Sustaining Agriculture through Adaptive Management Resilient to a Declining Ogallala Aquifer and Changing Climate

Introduction

The Ogallala Aquifer, the largest freshwater aquifer in the world, is a main source of agricultural and public water supplies that has sustained economic development in the region for more than 80 yrs. It underlies 450,660 km^2 in parts of eight states (Fig. 1c; Thelin and Heimes 1987). The Ogallala Aquifer region (OAR) currently accounts for 30% of total crop and animal production in the U.S and more than 90% of the water pumped from the Ogallala Aquifer is used for irrigated agriculture. Irrigated crop production has a tremendous impact on rural economies in the OAR (Terrell et al. 2002, Leatherman et al. 2004, Guerrero et al. 2010), increasing land production values by more than $12 billion annually (Hornbeck and Keskin 2014).

Agriculture, water, and soil management in the OAR has come full circle over the past century. In the early 20th century, conversion of native grasslands to annual crop production and prolonged drought led to the Dust Bowl of the 1930s (Fig. 1a; Stewart et al. 2010). The adoption of irrigation and soil conservation methods (Fig. 1b) sustained the region's economy while reducing soil erosion. However, the Ogallala Aquifer is an exhaustible resource. In the 21st century, reduced well outputs (Fig. 1c) coupled with prolonged drought events have led to dust storms reminiscent of the Dust Bowl (Fig. 1d). Compounding these challenges, are climate change forecasts that predict increases in the duration and intensity of dry spells over much of the OAR over the next 50 years (Fig. 1e; NCA, 2014).

> ***Our long-term goal*** *is to optimize use of groundwater in the Ogallala Aquifer Region to sustain food production systems, rural communities and ecosystem services.*

The Ogallala, along with many of the world's aquifers, is declining on a path many consider to be unsustainable (Richey et al. 2015). Current management, policies and institutions in place in the OAR are not sufficient to adapt to declining groundwater levels (Gold et al. 2013; Morton 2015). Groundwater policies, for example, vary by state and often lack adequate hydrologic and crop water use data to manage pumping rates (Wohlers et al. 2014). ***We lack an integration of scientific knowledge, policy scenario evaluation, and the political and social frameworks to extend the life of our shared groundwater resources. Our interdisciplinary team seeks to develop a successful model of integration that leads to wide-scale changes in the management of the OAR and informs aquifer management across the world.***

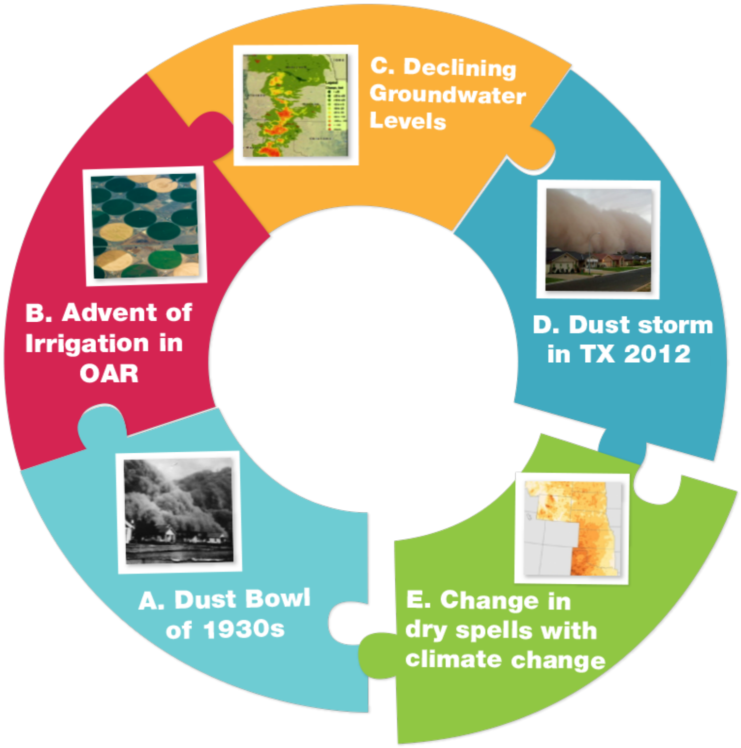

Figure 1. Historical cycle of agriculture and groundwater use in the Ogallala Aquifer region.

While groundwater levels continue to decline rapidly throughout much of the OAR, slower rates of decline in other areas suggest that a uniform set of policies and management strategies for the entire OAR would not be effective. For example, levels are rapidly declining in the southern OAR covering large areas of Kansas and Texas due to excessive pumping to meet high crop evapotranspiration (ET) demand with relatively low recharge (Gutentag et al. 1984; Luckey and Becker 1999; Scanlon et al. 2010). In contrast, higher recharge rates replenish much of the water harvested in the northern OAR. Consequently, a range of strategies will be needed from exclusive reliance on blue water (groundwater) to reliance only on green water (precipitation) sources, including different technologies, crops and crop rotations and, in some cases, the transition to rain fed (dryland) management (Fig. 2).

Achieving our long-term goal requires integrated management strategies to improve use of the right water (blue or green) at the right time in the right place across the OAR. We will use the climatic and hydrologic gradients in the OAR as a research platform to identify best management practices and corresponding policy frameworks to support optimal use of green and blue water sources today and under future climate scenarios (Fig. 2). To integrate our work across these gradients, our research and extension activities will focus on 6 'hub' research and extension sites that span these OAR gradients (Fig. 3). Our **specific objectives** are to:

1. Integrate hydrologic, crop, soil, and climate models and databases to provide baseline data for evaluating management and policy scenarios.

2. Develop and identify the best irrigation technologies, cropping system management practices, and decision support tools to improve water use efficiency.

3. Analyze current social, policy, and economic frameworks in the OAR and identify incentives and policies to increase the adoption of adaptive strategies.

4. Enable the adoption of tools and recommended strategies for improved water use through highly integrated and effective communication among the project team and technology transfer with stakeholders.

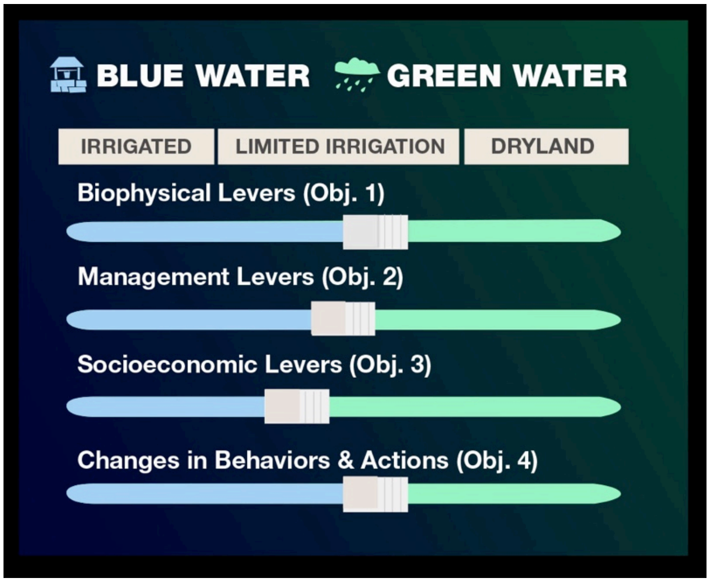

Figure 2. Through our specific objectives, we will develop new knowledge and management strategies across the multiple levers that regulate water use (biophysical (e.g., recharge rates, climate change), management practices (e.g., irrigation, crop selection), and socioeconomic (e.g., policies, social beliefs)) to cause changes in behaviors and actions that improve use of the right water (blue or green) at the right time in the right place across the Ogallala Aquifer region.

