Colorado Water

November/December 2017

THE OGALLALA AQUIFER

Colorado State University

Features — The Ogallala Aquifer

Irrigated farms near Haxton, Colorado Photo by WIlliam A. Cotton

References can be found in the online version of this newsletter at http://cwi.colostate.edu/newsletters.asp

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Published by
Colorado Water Institute
Reagan Waskom, Director

Editor
Melissa Mokry

Design
Emily Pantoja

Production Director
Nancy Grice

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Director's LETTER

Journalists regularly hold up the Ogallala Aquifer as the poster child for mismanaged groundwater systems across the globe. Is this an accurate depiction and is it true that the entire aquifer is declining precipitously? While parts of the aquifer have declined significantly, nearly two-thirds of the saturated thickness of the aquifer is located in Nebraska where the data show that in some places, recharge rates are closer to groundwater withdrawals. Across the entire High Plains Aquifer, of which the Ogallala Formation is a major component, we have depleted slightly less than 10% of the total predevelopment water volume according to the USGS. Is it accurate that the states were blind to the fact that the aquifer was a limited resource when devising allocation and management regimes? The eight Ogallala states all knew by the 1950s or 1960s when much of the current management framework was developed that the aquifer was a finite resource. Most crop producers also understand the limits they are facing and have adopted some irrigation efficiency practices, but more remains to be done. Will the aquifer eventually be depleted to the point that the towns and communities in the region lack water to support their populations? Large-scale irrigation becomes economically infeasible when well capacity declines to a few hundred gallons per minute that must be pumped from increasingly greater depths, which still leaves a great deal of water remaining in the aquifer system for other uses.

So, is there anything to be done to prolong the economic life of the aquifer for agriculture? We think there is, but it is not going to be easy, as reducing irrigation pumping comes at a cost to producers and agriculturally dependent communities. Expecting an individual farmer to reduce pumping while those all around continue the status quo is unreasonable. Thus, it is going to take collective action to avoid the 'tragedy of the commons' the region faces as the resource declines. Indiana University Professor, Elinor Ostrum, documented in many places around the world how communities either fail or succeed in devising ways to govern common pool resources through collective action to promote sustainability for present and future generations. Ostrum developed her eight principles for protecting a common pool resource and won the Noble Prize in Economics by demonstrating how a commons such as an aquifer can be successfully managed by user associations and how economic analysis can shed light on social organization.

Colorado State University is currently leading a large, multi-state Ogallala research project funded by the USDA-NIFA that couples groundwater hydrology modeling to irrigation and crop production practices and economic analysis of policy options for reducing pumping. This issue of *Colorado Water* newsletter showcases the interdisciplinary nature of the project led by CSU Soil & Crop Sciences Professor Meagan Schipanski. With some 40 faculty and their graduate students representing a wide array of disciplines from eight university partner institutions and USDA-ARS, the group seeks to identify production practices, technologies and policies that can help sustain the people and ecosystems that depend on the aquifer. The project is guided by an outstanding group of practitioner-advisors who help validate the assumptions and outputs of the project team.

Cultural and practice changes are underway on the High Plains. In particular, we see a shift in dialogue that prioritizes maximizing return on investment rather than maximizing yield, and increasing resiliency by reducing risks related to markets, weather, equipment, and labor. Producers are concerned about the aquifer. The fact remains that the High Plains Aquifer is a limited resource that will not sustain current withdrawal rates, yet it is currently a very significant component of the overall U.S. food production system. Depletion of groundwater has been accelerating across the globe since World War II. Finding the political will, technologies, practices, and policies to preserve the communities and resources of the High Plains can help point the way towards sustainable groundwater management and food security in the U.S. and internationally.

Reagan Waskom

Director, Colorado Water Institute

THE FUTURE of the Ogallala Aquifer

We Can Measure It, But Can We Manage It?

Meagan Schipanski, Colorado State University;
Brent Auvermann, Texas A&M AgriLife Research and Extension Center at Amarillo;
Prasanna Gowda, USDA-ARS - Grazinglands Research Laboratory;
Bridget Guerrero, West Texas A&M University;
Amy Kremen, Colorado State University;
Dana Porter, Texas A&M University;
Chuck Rice, Kansas State University;
Matt Sanderson, Kansas State University;
Kevin Wagner, Oklahoma State University;
Jason Warren, Oklahoma State University;
Chuck West, Texas Tech University;
Reagan Waskom, Colorado State University

Background

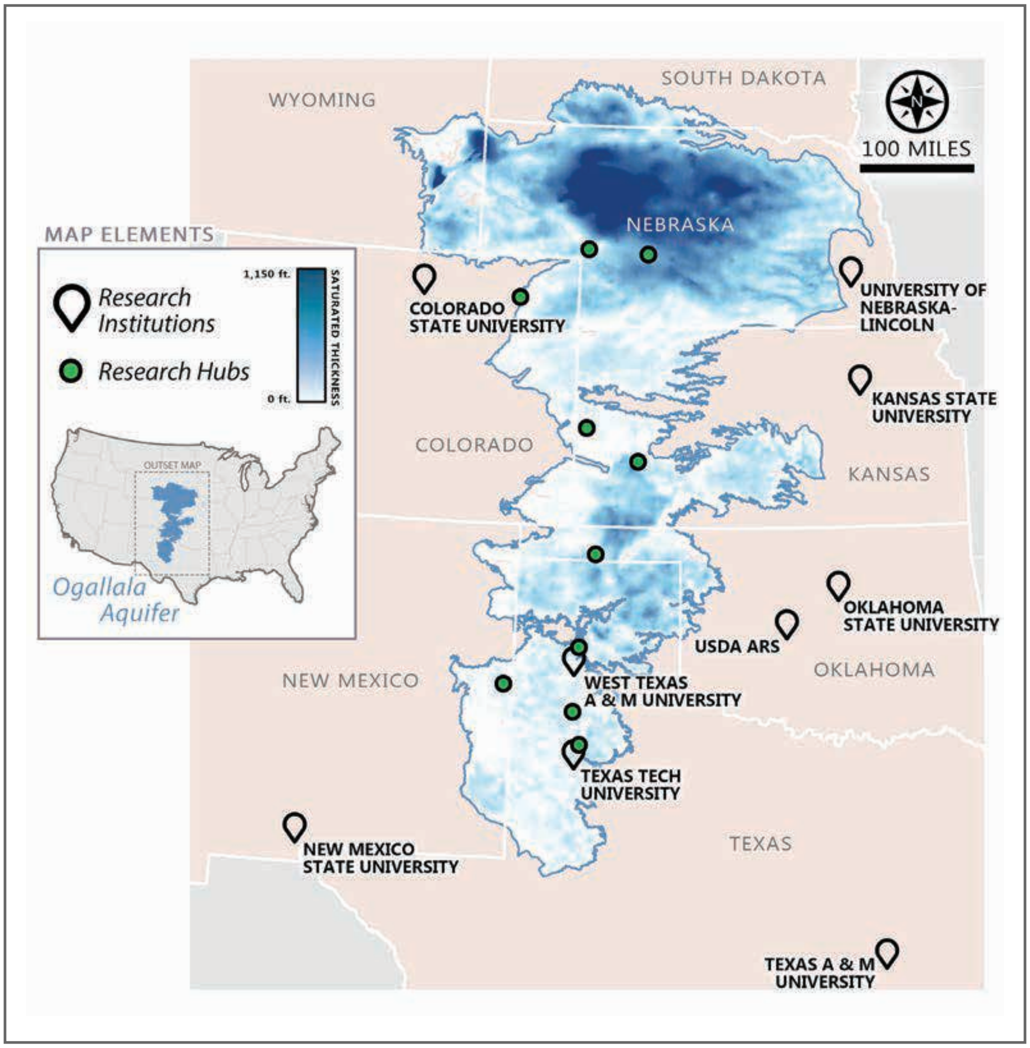
Ensuring the availability of fresh water resources in sufficient quantity and quality to support human populations and surrounding ecosystems represents one of the grand challenges of our time. Globally, groundwater resources supply about 42, 36, and 27 % of the annual water used for agriculture, households, and manufacturing operations, respectively (Döll et al., 2012). In the U.S., 60% of irrigated crop production relies on groundwater for supplemental or full supply (Siebert et al., 2010). There are multiple pressures to increase groundwater consumption including increasing food demand, growing urban areas, and changing climates. How we manage groundwater resources has cascading effects on producers, food production systems, the communities reliant on irrigated agriculture, and surrounding ecosystems.

The Ogallala Aquifer, one of the largest freshwater aquifers in the world, is a prime example of the challenges facing groundwater resources and management. The Ogallala Aquifer is the principal geologic formation that of an aquifer system that underlies 450,660 km^2 (174,000 mi^2) in parts of eight states. It is a main source of agricultural and public water supplies that have sustained economic development in the region for more than 80 years.

The Ogallala Aquifer Region (OAR) consists of nearly level

Corn at the UNL-WCREC field research plots.
Photo by Amy Kremen

Map by Lacey Moore



Map 1. Saturated thickness, OWCAP research institutions, and hubs.

land, rolling and hilly topography, riverine wetlands, and playa lakes. The more level and gently sloping areas are best suited to cultivating crops. About 45.6 million acres in the region are cropped; 27% of that area is irrigated (12.2 million acres). 52.7 million acres are in pasture and range.

More than 90% of the water pumped from the Ogallala Aquifer is used for irrigated agriculture (Maupin and Barber, 2005). Irrigated crop production has a tremendous impact on rural economies in the Ogallala Aquifer Region (OAR) (Guerrero et al., 2010), increasing land production values by more than $12 billion annually (Hornbeck and Keskin, 2014). Irrigated corn is the predominant cash crop grown across the OAR, with cotton predominating in the Texas Panhandle. Not all of the OAR land is irrigated because of insufficient water supplies or inappropriate soil conditions and steeper topography. Some winter wheat and grain sorghum (milo) crops are irrigated, but these crops can also produce profitable yields in most years with little or no irrigation and are often grown in rotation with corn.

Irrigation in the OAR supplements water from precipitation. Annual precipitation in the OAR averages 18-21 inches, with around 12-15 inches of that occurring during April-September, the main growing season for corn. The semi-arid nature of the OAR means that precipitation is much less than the amount of water that is potentially evaporated or transpired from soil and crop to the atmosphere, creating a deficit that is only partially replaced by irrigation. This deficit, as estimated using pan evaporation data, ranges from around 50 inches in the South Plains of Texas to 40 inches in northern Nebraska for the period of April through September.

