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Sustaining the Ogallala Aquifer: From the Wells to People, A Holistic CNH Model

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Abstract. The impact of water policy on sustaining the Ogallala Aquifer is analyzed using a system-level theoretical approach integrating agricultural water and land use tendencies, changing climate, economic trends, and population dynamics. In so doing, we 1) model the current hyper-extractive coupled natural-human system (CNH), 2) forecast future outcomes of policy scenarios transitioning the current groundwater-based economic system toward more sustainable paths for the social, economic and natural components of the integrated system, and 3) communicate model projections to inform public policies for enhanced sustainability while minimizing the economic pain for the region's communities. The findings corroborate previous studies showing that conservation often leads initially to an expansion of irrigation activities. However, we also find that the expanded presence of irrigated acreage will reduce the impact of an increasingly dryer climate on the region's economy and create greater long-term stability in the farming sector along with increased employment and population in the region. The primary negative aspect of more extensive conservation policies are on the net present value of farmers' current investments in their operations. This study reinforces the salience of interdisciplinary linked CNH models to provide policy prescriptions to untangle and address significant environmental policy issues.

1 Introduction

Our world faces a public policy conundrum. Crop yields on many varieties have tripled over the past 50 years, with irrigated cropping practices accounting for 40% of the total increased level of production (United Nations, 2011, p.3). Even so, food deserts, often created by market inequities, leave over 1 billion people worldwide malnourished (United Nations, 2011, p.ix). If projections are correct, the situation in the future does not improve. By 2050, the U.N. estimates that the world's population will have grown by another 2 billion people, most of whom will live in impoverished countries (United Nations, 2015), while demand for crops and meat products will soar by 70% (United Nations, 2011, p.7). Irrigated crops will continue to be crucial for meeting the world's future demands for sustenance. Unfortunately, many irrigated croplands are in regions that are, or are becoming, fresh water challenged (United Nations, 2011, pp.7-12).

This is the case for the High Plains Aquifer in the United States, also referred to as the"Ogallala Aquifer" (see Figure 1) The entire aquifer spans 450,000km^2 and underlies 27% of the irrigated land in the United States (Dennehy, 2000). Powell (1879) classifies this semi-arid grassland ecosystem as an arid land lying west of the 100th meridian with a mean annual precipitation less than 500mm (20in). The aquifer is one of four "critical areas" for "annual renewable water" in the Western Hemisphere and one of 22 worldwide (Montaigne, 2002).

Thus far, the scientific community has proved adept at developing hydrological models that confirm what we already know; that this natural system aquifer is already past its peak groundwater depletion (Steward and Allen, 2016) and will soon be so diminished that it can no longer sustain its current hyper-extractive (Aistrup et al., 2013) irrigation farming practices (Scanlon et al., 2012; Steward et al., 2013). This is a coupled natural-human system (CNH) policy study that leverages an integrated, cross-disciplinary, system-level, theoretical approach, linking agricultural land and water use tendencies, changing climate patterns, economic trends, and population dynamics to issues of groundwater sustainability. In so doing, we 1) accurately model the current hyper-extractive CNH system, 2) forecast into the future the outcomes of policy scenarios to transition the current groundwater-based economic system toward avenues that are more sustainable for the social, economic and natural systems, and 3) communicate the model's outcomes for the purpose of informing policy designed to enhance sustainability while minimizing the economic pain for the region's communities.

2 Methods

The scope of this study is the 12 counties of Groundwater Management District #3 (GMD3) in Southwest Kansas (Figure 1). Farmers in this region of the Ogallala, similar to other regions of this aquifer, tap groundwater to raise corn, sorghum, soybeans, wheat and alfalfa. In turn, the irrigated grains and alfalfa supply inputs for large-scale confined feedlots that deliver finished cattle for several of the world's largest meatpacking factories (Broadway and Stull, 2005), making GMD3 one of the most productive value-added agricultural regions in the U.S. and world (Steward et al., 2013). However, as illustrated in Figure 1, the emergence of this hyper-extractive (Aistrup et al., 2013) value-added agricultural economy has imposed a heavy toll on the aquifer, reducing its saturated thickness and altering its recharge (Custodio, 2002). With irrigated crops accounting for 97% of the water withdrawals from the Ogallala Aquifer in Western Kansas (United States Department of Agriculture, 2013), developing policies that sustain the life of the aquifer is essential for maintaining the economic health and vitality of the region and Kansas.

Our framework for studying GMD3 is explicitly a coupled natural-human system approach. CNH studies 1) take advantage of both social and natural systems variables, 2) are multidisciplinary in theoretical approach, 3) integrate research methods across disciplines, and 4) are "context specific" while understanding temporal dynamics (Liu et al., 2007). Within CNH studies, our framework fits under a class of hydro-economic models that Brouwer and Hofkes (Brouwer and Hofkes, 2008) identify as

