defines $GIR_{i,t}$. Figure 1 illustrates the dynamic production for corn in northwest Kansas.

Data

The dynamic simulation model as previously described is applied to a small sub-basin in Sheridan County, located in northwest Kansas. Table 1 reports the basin characteristics and hydrological data used in this research. The Kansas Geological Survey High Plains Aquifer Section-Level Database, accessed through the WIZARD system, was used to obtain the saturated thickness, recharge, hydraulic conductivity, specific yield, and average decline in saturated thickness data. These data are used to estimate the current average well capacity as well as provide the parameter estimates for the hydrological aquifer model.²

The total water-use data as well as the total irrigated acres and crop mix were obtained from the Kansas Department of Agriculture Division of Water Resource's Water Right Information system. These data consist of time-series observations for each water well in the sub-basin and report the annual acre-foot water usage, the number of irrigated acres,

² Based on recommendations from the Kansas Geological Survey certain parameters were calibrated to insure that model predicted aquifer decline rates matched historically observed decline rates.

the crop grown on the irrigated parcel, and the technology used to irrigate the associated parcel.

Table 2 reports the crop specific parameter estimates used in this analysis. The fully watered yield was obtained from Stone et al. (2006). Data provided by Stone and Schlegel (2006) formed the basis for slope parameter (b_1) necessary to estimate the yield- ET relationship as well as a point estimate for the evapotranspiration requirement of a fully water crop (ET_{FWY}).³

The growing season precipitation (GSP) was estimated by combining county-level normal monthly precipitation data obtained from National Climatic Data Center with the normal crop-specific growing season data obtained from state extension publications. The effective precipitation (EP) proportion was set at 88% based on O'Brien et al. (2001). The change in soil moisture (ΔSM) can be defined as the total amount of water that was stored in the soil at planting time and used during the growing season. These data are site specific and prove difficult to estimate. Extension professionals from northwest Kansas suggested a value of 2.5 inches was appropriate.

Extension professionals from northwest Kansas suggested that the impact of temperature on ET in the future could be approximated by estimating the current relationship between temperature and ET across western Kansas. That is, the ET requirements in northwest Kansas in the future (when mean temperatures are expected to increase) will be similar to the ET requirements observed in southwest Kansas today (where the temperature and ET are higher today). Historic evapotranspiration and temperature data were obtained from the Kansas Weather Library. OLS regression was used to develop estimates of the relationship between evapotranspiration and temperature (λ).

Returns to land, management, and equipment is the economic metric used in this analysis. The metric was constructed based on 2007 KSU extension budgets for western Kansas. This dynamic metric changes as crop yield changes and as saturated thickness diminishes.

Scientists that study the dynamics of climate change use General Climate Models (GCM) to develop possible future climate change scenarios. Predictions are based on assumptions associated with future population growth, the structure of the world economy, the rate of technological advancement, and the level of mitigation activities. As a result, it is not surprising that climate change predictions obtained from GCMs vary considerably. Additionally, the current spatial resolution used in GCMs is very coarse and proves problematic for regional modeling (Antle, 2002). With these constraints noted, several studies have modeled a variety of climate change scenarios obtained from multiple GCMs (Hurd, 2007) or aggregated many the results from several GCMs into a single scenario.

³ Based on recommendations from the Kansas Water Office and producer groups certain parameters were calibrated to insure that sum of the model predicted annual individual crop water-use matched historically observed aggregate water-use.

The climate change scenario used in this analysis is based on estimates provided by North (2008) for the Great Plains area.⁴ North (2008) based his analysis on the 2007 assessment by the International Panel on Climate Change (IPCC) which made use of more than 20 General Climate Mode. The 2007 IPCC assessment is reported by Carter et al. (2007). As reported in Table 2, this aggregation suggests a 2.5 degree Fahrenheit elevation in mean temperature and a 2.5% reduction in mean summertime precipitation over the next 50 years. Noah, Stuntz, and Abrams (2008) suggest that in the Ogallala Aquifer region, groundwater recharge may decrease by 20%, which is used as a proxy for the proportional change in recharge (α). As reflected in the preceding equations, these changes are assumed to occur in a linear fashion over the 50 year modeling horizon.