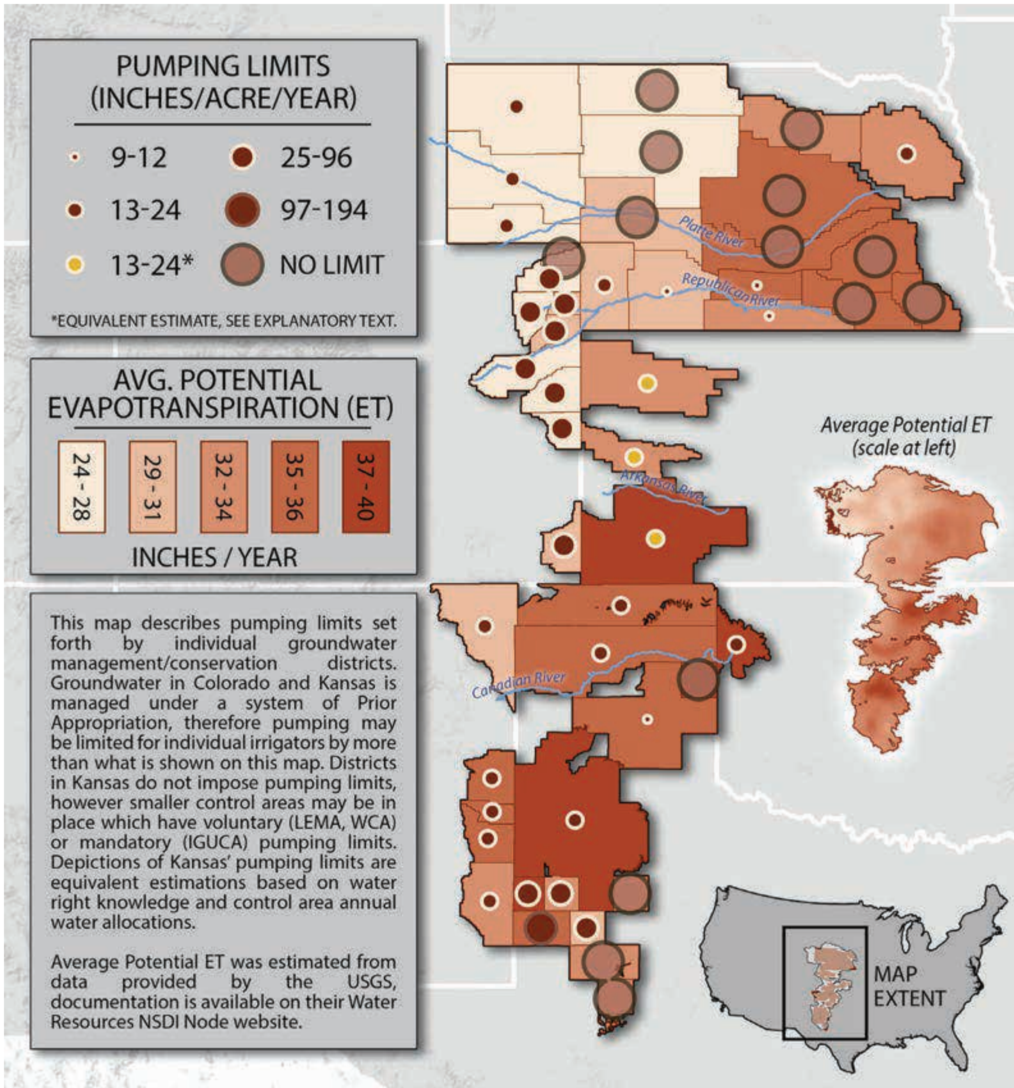
Groundwater management approaches across the OAR vary across and within states, both in terms of agricultural practice and policy. OAR states and communities face many similar challenges, however, and have much to share and learn from each other's ideas and experiences. Our U.S. Department of Agriculture-National Institute of Food and Agriculture (USDA-NIFA) funded Coordinated Agriculture Project leverages existing knowledge and expertise across state lines to identify opportunities that can extend the life of the aquifer and sustain agriculture and rural communities.

Our project is based on the understanding that the rate of groundwater declines and the challenges facing water management are not uniform across the OAR. A one-size-fits-all approach to groundwater management will not work because groundwater saturated thickness, recharge rates, and the policies and tools for managing water vary considerably across the region (Maps 1 and 2). We are focused on fostering cross-state collaborations and regional strategies in partnership with producers and rural communities. We are asking questions, such as: 1) what is the value of water today and in the future? 2) what innovative practices and technologies will reduce water use while improving producers' net profitability? and 3) what are effective, locally-developed policies and strategies to extend the life of groundwater resources and sustain farms and rural communities into the future?

What is the Value of Water Today and in the Future?

The Ogallala Aquifer has long been managed as a non-renewable resource across much of the OAR. Many groundwater management districts have developed planned or managed depletion targets, which accept the slow and steady decline of water levels. With aquifer withdrawals generally exceeding natural recharge, large areas of the Ogallala Aquifer are declining at unsustainable rates.

Groundwater model projections estimate that groundwater levels across 35% of the Southern High Plains region will decline below levels that are economically feasible for irrigation by 2050 (Scanlon et al., 2012). In some regions, these levels have already been reached. In other regions, such as in areas of Nebraska, groundwater levels have not decreased due to high saturated thickness and high recharge rates. In the Nebraska region, it is anticipated that sustainable use rates are possible through careful water management, while declines in water quality, particularly related to nitrogen leaching, are also of significant concern. Compounding these challenges are predicted increases over the next 50 years in the frequency and intensity of dry spells and increased crop demand over much of the OAR.



Map by Lacey Moore

Map 2. Pumping limits vs. average potential evapotranspiration rates.

Regardless of the region and the challenges, groundwater today impacts irrigated producers' bottom lines and, consequently, regional and broader economies. Assessing the present value of water and what its use today means for its value in the future is difficult, however. Does conserving water today result in a net positive economic impact to the region in the future? If so, by how much—and what can or must we forego today to achieve these savings? What shifts in management have the potential to reduce consumptive use and maintain or increase profitability? What is the social value of water to producers and their local communities? Irrigation water provides a buffer during drought periods. Does the value of water increase if drought frequency and duration increase in the future? These are the types of important questions to consider as we look to collaborate with communities to identify management and policy options moving forward.

What Innovative Practices and Technologies will Reduce Water Use While Improving Producers' Net Return on Investment?

At the individual farm level, water use efficiency has continuously improved over the past several decades through advances in irrigation management and technologies. Today, there are several strategies available for further improvements in water use efficiency and groundwater conservation. These strategies include: 1) adoption of more efficient irrigation technologies; 2) use of more precise irrigation scheduling methods and tools; 3) shifting toward more water efficient crop varieties and crops; 4) improving water conservation through soil and residue management; and 5) shifting more marginally productive irrigated lands to dryland management. Our field-based research team is conducting research around each of these strategies.

Our research is centered around six hub sites (Map 1) to ensure that we are representing the variability across the OAR in terms of crops produced, groundwater availability and demand, climates, and soil types. We are also synthesizing existing data across state lines to improve our understanding of how variability in climates and soils impact the potential of different management approaches to improve water use efficiency. This regional effort requires working across the spectrum from irrigated crops to dryland management systems, where soil-water conservation and precipitation use efficiency become increasingly important.

However, adoption of irrigation technologies and scheduling tools has been limited in some cases. Low adoption rates may be due to economic, social, and information barriers. The proliferation of products and technologies available to producers can also be overwhelming. Land grant institutions have an important role to play as honest brokers of information working in partnership with crop consultants, private industry, producers, and other partners. To this end, we are collaborating with producers and partnering with individual groups supported at the local, state, and federal level to develop or promote events that link research and private industry to highlight the most promising recent innovations.

By linking research with on-farm testing and outreach, we are creating learning opportunities across state lines to foster the development and adoption of improved water management practices. At University of Nebraska-Lincoln, researchers partnered with the Nebraska Water Balance Alliance to host a competition in which the management decisions (corn variety, water, and nutrient applications) of fifteen farmer teams were implemented on a research station field using variable rate irrigation (http://taps.unl.edu/). The goal was to identify which management choices led to the greatest water and nitrogen use efficiency and return on investment for irrigated corn production, and to understand more about the factors that guided or influenced producer decisions. As another example, collaborators at Kansas State University have been working with producers to host Water Technology Farms that compare different technologies and products on the market for improved water management (https://kwo.ks.gov/projects/water-technology-farms). In Clovis, New Mexico, we partnered with the USDA's Southwest Climate Hub and Southern Plains Climate Hub, the National Drought Mitigation Center, the National Weather Service, and collaborators from Texas Tech and New Mexico State University to facilitate a workshop to offer a wide-ranging practical look at climate trends, drought monitoring, and water availability in the Southern High Plains. Together, the assembled group discussed available on-line tools, production methods, and research results available to assist producers dealing with—or preparing for—drought.

What Policies and Strategies Balance Goals of Extending the Life of the Aquifer While Maintaining Farm Profitability and Rural Economies?

As groundwater management groups continue to review and revise existing use targets, pumping allocations, and well permits, data-driven decision support tools are needed to estimate the potential impacts of different management scenarios. Most states have groundwater models that estimate current and historical groundwater levels. There is limited work, however, that connects groundwater models with agricultural management practices as influenced by economic and policy drivers. Our project is working to help develop decision support tools that allow for a more dynamic evaluation of different policy options on agricultural production, water use, and economics. The models developed are being tested and validated using case study areas across the OAR. Once complete, they will be able to be used to evaluate different scenarios by local management groups. We are soliciting input from our advisory board and other producer groups across the region to define the different management and policy scenarios to evaluate. We will also be working in partnership with groundwater management groups to compare the potential regional economic impacts of a range of potential practices and policies to guide decision making and long-range planning.

Looking Forward

The challenges facing the Ogallala Aquifer region today are relatively well defined. We know how much groundwater is in the aquifer and how much it has declined since irrigation started with sufficient accuracy to identify key depletion hotspots and project decline rates moving forward. What has not been solved yet is how we will respond as a region to these challenges in a way that maximizes water use efficiency and even perhaps stabilizes groundwater levels. For some communities, there are options for improving water conservation practices to achieve sustainable pumping rates. For most communities, the conversations are more difficult as they will involve transition strategies into a future with new management approaches and associated economic, social, and cultural changes. Addressing these challenges requires a coordinated approach. Research and Extension have an important role to play in working with a wide variety of stakeholders to identify in-field management, local policy, regional investments, and needs shift in national policy with the greatest potential to preserve and extend the usable life of this vital resource.

Photo by Amy Kremen

The Ogallala Water Coordinated Agriculture Project (OWCAP) project team.

Photo by Amy Kremen

An OWCAP team meeting held on December 2016 hosted collaborators from six Ogallala region states.

TIME LINE

Development of the High Plains Aquifer System

Reagan Waskom, Colorado State University;
Amy Kremen, Colorado State University

The High Plains Aquifer System slowly formed as hundreds of feet of silt, clay, and gravel eroded from the Rocky Mountains and other sources were laid down by braided streams during the Miocene and Pliocene (23 to 2.6 million years ago) and Pleistocene (1.8 million years ago to 11,700 years ago) epochs. The largest unit in the hydrologically connected High Plains Aquifer System is called the Ogallala Aquifer. The water in the High Plains Aquifer System is relatively old, accumulating over thousands of years primarily through recharge from precipitation.

The High Plains Aquifer System covers a land area of approximately 174,000 square miles, across eight states. This region, mostly characterized as semi-arid grassland and steppe, was known as the "Great American Desert" on maps from1820 to1850. Early American explorers, including Major Steven Long and General Zebulon Pike, considered the High Plains region to be both unfit for farming and a natural barrier protecting civilization to the east from the nomadic horse people from the plains.