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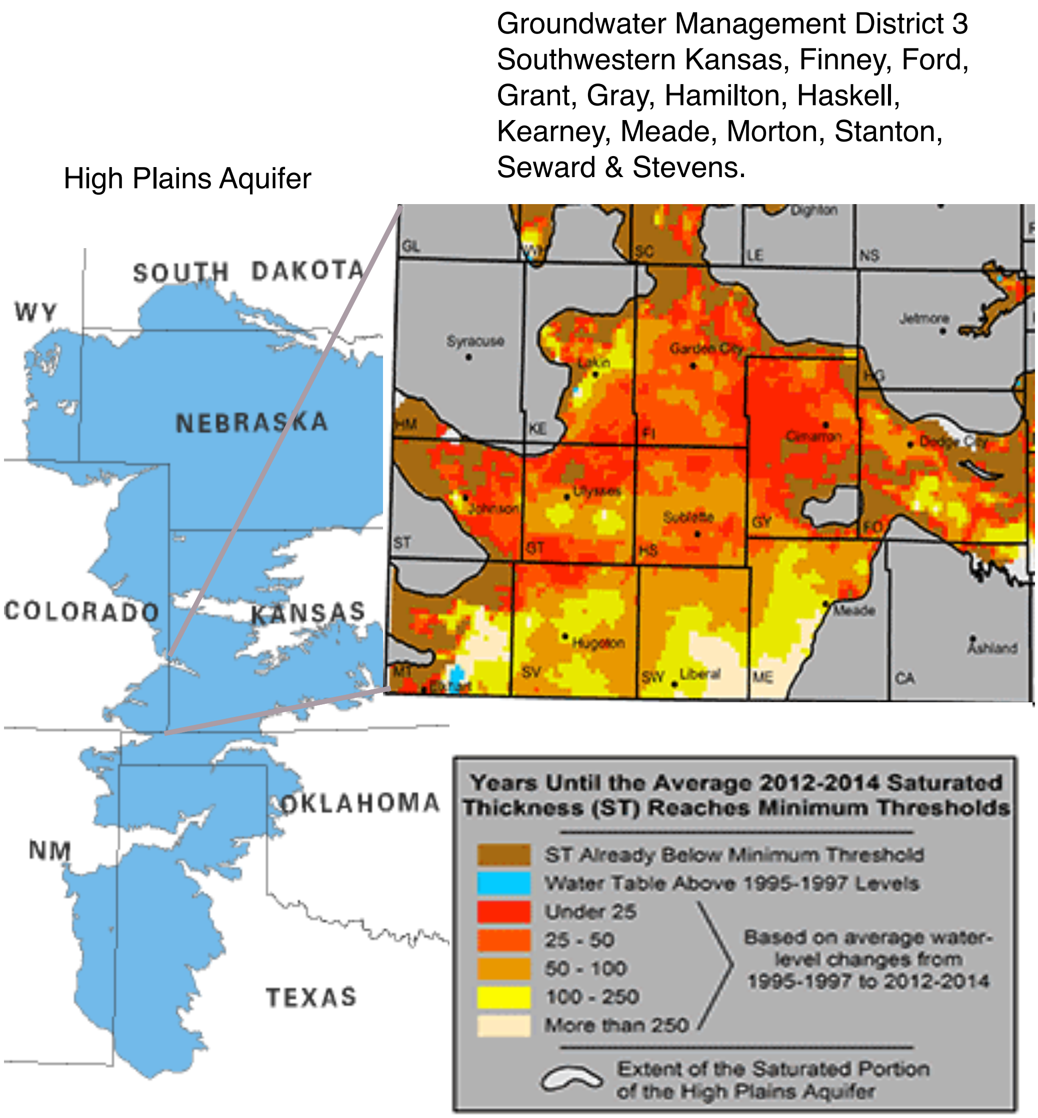

Figure 1. Estimated usable lifetime of High Plains Aquifer in Southwest Kansas. Most areas have between 20 and 50 years of usable lifetime. Source: Blake Brownie Wilson, Kansas Geological Survey (Wilson, 2005).

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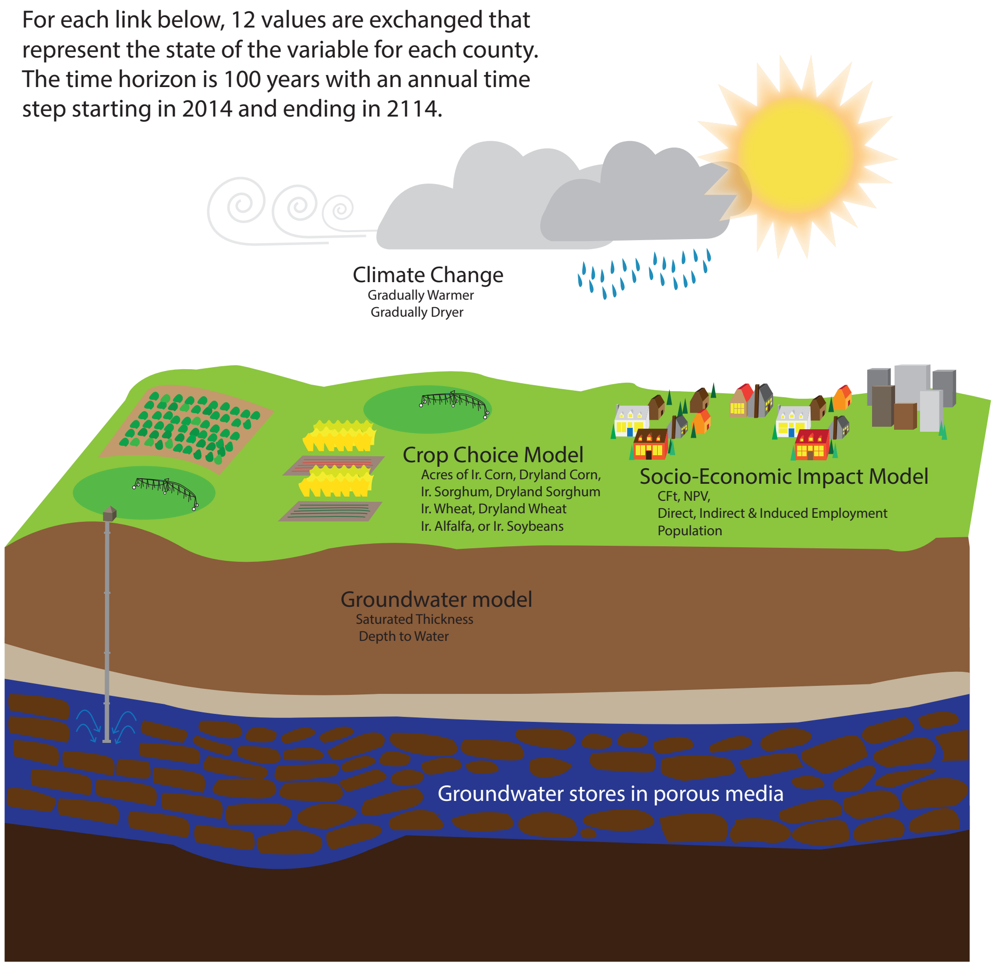