Results

The results suggest that there is little difference between the status-quo and climate change scenario from the perspective of well decline, saturated thickness, and total water-use. Figure 2 illustrates the time path for total water-use for the two scenarios. As would be expected in the near-term, as the climate warms and precipitation decreases the climate change scenario uses slightly more groundwater. Total annual water-use continues to increase until the saturated thickness declines to the point that existing well capacity, as defined in equation (5), imposes a pumping capacity constraint on total withdrawals. After the pumping capacity constraint is reached both scenarios use approximately the same amount groundwater. Since climate change scenario uses more groundwater in the early years, the saturated thickness declines at a faster rate and as a result there is slightly less water available toward the end of the simulation period. This is due to the fact that the basin is already very close to needing more groundwater than can be pumped. Since water has value, once a producer needs more water than can be pumped they use all the water they can pump regardless of the climate.

This research suggests that the most significant impact of future climate change may be on producer profits. Figure 3 illustrates the time path for the metric of returns to land, management, and equipment. After the pumping capacity constraint is reached, a profit maximizing producer will either accept lower crop yields for his historic crop choice or switch to a different crop. In either case, since water generates profits in the production process, with less irrigation water available the producer will receive a lower return. As illustrated, both the climate change scenario and status-quo scenario suggest reduced returns over time. However, in northwest Kansas, we would expect to see returns decrease significantly as a result of climate change relative to the status-quo scenario. In year 50 the status quo scenario results in the returns to land management and equipment being approximately 33%, or 65 dollars per acre, greater than projected with the climate change scenario.

Conclusion

The development of economic models that predict the future are, by their very nature, subject to error, and the results are most appropriately viewed as a ‘best guess’. From a policy analysis perspective, it is not imperative that the predictions be perfectly accurate. It is important to focus on the ‘difference’ between scenarios and not the scenario itself.

⁴ North (2008) provided a range estimate. The center point of that range is used in this analysis.

So long as consistency is maintained between methodology and assumptions, and all stakeholders are comfortable with the methodology and assumptions, comparisons of different scenarios are appropriate to evaluate water management options.

This research focused on a relatively small sub-basin in northwest Kansas. The aquifer in this area is rapidly approaching the point where hydrological characteristics will limit groundwater withdrawals and result in reduced profitability. Local stakeholders are actively engaged in defining policy options to conserve groundwater and extend the economic life of the aquifer. The basis for policy comparison is the relationship between current policy costs and future revenue streams. This research suggests that status-quo scenarios constructed without the inclusion of the possible climate change consequences may significantly overestimate future revenue streams and underestimate the benefits of groundwater conservation. Conservation policies that reduce water-use today will allow that water to be used in the future to mitigate the impacts of climate change.

The literature suggests that production agriculture will have little problem adapting to climate change. The most significant finding of this research is that in areas where pumping capacity is limited or state policy limits water-use, irrigated agriculture may suffer as a result of climate change.

The dynamic simulation model developed for this research did not incorporate possible CO₂ fertilization effect, possible mitigation by farmers through the changing of planting dates, nor the impact of technology advancements on increasing crop yields and decreasing water-use. However, the characteristics of the dynamic production function used in this analysis should allow these factors to be addressed in future research.

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Tables

Table 1. Basin Hydrological Characteristics

Variable	Description	Value
<i>L</i>	Basin Surface Area (acres)	88500
<i>R</i>	Recharge (inches/year)	1.20
<i>DW</i>	Depth to Water (feet)	164.7
<i>ST</i>	Saturated Thickness (feet)	89.8
<i>HC</i>	Hydraulic Conductivity (ft/day)	40.4
<i>S</i>	Specific Yield	0.175
<i>TA</i>	Total Irrigated Acres	24855
<i>TW</i>	Total Water Availability Constraint at t = 0 (acre-feet)	26595

Table 2 Crop Parameters

Variable	Description	Corn	Sorghum	Soybeans
<i>A_i</i>	Crop Mix Acreage at t = 0	19506	969	4379
<i>FWY</i>	Fully Water Yield (bushels)	213	158	70
<i>b_l</i>	Slope of Yield- ET Function (bushels/inch of water)	13.3	9.4	3.8
<i>ET_{FWY}</i>	Evapotranspiration for a Fully Watered Yield (inch of water)	25	21	24
λ	Change in Evapotranspiration (inch of water per F°)	0.53	0.43	0.50
<i>GSP</i>	Growing Season Precipitation (inch of water)	14.3	12.2	14.3
ΔSM	Change in Soil Moisture (inch of water)	1.0	1.0	1.0
<i>EP</i>	Effective Precipitation	0.88	0.88	0.88
Climate Change Scenario				
$\Delta Temp$	Total Change in Temperature (F°)	2.5	2.5	2.5
ΔGSP	Total Change in Growing Season Precipitation (inch of water)	2.50%	2.50%	2.50%
α	Proportional Change in Recharge	0.20	0.20	.020