Technological advances in the early to mid-20th century led to an explosion of irrigated acres, from 2.1 million irrigated acres in 1949 to more than 15 million acres only half a century later. Today, it is hard to overstate the importance of water pumped from the High Plains Aquifer as a principal driver of the region's largely agricultural-based economy and way of life. Current annual withdrawals from the aquifer are estimated to be on the order of 19 million acre-feet. Water pumped from the High Plains Aquifer supports nearly 30% of the U.S. irrigated crop production and a significant proportion of the U.S. cattle, dairy, and hog industries.

At the beginning of the 20th Century, the High Plains Aquifer System contained roughly 3.3 billion acre-feet of water. Precipitation, the main source of the aquifer system's recharge, is limited, averaging 18-20 inches per year over the aquifer, while potential evapotranspiration exceeds 40 inches. Water withdrawals have greatly exceeded natural recharge for decades, leading to significant declines in water levels, particularly in parts of the Central and Southern High Plains. Portions of the aquifer also are affected by water quality issues related to agriculture, including nitrogen loading. Approximately 9% of the total original aquifer volume is estimated to have been withdrawn since its development. Based on current depletion rates, it is estimated that more than a third of the Southern High Plains will be unable to support irrigation within the next 30 years.

Each state developed groundwater administration on a slightly different timeline and with slightly different objectives. Scientific understanding of the connectivity of surface and groundwater systems lagged in relation to development of the resource. In general, the aquifer has been managed in most areas with an understanding that it is a limited resource. Water conservation efforts vary locally and on a state-by-state basis. As water levels decline, withdrawals from the aquifer will also decline as physical availability and economics dictate. The following timeline of the aquifer development helps us understand how we arrived at the current system of management and administration.

(Opposite) Photo by Tim McCabe, Courtesy of USDA Natural Resources Conservation Service


Wikipedia

1860 *First self-governing windmills installed in the region for livestock and drinking water*

1860s - 70s *Westward railroad extensions across the High Plains encouraged settlement and agriculture*

1862 *The Homestead Act began the homesteading period across the High Plains*

1866 *Post-Civil War cattle drives from Texas to railroad terminals in Kansas*

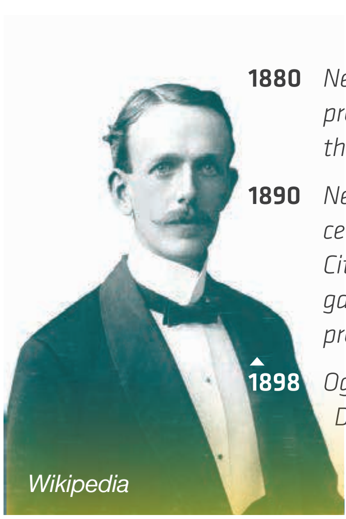
1868 *Kansas legislature established common law statutes for water*

1874 *Introduction of barbed wire, allowing farmers to fence livestock out of crop fields*

1860's - 70's

1880's - 90's

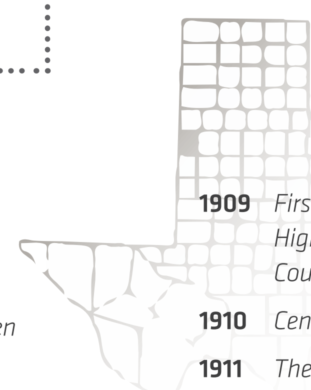
1900's - 10's


Wikipedia

1880 *Nebraska scientist Samuel Aughley promoted the theory that "rains follow the plow"*

1890 *New version of steam-powered centrifugal pump adopted around Garden City, Kansas. Improved versions using gasoline engines were in mass production by late 1930's*

1898 *Ogallala Aquifer named by geologist N.H. Darton after the formation outcrop near the town of Ogallala, Nebraska*



1909 *First high-capacity irrigation well on the High Plains was drilled in Bailey County, Texas*

1910 *Centrifugal pump technology expands*

1911 *The modern era of groundwater irrigation on the Ogallala begins with the first motor-driven irrigation well drilled near Plainview, Texas*

1917 *WWI demand for wheat encourages sod busting for cultivation*

1920's *Favorable precipitation patterns during this decade encouraged further cultivation and limited well development*

1927 *New Mexico, the last of Ogallala states admitted to Union in 1912, was first to enact groundwater legislation in 1927. Kansas followed in 1945*

1930s *Standard and reverse rotary drilling methods replaced cable-tool methods*

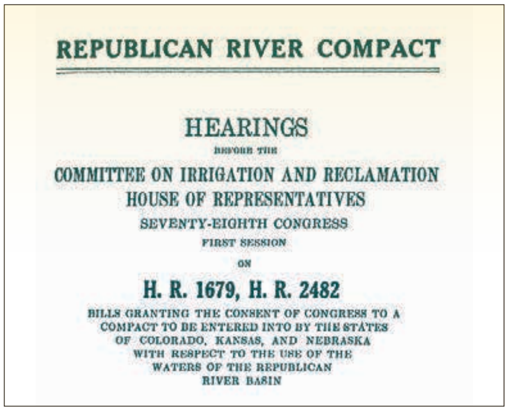
1930 *Onset of a decade of drought led to a period of rapid well development in the Texas Panhandle*

1932 *The Soil Conservation Service (SCS) was established in 1932 to address Dust Bowl concerns; SCS moved from the Department of the Interior to U.S. Department of Agriculture in 1935*

1933 *Fred Hoeme, an Oklahoma farmer, develops the chisel plow, helping curb wind erosion*

1936 *Congress established Rural Electrification Administration (REA) leading to electrification across the High Plains during the 1940's*

Wikipedia



REPUBLICAN RIVER COMPACT

HEARINGS
BEFORE THE
COMMITTEE ON IRRIGATION AND RECLAMATION
HOUSE OF REPRESENTATIVES
SEVENTY-EIGHTH CONGRESS
FIRST SESSION
ON
H. R. 1679, H. R. 2482
BILLS GRANTING THE CONSENT OF CONGRESS TO A COMPACT TO BE ENTERED INTO BY THE STATES OF COLORADO, KANSAS, AND NEBRASKA WITH RESPECT TO THE USE OF THE WATERS OF THE REPUBLICAN RIVER BASIN

1943 *Republican River Compact negotiated between Nebraska, Kansas, and Colorado to share the river's waters, fed in part by groundwater*

1945 *Kansas legislature passed the "Kansas Water Appropriation Act"*

1949 *First statutory law to regulate groundwater in Oklahoma was adopted imposing appropriation doctrine*

1951 *The High Plains Underground Water Conservation District No.1 (Texas's first groundwater conservation district) is established*

1952 *Frank Zybach, a Nebraskan farming east of Denver, Colorado invented the center pivot*

1954 - 57 *Severe drought began another period of intense well drilling that lasted into the 1960's across the region*

1957 *Colorado passes the 1957 Ground Water Law, requiring permits for new wells and establishing the Colorado Groundwater Commission, invested with the authority to identify critical groundwater areas that "have approached, reached or exceeded the normal annual rate of replenishment"*

1957 *Kansas legislature made significant amendments to the Kansas Water Appropriations Act*

1962 *New Mexico Interstate Stream Commission completed construction of Ute Dam and Reservoir*

1920's - 40's

1950's - 80's

1980's - 2017

1967 - 77 ***Irrigators in Colorado and Kansas create irrigation management districts on the High Plains to protect the interests of irrigators***

1972 ***Nebraska is divided into Natural Resource Districts, creating a localized level of government tasked with preserving groundwater resources***

1977 ***Peak number of acres irrigated reached in the High Plains region. Irrigation rose gradually until 1977 and has then mostly held steady, with slight decreases as water levels declined in some areas***

1972 ***Kansas Groundwater Management District Act***

1973 ***Oklahoma's 1949 groundwater law replaced with allocation system***

1980's ***Low energy precision application (LEPA) systems developed by Dr. Bill Lyle with the Texas A&M Research and Extension Center at Lubbock, Texas***

2005 ***U.S. adopts first Renewable Fuel Standard, requiring the use of biofuels and driving the price of corn to record highs***

2009 ***Congress authorized major federal funding for the Ute Pipeline Project, officially known as the Eastern New Mexico Rural Water System (ENMRWS), in the Omnibus Public Land Management Act. This milestone was ~45 years in the making***

2013 ***Kansas farmers set up a 10-square-mile conservation zone called the Sheridan 6 Local Enhanced Management Area (LEMA), where farmers agreed to a 20% reduction in irrigation for five years***

2017 ***U.S. Geological Survey reports that water level declines across the Ogallala slowed from 2013-2015, "likely related to reduced groundwater pumping"***

Groundwater Laws Across the Ogallala Aquifer Region

Bridget Guerrero, West Texas A&M University;
Bill Golden, Kansas State University;
Karina Schoengold, University of Nebraska-Lincoln;
Jordan Suter, Colorado State University;
Art Stoecker, Oklahoma State University;
Chris Goemans, Colorado State University;
Dale Manning, Colorado State University

The laws and regulations that govern groundwater use vary widely across the eight states that comprise the Ogallala Aquifer Region. The basic groundwater allocation rules in specific states include capture, reasonable use, correlative rights, and prior appropriation, but localized management rules, often implemented by groundwater districts, have also emerged (Kaiser and Skillern, 2001). With an eye towards informing producers and policy makers about the variety of institutions that influence water use, this article outlines the rules and local management institutions that exist in five Ogallala states.

Colorado

The Ogallala underlies approximately 14 percent of Colorado, which administers groundwater rights according to prior appropriation. Well permits, which are required of all groundwater users in the region, are issued and adjudicated by the Colorado Ground Water Commission (CGWC), a regulatory body established to manage groundwater resources within Designated Ground Water Basins in the State. The Designated Basins are located in areas with little surface water availability such that groundwater represents the primary irrigation source (CGWC, 2017). Although all eight of the Designated Basins are located in the eastern half of the state, only two (the Northern High Plains and the Southern High Plains) fall in the Ogallala Region.

A total of eight groundwater management districts (GWMDs) have been established in the Northern High Plains Designated Basin, while one GWMD represents the

(Above) Installation of telemetry units on flow meters by the North Platte Natural Resources District.

Photo by David Wolf, NPNRD Staff

Southern High Plains. Each GWMD has the authority to implement rules and regulations related to groundwater use to supplement the rules provided by the CGWC. Although the individual GWMDs have taken responsibility for monitoring and enforcing rules related to new well development and well spacing, they have done little to implement mandatory groundwater conservation policies within their borders (Best, 2014).

The biggest push to manage groundwater use in Colorado has come from obligations related to the Republican River Compact, signed by Colorado, Nebraska, and Kansas in 1942. A 2002 settlement approved by the U.S. Supreme Court required Colorado to deliver more surface water to Nebraska. To meet this obligation, the Republican River Water Conservation District (RRWCD) was formed, with a geographic extent covering the Northern High Plains Designated Basin. CD collects a fee from agricultural producers of $14.50 per irrigated acre and uses the funds to maintain compact compliance (Best, 2014). The main mechanism for ensuring compact compliance has been the operation of a pipeline, completed in 2012, which carries pumped groundwater directly into Nebraska. The RRWCD has also worked to support federal programs such as the Conservation Reserve Enhancement Program, which seeks to voluntarily retire irrigated land from agricultural production.