Figure 2. CNH Model Components.

modular (Volk et al., 2008; Jonkman et al., 2008; Barton et al., 2008), and holistic (Ward and Pulido-Velazquez, 2008a; Cai et al., 2008; Pulido-Velazquez et al., 2008).

2.1 Integration Methodology:

The integrated model is composed of independent disciplinary models that each conform to and are linked within the Open Modeling Interface (OpenMI) Standard (Gregersen et al., 2007). The linked model consists of four components with the input-output mappings shown in Figure 2 with one exogenous component, climate. The lowest common unit of analysis across all modeling components operates at the county level, of which there are 12 in GMD3, and the models conduct their simulations and exchange data over this set of 12 polygons. The components operate on an annual time step over the 100-year horizon from 2014 to 2113. For each year of the simulation, the economic impact model requests the crop acreage from the crop choice model and crop yield from the crop production model, which also requests the crop acreage from the crop choice model. The crop choice model in turn requests the saturated thickness and depth to water from the groundwater model (for the previous year), which triggers the groundwater model to simulate the previous year and provide the data. The crop choice model then calculates the acreage data for the current year and provides them to the crop production and economic impact models. The crop production model then calculates the yields for the year and provides them to the economic impact model, allowing it to calculate its outputs for the year.

2.2 Socio-Economic Impact Model

The socio-economic impact model uses Cash Flow at time t (CF_t), also referred to as "Gross Profit." CF_t = Revenue (i.e. Price*Yield) - Costs (Fixed Costs + Variable Costs + Lift Costs). Based on CF_t, the Net Present Value (NPV) is the discounted CF_t, calculated as $\Sigma\ (\mathrm{CF}_t/(1+\mathrm{K}_t))^t$ where K is the discount rate on investments (set at 4%) and t is a counter for the year, starting with 1 in 2014. In this model and in the crop choice model, all monetary variables are in inflation-adjusted 2014 dollars. Many economic impact models also estimate economic multiplier effects using Impact Analysis for Planning (IMPLAN) (Group, 2010). IMPLAN produces direct, indirect and induced impacts on total economic activity, value-added activity, and employment. Our linked CNH model focuses on community impacts that yield employment opportunities to support a stable population base. Over years, as agricultural production has become increasingly mechanized and technologically based, farms have consolidated, creating larger farms with fewer employees (Flora et al., 1992). This has led to considerable population decline in most rural farming dependent communities in the Great Plains region. Even though wealth creation from farming is important, from a community development standpoint, this wealth is most important when it translates to jobs and population. In Western Kansas, IMPLAN estimates that it takes about $1 million CF_t to produce 1.2 full-time equivalent (FTE) employees, of which .88 FTE are directly tied to crop production agriculture and .32 FTE represent indirect and induced employment. There are slight variations between CF_t for irrigated cropland and non-irrigated cropland, which are detailed in Table A1 in the Supplementary Materials.

To estimate the population impact of this employment, we conducted a cross sectional time series analysis with panel corrected standard errors (TSCS) (Beck and Katz, 1995, 2011) from 1970 to 2010, where the time increments are every 5 years (1970, 1975, 1980 etc.), the cross sections are the 12 counties of GMD3, and the error terms are both heteroskedastic and serially correlated (AR1).

$$y_{i,t} = \beta_n x_{i,t} + \epsilon_{i,t} \tag{1}$$

Where: $\epsilon_{i,t} = \upsilon_{i,t} + \rho\epsilon_{i,t-1}$. In this 40 year TSCS regression model, the independent variables are each county's employment in levels (# of employees) in agriculture, manufacturing, construction, health care, government services, and education, while the dependent variable is each county's total population. We obtained U.S. Census population data and Bureau of Economic

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Analysis employment data from Woods and Poole (Woods and Economics, 2012). This equation explained 92% of the variance in total population in these counties during this time period (See Supplementary Materials for model results). We multiplied the regression coefficient for agricultural employment (2.15) by the IMPLAN's employment multiplier to calculate the impact on population (2.15*(.88)= 1.88 people). Thus, each $1 million CF_t from crop production in GMD3, supports an additional .88 FTE and 1.88 residents in region. Given the connection between agriculture and value-added meat production, we assign the other .32 FTE emanating from indirect and induced employment impacts to the coefficient for manufacturing (.32*1.33 = .43 people). Taken together this suggests that each $1 million in CF_t from crop production supports 1.2 additional jobs and 2.3 more people living in the region.

