Projecting the Economic Impact and Level of Groundwater Use in the Southern High Plains under Alternative Climate Change Forecasts Using a Coupled Economic and Hydrologic Model

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Abstract

This research estimates the impact that eight alternative climate change scenarios are likely to have on agricultural returns and the useful life of the Ogallala aquifer in the Southern High Plains (SHP) over a 90-year planning horizon, relative to the situation where climate conditions are maintained at the historical average condition for 1960 to 2009. The empirical analysis is accomplished with the aid of an integrated water policy model that couples a dynamic economic optimization model to a detailed aquifer model of the Southern Ogallala Aquifer. The integrated model controls for the effects of spatial heterogeneity in land use practices and aquifer characteristics. For each climate scenario, changes in annual economic returns, irrigated acres, water use, and aquifer storage levels are measured relative to respective estimates derived from the historic no change climate scenario. The annual 90-year time path of economic returns, water use, and cropping patterns under the eight climate change scenarios significantly varies from the baseline forecast. Moreover, relative to a baseline condition that estimates significant annual decreases in economic returns due to continued groundwater mining, the climate change scenarios generally suggest climate change will mitigate the cost of increasing groundwater scarcity due to a complimentary effect between crop yields and the various climate change scenarios.

Introduction

It is widely acknowledged that the Southern Ogallala Aquifer has been mined as an exhaustible resource for over 60 years and aquifer supplies are now approximately 50 percent of their 1940 storage level (Ogallala Commons 2004). Current withdrawals by irrigated agriculture are estimated to be 95% of all withdrawals and exceed natural recharge by as much as ten times (Guru and Horne 2000; Das and Willis 2012). Most prior agricultural groundwater research in the Texas High Plains has focused on the optimal time path of agricultural land-use practices under the condition of increasing groundwater scarcity and associated higher pump lifts given existing and constant climate conditions. This prior research tells a consistent story where irrigated crop acreage is slowly transitioned into either dryland crop acreage or rangeland, and future irrigated production is restricted to high valued crops under the most efficient irrigation application technologies. This prior research also consistently reports that annual per acre net revenue will decrease through time because of reduced groundwater supplies and higher pumping lifts. However, given limited agricultural cropping options in the THP, conservation quotas that restrict groundwater withdrawal and would extend aquifer life, do not increase per acre agricultural net present value because the restrictions essentially cause irrigated agriculture to delay extraction only to later apply the water to the same cropping activities at a later date with the same productivity.

Climate changes may significantly affect the long-term implications of this prior research. A recent national USDA-ARS study (Malcolm et al., 2012) found that within a given geographic region, climate change differentially affects individual crop yields, and in many climate scenarios enhances crop yield response to applied irrigation water when expected future

carbon dioxide levels are controlled for. They also found that the climate change yield effect tended to increase dryland profitability more than irrigated profitability because of the lower per acre dryland production cost. These findings may have a significant impact on how irrigated agriculture adapts to water scarcity over time and the value of groundwater conserved under conservation policies. If, over time climate change and applied water prove to be complimentary production inputs, the economic value of water conservation could significantly increase.

We have two primary research objectives. The first objective is to determine the range of impacts possible climate change scenarios are likely to have on the economically efficient time path of agricultural groundwater use in the SHP of Texas relative to a baseline condition of no climate change. The second objective is to estimate the change in economic benefits and costs of groundwater conservation policy that restricts annual groundwater use to 15 acre inches per irrigated acre to extend the useful agricultural life of the Southern Ogallala Aquifer.

Data and Methods

This study couples a nonlinear dynamic optimization model to a detailed spatially disaggregated hydrologic model of the Southern Ogallala Aquifer that has the capacity to determine the optimal temporal and spatial allocation of groundwater use in one agriculturally intensive county that overlies the Southern Ogallala Aquifer under eight alternative climate change scenarios. The coupled dynamic model used in this study is based upon the Texas High Plains water policy model developed by Das and Willis (2012) that spans 19 Texas counties. In this study, the model is adapted for one county in the Texas High Plains. Hale County was selected as the representative county because the hydrologic data for the county had recently been updated and the county is a heavy user of groundwater for irrigation use.

Climate Data

The effect of climate change on agricultural water and per acre economic returns is measured relative to a baseline status quo climate condition for eight potential climate change scenarios over a 90-year period. The baseline climate condition is defined as the average annual climate condition for the Plainview weather station located in Hale County, Texas over the 1960 to 2009 time period. The eight potential 90-year climate change scenarios were developed by combining the quantitative projections for precipitation, potential evapotranspiration and temperature trends driven by simulations from the latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4) Global Climate Models (GCM) under two specific emissions scenarios, A1B (balance future fossil fuel versus non-fossil fuel energy use) and A1FI (a continuation of the historically intensive use of fossil fuels as an energy source).

The four selected GCM employed to create the 90-year climate forecasts are: (1) the Parallel Climate Model (PCM); (2) version 3 of the Community Climate System Model (CCSM); (3) Version 3 of the Hadley Climate Model (HadCM3); and (4) the Geophysical Fluid Dynamics Laboratory model (GFDL). Quantitative projections of precipitation, potential evaporation, and temperature trends for the 90-year duration were selected from a downscaled set of high-resolution (one-eighth degree) daily climate and hydrological simulations covering the entire Great Plains region. The downscaling was accomplished by taking the high-resolution daily temperature and precipitation projections from the four climate models in combination with the two emission scenarios (A1B and A1FI) and using a statistical asynchronous regression model based on long-term daily station observations from Plainview TX (located in Hale county) to generate eight 90-year climate scenarios for the 2010 to 2099 period (Hayhoe 2007). Table 1 reports the simulated climate data for the eight climate scenarios plus the baseline condition for

the variables of temperature, precipitation and $C0_2$ concentration. Due to space limitation and to facilitate presentation the reported data for each climate scenario is reported as annual average over three thirty year times frames: near future (2010-2039), mid future (2040-2069), and distant future (2070-2099).

Crop Yield Data

Four crops account for 97 percent of all crops that are irrigated in Hale County. These four crops are cotton, wheat, sorghum, and corn. The Decision Support System for Agrotechnology Transfer (DSSAT) was used to estimate annual a 90-year crop yield sequence for each of the four crops under dryland production and seven alternative irrigation application levels for each climate scenario including the baseline. The annual irrigation levels ranged from five acre-inches per acre to 35 acre-inches per acre in five inch increments.

Version 4.5 of the DSSAT crop model (Hoogenboom et al., 2010; Jones et al., 2003) was used in this study. One major benefit of using DSSAT to simulate crop growth is that it allows for CO_2 fertilization effects, which is an important aspect of plant growth and response (Nelson et al., 2009). As $C0_2$ levels increase most crops more efficiently use available water and yields increase ceteris paribus. Effects on crop production of changing climate as well as CO_2 emission changes have been incorporated in prior assessment studies regarding climate change impacts (e.g. Rosenberg and Crosson, 1993; Rosenzweig and Parry, 1994). The conventional approach involves incorporating future climatic conditions provided by climate models and incorporating them into the crop growth simulation models. To ensure uniformity in results, the soil type and profile description for a particular study area are specified when running the crop models. This procedure was followed to generate the annual crop yield series for the four crops for each of the eight climate scenarios in combination with the eight water application rates (including dryland

production). Table 2 reports the average simulated dryland yield values for the four crops grown under eight climate scenarios and the baseline condition for four different time periods. The four time periods consist of 1960-2009 (historic baseline), the near future (2010-2039), the mid future (2040-2069), and distant future (2070-2099). Due to the increasing CO_2 concentration level over time average dryland yields tend to increase for all crops under all climate change scenarios.