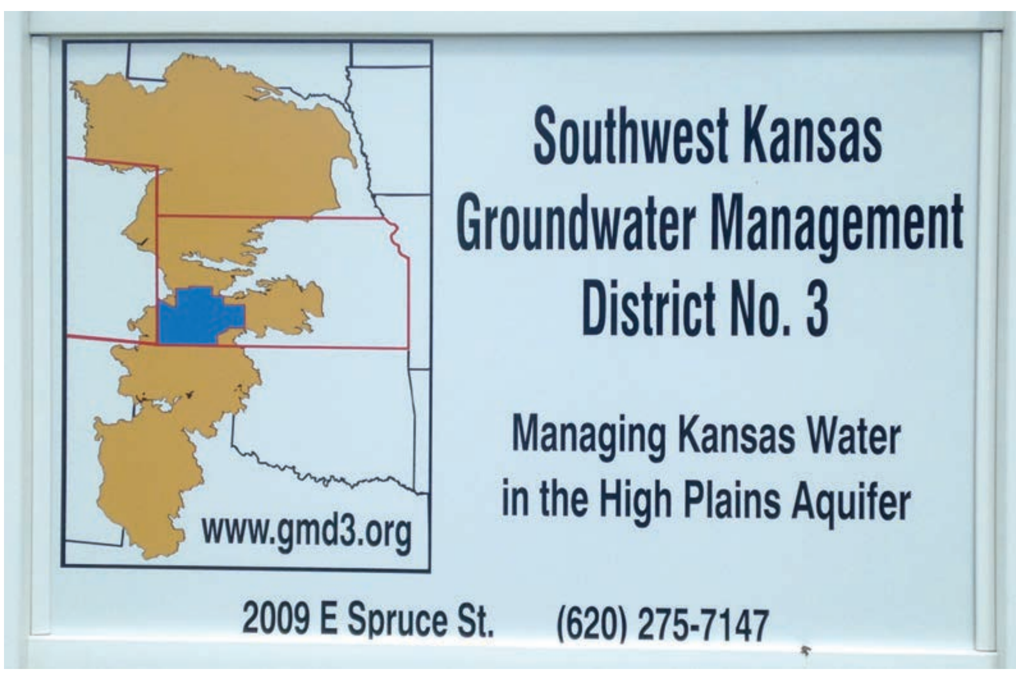
Kansas

Groundwater law in Kansas is based on the concept of prior appropriation as established by the Kansas Water Appropriation Act of 1945. This act defined the process for an appropriated water right, dedicated all water within the state to the benefit of all the people of Kansas, and charged the Chief Engineer to administer the Act for the benefit and beneficial use of all its inhabitants. The Kansas Groundwater Management District Act, passed in 1972, created five groundwater management districts (GMDs) in western Kansas. These groundwater management districts are locally controlled and have become the most powerful force in Kansas groundwater policy (Griggs, 2014).

In general, over the Ogallala (GMDs 1, 3, and 4), groundwater is appropriated based on an annual allocation of 24 acre-inches per acre. Due to the continued overdraft of the aquifer and the resulting loss in well capacity, relatively few wells are currently capable of pumping their full allocation. All wells currently have flowmeters and there is a moratorium on new well development. Although these actions are a positive step towards management, the State and GMDs have yet to reconcile the existing rules of prior appropriation and the resulting over-appropriation with the ongoing depletion of the Ogallala.

Kansas law provides the Chief Engineer with the ability to address the issue of over-appropriation. For example, the Intensive Groundwater Use Control Area (IGUCA) statute enables the Chief Engineer to reduce the authorized quantities of groundwater rights even where such a reduction does not strictly follow prior appropriation (Griggs, 2014). The IGUCA is a non-voluntary, top-down management concept and has proved to be politically unacceptable in areas overlying the Ogallala, even though it has been applied in other areas of the state.

Due to the political infeasibility of the IGUCA and a need to reduce groundwater use, in 2012 Kansas enacted a statute authorizing the voluntary, bottom-up management concept of Local Enhanced Management Areas (LEMAs). This law gives GMDs the authority to initiate consideration of specific conservation plans to meet local goals. Water management strategies developed by LEMAs for a specific geographic area are promoted through a GMD and then reviewed and approved by the Chief Engineer. Once approved, the LEMA plan effectively modifies prior appropriation rules. The first approved LEMA (the Sheridan 6 high priority area) restricted producers to a 5-year allocation of 55 inches per acre, which is approximately 20% less than historic use. In late August 2017,



Stephen Lauer

Kansas' Chief Engineer issued an order formally accepting the proposal to extend this LEMA for the period of 2018-2022, maintaining the same 5-year allocation and allowing users to carry over five inches per acre from unused allocations from the 2012-2017 period. Several other LEMAs are in the planning stages across western Kansas. This includes a proposal for a district-wide LEMA for the entirety of Kansas GMD 4 in Northwest Kansas that was approved in June 2017 to proceed through the formal hearing process.

In 2015, Kansas enacted a second statute authorizing the voluntary, bottom-up management concept of Water Conservation Areas (WCAs). The WCA is a tool that allows any individual water right owner or group of owners the opportunity to develop a management plan to reduce withdrawals. At present, nine WCAs have been established with several others in the planning stage, including a district-wide WCA in southwest Kansas's GMD 3.

Nebraska

Groundwater law in Nebraska uses correlative rights with a reasonable use clause. In practice, this means that all groundwater users are affected when use restrictions are implemented. Although the Nebraska Department of Natural Resources (NDNR) requires registration of every groundwater well, management decisions are made through a system of 23 Natural Resource Districts (NRDs) (Nebraska Association of Resource Districts, 2012). Each NRD is governed by a locally-elected Board of Directors. The NRDs are government entities with the power to tax landowners and pass and enforce regulations. There is a limited amount of state oversight, particularly in NRDs where groundwater is hydrologically connected to surface water. Since the passage of LB 962 in 2004, the NDNR and the local NRDs are jointly responsible for developing Integrated Management Plans that incorporate hydrologically connected surface and groundwater. Examples of groundwater regulations in two NRDs are provided below. A comprehensive map of policy differences among NRDs in 2014 is available at https://www.nrdnet.org/sites/default/files/state_map_water_management_status_14feb2014.pdf.

The Upper Republican NRD (URNRD) was the first NRD in the state to require flowmeters on every irrigation well and to establish groundwater allocations (Upper Republican NRD, 2015). Per-acre groundwater allocations are set for multi-year periods and no new (net) irrigated acres are allowed. Under a common landowner/operator, allocations can be pooled for fields within a limited geographic area. Allocations can also be permanently transferred. The primary need to limit groundwater use in the URNRD is to meet streamflow obligations for the Republican River Compact, and an annual $10 per irrigated acre-feet helps to fund actions associated with compact compliance such as the Rock Creek Water Augmentation Project.

The Central Platte NRD (CPNRD) does not require flowmeters on its wells. However, it does not allow any increase in total irrigated acres. It maintains a groundwater bank, which has purchased groundwater rights from irrigators who switch from irrigated to dryland farming. Irrigators can buy acreage in the "fully appropriated" areas from the bank, but not from areas which are "over appropriated". CPNRD also has had two rounds of a groundwater exchange program, which is a bank for temporary (leasing) water purchases. It also allows irrigation rights to be transferred between parcels (Central Platte NRD, 2016) with spatial restrictions on where irrigated acreage can be added. In addition to allowing some permanent transfers, the CPNRD has had two rounds of an exchange for water leases (temporary transfers). The primary need to limit groundwater use in the CPNRD is to maintain adequate streamflow for endangered species that rely on Platte River habitat.

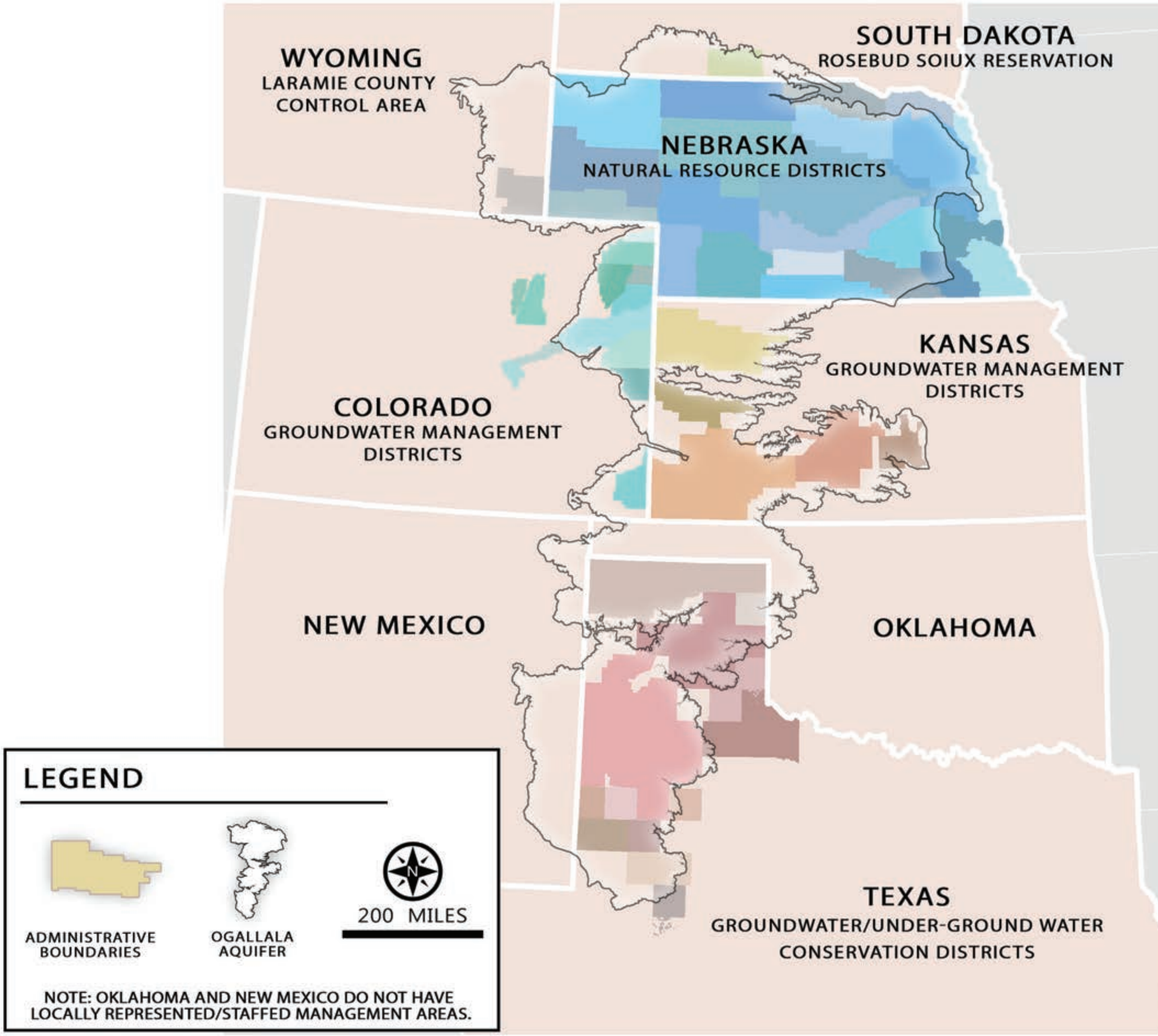
Oklahoma

In Oklahoma, a permit from the Oklahoma Department of Water Resources (OWRB) is required for groundwater use in feedlots, irrigation of more than three acres, and for commercial uses of more than 5 acre-feet per year. A regular permanent permit can be issued following a hydrologic survey and determination of the maximum yield within the groundwater basin. The maximum yield from the Ogallala basin in the Oklahoma Panhandle is 2 acre-feet per dedicated acre per year. The owner must publish a notice of the permit and mail a copy to surrounding landowners, who may protest the application. A public notice for changing places of use, points of diversion, or types of use for groundwater is not required. Thus, this makes it very difficult to track water market activity. If the permit is issued, annual groundwater use is to be reported to the OWRB.