2.3 Crop Choice Model:

The crop choice component is an iterative Positive Mathematical Programming (PMP) model (Howitt, 1995) that simulates farmers' allocation of arable land to different crops in each county. The model operates on an annual time step, with each execution predicting farmers' choices in a single growing season. In addition to harvested crop prices and crop-specific costs of production, the model accepts as inputs the current (county average) depth to water and saturated thickness of the aquifer. Depth to water affects water extraction costs, while saturated thickness affects the pumping rate of wells, which in turn creates an upper bound on the annual extraction of irrigation water. The model simulates land allocations as the solution to a constrained optimization problem that represents farmers' profit-maximizing mix of land uses, given price conditions, water extraction costs, and the constraints on water and land availability. The model outputs are the predicted acres planted to each crop.

A separate instance of the model was calibrated to data from each county in the study region. Each county model simulated acreages for irrigated and nonirrigated plantings of the five dominant in crops in the region: wheat, corn, sorghum, soybeans, and alfalfa. Nonirrigated production of soybean and alfalfa is unfeasible given regional hydroclimatology and so are only included as irrigated crops. Thus, eight crop categories were modeled. The models were calibrated to the 2006-08 average of observed acreages, yields, and prices for the eight crops by county, the most recent period for which comprehensive county-level data are available from the National Agricultural Statistics Service (NASS). Expected crop yields were simulated within the model from water response functions in Martin (1984), which were calibrated to yield data from NASS and weather data from the Kansas Weather Data Library.

There is a long history of increasing crop yields due to genetic improvements in plant varieties (United Nations, 2011, p. 46). Considering this history and the continued investment in plant genetics by industry and governmental agencies, the crop choice model assumes that yields will continue to improve into the future based on the noncompunded percentage growth rates estimated from time series regression of Western Kansas yields for irrigated and non-irrigated plant varieties from 1974 to 2009 (see Supplementary Materials) (Rogers and Lamm, 2012). The average annual improvements in yield range from a high of 1.28% for irrigated corn, to a low of .55% for dryland wheat and .53% for irrigated sorghum. Crop production costs, excluding irrigation, were obtained from Kansas State University Extension enterprise budgets and were increased over time at noncompounded percentage rates in proportion to yields based on a regression analysis of budget and yield data using 2006-12 observations. While base level yields and costs were calibrated to 2006-08 data, growth percentages were applied to adjust the