Climate specific crop yield response functions to the applied irrigation water level were derived for each crop using the simulated DSSAT yield data for a specific climate scenario. Due to a changing relationship between crop yield and applied water over time, as well as the simulated general trend for dryland crop yields to increase over time in each 90-year climate scenario, each 90-year scenario was subdivided into three 30-year periods for purposes of estimating a more stable crop yield response to applied water at different points in the 90-year planning horizon. Thus, by construction, for a given 30-year sub-period three individual 30-year dryland yields and crop yield response functions to applied water were estimated for each crop in a given climate scenario. The consequence of this modeling framework is that for a given crop and climate scenario, dryland crop yield and crop yield response to applied water differ between 30-year sub-periods, but are constant within a specific 30-year sub-period. This estimation procedure allowed for the estimation of statically significant and correctly signed crop response parameters for each estimated response function. Moreover, the time dependent crop yield functions provide a means to effectively capture the impact of alternative climate change scenarios on optimal agricultural water use time path as determined by the dynamic economic model.

Two functional forms were utilized to estimate crop yield response to consumptively used applied water. Following Hexem and Heady (1978) the crop yield response functions to

applied water were expected to have a quadratic form. However, statistical estimation suggested the quadratic form was only appropriate for the simulated DSSAT crop yields for wheat, corn, and sorghum. A cubic relationship between yield and applied water under LEPA technology provided a superior fit than the expected quadratic relationship for cotton. The generic functional relationships between crop yield (Y) and total seasonal applied irrigation water (W) under LEPA technology are reported below. Estimated parameter values are available on request.

The generic functional form for the cotton production function is:

$$Y = \beta_0 - \beta_1 W + \beta_2 W^2 - \beta_3 W^3$$

And, the generic functional form for the corn, wheat, and sorghum production functions are:

$$Y = \beta_0 + \beta_1 W - \beta_2 W^2$$

In both functional relationships, the β_0 represents average dryland yield under average growing season rainfall, temperature and other climatic conditions, including the CO_2 level in a specific 30 year sub-period. Corn cannot be grown under dryland conditions in Hale County. Thus average dryland yields are not reported in Table 2.

Coupled Model: Overview

Conceptually, the coupled, or integrated, model consists of three linked sub-models. Figure 1 illustrates the data flow between and linking of the three sub-models, where each model is associated with a specific stage. The first stage consists of a dynamic economic model of agricultural land use practices, the second stage is a detailed hydrologic model of the of the aquifer below the study region county which utilizes the first stage data to simulate the hydrologic feasibility, or capacity to support, the first-stage economic driven water stresses. The third stage simulation model ameliorates any differences between the first stage simulated water

demand and aquifer supply capacity over time and space. A brief overview of the coupled model data sources and design is now presented which is then followed by three sections that more fully discuss the data requirements for the three sub-models and their linkages.

Broadly speaking, the coupled model is designed to control for the impact that spatial variability in land use practices, irrigation technology, and aquifer characteristics have on the expected groundwater use over a ninety-year planning horizon under alternative climatic scenarios. The first stage dynamic economic model estimates the optimal agricultural ground water extraction time path that maximizes the present value of agricultural net returns over a 90-year planning horizon for each climatic scenario. To accomplish the optimization, dryland and irrigated crop production functions were derived for each crop under the various climate scenarios. Output from the DSSAT program was used to develop the non-linear crop yield response functions to each climate scenario and water application rate for given soil type, and irrigation system. In total, 100 irrigated production functions were estimated (8 climate scenarios multiplied by four crops multiplied by 3 time periods within each climate scenario plus 4 baseline irrigated production functions). Soil type (Pullman Clay Loam) and irrigation system (LEPA) were held constant in deriving all crop response functions. The variable production cost for dryland crop production and irrigated crop production were taken from enterprise budgets developed for Texas Extension District 2 (Texas Agricultural Extension Service Budgets 2008-2012). Additional county-specific data input into the first-stage dynamic economic model include county average values for initial saturated thickness, initial average pump lift, initial average well yield, initial average acres served per well and were computed from the MODFLOW model developed for Hale County. Data for the initial number of irrigated and dryland acres by crop, is also used to parameterize each county level model.

In determining pumping cost, the energy use factor for natural gas is 1.45×10^{-3} mcf per foot of lift per acre inch, system operating pressure of 20 pounds per square inch, and pump engine efficiency of 75%. The mcf cost of energy is $8.10 (Hayhoe et al. 2012). Other costs include the per acre cost of each irrigation system of $416 per acre, irrigation system depreciation of 5%, annual per acre irrigation system labor of 1.4 hours per acre, and labor cost of $9.60 per hour (Hayhoe et al. 2012). Annual maintenance cost was estimated to be 8% of initial irrigation system cost, and a real discount rate of 3% was used to calculate net present value. Average crop price was calculated using NASS price data for the years 2008-2012 as reported by the Texas Agricultural Statistics Service.

The MODFLOW software program was used to build the hydrology model of the Southern Ogallala Aquifer is used in this analysis (Stovall 2013). MODFLOW is the most widely-used ground water simulation program (McDonald and Harbaugh 1988). As constructed the MODFLOW model divides the land overlying the aquifer into a rectangular grid comprised of one-mile square cells. The Southern Ogallala Aquifer grid consists of 246 rows and 184 columns, or 45,264 grid cells. The rectangular grid for Hale County consists of 900 cells. Each grid cell contains parameter values for hydraulic conductivity, specific yield, recharge rate, initial saturated thickness, and the initial (current) volume of water withdrawn from each cell in the baseline calibration period. Given user-provided parameter values for the aquifer's physical characteristics, MODFLOW uses a finite numerical difference equation procedure in combination with water budgets that account for recharge, withdrawals, and net lateral inflows to monitor saturated thickness and water table elevation through time (McDonald and Harbaugh 1988). The Southern Ogallala Aquifer grid provides the means to link agricultural water use withdrawals provided by the first-stage dynamic economic model to the hydrologic model at a

one square mile resolution level. By linking the economic models to the hydrologic model, the integrated modeling approach is able to maintain the spatial variability in hydrologic response to agricultural ground water stresses. Each of the three sub-models are now summarized.