Texas

Texas is the only state to operate under the common-law rule of capture under which the landowner owns the water beneath their land and has the right to pump the water beneath their land. The rule of capture is commonly referred to as the "law of the biggest pump", indicating that landowners face incentives to pump groundwater before their neighbors do. The rule has been modified to prevent waste, subsidence, and harmful or malicious use (Texas Water Code § 36.002).

Although the rule of capture alone may lead to increased use in some instances, legislative actions have been taken to help conserve and protect groundwater resources in Texas. The state government has begun to exercise its right to control groundwater resources through a change to the Texas Constitution, known as the conservation amendment. The amendment provides for the creation of groundwater conservation districts (GCDs) to manage natural resources (Texas Water Code § 36.0015). As a result, Texas has witnessed the formation of groundwater management areas (GMAs) to facilitate



Map by Lacey Moore

OAR Management Districts.

planning between GCDs within a common area that share the resource. In 2005, GMAs were required to adopt desired future conditions (DFCs), which amount to quantifiable goals for the future state of the resource (Mace et al., 2006). The individual conservation districts are then tasked with developing their own plans for meeting the applicable DFC.

The most common DFC in the Texas High Plains is the 50/50 rule, meaning that 50 percent of the current aquifer level remains in 50 years. Implementation of this DFC has not been easy and different conservation districts have taken different approaches. For example, the North Plains Groundwater Conservation District has set a limit for allowable annual use of 1.5 acre-feet of water per acre per year. Adjustments may also be made to the limit in order to reach the targeted DFC. In this particular district, the DFC is set at 40/50 for counties with higher historical water use and at a 50/50 for all other counties (North Plains Groundwater Conservation District, 2015).

Summary

With the continued depletion of the Ogallala Aquifer, new and innovative management policies and institutions continue to be developed, especially in areas with high aquifer overdraft. This article has provided an overview of the diversity of state and local management policies currently in place, with the hope that this knowledge will help producers and policy makers to stay informed and involved in managing and conserving groundwater in their respective states.

"We're Civilized People Out Here"

Managing Groundwater Together in Western Kansas

Stephen Lauer, Kansas State University;
Matt Sanderson, Kansas State University

Our goal as sociologists on the collaborative, USDA-NIFA-funded Ogallala Coordinated Agriculture Project is to identify ways of managing groundwater that are most useful and meaningful to the people living in the High Plains region. Through in-person interviews and a survey, we are trying to better understand the values and motivations that influence producers' groundwater management decisions.

Some of our preliminary results suggest that producers from western Kansas draw on a range of values to make decisions about groundwater, weighted towards economic considerations. Producers are very concerned about the costs of inputs and commodity prices, for example, when they talk about water.

From there, conversations can quickly turn to broader and deeper issues, often leading producers to ask: What would it mean to be unable to pass on a viable operation to the next generation because of wells becoming unproductive? What is really being saved when water is conserved? What should be the role of producers in society? To whom, or what, are we responsible for as producers? What is the real value of water?

Producers experience conflicting values, succinctly summarized by one producer as: "a tension between rugged individualism and some sort of a community social contract." How do producers act on these core values to manage their water resources in a depleting aquifer? One area that shows great promise is the recent development of voluntary efforts of producers in Kansas's Sheridan and Wichita Counties that combine technological and policy tools to conserve water.

Several years ago, producers near Hoxie in Sheridan County, Kansas approached the constraints of a declining aquifer as an opening for community conversations. A series of formal, four-hour-long and sometimes contentious meetings about groundwater management were held, using an "everybody speaks" format. Meanwhile, informal conversations took place among two or three producers at a time as they ran into each other or sought each other out to pitch ideas and reflect on the previous formal meeting.

The give-and-take of formal and informal conversations generated an iterative process of deliberation and negotiation through which producers recognized that there is a shared problem with groundwater. The outcome was a plan to conserve groundwater through the Sheridan 6 Local Enhanced Management Area.

A Local Enhanced Management Area (LEMA) is a Kansas legal tool under which producers voluntarily draw up a contract with rules on water use. Upon approval by the local Groundwater Management District and the Chief Engineer, this contract becomes binding on all producers in the geographic area.

Established in 2013, the locally-developed Sheridan 6 LEMA is broadly supported, as it respects the values of upholding the "community social contract" and "rugged

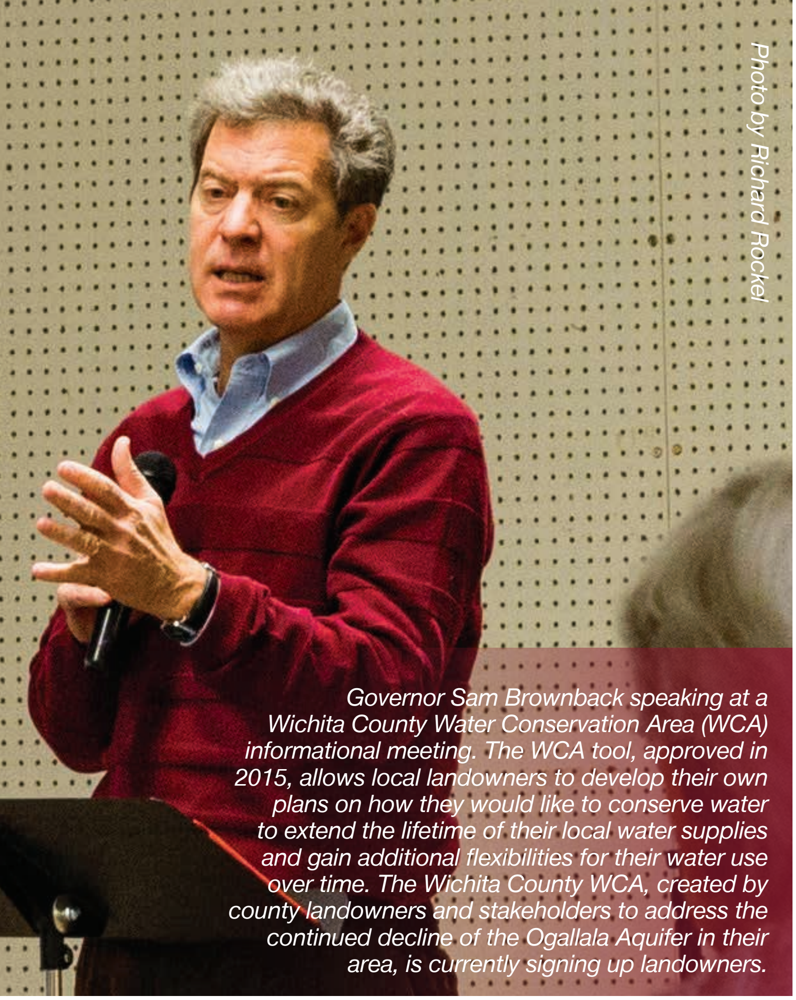


Photo by Richard Rockel

Governor Sam Brownback speaking at a Wichita County Water Conservation Area (WCA) informational meeting. The WCA tool, approved in 2015, allows local landowners to develop their own plans on how they would like to conserve water to extend the lifetime of their local water supplies and gain additional flexibilities for their water use over time. The Wichita County WCA, created by county landowners and stakeholders to address the continued decline of the Ogallala Aquifer in their area, is currently signing up landowners.

individualism." So far, participating producers tend to believe that they have become better groundwater managers. One producer remarked, for example, that "you don't see irrigation pivots running after a rainstorm anymore."

Area producers are also encouraged by recent findings from the Kansas Geological Survey, which show that the Ogallala Aquifer in their LEMA is declining much more slowly, and perhaps even rising slightly, compared to adjacent areas.

Area producers describe a change in mindset towards greater enthusiasm for voluntary groundwater conservation: "I think about [water] all the time. In many ways, we're 15 to 20 years too late. But I think about it like an NFL quarterback. No, you don't forget about the last play, but you always move forward and focus on what you can do now… we're all doing our part to keep our families and traditions afloat, maintain what we have and pass it on."

> "What would it mean to be unable to pass on a viable operation to the next generation because of wells becoming unproductive?"

Meanwhile, similar efforts are emerging in other areas over the aquifer.

In Wichita County, Kansas, the Ogallala Aquifer is 65% depleted and recharges extremely slowly. At current use-rates, the aquifer will not be viable for irrigation in 20 years, but some farms are already unable to pump enough groundwater to irrigate.

We heard stories of families that have abandoned the homesteads that their great-great-grandparents built because the domestic wells ran dry and it was too expensive to pipe in drinking water. While most homes still have access to drinking water, folks in the area expect these experiences to become much more common over the next 50 years.

Faced with this reality, producers in Wichita County are taking voluntary group actions to create a different future. Their effort began with a team of eleven producers and local leaders meeting in the basement of an area cattle feeder. They hired a pastor to facilitate a year of conversations – many of which were described as "difficult" – about sustaining water to preserve their economy, their community, and their way of life.

Their effort bore fruit this year in a county-wide Water Conservation Area (WCA), which provides water management flexibilities to water right owners who work to conserve and extend their water supply.

With widespread participation, the Wichita County WCA is expected to extend the irrigation horizon to 50 years. The hope is that technological advances during this time will make dryland agriculture sufficiently productive to sustain Wichita County communities after irrigation is no longer possible.

Matt Long, a co-organizer and participant in the Wichita County WCA, describes significant early progress towards this goal. "We are only a few months in," Long says, "but already our WCA, through voluntary participation, has committed to saving enough water to support 22,000 people for one year."

In Hoxie on Tuesday, July 18th, 2017, Kansas Governor Sam Brownback and state representatives met with local water leaders who have been instrumental in developing the Sheridan 6 LEMA and the Wichita County WCA. Governor Brownback congratulated producers for their successes.