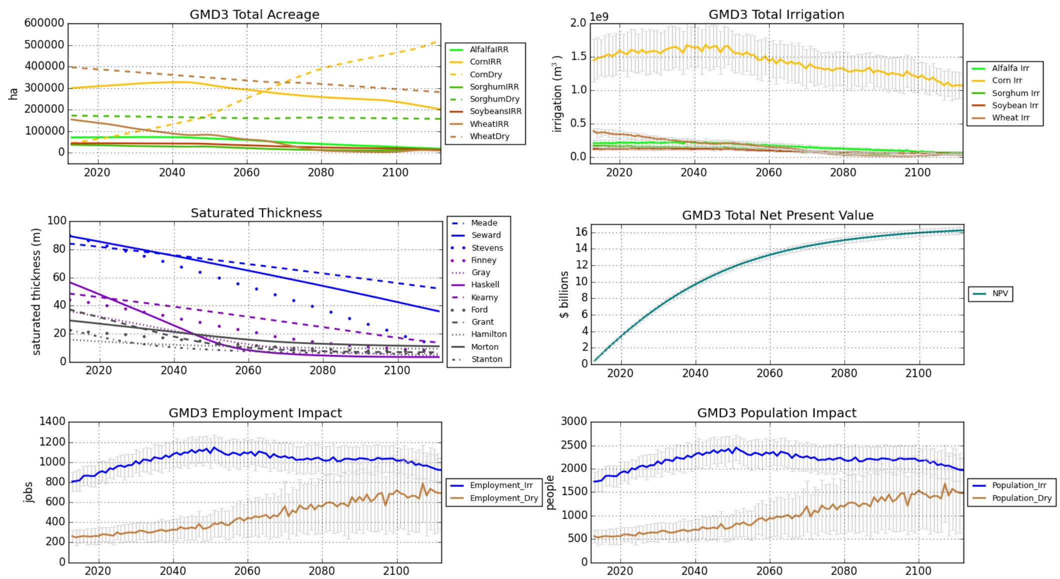

Figure 3. Baseline Outcomes of Current Irrigation Practices in GMD3: 100 simulations. Top Row: The left graph shows the acreage planted for dryland and irrigated crop varieties. Note the demise of irrigated corn and the rise of dryland corn over the course of the simulation.$\hat{*}$ The right graph depicts total water consumed in GMD3 by each irrigated crop. Middle Row: The left graph shows the average level of saturated thickness of the Ogallala in each of the 12 counties over time. Note that only two of the 12 counties end the simulation with an average saturated thickness greater than 15m. Generally, more than 15m of saturated thickness is need to irrigate using center pivots.$\hat{*}$ The right graph sums the NPV across all 12 counties over time. Bottom Row: The left graph illustrates the predicted number of additional jobs created in a simulated year due to the direct, indirect and induced impacts of irrigation and dryland crop production, respectively. Note that over time, the level of variation in employment due to dryland crop production is exceptionally large, reflecting the greater levels of uncertainty introduced by a gradually warmer climate. The graph on the right depicts the number of additional people who live in the GMD3 in that year because of irrigated and dryland crop production. The population impact mirrors the level of variation shown in the previous graph. $\hat{*}$ The whiskers denoting the level of uncertainty are excluded on this graph to maintain the clarity of presentation.

initial simulation year to correspond to 2014. The cost of irrigation water was calculated separately based on the energy costs from pumping lifts (Rogers and Alam, 1999). Details on the model development and calibration methods are in Clark (2009), Bulatewicz (2014), and Armoa (2015).

2.4 Crop Production Model:

The crop production component projects grain yield and irrigated water by using the Erosion-Productivity Impact Calculator (EPIC) model (Williams, 1995). EPIC simulates daily crop growth by representing three major processes: (1) phenological development; (2) dry matter production and partitioning to plant tissues resulting in growth; and (3) economic yield. The model reproduces the results of irrigation, fertilization, tillage, variety selection, alternative production calendars, etc. Plant growth is estimated from intercepted solar energy and plant leaf area. Daily dry matter is accumulated for the growing season as controlled by heat units or environmental conditions (typically freeze events for summer crops) and yield is estimated using a total biomass to grain ratio. EPIC is able to simulate multiple crops because it embodies a generic plant model that can be re-parameterized to represent different species.

We previously calibrated the model for use in western Kansas (Bulatewicz et al., 2009) and further refined the parameters to support non-irrigated cropping for this study. The model component, developed in an earlier effort (Bulatewicz et al., 2014) and implemented using the Simple Model Wrapper (Castronova and Goodall, 2010), has an embedded set of simulated output data from EPIC collected by executing the model for all combinations of the relevant inputs (soil, crop, management, weather). The component operates over a set of (independent) polygons of variable size, accepting inputs for soil type, weather station, and crop, and providing outputs for yield and water-use.

2.5 Climate:

Each simulated year's weather is determined by a random draw from meteorological records between 1985 and 2012. We build the likelihood of climate change into our simulation about the future of GMD3. ECHAM5 climate change models for the High Plains region suggest future regional warming and a gradual increase in extreme weather events, pointing toward a less suitable climate for agricultural production (Zabel et al., 2014). To model this climatic progression, we weight the weather data from 1985 to 2012 such that years of below-average dryness will, over 100 years, gradually become 25% more likely to occur than they are now. We find that this captures both the prolonged periods of drought that are likely to become typical, while allowing for shorter-lived periods of plentiful precipitation.

2.6 Groundwater Model:

The groundwater modeling component provides estimates of groundwater storage and the changes in storage due to pumping and natural hydrologic processes. This model is linked to the crop production and economic crop choice model using OpenMI (Gregersen et al., 2007), and operates at the common county level scale. Conservation of mass requires that recharge minus extractions is equal to the annual change in storage:

$$\mathrm{Recharge} - \mathrm{Extraction} = \mathrm{Storage}_{t+1} - \mathrm{Storage}_{t} \quad (2)$$

This groundwater model integrates these spatially and temporally variable components of the hydrologic cycle to provide these fluxes at the common county-level aggregation scale, which are consistent with the scales of previous studies in the study region (Steward and Allen, 2013, 2016).

Specific steps used to prepare groundwater data follow. Storage is obtained from groundwater observation wells, kriging across wells to give a surface of saturated thickness, multiplying by specific yield to give water content, and integrating across the aquifer area within a county (Steward and Allen, 2013). Recharge is obtained by spatially integrating results from Hansen (1987), and extraction is obtained from the crop irrigation component, which was parameterized against historical pumping rates recorded in the WRIS water-use reports. The county level model ignores the changes in storage resulting

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from groundwater movement between counties, since groundwater moves with an average velocity of only 30 cm/day driven consistently by the west-east sloping aquifer (Gutentag et al., 1984), and the differences between what enters and leaves each county represents a very small fraction of changes in storage. This county level model provides groundwater availability for the crop production model, and also ignores other water use such as municipalities, industry and feedlots, which have historically used much less than 5% of the groundwater extractions in each county.

3 Baseline, Point Estimates and Estimates of Uncertainty

This integrated model is used to develop point estimates for important variables and also estimates of uncertainty by simulating a policy scenario 100 times. Figure 3 illustrates the significant findings from the groundwater, crop choice, crop production and socio-economic impact models. The point estimates for each component of each year is presented as the average from the 100 simulations and the estimates of uncertainty are the standard deviations around each point estimate.