Previous work

Individually, partner institutions in this proposal have had strong programs related to sustaining agricultural benefits derived from the Ogallala Aquifer. The investigators and collaborators on this project are recognized national and international experts on climate change adaptation and crop modeling (Gowda et al. 2007), water and aquifer modeling (Bailey et al. 2013), economic modeling and decision making (Wheeler et al. 2008; Guerrero et al. 2010; Suter et al. 2012), soil, crop and irrigation management (Rice et al. 2007; Schipanski et al. 2014; Andales et al. 2014; Rogers 2012; Bordovsky and Porter 2008), and water resources extension and outreach (Gold et al. 2013). However, these efforts have focused primarily on local aspects of the problems associated with declining blue water levels in the OAR.

Several team members have been working together for the last decade as partners in the Ogallala Aquifer Program (OAP). The OAP was created in 2003 to: 1) develop knowledge and technologies that conserve water and promote agricultural production; and 2) provide knowledge by which policymakers can make effective decisions regarding water use and conservation. This project has had great success since its inception.

Accomplishments from the OAP that conserve water and promote agriculture include: 1) development and adoption of irrigation scheduling has reduced water application by 15% over the past 10 years, saving farmers approximately $200 million; 2) advances in the design and management of subsurface drip irrigation have led to the doubling of the acres using this water conserving technology since 2003; 3) new irrigation automation systems have been developed on 6 million acres that reduce labor costs by $7 per acre, maintain crop yields, and reduce water demand; 4) development of drought and heat resistant crop varieties has been advanced for corn, cotton, sorghum, wheat and peanuts; and 5) thousands of farmers have been educated in water conservation practices through extension programs and millions have been exposed to the importance of the Ogallala Aquifer via public media stories.

Despite the many successes of the OAP and other research efforts by our team members, data are site specific, often ignore the effect of predicted climate change, and lack the multi-disciplinary integration needed to address such a complex problem. Research information from the OAP, a distributed network of research and extension centers, and universities will be summarized, synthesized and analyzed in this project to develop adaptive strategies for current and future climate scenarios. We will leverage existing stakeholder networks through outreach and extension activities to meet our long-term goal of optimizing blue water use in the OAR for multiple production, environmental, social, and economic outcomes.

Rationale and Significance

With climate change projections and the certain reduction of blue water availability, there is the potential for irreparable economic, environmental, and community impacts. Thus, mid-term and long-term strategies are needed to sustain the communities of the OAR. **A new level of interdisciplinary understanding is required to identify and promote the adoption of management strategies and policies that maximize the value of this scarce resource.**

With the challenges facing the OAR, substantial improvements in water management practices have been limited and current efforts are not integrated despite the shared nature of the resource. Some of the primary knowledge gaps and barriers that this project will address include: 1) quantifying the status of the aquifer under historical, current and future climates; 2) integrating models, field research and new technologies to identify the best management practices to improve water use efficiency and crop productivity; 3) evaluating policy frameworks that may promote long-term conservation strategies, while balancing short-term economic costs;

and 4) identifying the sociological barriers to improved water management and integrating this understanding into extension and outreach plans.

This project addresses four of the six priority questions. 1) What technologies and training are needed to assist agricultural producers and processors identify the "right water" for the specific use, timing and location? 2) How can agricultural production and processing practices be improved to more efficiently use and conserve water, and be less polluting? 3) What scientific information is necessary for appropriate institutional, policy, regulatory, and governance decisions that will secure water for agriculture at the watershed or regional scales to meet diverse and conflicting water needs? 4) How will new knowledge and action necessary to solve water problems be communicated to agricultural and nonagricultural water users?

Our team has a track record of working effectively on projects focused on sustaining the Ogallala Aquifer and this proposal represents an opportunity to leverage ongoing work to develop an integrated framework that currently does not exist. The socioeconomic component of the research will evaluate the financial and social motivations producers face in responding to conservation policies and adaptive management practices in the face of changing hydrologic and climate conditions. The hydrologic and agronomic analyses bring the needed technical information, revealing whether a policy prescription yields a positive impact to the aquifer and crop production in different climate scenarios. Our outreach and extension approach will provide the much needed integration across space, time, and research disciplines to effect real changes in attitudes and behaviors. Through iterative feedback from an external stakeholder advisory group, including groundwater management districts, producers and producer groups, we will identify policies that have a high chance for successful outcomes.

Approach

Our approach will utilize a network of six sites that span the climatic, hydrogeologic, and management gradients across the OAR (Fig. 3). Site locations include agricultural research and extension centers in: 1) North Platte, NE; 2) Akron, CO; 3) Tribune and Garden City, KS; 4) Goodwell, OK; 5) Clovis, NM; and 6) Lubbock, TX. These sites already serve as knowledge 'hubs' in their region and have established producer and stakeholder networks. Each of our specific research and extension activities will include a minimum of 3 hub sites to ensure an integrated, aquifer-wide approach. This will build long-range capacity for adaptive management.

Research approach: Research activities will include development and validation of models to simulate management systems and groundwater hydrology, data synthesis to identify best management practices, and research on cutting edge technologies. Research findings will inform the development of decision support tools, extension activities, and extension products.

Extension approach: Integrated research/extension teams can rapidly transfer innovations from public research and the private sector to crop producers and advisors. We will employ high impact methods such as hands-on workshops and on-farm demonstrations to educate users on new decision support tools and irrigation methods. Producers' experiences will be tapped to strengthen tools and the credibility of extension information.

Together, our research and extension approach integrates biophysical models, field-based solutions, and socioeconomic analysis into effective outreach and extension. Objective 1 will develop critical base models for aquifer hydrology and crop-water production functions that will be utilized for the socioeconomic modeling (Obj. 3). Objective 2, on technology and management options, bridges across all other objectives to inform the crop-water management scenarios that will be integrated into crop modeling in Obj. 1 and evaluated by Obj. 3, and the development of decision support tools informed through our extension efforts in Obj. 4. Objective 4 will focus on integrating outputs and extension activities for Obj. 1, 2, and 3.