Stage 1 Dynamic Economic Sub-Model

The first-stage economic model is a dynamic non-linear model of production agriculture for Hale county. The optimization model maximizes the net present value of annual per acre returns to land, management, groundwater stock, risk, and investment over a specified planning horizon. For a given county, Hale in this study, annual net income is expressed as:

$$NI_t = \sum_c \sum_i \Theta_{cit} \{(P_c * Y_{cit}(WP_{cit})) - TVC_{cit}(WP_{cit}, L_t, ST_t)\}, \quad (1)$$

where c represents the crop grown, i represents the irrigation technology (center pivot irrigated or non-irrigated), and t represents the time period, Θ_{cit} represents the percentage of crop c produced with irrigation system i in period t, P_c represents the price of crop c, Y_{cit} represents the yield per acre of crop c produced with irrigation system i in period t, WP_{cit} represents the amount of water pumped to irrigate crop c through irrigation system i in period t, TVC_{cit} represents the total variable cost of production per acre of crop c produced with irrigation system i in period t, L_t represents the pump lift in meters in time t, ST_t represents the saturated thickness of the aquifer in time t, and NI_t represents the net income over variable cost in time t. Dryland yields, i = dryland, are five year average yields for each crop as reported by TASS for the period 2008-2012 under baseline climate, and simulated 30-year average yields for each of the three 30-year periods within each 90-year climate change scenario. Irrigated yield for crop c (Y_{cit}) in time period t is a function of average precipitation in the county and the volume of irrigation water applied. Recall, that for a given crop and climate change scenario, there are three alternative irrigated production functions, one corresponding to each thirty year period. As noted, the

irrigated crop production functions for yield response (Y_{cit}) to applied irrigation water were derived using the DSSAT simulated yield data and applied water level for a given climate scenario. DSSAT models yield as a function of consumptive water use. For a given climate scenario, crop, soil type, and irrigation technology, DSSAT converts acre-inches of applied water into acre-inches of water that is consumptively used by a given crop at each per acre level of applied water. Water that is consumptively used nets out application losses to runoff, evaporation, and recharge. Other studies including Kim et al (2000), Kim and Schaible (2000), and Schaible et al. (2010) have demonstrated the need to differentiate between consumptive use and applied water. Use of applied water over-estimates the benefits of groundwater management.

The objective function for the generic model that is maximized over the 90-year planning horizon is shown in Equation 2:

(2) $$Max\ PVNI\ = \sum_{t=1}^{90} NI_t * (1+r)^{-(t-1)}$$

Substitution of equation 1 into equation 2 results in equation 3.

(3) $$Max\ PVNI = \sum_{c}\sum_{i}\sum_{t} \Theta_{cit} * \{(P_c * Y_{cit}(WP_{cit})) - TVC_{cit}(WP_{cit}, L_t, ST_t)\} * (1+r)^{-t}$$

where *PVNI* is the present value of net income and *r* is the 3% social discount rate.

Equation 3 is maximized subject to the following set of constraints:

(4) $$ST_{t+1} = ST_t - [(\sum \sum \Theta_{cit} * WP_{cit}) - R_t] / S$$

(5) $$L_{t+1} = L_t + [(\sum \sum \Theta_{cit} * WP_{cit}) - R_t] / S$$

(6) $$GPC_t = 6.364 * (IWY / AW) * (ST_t / IST_t)^2$$

(7) $$PER\ ACRE\ WATER\ USE_t = \sum_{c}\sum_{i} \Theta_{cit} * WP_{cit}$$

(8) $$PER\ ACRE\ WATER\ USE_t \le GPC_t$$

(9) $$IRENGERYCOST_{cit} = \{[EF(L_t + 2.31 * PSI_i) * EP]/EFF\} * WP_{cit}$$

(10) $$TVC_{cit} = NIRVC_{ci} + IRRENERGYCOST_{cit} + HC_{cit}(Y_{cit}) + MC_i + DP_i + LC_i$$

(11) $$\sum_c \sum_i \Theta_{ci} \le 1 \text{ for all } t$$

(12) $$\sum_c \sum_i \Theta_{cit} \le Initial\ Total\ Percent\ Irrigated\ Acreage$$

(13) $$\Theta_{cit} \ge 0.9 * \Theta_{cit-1}$$

(14) $$\Theta_{cit} \ge 0$$

(15) $$TotalWaterUse_t = PerAcreWaterUse_t * TotalAcres$$

Equations 4 and 5 are the equations of motion for the two state variables. The state variables are saturated thickness (ST_t) and pumping lift (L_t) which are both measured in feet. R_t is the annual recharge rate in acre inches per acre to the aquifer, S represents the specific yield of the aquifer which varies from .015 to .017 for the nineteen THP counties, and WP_{cit} is the acre inch volume of water withdrawn from the aquifer in period t and applied to crop *c* using irrigation technology *i* in period *t*. The 12 in the denominator converts inches to feet. Data for initial year saturated thickness and pump-lift was compiled by Stovall (2013).

Equations 6, 7, and 8 express the relationship between the volume of water pumped and groundwater supplies. Equation 6 estimates the maximum volume of water that can be applied per irrigated acre in each time period. Per acre gross pumping capacity in period *t* (GPC_t), is a function of initial saturated thickness *(IST)*, average initial well yield for a county *(WY)*, and average number of wells per irrigated acre within the county *(AW)* (Terrell, 1998). The unit of measure associated with the factor 6.364 is acre-inches per gallon per minute (ac-in/gpm) and the

value was developed assuming a well pumps 2880 hours in a 120 day growing season.[1] Equation 7 calculates the volume of water pumped per irrigate acre (*PER ACRE WATER USE*$_t$) as the sum of water pumped on each crop under each technology weighted by the percent to total crop acreage produced under the crop and irrigation technology combination. Equation 8 is a constraint that assures the per acre volume of water pumped (*PER ACRE WATER USE*$_t$) is less than or equal to the per acre volume of water available for pumping (GPC_t).

Equation 9 calculates the per acre irrigation energy cost of pumping and applying irrigation water to crop *c* produced using irrigation system *i* in period *t* ($IRENERGYCOST_{cit}$), where *EF* represents the energy use factor for electricity, L_t is well lift in period *t*, PSI_i is irrigation system operating pressure in pounds per square inch, *EP* represents energy price per unit of electricity, *EFF* represents pump engine efficiency, and the factor 2.31 is the height in feet of a column of water that will exert a pressure of 1 pound per square inch (Terrell, 1998). Equation 10 calculates the total variable cost per acre (TVC_{cit}) for crop *c* produced by irrigation system *i* in period *t.* Per acre TVC_{cit} is calculated as the sum of all non-irrigation related variable costs $NIRVC_{ci}$, for crop *c* under irrigation technology *i,* plus HC_{cit} the per acre harvest cost for crop *c* under irrigation system *i* which varies with crop yield, plus MC_i the annual per acre maintenance cost for the irrigation system *i*, plus DP_i the annual per acre depreciation cost for irrigation system *i*, and LC_i the per acre irrigation labor cost for irrigation system *i*.

Equation 11 limits the sum of the percentage of an area planted to all crops produced by all irrigation systems *i* (irrigated or dryland) in each period *t* to be less than or equal to 1. Equation 12 ensures that the percentage of acres irrigated does not increase above the initial percentage at the beginning of the optimization. Without this restriction and given the time value

[1] [(2880 hours) * (60 minutes/hour) * (43,560 cubic feet/acre-foot)] /[(7.48 gallons/cubic foot) * (12 inches/foot)] = 6.364 acre-inches/gallon per minute.

of money the optimization procedure found it more profitable to increase irrigated acreage in the short-run. However, increasing irrigation acreage in the short-run is inconsistent with the fact that irrigated acreage has been decreasing over time in the county.