Our wholistic CNH model predicts an unsustainable outcome for the aquifer in all counties if current conditions remain unabated, which is consistent with similar results obtained using different methodological approaches (Scanlon et al., 2012; Steward et al., 2013; Steward and Allen, 2016). Results in figure 3 illustrate that the acreage for irrigated corn continues to increase until 2040 (ca. 325K ha), but as the saturated thickness of the aquifer falls below an average of 15m in all counties but Meade and Seward, the amount of acreage planted in irrigated corn also declines. By 2113, there are fewer than 200K ha of irrigated corn. On the other hand, the acres planted to dryland corn soars to 500K ha, surpassing by 2070 the acreage planted in dryland wheat. As the capacity of the aquifer to support irrigation decreases overtime, the average saturated thickness in each county stabilizes at 10m to 15m, reflecting that, for the most part, farmers no longer have the capacity to consistently draw the high volumes of water necessary for center pivot irrigation. Even though the CF_t from irrigated crops will increase from $400M to just over $600M, the CF_t from dryland crops will increase from $50M at the beginning of the simulation to about $400M at the end of the simulation. This leads to continued positive employment impacts for irrigated and dryland agriculture, increasing from a total of 1,000 workers currently to 1,800 workers at the end of the simulation. The NPV reaches $10B by 2040 and $13B by 2060.

However, hidden behind these point estimates is much uncertainty that comes from relying on dryland farming in the counties of GMD3. This is the most apparent by examining the outputs of the socio-economic model. Although the CF_t for all dryland production is generally positive, the variation around that average grows (wiskers represent 2σ's from the average) over time relative to the increased number of acres planted to dryland crops and the increased prevalence of a dryer climate. This creates a higher probability for dryland crop failure. Currently, farmers in GMD3 and U.S. mitigate the risk from drought and other weather related calamities with federally subsidized crop insurance, administered by the Risk Management Agency of the USDA. In the event of crop failure, insured farmers receive a settlement based primarily on the price of the crop during harvest multiplied by the average yield in that county over the past 10 years (Risk Management Agency of the United States Department of Agriculture, 2016). The impact of crop failure on local communities is significant. Farmers who experience crop failure will not be employing as many others to assist them with harvest even if they do collect crop insurance. This suggests

Table 1. Summary of Major Outcomes from each Scenario

Scenario	Status Quo	1st	2nd	3rd	4th	5th
Description	Baseline	Jr. Rights	2X Interval	3X Interval	4X Interval	6X Interval
Water Reduction	0%	21%	12%	26%	35%	48%
#Counties <15m	10	7	8	6	6	4
ha Irrig. Corn 2014	300K	290K	300K	300K	300K	300K
ha Dry Corn 2014	50K	150K	50K	50K	50K	50K
ha Max Ir.Corn/Year	320K/2045	320K/2060	350K/2055	380K/2065	400K/2085	425K/2100
ha Irrig. Corn 2113	200K	280K	280K	340K	370K	400K
ha Dry Corn 2113	500K	450K	450K	345K	300K	250K
NPV 2060 in Billions	$13.3	$11.5	$12.1	$10.8	$9.8	$8.6
NPV 2113 in Billions	$16	$14.5	$15.1	$14	$12.5	$11.5
# Employ 2014	1050	950	1000	950	900	850
# People 2014	2300	2100	2150	2000	1900	1750
# Employ 2113	1500	1900	1900	1950	1900	1900
# People 2113	3500	4000	4000	4200	4000	4000

that as the climate becomes hotter and dryer, the negative swings in employment and population will be large even if farmers' incomes from dryland fields are insured. This reinforces an important historical lesson. One of the major benefits of irrigation agriculture is that it mitigates the impact of drought, assuring farmers and the communities that rely on agriculture of bountiful crops and all of the positive economic benefits therein.

4 Sustainability and the Ogallala

Our definition of sustainability parallels that of Peter H. Gleick, who defines sustainability in terms of using water to allow "human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it." (Gleick, 2000) We add, however, one proviso to this definition. The hyper-extractive economies of the High Plains Aquifer region have already substantially depleted the aquifer (see Figure 1). Stream flows for riparian and aquatic ecosystems have been impaired (Ahring and Steward, 2012). Reversing the impacts of the past 50 years may not be possible without ceasing all irrigation activity in the region. Even then, given the recharge rates of the aquifer, it would take 500 to 1,300 hundred years to fully recharge the aquifer in Western Kansas (Steward et al., 2013). This is not a viable scenario. Thus, our sustainability policy scenarios focus on maintaining current saturated thicknesses and stemming the current pattern of continuous depletion, while maintaining to the extent possible the employment levels, wealth generation, and population impacts in the region.