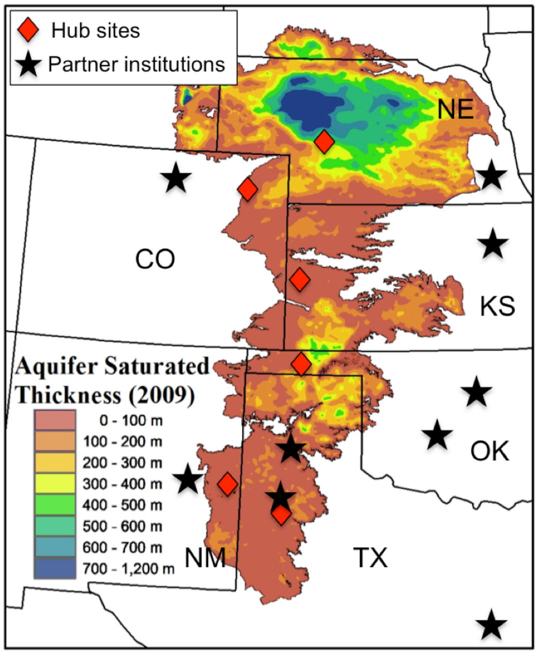

Figure 3. Network of hub sites and partner institutions across the OAR.

Objective 1: Integrate hydrologic, crop, soil, and climate models and databases to provide baseline data for evaluating management and policy scenarios

Sub-objective 1.1 Compile and develop hydrologic models and databases for the OAR. A comprehensive hydrologic model exists for the Northern High Plains region of the Ogallala (Peterson et al. 2008, Stanton et al. 2013), but we lack an aquifer-wide hydrologic model. While we will not be able to develop a full aquifer model during the timeframe of this project, we will expand the current modeling efforts to include regional-scale watershed-groundwater sub-models in the Central and Southern aquifer regions. An expanded model will provide an important baseline tool to estimate climate change and management impacts on groundwater levels across the OAR. *Methods:* We will use the coupled SWAT-MODFLOW model (Bailey et al. 2015) to evaluate available groundwater resources in the Southern, Central and Northern High Plains regions of the OAR. The model accounts for coupling between land surface hydrology and subsurface hydrology. The modeling code has been developed, tested, and applied in recent years by members of the project team in coordination with personnel at the ARS Grassland, Soil, and Water Research Laboratory in Temple, Texas. As such, use of the model will be facilitated for this project. Available land use maps, soil maps, digital elevation maps, geologic maps, and compiled hydrogeologic data (McGuire 2013) will be the basis for model construction. The sub-models will account not only for east-west precipitation and north-south temperature gradients, but also for the different groundwater policy regimes in Texas, Kansas and Nebraska. Model verification will build on recent efforts described in Hernandez et al. (2013) and include comparison with historical water table levels throughout the region.

Sub-objective 1.2. Calibration and validation of DSSAT System. To extend the analysis timeframe beyond 4 years, we will calibrate and validate one of the top crop models available for the OAR. *Methods:* The DSSAT system will be calibrated and validated for daily ET and yield using the long-term (1989-2015) data from lysimeter fields managed by USDA-ARS Conservation and Production Research Laboratory at Bushland, TX. Two lysimeter fields each were managed under irrigated and dryland management practices representing typical water management practices in the OAR. Lysimeter data include crop growth characteristics such as leaf area index, crop height, and biomass; measured ET; timing and rate of irrigation applications; soil moisture measurements in different soil horizons; and crop yield for major crops grown in the OAR (corn, sorghum, winter wheat, cotton, and soybean). Calibration and validation of the DSSAT models will be conducted separately for both irrigated and dryland conditions to assess capability to simulate ET and crop yield under the two major prevailing water management systems (irrigated and dryland). The period of record (1989-2015) will be equally divided under each water management treatment for calibration and validation purposes. Dry, normal, and wet crop production years will be equally represented in calibration and validation periods. Validation of the DSSAT system will be repeated with measured ET data from long-term experiments in Colorado, Kansas, and Nebraska to verify that the model predicts ET satisfactorily under varying soil and climatic (arid in the south to sub-humid in the north) conditions. Performance of the DSSAT model will be assessed using performance statistics recommended by Moriasi et al. (2007).

Sub-objective 1.3. Identify environmental factors driving variability in crop yields using historical climate datasets. To determine the most critical environmental factors driving the variability in crop yields under irrigated and dryland (rain-fed) conditions, we will compare actual and simulated crop production across the OAR using historical climate information. We will then use these findings to inform model simulations of climate change impacts on crop yields in Obj. 1.4. *Methods:* Available long-term (~100 years) climate data for all the weather stations across the study area will be obtained from the High Plains Climate Center. Similarly, county-level yield data of crops (sorghum, wheat, corn and cotton) under rain-fed and irrigated conditions will be obtained from available databases. The changes in the variability of maximum and minimum temperature, occurrences of first and last freeze, monthly temperature deviations during critical phases of crop growth, and monthly rainfall distribution will be analyzed. Thereafter, the correlations between the various individual weather parameters and yields of specific crops at county level will be evaluated. For a better understanding of annual variability in baseline water demand, water availability, and crop yield, the exceedance probability (P) for ET, and crop yield will be calculated and analyzed as described in Gowda et al. (2007).

Sub-objective 1.4. Quantify climate change scenario impacts on crop, soil, and water management. The calibrated DSSAT model will also be used with downscaled GCM outputs at daily time scale and under alternative crop, soil, and water management systems. The baseline scenario will include prevailing crop, soil and water management practices that reflect water policies and regulations at both local and state levels. *Methods:* We will develop downscaled GCM outputs for the OAR using the IPCC's RCP 4.5 and 6.0 (Representative Concentration Pathways; Meinshausen et al. 2010) scenarios. The GCM outputs will be obtained from CMIP5 website (Taylor 2012) for the baseline (1975-2005) and future period (2021-2100). Downscaling of climate variables such as precipitation, maximum and minimum temperatures, and wind speed at daily time-step will be done with both dynamic and statistical downscaling methods and evaluated for their suitability in hydrologic and crop simulations. For statistical downscaling, a delta-change approach will be employed (Anandhi et al. 2011). In this approach, the change factor is calculated multiplicatively/additively from the mean values of the climate variables in the future and baseline time periods. The change factors are then applied to the observed time series climatic variables to obtain future climate change scenarios. Observed climatic data for this method will be obtained from the TX High Plains ET Network (TXHPET; Porter et al. 2012), KS Weather Network, and NWS data sources. An improved dynamic downscaling method (Xu and Yang 2012) will also be used to downscale GCM outputs. This method is expected to improve accuracy of climatological means and extreme events. Regional climate simulations will be performed using the Weather Research and Forecasting Model (WRF) version 3.6 embedded in the National Center for Atmospheric Research's (NCAR) Community Atmospheric Model (CAM). Downscaled climate variables will be evaluated against local observations. Performance statistics (Moriasi et al. 2007) will be used to select the best downscaled climatic variables of future scenarios for crop and hydrologic simulations.