Equation 13 restricts the annual reduction in crop acreage under a specific irrigation technology to be no more than 10.0% of the previous year's acreage. This limit on the rate of transition between crop enterprises controls the rate at which the model allows producers to switch from one enterprise to another in order to replicate an agronomic orderly transition between crop enterprises. Equation 14 ensures that the values of the decision variables, Θ_{cit}, that the percent share of acreage devoted to a given crop and irrigation technology is non-negative. Equation 15 is an accounting equation that calculates the total volume of ground water withdrawals in a region in each time period t. Total ground water use in each period t is calculated as the average quantity of groundwater withdrawn and applied per acre of cropland multiplied by the total quantity of cropped acres in the initial time period. Total cropped acreage in a county is the sum of irrigated and non-irrigated acres in the initial period. As the quantity of water applied to an irrigated crop decreases and/or the percent of land in dryland crop production increases the average quantity of water applied per cropped acre decreases. The Generalized Algebraic Modeling System (GAMS) is used to derive the optimal solution (GAMS, Development Corporation 2007).

Stage 2 Hydrologic Sub-Model

The first step toward overcoming the limitations of conventional economic water policy models that treat aquifer characteristics as homogenous is to link a detailed hydrologic model to the dynamic economic model to more accurately capture the relationship between land use activity and aquifer status. Coupling the hydrologic equations of motion governing pumping costs,

pump-lift and aquifer withdrawals embedded within the structure of the dynamic economic optimization model with the cell level information contained in each MODFLOW cell is the mechanism that provides the ability to more accurately track the impact of optimal agriculturally driven water use decisions on aquifer storage values and pump-lift over the 90-year planning horizon.

The MODFLOW aquifer grid for Hale County consists of 900 one-square mile cells. These cells are the basic unit of the hydrologic analysis. Hale County aquifer storage estimates for each year of the 90-year planning horizon are calculated by aggregating the values for the county specific cells. Based on the initial water head, the water use, recharge, saturated thickness, hydraulic conductivity and other physical characteristics of the aquifer cell, each one-square mile cells remain operational through time unless the cell water supply is fully depleted at a point in time. If a cell is depleted, it remains so for all remaining simulation years and land above the cell can no longer support irrigated agriculture for the remainder of the simulation. Lateral groundwater flow within the Southern Ogallala aquifer is a slow process and the possibility for rapid withdrawal in one region increasing the pump lift or decreasing the saturated thickness in a neighboring region although possible is not very probable in a short time frame. Groundwater flow rates are impacted by the viscosity of the water, the porosity of the soil and the hydrologic gradient (Fetter, 2001).

The optimal annual Hale County time path for groundwater withdrawals estimated by the first-stage economic model over the 90-year planning horizon are written into an Excel spreadsheet using the GAMS data export commands. This data is subsequently used by MODFLOW to simulate the impact of the optimal first-stage withdrawal time path on groundwater depletion. The calibrated recharge parameter values for the fraction of applied

water lost to seepage in each MODFLOW grid cell is derived under the assumption that a low-pressure center pivot irrigation system having application efficiency of 90 percent is the exclusive irrigation technology used. Low-pressure center pivot technology is the only irrigation technology considered because over 90% of all irrigated lands in the THP use this technology (TAES, 2003). The annual county level water diversion levels provided by the first-stage dynamic optimization model are spatially distributed over the calibrated irrigated baseline acreage in each simulated year. The weighting scheme used to distributed the county water use data was developed from detailed irrigation survey maps provided by High Plains Underground Water Conservation District #1 (HPWD #1) and the South Plains Underground Water Conservation District (SPWD) that inventoried the location of each center pivot irrigation system in use in 2009 (Stovall, 2013). MODFLOW was used to execute each climate/policy simulation for the spatially distributed groundwater stresses as predicted by the first stage economic model. The resulting annual MODLFOW output for water use and pump-lift by cell is subsequently imported into the third stage economic simulation model.

Stage 3 Economic Simulation Sub-Model

The structure of the third-stage economic simulation sub-model is similar to the first-stage dynamic economic sub-model with two major differences. First, the equations of motion are removed from the economic simulation model. Secondly, the annual county estimates for groundwater withdrawals and the average pump-lift derived from the hydrology simulation are imported into the economic simulation model as parameter values instead of variables. The cell-level MODFLOW data on ending groundwater supplies, pump-lift and dry cells (denoting areas losing irrigated acreage) is used by the multi-period third-stage economic model. The multi-year third-stage sub-model re-optimizes available groundwater supplies at each point in time using the

yearly cell-level pump-lift and groundwater withdrawal data provided by the second stage MODFLOW model.

By interactively linking the economic models to the hydrologic model at the one square mile level of resolution, the coupled modeling approach controls for both the spatial variability in hydrologic response to agricultural groundwater stresses and the location of agricultural stresses. Specifically, the integrated model more accurately simulates the relationship between hydrologic stresses (groundwater withdrawals) imposed by economic activity and the resulting change in aquifer status than an approach that treats regional land use practices and aquifer characteristics as homogeneous throughout the region. This additional spatial sub-regional detail is essential because it provides policy makers with a tool for targeting specific water uses and/or geographic regions that can most-cost effectively achieve a policy dictated reduction in groundwater use.

Results

Preliminary results are summarized in tables 3 through 9. Each table presents a comparative analysis of a specific economic or hydrologic variable of interest for each of the eight climate change scenarios relative to the baseline status quo condition. The nine climate scenarios are listed in column 1 of each table, correspond to the baseline status quo scenario (no climate change) and the eight alternative climate scenarios. The descriptor name for each climate consists to two parts. The first part of the name identifies one of the four GCM used to generate the data (CCSM, GFDL, HADCM3, and PCM) and the second part represents the associated AR4 emission scenario (A1B or A1FI). The average 30-year climate condition for average growing season temperature, precipitation, and CO_2 level under each climate scenario is reported in table 1. Each summary table also reports the likely effect of a water conservation strategy

now being considered by the Texas High Plains Underground Water Conservation District on a specific economic or hydrologic variable of interest. In an effort to conserve groundwater for future use the Groundwater District is considering using its regulatory powers to restrict the volume of applied water applied to an irrigated acre to 15 acre-inches. This per acre acre-inch restriction is labeled "15 Inch per Acre Restriction Policy" in column three of tables 3 to 9.

Table 3 reports the per acre net present value of the unrestricted ground water use policy and the restricted ground water use policy for the eight climate scenarios relative to the baseline condition. As reported, despite significant reductions in irrigated acreage over time due to increasingly expensive per acre-inch pump-lifts, per acre net present value (NPV) increases under all climate scenarios. That is, nominal annual per acre returns minimally decrease over time despite significant reductions in irrigated acreage in the climate change scenarios due to the fertilization effect of increasing CO_2 levels. In fact, under the restricted irrigation policy, per acre net present value under all climate scenarios is greater than it is under the baseline climate condition and unrestricted water use. In the absence of climate change, under baseline climate conditions, the water restriction policy reduces per acre NPV by 32.4% ($2,977 versus $2,013).