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4.1 Scenarios 1 & 2

The first two policy scenarios use two separate Kansas water conservation statutes to model different policy approaches for achieving a 10% to 20% reduction in irrigation. The Kansas Groundwater Management District Act contains provision K.S.A. 82a-1036, which allows the Chief Engineer to designate an Intensive Groundwater Use Control Area (IGUCA) to implement corrective control provisions reducing the permissible groundwater withdrawal based upon relative dates of priority of such rights (this statute also allows for a rotating schedule(Steward et al., 2008)). Thus, this first scenario takes at least 20% of fields out of irrigated crop production based on senior versus junior water rights. This is modeled by reducing by 20% the acreage assigned to irrigation in each county. We assume that this acreage will be returned to dryland production. The second policy scenario emanates from K.S.A. 82a-1041(d)(1), which allows adjacent water users in a region to create "Local Enhanced Management Areas" (LEMA). Under this statute, if a majority of irrigators in a contiguous area agree to limit water use by a prescribed percentage then that reduction becomes a legally enforceable limitation on all irrigators. Currently, there is one LEMA restricting irrigation in Kansas located in Sheridan and Thomas counties, which are north of GMD3. LEMA's have two advantages over the IGUCA approach. First, it is a bottom-up process, where irrigators in an area agree to the restrictions instead of them being forced upon them by the Chief Engineer. Elinor Ostrom's (2010) work suggests that this is a better institutional design for managing common pool resources. Second, this represents a shared pain approach; an approach that is preferred by irrigators over the enforcement of junior vs. senior water rights. We operationalize the LEMA policy scenario by assuming that irrigators in GMD3 agree to create a LEMA that doubles the interval between irrigation applications, thus slowing the rate of water application by about 12% across the management district. Based on previous research, we do not anticipate that either of these scenarios will produce a sustainable outcome. Rather, the focus here is on the effects of restrictions on farmers' NPV and the local communities.

Table 1 reports the results of simulations for scenarios 1 and 2 compared to the baseline analysis. Removing 21% of fields from irrigation based on junior water rights means there is an immediate reduction in the number of irrigated acres in all the crop varieties, however irrigated corn only decreases by 10K ha (300K ha in the baseline to 290K ha in junior rights scenario). The Crop Choice Model suggests that the bulk of acres taken out of irrigated production will move to dryland corn (an increase of 80K ha in 2014 over the baseline) production. By contrast, doubling the irrigation interval has little appreciable impact on crop choices in GMD3 compared to the baseline. For scenario 1, the maximum number of acreage for irrigated corn tops out in 2060 at 320K ha compared to 350K in 2055 in scenario 2. Both improve the lifespan of the aquifer by 10 to 15 years, but neither comes close to achieving aquifer sustainability. Both approaches produce similar types of outcomes for CF_t and employment. The NPV by 2060 is just over \$11.5B for the junior rights scenario and \$12.1B for the LEMA scenario, compared to \$13.3B for the baseline. Interestingly, in the long term, communities in GMD3 benefit from conservation. Extending the life of the aquifer in both scenarios leads to more people being employed by the direct and indirect impacts of production farming (an average of 400 workers a year by 2113).

4.2 Scenarios 3, 4, & 5

Given that neither of first two policy options achieves sustainability, we explore two questions. 1) At what level of water conservation is sustainability achieved and 2) what are the associated socio-economic consequences for the farmers and communities of GMD3? To explore these questions we simulated the implementation of a LEMA across GMD3 that incrementally increases the interval for irrigation by 3X (a 26% reduction compared to 2014 usage), 4X (a 35% reduction), and 6X (a 48% reduction). We focus on the LEMA policy approach because it is a theoretically more pleasing policy prescription (see arguments above and Ostrom's work (1990)). Significantly, increasing the interval by 6X stretches to the maximum limit of the marginal utility of irrigation for the purpose of assuring increased crop yields. Thus, at this point, the LEMA approach begins to lose its policy integrity.

Tripling the irrigation interval for irrigated corn production gradually increases the acres in production from 300K ha in 2014 to a peak of 380K ha by 2070. Dryland corn, which in the baseline analysis becomes the most predominant crop after 2080, only surpasses irrigated corn in acres planted in 2110, at the end of the 3X simulation. Given the large variation in yields and revenues associated with dryland corn production, policies that reduce dependence on this high risk crop are desirable. The 3X scenario tends to benefit the communities of GMD3 as the number of additional people employed due to the direct and indirect impacts of production agriculture increases from fewer than 1,000 in 2014 to 1,950 in 2113. Similarly, the number of people living in the region because of direct and indirect economic impacts from irrigation and dryland farming increases from 2,000 in 2014 to 4,200 in 2113.

Disappointingly, increasing the irrigation interval by 4X or 6X does not produce sustainable outcome for the aquifer. Six of the 12 counties under the 4X scenario and 4 of 12 counties under the 6X scenario still end the simulation with average saturation depths of 15m or less. There is also an economic cost to irrigators to achieve this level of water savings. The NPV in 2060 shrinks to $9.8B for 4X scenario and $8.6B for the 6X scenario. On the positive side, after an initial decline in employment and population early in the simulation, both grow and by the end of the simulation surpass the baseline by 500 employees.

5 Conclusions

These results corroborate previous studies that show that conservation often leads initially to an expansion of irrigation activities, as farmers use their water savings on more fields to increase their capital returns (Ward and Pulido-Velazquez, 2008a, b; Steward et al., 2013). However, our coupled model extends this finding by showing that the expanded presence of irrigated acreage in GMD3 will reduce the impact of an increasingly dryer climate on the region's economy and create greater stability in the farming sector along with increased employment and more people living in the region.

For irrigators today, however, there is a negative economic component to water conservation. Under every scenario, there was a moderate to significant loss in the NPV. Moreover, even increasing the irrigation interval by as much as 6X still does not produce a fully sustainable outcome for the aquifer. Four of the 12 counties in GMD3 are likely to have an average saturated thickness of less than 15m in 2113. So, conservation appears beneficial for long-term employment and increases the number of acres under irrigation, which should help farmers buffer the effects of drought in the face of climate change. On the other hand, conservation reduces short-term returns because of decreased yields and profits.