The downscaled GCM outputs will then be used for a scenario analysis with current and a set of alternative and novel production systems developed under Obj. 2, which will include crop genetics, irrigation technologies, water management policies, crop rotation systems, and soil management. The calibrated DSSAT system will be used to assess crop water demand and crop yields associated with current and alternative crop, soil, and water management practices. The impact of management practices will be analyzed to identify options that improve water use efficiency, crop yields, and profit for producers. Appropriate statistical tools will be used to determine the best available management practices. Results will provide key crop-water production functions for socioeconomic modeling in Obj. 3 and will help guide future research directions and outreach materials to maximize water conservation.

Objective 2: Develop and identify the best irrigation technologies, cropping system management practices, and decision support tools to improve water use efficiency

In this objective, we will synthesize data, develop water management tools, and conduct field research to identify best management practices (BMPs) across the spectrum of water availability from fully irrigated to dryland. The most promising practices will then be selected with feedback from our stakeholder advisory board and integrated into modeling scenarios in Obj. 1 and 3, and outreach activities in Obj. 4.

Sub-objective 2.1: Develop and identify new technologies for precision irrigation that improve water use efficiency and have the greatest potential for adoption. Declining blue water supply will force users to adopt innovations in two areas: 1) use of efficient irrigation application technologies that minimize losses (evaporation, runoff and deep percolation), and 2) tracking crop demand and available soil water so that the best timing of root uptake is achieved for maximum crop yield response. *Methods:* There has been limited integration of the many regional trials on crop responses to irrigation as affected by application type, timing and amount of delivery, and crop genetics. We will conduct a meta-analysis of past and present experiments including data from USDA climate hub sites, the Ogallala Aquifer Program, and hub sites (e.g., Bronson et al. 2006; Lamm et al. 2014), to quantify the relative effect of irrigation technology and management systems on water use efficiencies and agronomic yields (Stanley and Jarrell 1989; Thompson and Higgins 2002). The meta-analysis will identify the most promising management systems. We will further quantify relationships with irrigation types and rates, weather, north-south climatic gradients, soil characteristics, and cropping systems. The meta-analysis will also produce probability relationships allowing producers and consultants to compare the relative benefits and risks of adopting novel technologies for their locations and cropping systems. Technologies pertaining to irrigation equipment include low energy precision application (LEPA) and low elevation spray application (LESA); subsurface drip irrigation (SDI); precision mobile drip irrigation (PMDI); and variable rate irrigation (VRI). Examples pertaining to crop-water tracking are soil-water and canopy-temperature sensors, water-balance calculations based on ET+weather+crop development, and remote sensing of crop-canopy water status via unmanned aerial systems (UAS; Chavez et al. 2010) and radar precipitation estimates and satellite soil moisture availability (Brown et al. 2013).

In addition to synthesizing past research, we will conduct targeted field research on advanced emerging technologies (e.g., VRI and UAS) aimed at high-precision crop water use. The VRI technology has been installed on center pivots at the University of Nebraska WCREC for corn production under variable nitrogen regimes. Management of the VRI systems will include 1) fixed management zone delineation using geo-referenced soils and yield maps, and 2) dynamic in-season zone delineation using spatial crop water stress indices. Water use and irrigation water-use efficiency with respect to grain yield will be calculated. At Fort Collins, CO, multispectral, high resolution, UAS will collect surface/canopy reflectance and temperature data and produce maps of corn water use (WU) and stress (WS). We will demonstrate how high resolution WU and WS maps can be integrated into a decision support tool to generate water application prescription maps for the operation of variable rate irrigation systems. Investigators working with VRI in NE, will collaborate in the later years of this project to combine the technologies of VRI and UAS to develop in-season control of precise water and nitrogen application in large-scale pivot-irrigated fields. Promising soil moisture monitoring technologies will also be explored for inclusion in irrigation scheduling tools, as described in Obj. 2.2.

Sub-objective 2.2. Develop user-friendly irrigation scheduling tools. In the U.S., there are low adoption rates (<9% of farms) for precise irrigation scheduling methods such as soil water sensing, plant water sensing, commercial or government scheduling services, and daily crop ET reports (USDA–NASS 2008). The top two irrigation scheduling methods in farms are “looking at crop condition” (78%) and “feel of soil” (43%) and some farms use both methods (USDA–NASS 2008). These methods are not based on actual consumptive water use or profile soil water content and can result in significant over- or under-irrigation. More accurate irrigation scheduling methods based on soil water and ET tracking have had low adoption rates because of lack of economic incentive (e.g., low value crops), low energy costs (e.g., gravity irrigation), use of less efficient irrigation methods (e.g., furrow), lack of technical support (Leib et al. 2002), or lack of confidence in the tools (Lamm and Rogers 2015). Increased accessibility of the Internet and online data sources for automated soil water balance calculations has allowed the development of web-based irrigation scheduling tools (Andales et al. 2014; Rogers 2012). Accuracy of short-term weather forecasts is improving and may also be used for forecasting ET and irrigation requirements (Gowing and Ejieji 2001) or rainfall (Cai et al. 2011). *Methods:* Existing irrigation scheduling tools in the OAR (e.g., Andales et al. 2014; Bartlett et al. 2015; Rogers 2012, Dashboard for Irrigation Efficiency Management – DIEM) will be surveyed and preferred features from each tool will be identified. A stakeholder focus group will be formed to provide feedback and suggestions on existing tools. Opportunities for “cross-pollination” between tool features will be identified and the tools will be improved to increase adoption in the OAR. Existing irrigation scheduler(s) already automatically access online weather data and soil characteristics to provide daily irrigation advisories that are field-specific, but improved short- and medium-term weather forecasts in the OAR will be integrated in the tools to forecast irrigation requirements. Appropriate crop coefficients for estimating ET of major irrigated crops across hub sites and other available data sources will be compiled, and common challenges such as weather data reliability, accessibility, and accuracy will be addressed. In collaboration with extension team members (Obj. 4), this will result in user-friendly irrigation scheduling tools that are reliable and widely accessible to irrigators via the Internet and mobile devices in the OAR and will reduce water losses and increase irrigation efficiency.

Sub-objective 2.3: Quantify water-production functions and best management practices under limited-irrigation. The continuous decline in well capacities across the OAR will result in the expansion of limited irrigation and, ultimately, many irrigated acres will transition to dryland management systems. Limited irrigation by definition occurs when water supply is restricted to below that required to replace full ET (English 1990). As such the blue water supply at which limited irrigation occurs is dependent on the crop selected and the average evaporative water demand. When irrigation capacity is available, minimizing irrigation during the vegetative growth stage can reduce irrigation needs and improve green water use efficiency (Kirda 2002; Schneekloth et al. 2012). In contrast, when pumping capacity limits irrigation, producers may initiate irrigation earlier in the season, replace the primary irrigated crop with crops that are more drought tolerant or have differing water timing needs, reduce irrigated crop area or manage some crops without irrigation.