As reported in table 4, relative to unrestricted baseline water use level, total ground water use under the per acre use restriction, is greater in six of the eight climate change scenarios. Ironically, total water use in five of eight climate change scenarios is also greater under the water use restriction than without the restriction, despite the fact that per acre NPV is always less with the restriction within a given climate scenario. This unanticipated outcome is explained by the fact that while in the absence of a water use restriction it is more profitable to accelerate groundwater use to earlier time periods and then heavily convert to dryland production practices, the conservation policy postpones a large portion of baseline groundwater use to the future, and

in the future under some climate scenarios it remains more profitable to continue using ground water relative to converting to dryland practices. Another complimentary factor is that under the water use restriction areas that were completely mined in the absence of the restriction remain in production for a longer and benefit from additional recharge supplies which both lower the cost of pumping and increase available groundwater supplies. In the two scenarios, the GFDL-A1B and GDFL-A1FI, where total water use is less under the water use restriction, this is explained by the fact that in the two subsequent 30-year sub-periods, the changes in the climate change variables, and crop yield response to applied water, create a situation where dryland production because relatively more profitable than irrigated production.

Table 5 illustrates the finding that given current economic incentives and agronomic options, the great majority of all groundwater use occurs in the first 30 years of the 90 year planning horizon regardless of climate change scenario considered. However, under the water restriction policy water is shifted toward the future and in some climate scenarios more water is used in the second and third thirty year sub-periods than in the first thirty year period (CCSM-A1B, CCSM-A1FI, PCM-AIB, and PCM-A1FI). The fifth column of table 5 which compares total water use in each 30-year period relative for the water restriction policy under each climate change scenario relative to the unrestricted water use level under baseline climate report the volume of water shifted toward the future. Moreover, the quantity of water shifted toward the future 30-year periods, relative to the unrestricted baseline, is much greater under each climate change scenario when combined with the restricted water use policy than for each climate change scenario in the absence of the water restriction.

Table 6 reports the percentage of acreage under irrigation in years 31, 61, and 90 of the 90-year simulation for each climate scenario. Consistent with prior results, the percent of

cropland under irrigation, while variable between scenarios, drastically decreases over time for nearly all scenarios and both policies. The only exceptions to this general theme are for the CCSM-A1B, CCSM-A1FI, and HADCM3-A1B climate scenarios under the water restriction.

Table 7 reports the average saturated thickness for the aquifer for all MODFLOW cells (639) that were agriculturally active in year 1 (pumping groundwater for agricultural use in the initial simulation year).

Table 8 reports the number of MODFLOW cells that were hydrologically active in years 31, 61, and 90 for each climate scenario simulation under the unrestricted and restricted water use polices. In the initial simulation year, 639 of the MODFLOW aquifer grid cells in the 900 cell grid that is used to model Hale County were pumping groundwater. In year 31, under baseline conditions and unrestricted groundwater use the number decreased to 313 cells, however under the water restriction policy the number of cells still active was 608. A cell becomes non-active when water storage within a cell becomes zero. When this situation occurs, the land above the cell can no longer support irrigated agriculture and is converted to dryland production.

Table 9 reports acre-inches of applied water per irrigate acre for under each climate scenario for simulation years 1, 31, and 61. It is important when reviewing this table to recall that the great majority of cropland that was initially irrigated, is grown under dryland practices in the last third of all 90-year scenarios (table 6). Due to time constraints I was unable to flesh out tables 5 to 9 before I had to upload! I will revise and replace this manuscript with a more complete paper before the meetings.

Conclusions and Policy Implications

Using DSSAT to simulate crop yield response to the climate change data provided by the four GCM in combination the AR4 CO_2 emission data clearly suggest that climate change will likely increase the marginal productivity of applied water over time in agricultural use. This suggests that conservation quota policies that restrict the current agricultural use of ground water for conservation purposes, but are not cost-effective to agriculture under current climate conditions may become cost-effective in the future. This is more likely to be the case where there is greater variability between low value and high value agricultural crops. Additionally, policy makers should increase research emphasis on those dryland crops that are likely to be most profitable under future production conditions. Under the climate change scenarios considered, the CO_2 yield affect disproportionately benefits dryland profits due to lower production cost. Thus, the transition from irrigated to dryland production technologies in areas where it is becoming prohibitively cost to lift ground water may not be as costly as previously estimated. However, there is a major caveat to these results. Given the sensitivity of the technical complimentary yield relationship which seems to exist between the production inputs of applied water and the CO_2 additional research is needed to rigorously justify this apparent relationship. In this study, the fertilization effect for an increase in the $C0_2$ level, for a given GCM, is always greater for the A1FI emission scenario (continued heavy dependence on fossil fuel for energy) than for the A1B emission scenario (balance future energy use).

References

Brooke, A., D. Kendrick, A. Meerdus, R. Raman, and R.E. Rosenthal. 2007.GAMS: A User's Guide, Washington, D.C. 1998: GAMS Development Corporation.

Das, Biswaranjan, David B. Willis and Ken Rainwater. "An Interdisciplinary Regional Groundwater Model: A Study of the Ogallala in the Texas High Plains". *Regional Science, Policy and Practice*, Vol. 5(1):113-133: March, 2013.

Fetter, C.W. "*Applied Hydrogeology*", Fourth edition, New Jersey, Prentice Hall, (2001).

Guru, M.V. and J.E. Horne, *The Ogallala Aquifer*, (2004). Available on: www.kerrcenter.com/publications/ogallala_aquifer.pdf.

Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy, and D. Wolfe. 2007. "Past and future changes in climate and hydrological indicators in the U.S. Northeast." *Climate Dynamics* 28:381-407.

Hayhoe,K, A. Hernandez, R. Tewari, J. Johnson, and K. Rainwater. 2012. Climate Projections for West Texas: Implications for Water & Agriculture. Report submitted to National Commission on Energy Policy, Washington, DC, October 2012.

Hexem, R. and E. Heady. 1978. Water Production Functions for Irrigated Agriculture. Iowa State University Press, Ames, Iowa.

Hoogenboom, G., Jones, J.W., Wilkens, P.W., Porter, C.H., Boote, K.J., Hunt, L.A., Singh, U., Lizaso, J.L., White, J.W., Uryasev, O., Royse, F.S., Ogoshi, R., Gijsman, A.J., Tsuji, G.Y., 2010. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM]. University of Hawaii, Honolulu, Hawaii.

IPCC (Intergovernmental Panel on climate change). 2007. Climate Change 2007: Synthesis Report. Available from: http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms3.html.

Jones, J. W., G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. A. Hunt, P. W. Wilkens, U. Singh, A. J. Gijsman, and J. T. Ritchie. The DSSAT cropping system model. 2003. *European Journal of Agronomy* 18(3–4): 235–265.

Kim, C. S., and G. D. Schaible. (2000) Economic Benefits Resulting from Irrigation Water Use: Theory and an Application to Groundwater Use. *Environmental & Resource Economics*, 17: pp. 73-87.

Kim, C. S., G. D. Schaible and S. G. Daberkow. (2000). An Efficient Cost-Sharing Program to Reduce Nonpoint-Source Contamination: Theory and an Application to Groundwater Contamination. *Environmental Geology* 39 (6) pp. 649-59.

Malcolm, S, E. Marshall, M Aillery, P. Heisey, M. Livingston, and K. Day Rubenstein. 2012. *Agricultural Adaption to a Changing Climate: Economic and Environmental Implications Vary by U. S. Region*. ERR-136, U.S. Department of Agriculture, Economic Research Service.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee. 2009. Impact on Agriculture and Costs of Adaptation. International Food Policy Research Institute (IFPRI).

Rosenberg, N., and P.Crosson. 1993, "An Overview of the MINK Study." *Climatic Change* 24: 159–173.