We recognize the research showing that economic systems relying on the unlimited use of a common-pool resource, in this case groundwater, can sputter when restrictions are implemented (see research on Atlantic coast fisheries (Schlager, 1994)). Even so, under every scenario the NPV for farmers remains in positive profit territory. This suggests that GMD3's hyper-extractive agricultural system can survive the transition to a more sustainable posture. Based on the experiences of irrigators in other parts of Kansas, where the declining saturated thickness of the aquifer has already restricted irrigation activities (GMD1 in the central part of Western Kansas), the answer appears to be that irrigators with less water do transition, adapting to their new conditions to remain in business.

Perhaps the most important outcome is that this study establishes the salience of interdisciplinary linked CNH models that seek to untangle and address significant environmental policy issues. Other studies of intensive water use regions have been insightful, but none have incorporated the breadth of our model's components or have used an OpenMI framework with easy extensions to investigate other policy issues. Our modular-holistic model, which includes the major variables of socio-economic impact, crop choice, crop production, and groundwater supply, points toward the meaningful policies that can be implemented today to bring a more sustainable future to this region – a region that produces 20% of the meat products of the U.S. today.

Additional research is necessary to refine this CNH model to 1) model the dynamic nature of the grain commodities market, 2) take into account new efforts by agra-industry and universities to double grain production levels over the next 15 years, and 3) take advantage of improved scientific models of climate change to more accurately portray the uncertainties that irrigators face and the additional demands for water that climate change may induce in this water challenged region. Researchers in the future can adapt this wholistic model to take account of these factors to build new models of sustainability from the wells that pump the water from the aquifer to the communities where people are affected.

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Appendix A: Supplementary Materials

A1 Socio-Economic Model

To estimate the population impact of this employment, we conducted a cross sectional time series analysis with panel corrected standard errors (TSCS) controlling for autocorrelation (AR 1) (Beck and Katz, 1995, 2011) from 1970 to 2010, where the time increments are every 5 years (1970, 1975, 1980 etc.), the cross sections are the 12 counties of GMD3, and the error terms are both heteroskedastic and serially correlated. We found:

$$
\begin{aligned}
\text{Total Population}_{i,t} = 1.09 &+ (2.15^{**})\text{Agriculture}_{i,t}\\
&+ (1.33^{**})\text{Manufacturing}_{i,t}\\
&+ (1.45^{**})\text{Construction}_{i,t}\\
&+ (8.14^{**})\text{Health}_{i,t}\\
&+ (3.42^{**})\text{Government}_{i,t}\\
&+ (6.38^{+})\text{Education}_{i,t}\\
&(^{**}p \leq .001, ^{+}p > .05)
\end{aligned}
$$

The manufacturing impact coefficient may seem low, however, most of the workers in meat packing plants are immigrants from Mexico and Central America, who are single or are married and have left their spouses and families in their home country to work in these meat packing facilities (Broadway and Stull, 2005). Thus, each employee in manufacturing in GMD3 does not yield the type of population impact that manufacturing would in other regions.

A2 IMPLAN Multipliers for Crops

Table A1 shows IMPLAN multipliers for crops in Western Kansas used in the socio-economic model. Estimating employment impacts can be controversial when computed as a function of total expenditures and revenues, which tends to overestimate the employment impact. We choose instead to calculate employment impacts as a function of CF_t (i.e. profits).

Table A1. IMPLAN Multiplier for Crops in Western Kansas

Irrigated	Direct	Indirect	Induced	Total
Total Industry Output	1.00	0.21	0.18	1.39
Employment	8.835E-07	1.905E-07	1.235E-07	1.197E-06
Non-Irrigated	Direct	Indirect	Induced	Total
Total Industry Output	1.00	0.18	0.25	1.42
Employment	8.817E-07	1.919E-07	1.245E-07	1.198E-06

A3 Increasing Crop Efficiency in Southwest Kansas

Table A2 shows the historic data used to estimate the increasing crop yields for corn, soybeans, sorghum, wheat and alfalfa, for both irrigated and dryland varieties.

Table A2. Historic Yields in Crop Varieties, Irrigated and Dryland

	Corn-IRR	Corn-DRY	Soy-IRR	Soy-DRY	Sorghum-IRR	Sorghum-DRY	Wheat-IRR	Wheat-DRY	Alfala-IRR
End year	2009	2009	2009	2009	2009	2009	2009	2009	2009
Start year	1974	1974	1984	1984	1974	1974	1974	1974	1974
Series length	35	35	25	25	35	35	35	35	35
Intercept	106.86	58.84	39.934	22.938	82.766	43.294	41.95	31.455	4.307
Slope	2.489	1.109	0.5687	0.3587	0.5442	0.8551	0.3193	0.2139	0.0578
End Yield*	193.96	97.658	54.152	31.906	101.81	73.222	53.126	38.942	6.33
Percentage**	0.01283	0.01136	0.01050	0.01124	0.00535	0.01168	0.00601	0.00549	0.00913

*Predicted end year yield ** Annual change/End year yield

Sources: Corn, Soybean, Sorghum, Wheat from Kansas Irrigation Trends (http://www.ksre.ksu.edu/irrigate/OOW/P12/Rogers12Trends.pdf)
Alfalfa from authors analysis of NASS data.