Despite the growing need for adaptive management, most studies reduce irrigation to a set fraction of full irrigation and there are few data sets available where imposed irrigation treatments have been based on pumping capacity across the season. Irrigation research in the region has been focused on determining the growth stage at which the limited blue water applications should occur and the amount applied per irrigation event needed to optimize efficiency (e.g., Norwood 2000). In addition, limited irrigation research has not kept pace with advances in irrigation technology, such as subsurface drip irrigation, and data is lacking for some crops such as wheat and sorghum, which may become more economically viable as water resources decline and breeding technologies advance. This situation is further complicated by the potential shifts in weather caused by climate change, which will shift the viability of heat and drought tolerant crops further north. *Methods:* We will synthesize limited irrigation data for crops including but not limited to corn, sorghum, wheat, cotton, alfalfa, and forage sorghum, to develop a comprehensive library of irrigation production functions. This data will be evaluated to determine the efficacy of limited irrigation management strategies such as the application of irrigation water at critical growth stages and the impact of cultural practices and variety/hybrid selection on production functions.

We will then conduct field experiments along the ET gradient provided by the hub sites to address gaps in our understanding of how these production functions are influenced by irrigation timing, pumping capacities and in some instances, both. For example, experiments at the Oklahoma Panhandle, Eastern Colorado, and Southwest Kansas research and extension centers will evaluate limited irrigation strategies (irrigation timing and quantity) on grain and forage sorghum production across the climatic gradient represented by these sites. Measurements will include yields, crop phenology, crop ET, and soil water content.

Finally, in coordination with the Obj. 3 activities, we will work with local groundwater management districts to conduct a survey to develop a database of production data. The database will include information on well capacity, cultural practices, and variety/hybrid selection. From this data and the literature synthesis, we will generate a regional analysis to predict geographic shifts in reliance on blue and green water sources using climate scenarios and hydrologic information from Obj. 1. For example, as temperatures increase, successful cotton and sorghum production will likely shift farther north than current production regions.

Sub-objective 2.4: Quantify the impact of soil management practices on ecosystem resilience and blue and green water use efficiency. Soil health is a critical component of agricultural system resilience to climate extremes and variability (Delgado et al. 2011). Soil health includes attributes of physical, chemical and biological aspects of soils. Transitioning from blue water to green water sources will increase reliance on soil health for improved green water use efficiency. Soil management as it affects soil health is critical during the transition to dryland management due to impacts on soil water dynamics and drought susceptibility (Palm et al. 2014). Soil organic matter (OM) is the catalyst for multiple soil processes that can improve soil water (blue and green) conservation. For example, soil OM can foster increased soil microbial activity, soil aggregation, increase soil porosity and improve water infiltration rates; thereby increasing green water capture efficiency and reducing susceptibility to wind and water erosion (Franzluebbers 2002; O'Neal et al. 2005; Rice et al. 2007). Key management strategies to building soil OM (and thus soil C) include increasing cropping intensity and diversity in semi-arid environments, which can improve soil health and water use efficiency (Sherrod et al. 2003; Shaver et al. 2013; Nielsen et al. 2005). Data synthesis of the relative impacts of soil management practices on crop water use dynamics and nutrient cycling are limited despite substantial investment in promoting management practices to improve soil quality or soil health (NRCS 2015). In addition, most cropping systems models do not capture soil C impacts on soil structure and soil moisture dynamics. *Methods:* We will complete a meta-analysis of the interaction of tillage management and crop rotations in semi-arid regions on soil water dynamics, including soil aggregation, water infiltration and water holding capacity. Meta-analysis results will inform the management scenarios evaluated with crop, hydrologic, and socioeconomic models as described in Obj. 1 & 3.

One key knowledge gap is the change in soil health during the transition from blue to green water management. Second, the biological measures of soil health have not been routinely employed (Lehman et al. 2015). We will quantify the effects of different management strategies during the transition from blue to green water on soil properties and soil water dynamics. We will leverage existing long-term (30-year) research plots across eastern Colorado to assess changes in soil health as a result of different dryland crop rotations and research underway at the Clovis, NM, hub site to identify soil quality effects of potential alternative crops for dryland systems. In addition, the OAR had significant enrollment of the Conservation Reserve Program (CRP). One likely strategy for the transition period is the establishment of perennial grasses for animal grazing. Preliminary data from a chronosequence of sites near Lubbock, TX, that have been transitioned from cropland to CRP shows increased microbial biomass C, labile C pools, shifts in microbial population to greater abundance of FAME biomarkers for fungi, and enhanced nutrient cycling based on enzyme analyses (Fultz et al. 2014). Using a broader chronosequence of sites across the OAR that have transitioned from blue to green water for crop production or CRP paired with current irrigated sites, we will quantify the interaction of climate and management effects on soil C, microbial communities (PLFA), aggregation, infiltration, and soil water holding capacity. Results will be integrated into outreach and extension activities (Obj. 4.2) to increase awareness of the connections between soil health and water use efficiency.

Objective 3: Analyze current social, policy, and economic frameworks in the OAR and identify incentives and policies to increase the adoption of adaptive strategies.

This objective involves the incorporation of social and cultural values into an integrated economic model. The primary goal of the modeling framework is to provide policymakers, producers, and other stakeholders with a means to evaluate the management interventions proposed in Obj. 1 and 2 as well as a set of conservation policy options with respect to local agricultural decision-making, aquifer health, and regional economic outcomes over time. The dynamic framework will integrate four classes of models: 1) local agricultural decision models, 2) dynamic economic-groundwater models, 3) regional economic impact models, and 4) social analysis models. These models will build upon and unify ongoing work in Colorado, Nebraska, and Texas (Amosson et al. 2009; Golden and Johnson 2013). The integrated modeling framework will allow for a comprehensive understanding of the economic and social impacts of a range of blue water conservation scenarios.

Multiple scenarios will be comparatively evaluated, including: 1) a status-quo scenario where water use continues at current levels; 2) reductions in blue water withdrawals due to legal restrictions on the quantity of water use or increases in the price of water use; and 3) changes in blue water use stemming from the adoption of proposed adaptive management strategies. The specific management strategies will be identified through Obj. 1 and 2 and simulated under multiple climate change scenarios developed through Obj. 1. The policy options and adaptive management strategies will be developed in consultation with the project advisory team, including representatives from producer groups, groundwater management districts, and state water planners.

The models will incorporate social and cultural influences on producer behavior and decision-making. Although producer behavior is assumed to be driven largely by financial motives, focusing exclusively on profit maximization as the driving force behind decision-making may conceal important cultural and social factors that can influence behavior beyond financial concerns. Understanding how, and why, these social factors shape decision-making will improve knowledge about the barriers to, and opportunities for adaptive management strategies. Valid and reliable measures of social and cultural factors drawn from fieldwork with stakeholders will be incorporated into the models described above by empirically integrating non-market values into farmer objective functions.