Rosenzweig, C., and M. Parry. 1994. "Potential Impacts of Climate Change on World Food Supply." *Nature* 367: 133–139.

Stovall, J. N. (2013). Revision of Stovall's 2001 Model developed for the Texas Southern High Plains. Professional Engineer, Project Manager Water Resources Department, Espey Consultants, Inc. Amarillo, TX

Schaible, G. D., C. S. Kim, and M. P. Aillery. 2010. Dynamic Adjustment of Irrigation Technology/Water Management in Western U.S. Agriculture: Towards a Sustainable Future. *Canadian Journal of Agricultural Economics*, Special Issue, 58 (4), pp. 433-61.

Terell, B. (1998) "Economic Impacts of the Depletion of the Ogallala Aquifer: An Application to the Texas High Plains." Unpublished M.S. Thesis, Texas Tech University.

Texas AgriLife Extension Service. 2013. "2012 Texas Crop and Livestock Enterprise Budgets. District 2 - South Plains." Extension Agricultural Economics. http://agecoext.tamu.edu/resources/crop-livestock-budgets/by-district/district-2.html. March 2013

Table 1. Plainview Texas Average Historic and Simulated Climate Data by Climate Scenario and time period

	Baseline	CCSM-A1B	CCSM-A1F1	GFDL-A1B	GFDL-A1F1	HADCM3-A1B	HADCM3-A1F1	PCM-A1B	PCM-A1F1
1960-2009									
Temp	74.22								
Precip	11.78								
C02	345.46								
2010-2039									
Temp		76.77	76.74	76.84	77.11	77.37	76.23	75.48	75.96
Precip		12.40	12.84	7.90	8.87	11.95	12.07	12.53	13.75
C02		431.92	433.02	431.92	433.02	431.92	433.02	431.92	433.02
2040-2069									
Temp		78.29	79.31	80.06	81.38	79.25	81.17	76.93	78.58
Precip		11.84	13.78	5.76	6.49	11.21	12.37	13.61	12.90
C02		540.37	589.38	540.37	589.38	540.37	589.38	540.37	589.38
2070-2079									
Temp		78.75	81.33	81.58	84.62	81.23	83.70	79.14	81.76
Precip		11.95	16.25	5.36	3.64	11.93	9.26	10.53	11.80
C02		653.30	825.07	653.30	825.07	653.30	825.07	653.30	825.07

Notes: Growing Season temperature is aannual average daily temperature May 1 - September 30 in each time period.
Precipitation is average annual precipitation for May 1 - September 30 in each time period.
CO2 concentration level in each 30-year period is the yearly average measured in ppm in each time period.

Table 2. Average Dryland Yield by Crop, Climate Scenario, and Time Period

		Time Period			
Climate Scenario	Crop	1960-2009	2010-2039	2040-2069	2070-2099
CCSM-A1B	Cotton (lbs/ac)	480.83	515.63	726.03	762.90
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	9.87	13.07	14.39
	Wheat (bu/ac)	26.88	34.43	38.37	47.24
CCSM-A1FI	Cotton (lbs/ac)	480.83	557.55	909.01	959.84
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	11.04	14.16	20.30
	Wheat (bu/ac)	26.88	31.08	42.55	48.20
GFDL-A1B	Cotton (lbs/ac)	480.83	562.28	663.08	748.77
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	9.10	7.78	7.88
	Wheat (bu/ac)	26.88	40.02	40.39	46.64
GFDL-A1FI	Cotton (lbs/ac)	480.83	560.74	725.77	829.05
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	8.59	9.13	7.63
	Wheat (bu/ac)	26.88	37.78	42.83	53.78
HADCM-A1B	Cotton (lbs/ac)	480.83	497.52	681.11	680.85
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	10.12	14.38	16.36
	Wheat (bu/ac)	26.88	27.30	34.25	39.34
HADCM-A1FI	Cotton (lbs/ac)	480.83	541.56	650.54	691.17
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	11.18	15.44	16.25
	Wheat (bu/ac)	26.88	28.39	32.14	34.27
PCM-A1B	Cotton (lbs/ac)	480.83	655.68	840.31	766.26
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	13.28	17.57	16.18
	Wheat (bu/ac)	26.88	38.30	42.80	54.80
PCM-A1FI	Cotton (lbs/ac)	480.83	776.64	847.44	896.15
	Corn (bu/ac)	NA	NA	NA	NA
	Sorghum (cwt/ac)	10.63	15.24	14.29	16.03
	Wheat (bu/ac)	26.88	40.81	54.86	58.80

Note: Corn is not grown under dryland production

Table 3. Per Acre Net Present Values by Climate Scenario and Relative to Baseline Conditions

Climate Scenario	Unrestricted Water Use	15 Inch per Acre Restriction Policy	Unrestricted Water Use plus Climate Change minus Unrestricted Baseline	Restricted Water Use with Climate Change minus Restricted Baseline	Restricted Water Use with Climate Change minus Unrestricted Baseline
Baseline	$2,977	$2,013	$0	$0	-$965
CCSM-A1B	$5,817	$4,192	$2,839	$2,179	$1,214
CCSM-A1FI	$6,667	$5,393	$3,690	$3,380	$2,416
GFDL-A1B	$5,704	$3,866	$2,727	$1,854	$889
GFDL-A1FI	$5,950	$4,200	$2,972	$2,187	$1,223
HADCM3A1B	$5,012	$3,356	$2,034	$1,343	$378
HADCM3A1FI	$5,360	$3,954	$2,382	$1,941	$976
PCM-A1B	$6,553	$5,334	$3,575	$3,321	$2,356
PCM-A1FI	$7,709	$6,563	$4,731	$4,550	$3,586

Table 4. Total Ac-Ft Water Use Over 90 Years by Climate Scenario and Relative to Baseline Conditions

Climate Scenario	Unrestricted Water Use	15 Inch per Acre Restriction Policy	Unrestricted Water Use with Climate Change minus Unrestricted Baseline	Restricted Water Use with Climate Change minus Restricted Baseline	Restricted Water Use with Climate Change minus Unrestricted Baseline
Baseline	6,347	2,902	0	0	-3,446
CCSM-A1B	6,377	8,020	30	5,119	1,673
CCSM-A1FI	6,397	8,280	50	5,378	1,933
GFDL-A1B	6,357	2,650	9	-252	-3,698
GFDL-A1FI	6,343	2,714	-5	-187	-3,633
HADCM3A1B	6,392	7,254	45	4,353	907
HADCM3A1FI	6,431	6,383	84	3,481	36
PCM-A1B	6,369	7,497	22	4,596	1,150
PCM-A1FI	6,435	7,364	88	4,462	1,016

Table 5. Total Ac-Ft of Water Use by 30-Year Period by Climate Scenario and Relative to Baseline Conditions