"The data reveals that the voluntary efforts happening as a part of the 50-year Water Vision are being rewarded," said Governor Brownback. "The Ogallala is replenishing itself faster than we previously knew. What was never thought possible is now within our grasp: sustainable use of the Ogallala Aquifer is attainable."

"It's all about leadership," said Scott Foote, owner of Hoxie Feedyard, along with his family, who hosted the event. "It's doing the right thing and working with your neighbors, and now look what we accomplished together."

(Stephen Lauer is a Sociology PhD Student working with Dr. Matthew Sanderson, Associate Professor of Sociology at Kansas State University.)

Stakeholder-Driven Research

Aaron Hrozencik, Colorado State University

Too often, a divide between research and stakeholder communities hinders the applicability and effect of research efforts, with researchers either answering the "wrong" question or insufficiently distributing research results to stakeholder groups. The key to avoiding these pitfalls is for researchers to engage stakeholders throughout the research process. This article highlights a success story of engagement between groundwater stakeholders and academic researchers that led to impactful research aiding the sustainability of groundwater resources in eastern Colorado.

Groundwater is a vital resource for the communities of eastern Colorado which rely on irrigation to support their agricultural economy. But the sustainability of irrigated agriculture is threatened by high rates of groundwater depletion. Recognizing the gravity of this threat, a group of groundwater users in the Republican River Basin (henceforth the Basin) formed the Water Preservation Partnership (WPP), which aims to conserve groundwater and preserve the local agricultural economy.

One of the chief factors that the WPP identified as hindering groundwater conservation efforts was a lack of information on the impact of conservation on agricultural profits and the rural economy. To address this lack of information, the WPP began a collaboration with Colorado State University (CSU), funded in part by the Colorado Water Conservation Board (CWCB). The WPP leveraged the expertise of research-

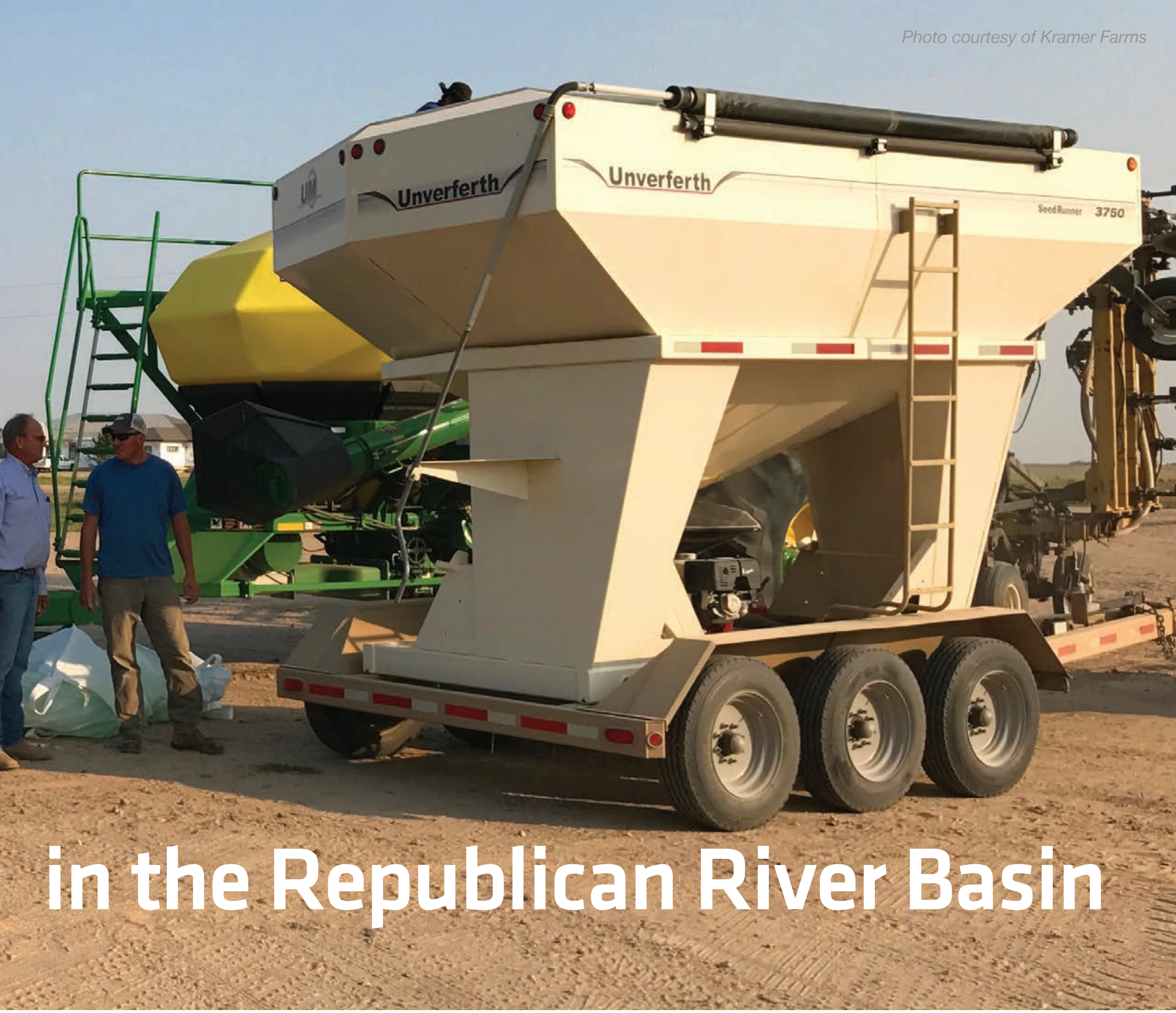


Photo courtesy of Kramer Farms

in the Republican River Basin

ers in the departments of Agricultural and Resource Economics and Civil and Environmental Engineering to evaluate the costs and benefits of groundwater conservation policies in the Basin.

The CSU research team began their analysis of groundwater conservation policies using informal phone interviews with producers. These interviews clarified factors that influence groundwater use and productivity (yields and profits) in the Basin, including aquifer dynamics, weather-related uncertainty, and variations in soil type. This engagement with stakeholders also educated the research team on the extent of variation in aquifer-related agricultural production conditions for the Basin's 3,000+ wells.

> "The sustainability of irrigated agriculture is threatened by high rates of grounwater depletion."

Armed with the understanding that no two producers face the same production conditions, the CSU research team began the process of developing a model that captures aquifer dynamics and variable agricultural production conditions. The crux of this model is an economic decision-making framework that predicts planting and groundwater use decisions for a well under given aquifer and agronomic conditions. Using input from WPP producers, this framework explicitly accounts for the role of weather uncertainty by modeling producer planting decisions made without full knowledge of the weather outcomes for the upcoming growing season.

To capture variation in yields and profits based on irrigation decisions, the research team coupled the decision-making framework with an agronomic model, AquaCrop, to derive relationships between crop yield and water application across the breadth of production conditions observed. Together, the integrated model describes the variation in water productivity and predicts annual pumping and planting decisions that form the core of the Basin's groundwater economy.

An additional, vital aspect of this research effort was to accurately portray how the aquifer responds to pumping across time, as many of the benefits of groundwater conservation are not realized until years after policy implementation. To address these dynamics, spatially explicit (well-level) groundwater use decisions generated by the decision-making framework served as input for MODFLOW, a groundwater flow simulation model calibrated for the Basin. This integration allowed the model to capture how an individual well's current pumping affects future groundwater availability and productivity of water.

With the integrated model developed, the research team engaged with stakeholders in order to identify conservation policies to analyze. Members of the WPP met with their respective groundwater management districts (GWMDs) to discuss their ideas, generating an extensive list of potential conservation policies. With the WPP's help, the research team pared this list down to three policies. The policies analyzed included a quantity restriction, an irrigated acreage fee and a pumping fee. The quantity restriction limited how much a well could pump annually, while the irrigated acreage fee and the pumping fee levied charges based on the number of acres irrigated or volume of water pumped, respectively. These policies were incorporated into the decision-making model, with their implementation simulated across time to reflect a range of conservation objectives.

The research team's findings were gathered in a report that was presented and distributed to the WPP and the broader community of groundwater stakeholders in the Basin. The report details the costs and benefits of groundwater conservation at both the Basin and GWMD level [http://webdoc.agsci.colostate.edu/DARE/PubLinks/PolicyImpactsRpt.pdf]. After the release of the report the research team travelled to the Basin to hold several informational meetings to provide an overview of research results. The dissemination of research results through the report and informational meetings has spurred ongoing discussion amongst GWMDs on potential strategies to manage their shared groundwater resources into the future.

A key overall takeaway from this research effort was that the costs and benefits of water conservation vary widely across GWMDs and policy types. For example, some benefits of groundwater conservation, including increased availability of groundwater in the future and the longer-term preservation of the agricultural economy, may be more immediately meaningful in areas contending with severe groundwater depletion as compared to districts with relatively more abundant groundwater resources. Costs of conservation include the possible reduction in profits producers experience due to diminished groundwater use. Overall, while conservation can be costly in the near-term, it has the potential to extend the productive life of the aquifer by increasing groundwater availability in the future.

The results of the integrated model informed a continuing discussion of groundwater conservation in the Basin. Engagement between researchers and stakeholder groups throughout the modeling effort ensured that the research addressed the most important questions and had credibility among the impacted communities. While this research does not guarantee an end of groundwater depletion, it is a step toward creating a sustainable future for the Basin's shared groundwater resources.

Photo courtesy of Kramer Farms

More on the Water Preservation Partnership

and its Collaboration with CSU

Adam Macaulay, Colorado State University;
Amy Kremen, Colorado State University

A few years ago, concern over decreasing groundwater levels in the Ogallala Aquifer spurred several farmers from eastern Colorado to form the Water Preservation Partnership (WPP). The WPP has ten partner members comprised of representatives from the eight groundwater management districts in eastern Colorado's Northern High Plains Designated Ground Water Basin, the Republican River Water Conservation District, and the Colorado Agriculture Preservation Association. The eight groundwater management districts are: Marks Butte, Frenchman, Sandhills, W-Y, Central Yuma, Arikaree, Plains, and East Cheyenne.

Initially, what "brought people to the table," said Steve Kramer, a producer from Bethune, Colorado who serves as Chair of the WPP, was a desire to discuss how producers might, on a voluntary basis, engage in and encourage more efforts to conserve water. As time went on though, the group started to wonder if opting into mandatory water conservation measures designed by producers might actually lead to greater water savings.

That shift in attitude is related to the fact that "more and more people are realizing the value of the water. We've got to have that water for so many reasons. Not just for ten, twenty or thirty years but way beyond that, because the value of the land is tied to the water," Kramer says. "The water is necessary to keep the people in the towns—in the cities, to run the services—water drives our ag-based economy. We realize we need to work together to make the water go as far as possible."

Compared to exploring voluntary measures, however, the nitty gritty of harnessing local decision making to develop regulations is a complex and lengthy process that requires stakeholders to engages in a lot of difficult discussions (See related articles, pages 12 and 16).