Figures

Figure 1. Dynamic Production function for Corn

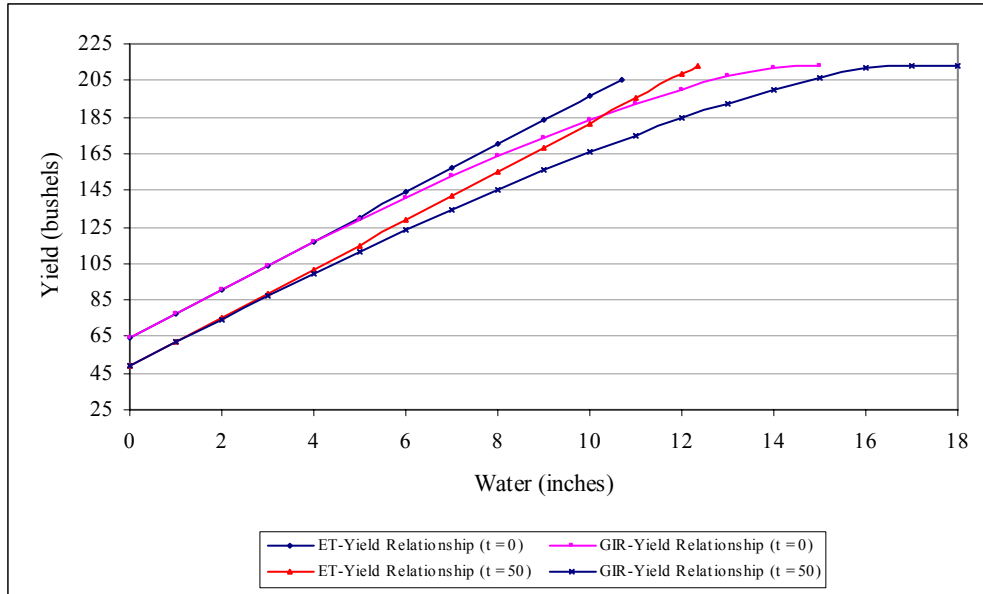


Figure 2. Time Path for Total Water-Use

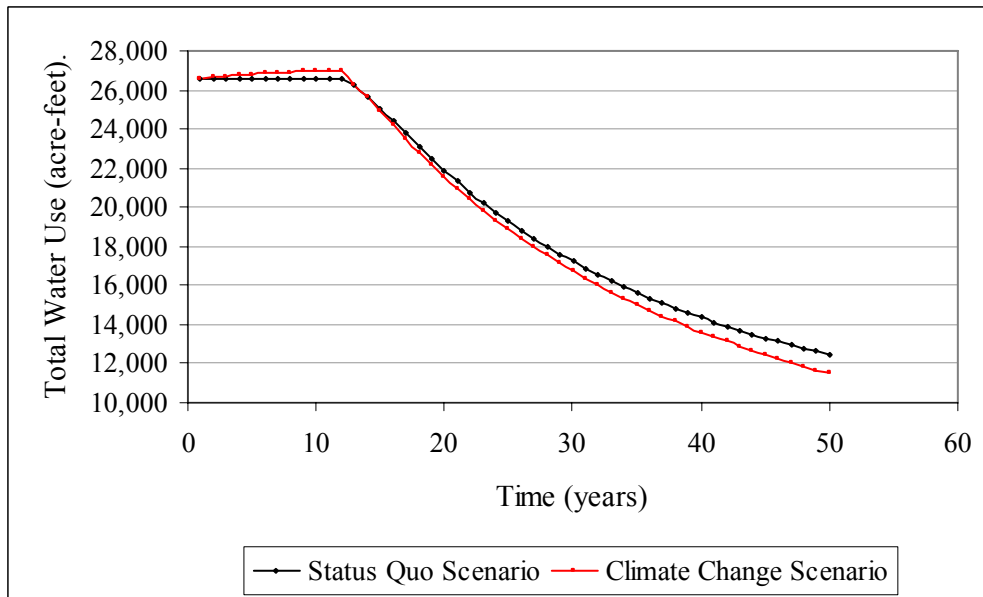


Figure 3. Time Path for Returns to Land, Management, and Equipment