Sub-objective 3.1: Develop a local agricultural decision model to predict water use decisions amongst agricultural producers. At the core of our evaluation framework, this model will incorporate refined understanding of the crop-water production functions developed under Obj. 1. This component of the framework will allow for evaluation of the best management practices identified in Obj. 2 to integrate potential adoption decisions with impacts on water use and productivity. *Methods:* The foundation of this model will be the crop-water production functions developed using agronomic data and calibrated crop models generated under Obj. 1 and 2. Establishing crop-water production functions will be necessary to predict producer behavior and resulting crop revenue and production costs. Previous research has established that production functions exhibit diminishing marginal returns with respect to water (Kastens et al. 2003; Llewelyn and Featherstone 1997; Moore et al. 1992). This project will incorporate dynamic production functions that account for improvements in crop yields, gains in water use efficiency, and changing climatic conditions. The dynamic production functions will enable the inclusion of climate change through changes in temperature and precipitation expectations over time.

Positive Mathematical Programming (PMP) approaches (Howitt 1995) will then be used to calibrate aggregate production and input use decisions at a local level. Recently, PMP frameworks have been developed that allow for flexible substitution between land and water inputs that are consistent with agronomic evidence, and are calibrated to historical observations

(Mérel and Howitt 2014). Previous applications of PMP models have simulated the sensitivity in crop acreages to changes in prices and land/water constraints under the assumption of constant production technology. Here, the production relationship will be allowed to shift and/or change shape over time due to climatic and technological changes, and account for the possibility that climate change affects the relationship differently across crops.

Cost functions will be generated through the use of crop enterprise budgets routinely produced by state extension specialists across the OAR. Coupling cost and production functions will allow for prediction of the profit-maximizing planting and irrigation decisions as a function of spatially explicit aquifer, soil, and economic characteristics and a comparison across crops.

The models will be calibrated to maintain consistency with the hydrological and agronomic evidence. More specifically, an iterative process will be used to generate data points along the relationships of interest (crop yield and irrigation water applied), estimate a flexible response surface, and use the computed elasticity at a base point on this surface to parameterize the functions in the PMP model. This time-intensive process has been applied in few previous studies, but will ensure consistency across disciplinary model predictions and will improve the accuracy of the results.

The producer model will serve two roles: 1) to identify economic and social barriers to adoption and evaluate the impacts of the various BMP's on water use and 2) to serve as the foundation of the modeling framework, thus allowing exploration of the impact of various groundwater conservation policies and BMPs on aquifer levels and regional economies.

Sub-objective 3.2: Integrate hydrologic groundwater models with the economic decisions produced with the local agricultural decision model. A dynamic economic-groundwater model will be used to make predictions related to blue water use and hydrologic conditions over time. Coupling the local agricultural decision model with the hydrologic models will allow an evaluation of the impact of policies and management strategies on regional aquifer levels and how hydrologic conditions faced by producers evolve over time. *Methods:* We will integrate the calibrated SWAT-MODLOW groundwater sub-models in the North, Central, and South portions of the aquifer (Obj. 1) with the local economic decision model (Obj. 3.1). The result will be a dynamically iterative model wherein the economic incentives faced by producers are influenced by the groundwater dynamics and changes in the groundwater resource are influenced by the groundwater use decisions from the economic model.

The temporal allocation solution will be based on the behavior predicted by the local agricultural decision model assuming competitive market conditions under alternative policy structures. The status-quo scenario will assume no change in policy or climate over the time horizon, which can be compared to the alternative scenarios to calculate economic tradeoffs from different policy approaches and management strategies, as well as the dependence of these impacts on climate change.

Crop-specific shifts in the production technology over time will capture any interactions between climate change and the aquifer. For example, in areas with relatively large initial supplies of water, climate change in the next few decades may actually raise the relative yield and profitability of water-intensive crops such as corn. In the longer term, when climate change effects are more severe, depleted water supplies will not be available to buffer against drought or to provide larger quantities of water that may be required as air temperature and/or the length of the growing season increases.

Sub-objective 3.3: Predict regional income and employment impacts in various sectors of the economy under different policy and climate scenarios. Regional economic impact models will use output from the dynamic model (Obj. 3.2). This approach will be flexible to potentially provide feedback at the county, groundwater district, and state levels of aggregation, depending on data availability. Depleted water supplies and adverse climate impacts are likely to reduce crop production in the future, causing negative impacts to agricultural revenue. When water use is restricted through policy intervention, this will have the effect of suppressing production in the near term, but will augment future water supplies and thus bolster future production.

The results of the dynamic model will be used as direct input for a regional economic model to understand the tradeoffs associated with blue water conservation. These direct impacts will ripple through the economy, creating additional indirect and induced impacts in other sectors of the economy. The level of these impacts will depend upon the magnitude of the blue water use reductions and the relative economic importance and composition of the agriculture sector in the affected communities. *Methods:* To estimate these impacts a generalizable dynamic regional computable general equilibrium (CGE) model will be developed that can be applied to areas throughout the OAR. CGE have long been used to model the economy wide impacts of changes in resource constraints, producer behavior, and/or the adoption of policies, without many of the restrictive assumptions imposed by other models (e.g., input-output models that only capture a single snapshot and assume fixed relationships between input requirements and output levels). Recent developments in CGE modeling allow researchers to examine how regional economies evolve over time explicitly accounting for the value of land and water as separate factors of production. A baseline model will be built that, using readily available data from IMPLAN Corp., will be generalize-able to each of the areas of focus in the project.

Sub-objective 3.4: Identify the social values and beliefs driving on-farm decisions about natural resource use and adaptive management. The social component will: 1) produce data on held values and beliefs to construct non-use values as inputs into the economic policy models; and 2) generate a stand-alone values-beliefs-norms (VBN) model (Dietz et al. 2005; Stern et al. 1999). Producer decisions about natural resource use are more complex than those made by the general public (Rogers et al. 2012), involving tradeoffs between valuing natural resources for their utility value and their intrinsic value (Dietz 2015). To optimize the economic and policy models, it is crucial to include non-use values in producer objective functions. To produce non-use value data, the social component will draw on the (VBN) model and integrate stated preference valuation methods to develop measures that assess how farmers trade off profit and other non-monetary benefits. VBN is especially well-suited for identifying non-market values and it is also designed to model resource decision-making. VBN posits that decisions about natural resource are an outcome of a causal chain linking values to general worldviews to more specific risk perceptions to norms for taking action to adapt or mitigate those risks, and finally to particular resource use decisions and valuations. *Methods:* A self-administered, structured survey will elicit responses on the VBN items using the Stern-Dietz supplemented Schwartz value scale (Stern and Dietz 1994), the NEP scale (Dunlap et al. 2000) and the battery of items measuring risk perceptions and norms, which will be developed specifically for this project in consultation with the researchers. A random sample of producers across the states included in the study will be identified through a subcontract arrangement with the National Agricultural Statistics Service office in Lincoln, which has a complete database of all producers who file with the Farm Service Agency. Team members have worked with the NASS office in

Lincoln for similar survey administration. All USDA prescribed protocols necessary to protect the identities of respondents will be followed and NASS will ensure data confidentiality before release to the PIs. A usable return of at least 1,000 surveys is sufficient to identify key relationships. Based upon the potential for a response rate of approximately 30%, which has been achieved in past cooperation with NASS, a representative random sample of 3,000 respondents will be selected. The survey will be pre-tested using a random sample of approximately 40 stakeholders across the OAR to ensure the validity and reliability of the survey items. In addition, interviews and/or focus groups may be used where necessary to further investigate findings arising from the surveys.