"It just seemed like an overwhelming problem," Kramer said. The WPP already had a good grasp on the region's water balance situation (the rate of change of water stored in a watershed), but wanted more information to support their decision making, so they reached out to MaryLou Smith, a specialist with the Colorado Water Institute (CWI) at Colorado State University (CSU). "They were interested in economic analysis that could help them choose a sound economic strategy as the best way to get buy-in from their fellow farmers to reduce pumping," Smith said.

Smith reached out to a group from CSU's Department of Agricultural Resource Economics (DARE) to ask if they could do some modeling and survey work to compare different "what-if" scenarios and outcomes of alternative policies, including voluntary versus mandatory options, as well as other policies that mandated pumping restrictions or reduced water use (see related article, page 18).

Which Policy Path to Choose? The Challenge of "One Size Does Not Fit All"

All producers are different: some embrace the latest technologies, while others stick to tried and true techniques. Significant variation in groundwater availability and soil types throughout the Ogallala Aquifer Region also significantly affects water use as well as producers' perspectives about the best ways to use and conserve water.

"I was surprised about how real the problem was—how immediate it was. This wasn't, 'we're worried about 50 years from now,' some of the farmers were worried about right now," Chris Goemans said, Associate Professor in the Department of Agricultural Economics Department at CSU

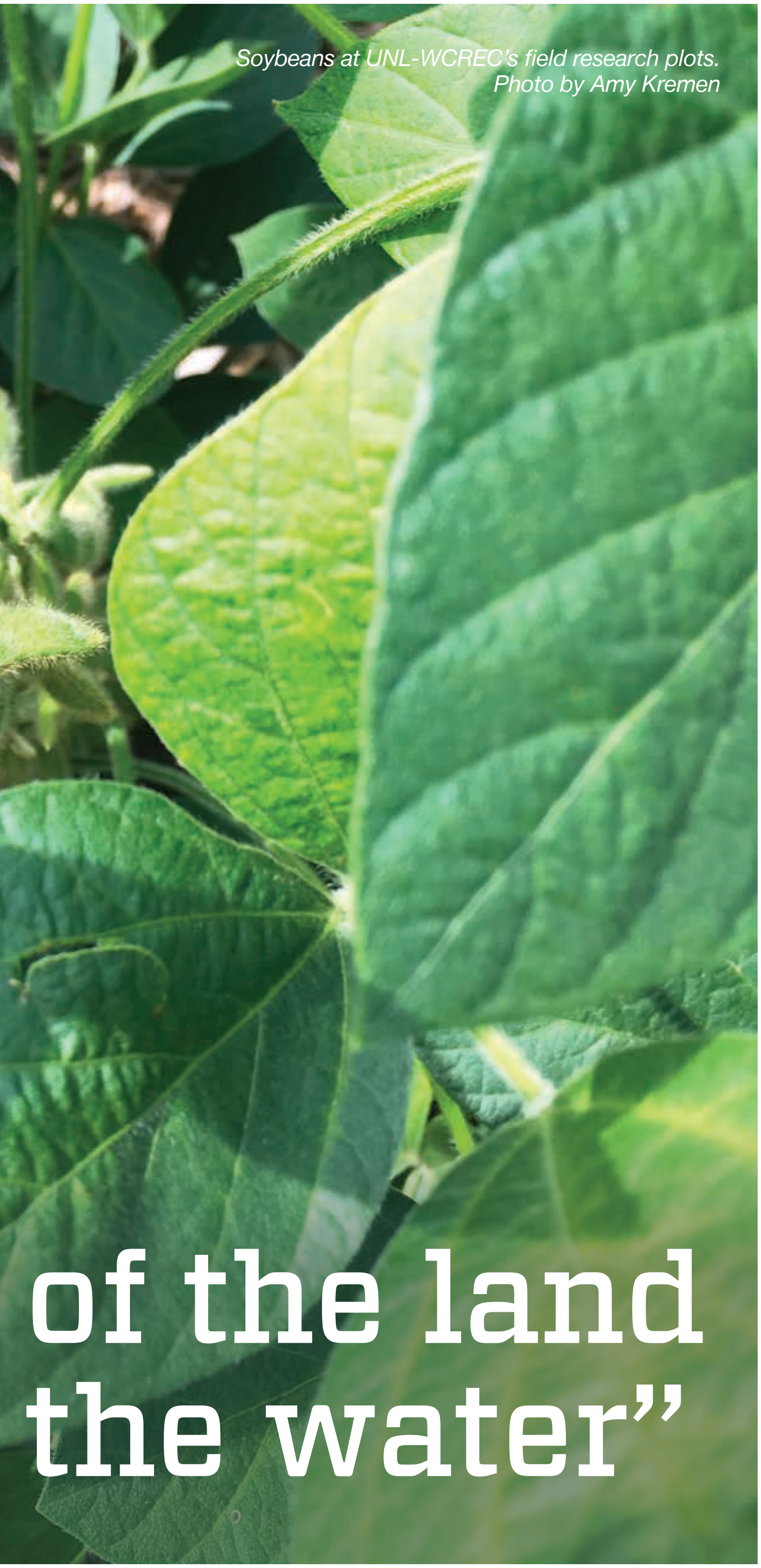
"For some people, this is an urgent issue, and for others, things don't seem so urgent," clarified Dale Manning, Assistant Professor in the Department of Agricultural and Resource Economics at CSU. "There's been a call for flexibility across the districts—there are distinct differences in Colorado's groundwater districts in terms of water availability, so one policy to be applied uniformly is a tough sell," Manning said.

The Importance of Listening—and Asking Questions

The DARE team discovered that probably one of the most useful ways they could productively contribute was to listen to producers as they waded through the daunting task of considering different options that might help reduce aquifer depletion.

"MaryLou took us out to meet the folks before we did any [modeling] work at all," Jordan Suter, Associate Professor in the Department of Agricultural Resource Economics at CSU,

recalls. The group attended several WPP meetings and made follow-up phone calls to many producers across the region, which helped lay the groundwork for narrowing in on different policies with meaningful and practical potential.



Soybeans at UNL-WCREC's field research plots. Photo by Amy Kremen

The DARE team, including graduate students Ryan Shepler and Aaron Hrozencik, also worked with the WPP to develop and administer a survey to capture the perspective and concerns of more farmers in the region. This crucial information was used to weigh the advantages and disadvantages of "what-if" policy scenarios and to refine their economic model. Ryan Bailey, Assistant Professor of Civil and Environmental Engineering at CSU also contributed his expertise on watershed modeling to help DARE prepare to investigate how different policies might affect the amount of water left available to pump over time.

"Working with the University has been extremely helpful," said Deb Daniel, General Manager of the Republican River Water Conservation District (RRWCD). "If nothing else, they ask questions that the rest of us just take for granted."

"We just listened to hear about the ways people made decisions about water, how they might respond to reduced water availability, and how concerned they were," Suter said. "That was really quite useful because there were a lot of things that differed across the people that we spoke to. It was clear early on that assuming every well was the same and essentially facing the same incentive [to increase water conservation] was not going to be appropriate."

Next Steps

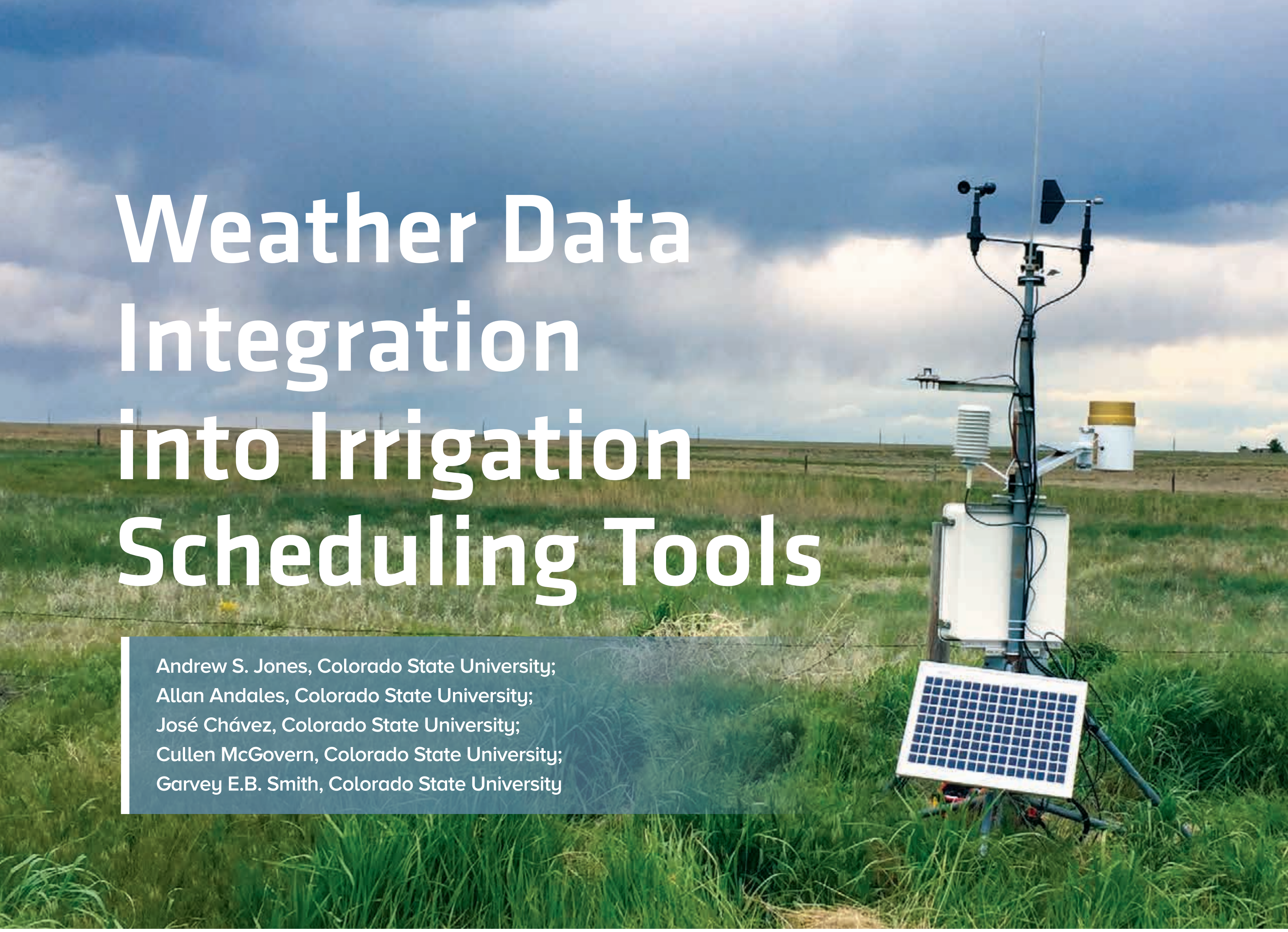
"Our approach was: 'we won't tell the producers what to do. We will provide some information that they asked us to provide and, when we hand over what we've learned, the producers will understand that they have more work to do,'" Goemans notes.

The WPP has indeed been hard at work. Earlier this year, the WPP put together a resolution to consider stipulating a reduction in groundwater pumping of 25% in Groundwater Management Districts by 2025. "The group was divided in terms of having everyone in the same boat policy-wise instead of district by district," notes Smith. "We did think it was important that each district could have its own choice because that would improve buy-in." The WPP's outreach and discussions on the proposed resolution are ongoing and will continue after this year's corn harvest.