Climate Scenario	Unrestricted Water Use	15 Inch per Acre Restriction Policy	Unrestricted Water Use with Climate Change minus Unrestricted Baseline	Restricted Water Use with Climate Change minus Restricted Baseline	Restricted Water Use with Climate Change minus Unrestricted Baseline
Years 1 - 30					
BASE	5,177	2,783	0	0	-2,393
CCSM-A1B	5,190	2,882	13	99	-2,295
CCSM-A1FI	5,200	3,125	23	341	-2,052
GFDL-A1B	5,178	2,541	1	-242	-2,635
GFDL-A1FI	5,170	2,607	-7	-176	-2,570
HADCM3A1B	5,200	5,279	23	2,495	102
HADCM3A1FI	5,217	5,362	41	2,579	186
PCM-A1B	5,161	2,579	-15	-204	-2,597
PCM-A1FI	5,027	2,615	-149	-168	-2,562
Years 31 - 60					
BASE	698	114	0	0	-584
CCSM-A1B	710	4,045	12	3,931	3,347
CCSM-A1FI	717	333	19	219	-365
GFDL-A1B	702	104	4	-10	-594
GFDL-A1FI	698	103	0	-11	-595
HADCM3A1B	714	607	16	494	-91
HADCM3A1FI	728	883	30	770	185
PCM-A1B	726	4,410	28	4,297	3,712
PCM-A1FI	883	4,341	185	4,227	3,643
Year 61 - 90					
BASE	698	114	0	0	-584
CCSM-A1B	477	1,094	-221	980	396
CCSM-A1FI	480	4,823	-218	4,709	4,125
GFDL-A1B	477	5	-221	-109	-693
GFDL-A1FI	475	4	-223	-109	-693
HADCM3A1B	478	1,368	-220	1,255	670
HADCM3A1FI	486	137	-212	24	-560
PCM-A1B	482	508	-216	394	-190
PCM-A1FI	525	408	-173	294	-290

Table 6. Percentage of Total Crop Acreage Irrigated by Selected Years and Percent Relative to Baseline (Initial Year 1 Percent Irrigated in all Scenarios is 77.79%)

Climate Scenario	Unrestricted Water Use	15 Inch per Acre Restriction Policy	Unrestricted Water Use with Climate Change minus Unrestricted Baseline	Restricted Water Use with Climate Change minus Restricted Baseline	Restricted Water Use with Climate Change minus Unrestricted Baseline
Year 31					
BASE	4.22%	3.30%	0.00%	0.00%	-0.92%
CCSM-A1B	4.84%	39.34%	0.62%	36.04%	35.12%
CCSM-A1FI	4.56%	3.72%	0.34%	0.43%	-0.50%
GFDL-A1B	3.73%	3.30%	-0.49%	0.00%	-0.92%
GFDL-A1FI	3.78%	2.62%	-0.44%	-0.67%	-1.59%
HADCM3A1B	4.83%	15.66%	0.61%	12.36%	11.44%
HADCM3A1FI	5.10%	11.88%	0.88%	8.58%	7.66%
PCM-A1B	5.26%	20.14%	1.04%	16.84%	15.92%
PCM-A1FI	6.33%	20.00%	2.11%	16.70%	15.78%
Year 61					
BASE	1.98%	1.98%	0.00%	0.00%	0.00%
CCSM-A1B	2.25%	12.91%	0.28%	10.93%	10.93%
CCSM-A1FI	2.47%	29.73%	0.50%	27.75%	27.75%
GFDL-A1B	1.55%	0.14%	-0.43%	-1.84%	-1.84%
GFDL-A1FI	1.53%	0.11%	-0.44%	-1.86%	-1.86%
HADCM3A1B	2.19%	13.76%	0.22%	11.78%	11.78%
HADCM3A1FI	1.97%	3.43%	-0.01%	1.46%	1.46%
PCM-A1B	2.08%	12.98%	0.10%	11.00%	11.00%
PCM-A1FI	2.09%	10.54%	0.11%	8.57%	8.57%
Year 90					
BASE	1.59%	0.01%	0.00%	0.00%	-1.59%
CCSM-A1B	1.80%	6.40%	0.20%	6.40%	4.81%
CCSM-A1FI	1.98%	16.17%	0.38%	16.17%	14.58%
GFDL-A1B	1.24%	0.01%	-0.35%	0.00%	-1.59%
GFDL-A1FI	1.23%	0.01%	-0.36%	0.00%	-1.59%
HADCM3A1B	1.75%	7.22%	0.15%	7.21%	5.62%
HADCM3A1FI	1.54%	0.16%	-0.05%	0.16%	-1.43%
PCM-A1B	1.60%	0.61%	0.01%	0.60%	-0.98%
PCM-A1FI	1.55%	0.50%	-0.05%	0.49%	-1.10%

Table 7. Average Aquifer Saturated Thickness by Selected Years and Relative to Baseline (Year 1 Average Saturated Thickness is 77.75 Ft in all Scenarios)

Climate Scenario	Unrestricted Water Use	15 Inch per Acre Restriction Policy	Unrestricted Water Use with Climate Change minus Unrestricted Baseline	Restricted Water Use with Climate Change minus Restricted Baseline	Restricted Water Use with Climate Change minus Unrestricted Baseline
Year 31					
BASE	23.67	67.44	0.00	0.00	43.76
CCSM-A1B	23.61	63.63	-0.06	-3.81	39.96
CCSM-A1FI	23.58	63.84	-0.10	-3.60	40.17
GFDL-A1B	23.63	69.94	-0.04	2.50	46.27
GFDL-A1FI	23.64	69.33	-0.03	1.89	45.66
HADCM3A1B	23.60	40.28	-0.07	-27.16	16.60
HADCM3A1FI	23.56	41.95	-0.11	-25.48	18.28
PCM-A1B	23.89	68.49	0.21	1.05	44.82
PCM-A1FI	25.82	68.16	2.15	0.72	44.49
Year 61					
BASE	28.66	88.25	0.00	0.00	59.58
CCSM-A1B	28.55	42.15	-0.11	-46.10	13.48
CCSM-A1FI	28.49	80.45	-0.17	-7.80	51.79
GFDL-A1B	28.64	90.59	-0.02	2.34	61.92
GFDL-A1FI	28.65	90.03	-0.01	1.79	61.37
HADCM3A1B	28.52	56.20	-0.14	-32.05	27.53
HADCM3A1FI	28.48	52.61	-0.18	-35.63	23.95
PCM-A1B	28.62	40.87	-0.05	-47.37	12.21
PCM-A1FI	28.92	41.36	0.26	-46.89	12.69
Year 90					
BASE	34.48	107.47	0.00	0.00	72.99
CCSM-A1B	34.39	49.11	-0.08	-58.36	14.64
CCSM-A1FI	34.33	44.88	-0.14	-62.59	10.41
GFDL-A1B	34.45	109.48	-0.02	2.01	75.01
GFDL-A1FI	34.47	108.99	-0.01	1.52	74.52
HADCM3A1B	34.36	55.08	-0.11	-52.39	20.60
HADCM3A1FI	34.33	72.61	-0.14	-34.86	38.14
PCM-A1B	34.43	59.07	-0.05	-48.40	24.60
PCM-A1FI	34.66	60.29	0.18	-47.18	25.81

Table 8. Number of Active Hydrologic Cells by Selected Years and Relative to Baseline (Year 1 Number of Agriculturally Active Cells is 639 in all Scenarios)