Objective 4. Enable the adoption of tools and recommended strategies for improved water use through highly integrated and effective communication among the project team and technology transfer with stakeholders.

In this final objective, we will integrate extension and outreach activities across all objectives to ensure that necessary linkages are made between the biophysical context, field management practices, economic and policy dynamics, and social norms that influence decision-making. There is a strong extension infrastructure across the OAR near each of the hubs through Land Grant extension services at state and local levels, as well as outreach and demonstration projects sponsored by federal, non-Land Grant institutions and local water conservation districts. This infrastructure is well represented on this project team and includes a strong linkage between research and extension in the Ogallala Aquifer Program, and collaborations of USDA-ARS (Bushland and El Reno), Kansas State University, Colorado State University, New Mexico State University, University of Nebraska, West Texas A&M University, Texas A&M AgriLife Research and Extension, Oklahoma State University, and Texas Tech University. Feedback solicited from participants will inform research and outreach activities as the project progresses (see Management and Evaluation Plans) to improve relevance and effectiveness.

Technology transfer audiences represent a range of interests and technical levels, including members of the research team (communication among the team and between hubs); educators and advisors; landowners and agricultural producers; policy makers and other decision makers; students and the general public. Established extension/technology transfer networks and delivery venues will be leveraged for efficient and effective education/outreach to these diverse audiences. Internet-available publications and presentations, educational events (workshops, conferences), mass media (public and commercial, including social media), and even individual mentoring activities will be used as appropriate. Established outlets and proven inter-agency and multi-state technology transfer teams are included in this project team. We will provide training workshops for team members on emerging technologies, such as effective use of social media. Technical levels of materials will match target audience needs for effective technology transfer.

Sub-objective 4.1: Facilitate integration of hydrologic, crop, soil, and climate models for the adoption of sustainable management strategies for the OAR. Selection of appropriate management practices (irrigation strategies, agronomic practices and other proven strategies) and appropriate interpretation (and therefore acceptability by stakeholders) of model results will require close communication among and between the project team and stakeholders. Collaboration of field-based extension team members and modeling team members will ensure better (more accurate) results. To overcome the understandable skepticism of some stakeholders to modeled outputs, transparency and clarity in communication with USDA-NRCS field staff, extension, technical service providers, and producers is essential to acceptability of results and recommendations.

Technical recommendations for water conservation practices (irrigation strategies, agronomic practices, and other proven strategies) will be made available to USDA-NRCS field staff, Technical Service Providers, irrigation and agricultural technical professionals, and farm-level decision makers through Internet-available publications and presentations, educational events (workshops, conferences), and other venues. Technical levels of materials will match target audience needs for effective technology transfer.

Sub-objective 4.2: Interpret research results and promote appropriate adoption of irrigation technologies, cropping system management practices, and decision support tools to improve water use efficiency. Research results and strategy recommendations from the various applied research and extension programs will be assembled and made available on a central depository website (and cross-linked on established agency websites) to improve accessibility of these materials to stakeholders and availability for use by extension educators. Research results and interpretations will be presented by research and extension team members in local and regional field days, workshops and conferences, (such as the Central Plains Irrigation Association Conference (rotates among CO, NE, and KS) and the High Plains Irrigation Conference in Amarillo, TX). Subject matter experts from multiple hub sites will bring a broader perspective and multi-state applicability to these established venues. These events encourage "cross-pollination" of ideas among academic, industry, and producer/landowner communities. Other media outlets such as newsletters, Twitter, and local newspaper articles will carry highlights of the same content, and will reach broader audiences.

"Train the Trainer" workshops will be held at the hub sites to demonstrate the use of the online and mobile tools. Barriers to adoption identified in Obj. 3.4 will inform the content and delivery methods of workshops. Workshops will be aimed at highly motivated learners who typically amplify the information transfer by virtue of their roles as crop advisors, extension agents, and locally reputable producers. Workshops will be stand-alone events and offered as supplemental events to conferences such as those mentioned above and the Texas Alliance for Water Conservation Water College (www.tawc.us). Farmer cooperators will be recruited to pilot the improved irrigation scheduling tool on their farms. Cooperators will be surveyed to obtain their suggestions for further improving the tools and removing barriers for adoption.

Sub-objective 4.3: Summarize and communicate results of analyses of social, policy, and economic frameworks and interpret incentives and policies to increase the adoption of adaptive strategies. A clearer depiction of the economic tradeoffs will provide regional and state groundwater management organizations with the inputs they need to make challenging and potentially costly policy decisions. Additionally, the spatially explicit nature of the modeling structure will provide further understanding of how these economic tradeoffs vary across the heterogeneous agronomic, hydrologic, and economic characteristics of the OAR. Results of social, policy and economic analyses will be interpreted for policymakers and stakeholders including adoption incentives, benefits, as well as potential externality effects of each of the strategies evaluated (Guerrero et al. 2008). Dissemination of results will occur through the stakeholder advisory group, the water regulatory agencies of all states, multiple web sites, and papers and professional meetings with the scientific community.

Sub-objective 4.4: Integrate extension/technology transfer to increase impact, efficiency and audience acceptance of the project results. Transparency of the process (internal and external communications; model inputs and applications; receptiveness to and incorporation of stakeholder feedback) and consistency of the recommendations/message will encourage adoption of the recommendations and therefore encourage water conservation in the OAR. Integration and collaboration of the hub sites will improve efficiency of effort and amplify impacts of the component programs. Finally, information packaged appropriately and readily available for the various stakeholders/audiences will increase awareness of the issues and appreciation for the necessity of water conservation strategies.

Expected Outcomes

Our integrated research and extension approach will forecast groundwater, crop production, and economic outcomes in the near term and 100 years into the future with climate change with the intention of effecting real change in blue water use and management, and serving as a model for other aquifer regions. Improved crop models (Obj. 1) and socio-economic analysis (Obj. 3) will be informed by data synthesis and field experiments (Obj. 2) to identify the most promising current and future technologies and management systems that will be shared with stakeholders (Obj. 4) to optimize blue water use in the OAR. Using feedback from the stakeholder advisory group throughout the life of the project and through our evaluation plan, we will revisit milestones annually and shift efforts as needed to meet our stated goals and objectives and effect measurable change among stakeholders. In addition, graduate students supported by the project will receive an unparalleled training in integrated, adaptive resource management research, which will position them to be future leaders in addressing complex, systems-based challenges.