Climate Scenario	Unrestricted Water Use	15 Inch per Acre Restriction Policy	Unrestricted Water Use with Climate Change minus Unrestricted Baseline	Restricted Water Use with Climate Change minus Restricted Baseline	Restricted Water Use with Climate Change minus Unrestricted Baseline
Year 31					
BASE	313	608	0	0	295
CCSM-A1B	315	608	2	0	295
CCSM-A1FI	316	608	3	0	295
GFDL-A1B	315	608	2	0	295
GFDL-A1FI	314	608	1	0	295
HADCM3A1B	315	608	2	0	295
HADCM3A1FI	316	608	3	0	295
PCM-A1B	315	608	2	0	295
PCM-A1FI	336	608	23	0	295
Year 61					
BASE	310	608	0	0	298
CCSM-A1B	311	608	1	0	298
CCSM-A1FI	312	608	2	0	298
GFDL-A1B	312	608	2	0	298
GFDL-A1FI	311	608	1	0	298
HADCM3A1B	311	608	1	0	298
HADCM3A1FI	313	608	3	0	298
PCM-A1B	312	608	2	0	298
PCM-A1FI	321	608	11	0	298
Year 90					
BASE	310	608	0	0	298
CCSM-A1B	311	608	1	0	298
CCSM-A1FI	312	608	2	0	298
GFDL-A1B	312	608	2	0	298
GFDL-A1FI	311	608	1	0	298
HADCM3A1B	311	608	1	0	298
HADCM3A1FI	313	608	3	0	298
PCM-A1B	312	608	2	0	298
PCM-A1FI	321	608	11	0	298

Table 9. Acre Inches of Water Applied per Irrigated Acre by Selected Years and Relative to Baseline

Climate Scenario	Unrestricted Water Use	15 Inch per Acre Restriction Policy	Unrestricted Water Use with Climate Change minus Unrestricted Baseline	Restricted Water Use with Climate Change minus Restricted Baseline
Year 1				
BASE	27.66	14.41	0.00	0.00
CCSM-A1B	23.32	12.99	-1.42	-1.42
CCSM-A1FI	22.52	12.99	-1.42	-1.42
GFDL-A1B	29.35	12.99	-1.42	-1.42
GFDL-A1FI	29.42	13.40	-1.01	-1.01
HADCM3A1B	22.15	12.99	-1.42	-1.42
HADCM3A1FI	21.22	12.99	-1.42	-1.42
PCM-A1B	25.36	12.99	-1.42	-1.42
PCM-A1FI	24.85	13.25	-1.16	-1.16
Year 31				
BASE	30.60	14.46	0.00	0.00
CCSM-A1B	28.86	14.85	0.39	0.39
CCSM-A1FI	31.32	13.42	-1.04	-1.04
GFDL-A1B	36.97	12.99	-1.47	-1.47
GFDL-A1FI	35.14	12.99	-1.47	-1.47
HADCM3A1B	29.12	14.76	0.30	0.30
HADCM3A1FI	27.69	14.78	0.32	0.32
PCM-A1B	26.78	14.70	0.24	0.24
PCM-A1FI	29.41	14.70	0.24	0.24
Year 61				
BASE	32.25	14.66	0.00	0.00
CCSM-A1B	28.74	14.99	0.33	0.33
CCSM-A1FI	26.31	14.99	0.33	0.33
GFDL-A1B	41.56	13.40	-1.26	-1.26
GFDL-A1FI	41.56	13.37	-1.29	-1.29
HADCM3A1B	29.58	14.99	0.33	0.33
HADCM3A1FI	33.62	14.97	0.31	0.31
PCM-A1B	31.55	14.99	0.33	0.33
PCM-A1FI	35.09	14.99	0.33	0.33

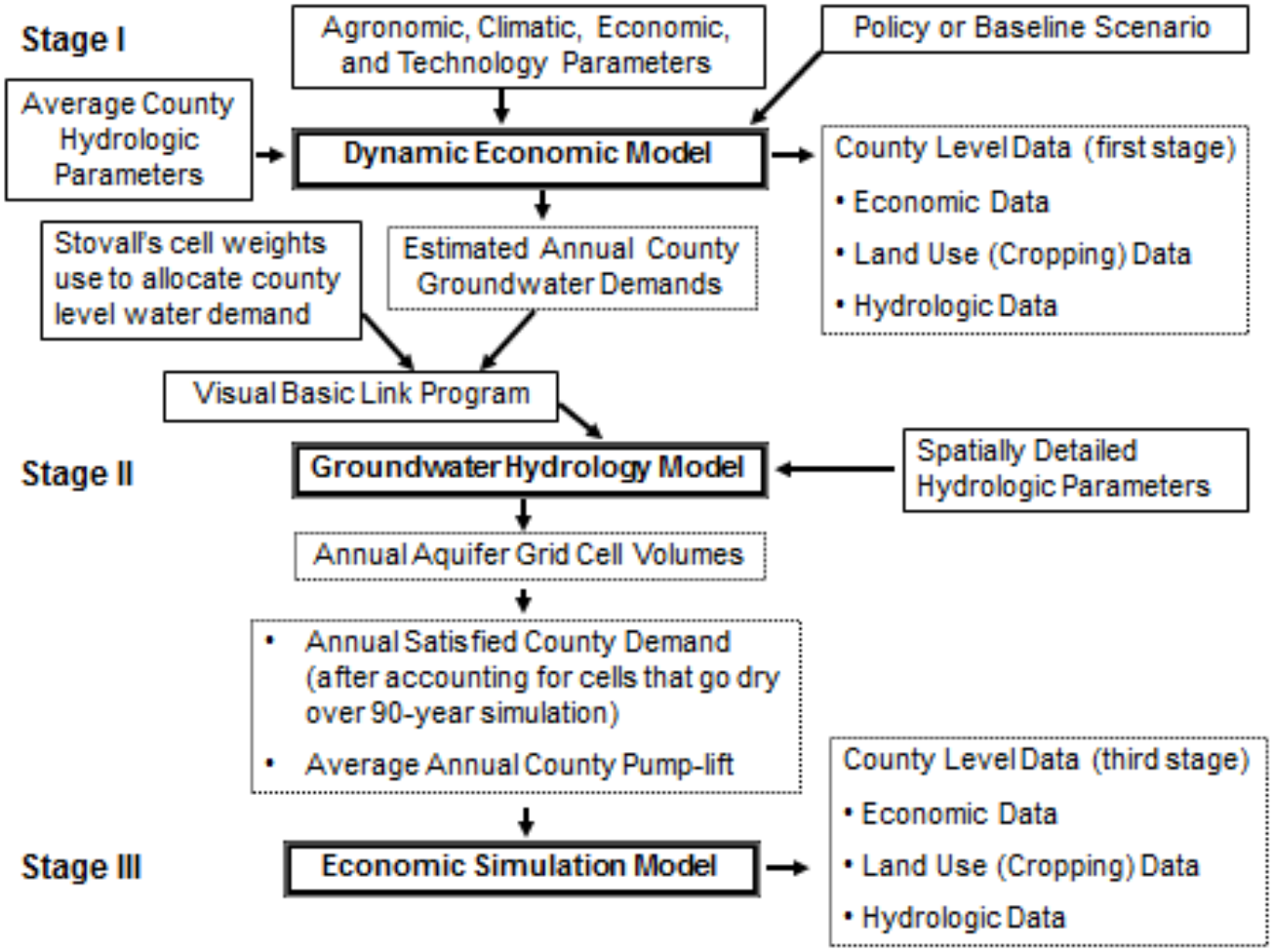

Figure 1: Data Flow and output in the Coupled Dynamic Optimization Model.