Major Research Outcomes: 1) Improved understanding of climate change impacts on water resources and the identification of emerging technologies and management practices that could extend the life of the aquifer; 2) Science-based road map for policy makers and stakeholders to evaluate groundwater policy for balancing water use and the sustainability of rural communities; and 3) Synthesized research databases made accessible to research and extension communities.

Major Extension and Outreach Outcomes: 1) Extended life of the aquifer through the adoption of water-efficient irrigation strategies and crop management technologies by 50% of the irrigators in the OAR; 2) Development of policies that reduce water use and sustain agricultural economies across a diverse set of groundwater districts; 3) Formation of new communication networks for integrated management across groundwater districts through coordinated outreach across the OAR; 4) Integration of private and public sectors in delivering objective, research-based recommendations and commercial products; and 5) Informed non-farm consumers about the role of water in food production.

Evaluation Plan

A comprehensive program evaluation, informed by current research and integrated into all program components, will be an essential part of this project. Evaluation is built on the project logic model, focusing on activities, outputs, and outcomes. The plan includes formative evaluation to assess performance and provide feedback to improve the project, and summative evaluation to assess and document impacts and outcomes. The evaluation will be conducted by the Office of Educational Innovation and Evaluation (OEIE), KSU, in collaboration with the Project Director and stakeholders. OEIE has extensive expertise in evaluation design, instrument development, assessment, and program evaluations for state and federally funded projects.

Overarching evaluation questions related to the project outcomes and indicators may include: *How has the project contributed to practical solutions and risk management for the Ogallala Aquifer? How have agricultural and policy actions changed as a result of this project? Has the project led to sustained food production systems, rural communities and ecosystem services? Were outreach programs successful in reaching target audiences and changing behavior? Were project activities/outputs completed on schedule?* Tools for assessing such questions will include interviews, focus groups, and/or web-based surveys. Evaluation strategies will include methods that utilize multiple evaluation approaches, draw on both qualitative and quantitative methodologies, and triangulate data for more robust findings where possible.

Evaluation indicators will include: for research objectives – review of records, research findings, resulting recommendations, and research publications; interview/survey of participants and stakeholders; assessment of project integration; and for extension and education objectives – surveys and/or focus groups with extension and education target audiences, interviews with project participants, review of extension outreach material, site visits, review of project outputs, checklist related to timeline/deliverables, documented completion of each activity. Milestones include completion of each output and benchmark noted in the timeline. See OEIE's letter that includes a matrix identifying indicators, methods and milestones.

How Results Will Be Used

There is a significant outreach component to this project. The results of this project will be disseminated through peer-reviewed papers and professional meetings within the scientific community. To ensure that results are disseminated to stakeholder groups, the research findings will also be presented in multiple meetings specifically designed to target legislative, regulatory, and producer groups, as well as in public circulars and open-access web publications. This research will provide an unrivaled means for educating and enlightening stakeholders on all of the ramifications involved in water conservation policy coupled with projected climate change.

Pitfalls and Limitations

Given the history of experience on the team, we do not anticipate any major pitfalls in terms of technology and expertise. Our scope of research and extension activities is ambitious in terms of spatial area and disciplinary diversity. This breadth of scope is both a strength and a potential weakness. The identification of key regional hub sites and a comprehensive management plan will ensure that we integrate activities across objectives. The team will communicate frequently and streamline information products to make them easily transferable to the partnering states. At the annual project meetings, the extension team will lead a dedicated work session involving all investigators to aggregate and interpret new findings, revise extension priorities as appropriate, coordinate content delivery for the next year, and explore emerging delivery approaches. In addition, it is not feasible within the timeframe of this study to develop a hydrologic model for the entire OAR. Our regional approach will provide critical new information and our goal is to extend collaborations beyond the life of this project to develop this full hydrologic model in the future. Our research approach includes field experiments, data synthesis and modeling efforts. We may encounter sociological barriers in trying to communicate results, such as deeply held values and beliefs that influence trust of new technologies and modeled outputs. We will address this common pitfall directly by identifying these sociological barriers through Obj. 3.4 and integrating these findings into outreach efforts (Obj.4).

Dissemination Plan

This integrated multi-state project will develop models, practices, economic data, policy analysis and an open-source data network that will be of great value to stakeholders, producers and communities across the OAR. The project has engaged key stakeholders from each state and partnering institution in the development of the proposal and will continue to involve them in project implementation, where appropriate, as well as evaluation activities. Our team includes directors of Water Centers at 4 partner institutions across the OAR. We will leverage these and other existing networks of stakeholders and social media tools to disseminate research results and management tools. In addition, Obj. 4 will integrate outreach activities across all objectives to improve consistency and to link policies, practices, and solutions. We will develop a project web page that will serve as a clearinghouse for information and links to institutional web portals for additional tools and documents (e.g., http://agwaterconservation. colostate.edu). The project will contribute to the eXtension learning network by sharing lessons learned through the workshops and trainings. Information will also be broadly shared in scientific conferences, agency meetings, and through annual meetings of stakeholders and practitioner groups. In addition, we will utilize social media and interactive mobile applications to improve the accessibility of our work to broader audiences. Outcomes will also be shared with the Global Alliance on Climate Smart Agriculture through CSU and KSU members.

Project Timeline

Activity	Yr 1	Yr 2	Yr 3	Yr 4
Objective 1: Integrate hydrologic, crop, soil, and climate models and databases				
Develop hydrologic models	■	■		
Calibrate DSSAT	■	■		
Analysis of variability in historical crop yields		■	■	
Modeling climate change impacts on crops and water use			■	■
Objective 2: Develop and identify innovative practices for improved water use efficiency				
Irrigation technologies and soil conservation meta-analyses	■	■		
Emerging irrigation technologies research		■	■	■
Irrigation scheduling tool development	■	■	■	
Limited irrigation gap analysis	■	■		
Limited irrigation research and database development	■	■	■	■
Dryland transitions research	■	■	■	■
Synthesis to identify management scenarios for modeling analysis		■	■	
Objective 3: Identify incentives and policies to increase the adoption of adaptive strategies				
Agricultural decision model development	■	■		
Dynamic economic-groundwater modeling		■	■	
Integrate management practices into economic impact scenarios			■	■
Social analysis of values and beliefs influencing water management	■	■	■	■
Objective 4: Enable the adoption of tools and strategies for improved water use				
Technical professional outreach on biophysical model scenarios		■	■	■
Development of web page for outreach materials	■			
Hub site field days and demos of best management practices		■	■	■
Train the trainer workshops for irrigation scheduling			■	■
Policy scenario analysis workshops with stakeholders			■	■
Evaluation and Dissemination				
Annual proj. mtgs, program evaluation, advisory board mtgs	■	■	■	■
Publish and disseminate results and data repository development		■	■	■