Overall, the experience of working together to research the economic impacts of hypothetical policy scenarios is viewed positively by WPP members and CSU researchers alike. "We put together something we could take to the public to show the economic value of sustaining this water," Kramer said, noting ongoing efforts to share the results of the CSU study more broadly. Meanwhile, CSU's DARE team is busy applying insights gained from their work with the WPP to help evaluate and model crop and water-use scenarios in sub-regions and watersheds located across the Ogallala Aquifer Region.

Weather Data Integration into Irrigation Scheduling Tools

Andrew S. Jones, Colorado State University;
Allan Andales, Colorado State University;
José Chávez, Colorado State University;
Cullen McGovern, Colorado State University;
Garvey E.B. Smith, Colorado State University



Introduction

More than 30% of all irrigated U.S. agricultural output in the western Great Plains comes from the lands sustained by the Ogallala Aquifer. Agricultural production practices—both consumptive and conservation-oriented—affect water use, availability, and quality. Tested methods at the field-scale are needed to optimize water use and crop production as the Ogallala water resource undergoes change.

Enhancing decision support tools with predictive weather and other related data (including local weather measurements, hydrologic models, and remotely sensed data sets) increases their dynamic potential to address challenging, multi-system problems. This article presents the Colorado State University (CSU) Water Irrigation Scheduler for Efficient (WISE) Application tool (Andales et al., 2014), and novel use of aWhere's integrated and scalable cloud-based software framework, to link predictive weather information to crop and irrigation scheduling applications and other decision support tools such as WISE.

The WISE Irrigation Tool

WISE (http://wise.colostate.edu/) was created by researchers at Colorado State University (CSU) in cooperation with growers throughout Colorado. The goal of WISE is to make recommendations for convenient and cost-effective irrigation scheduling to maximize crop yield and minimize water stress or excess irrigation. Currently, there are 329 WISE users and 810 active WISE projects. Most projects consist of center pivot sprinkler irrigated fields (typically 130 acres per field). Some WISE projects involve smaller fields that use other irrigation methods. The CSU Extension Water Resources team has been actively promoting WISE at workshops, field days, and producer conferences across Colorado.

The WISE web browser interface marries GIS capabilities with a friendly user interface. After a user draws the boundaries of an irrigated field, the tool automatically collects local soils and daily weather data from publicly available data sources, such as the SSURGO soils database (available through the U.S. Department of Agriculture's Natural Resources Conservation Service) and the Colorado Agricultural Meteorological Network (www.CoAgMet.com). To complete the set-up of a field for irrigation scheduling, the user also has to input the following information: (a) crop information: type, emergence

(Opposite) The Seibert CoAgMET site. Photo courtesy of the Colorado Climate Center

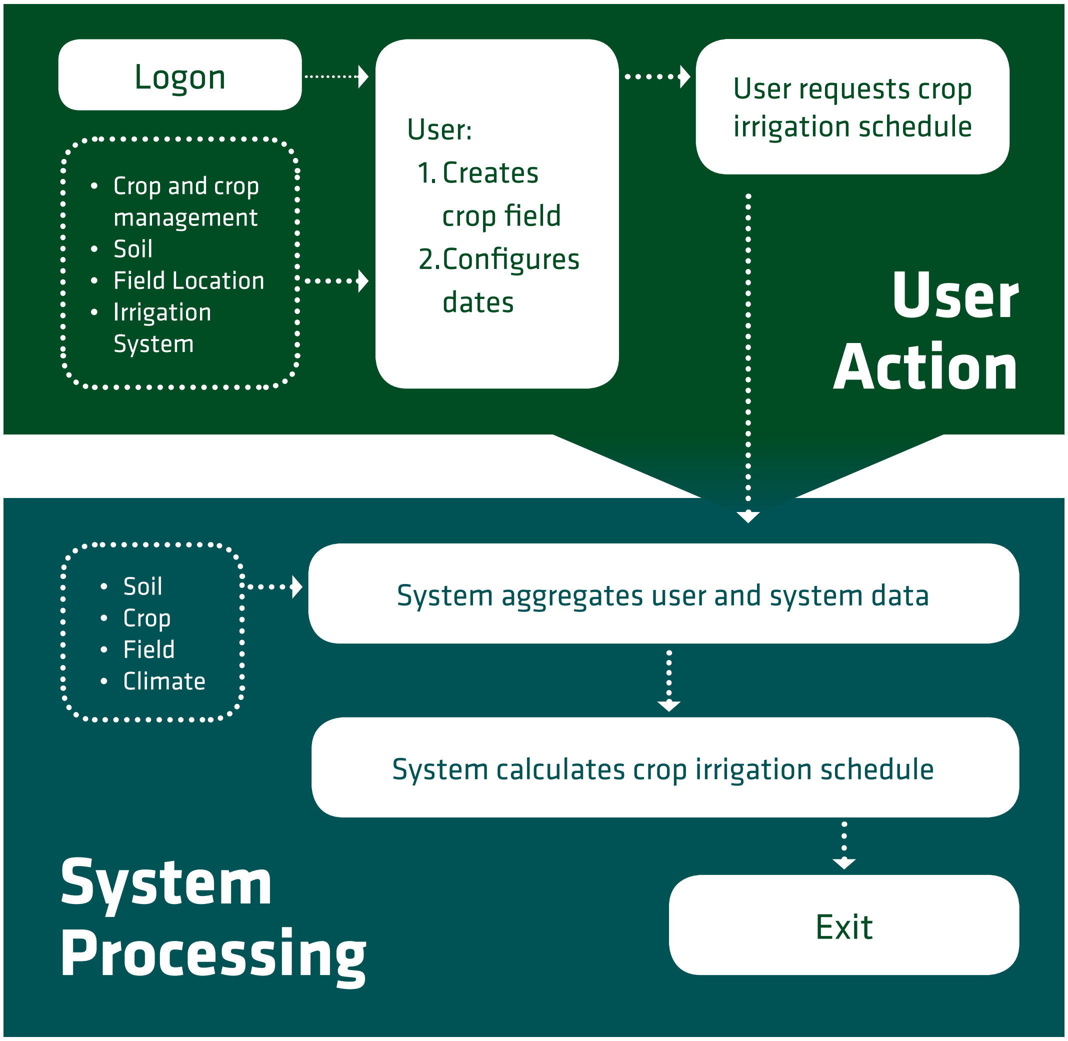
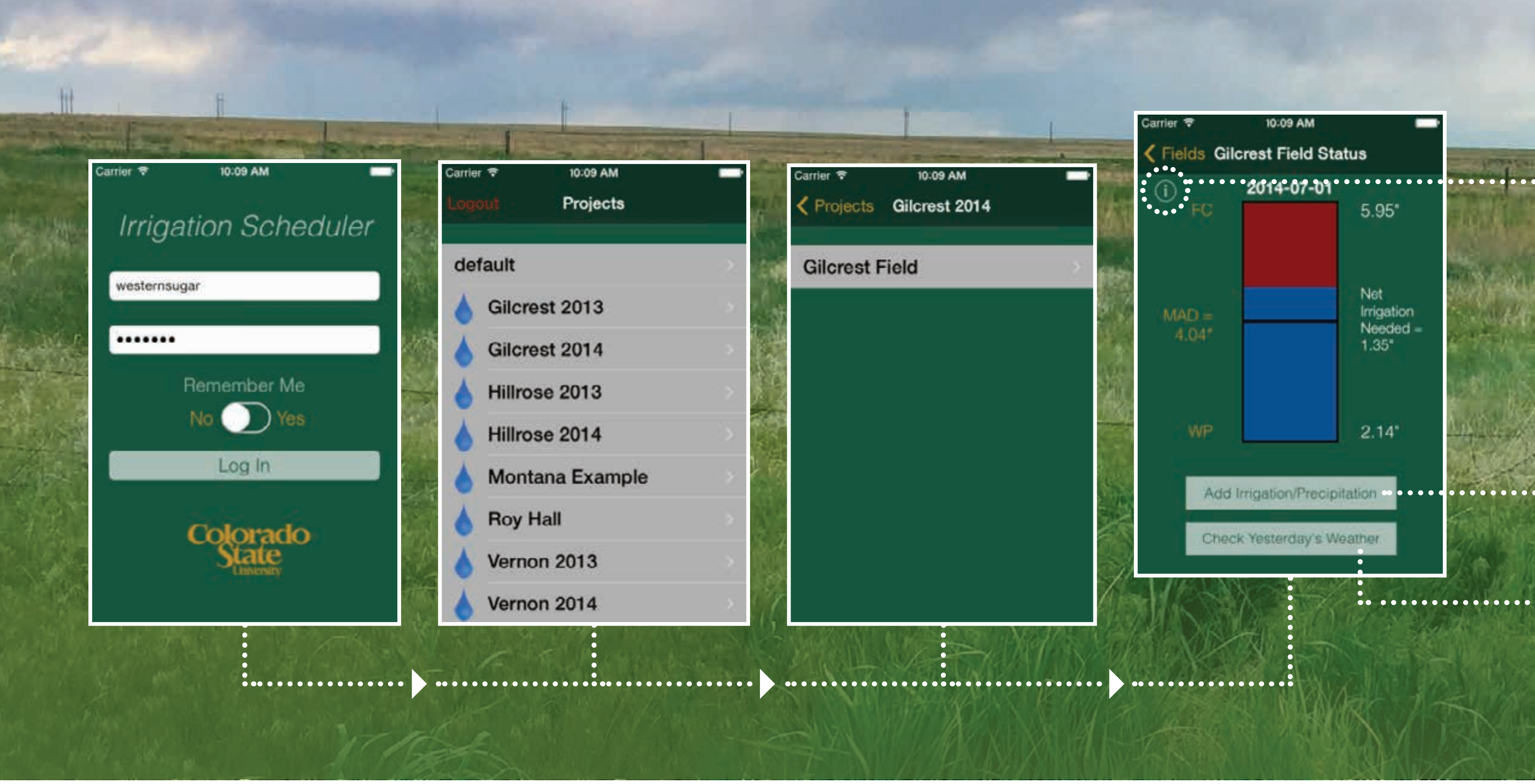


Figure 1. Flow chart showing steps in the operation of the WISE irrigation scheduler.

Figure 2. WISE irrigation scheduler output showing the dependency of plant available water or soil deficit as a function of time.



or green-up date, managed root depth; (b) irrigation system information: type and application efficiency; and (c) soil information: initial soil moisture content at emergence or green-up.

Once a crop type is selected, default values of crop coefficients (used to estimate crop water use from weather data) are provided to incorporate the effects of crop development on water use. Advanced users can modify the default values to better represent the crop variety they have planted. The tool will then estimate the daily soil water deficit (net irrigation requirement) of the root zone using local weather data and user-inputted values of actual applied irrigation (for example, inches of water entered into the pivot control panel). Using the estimate for the daily soil water deficit, the tool will recommend an amount of water depth to apply (inches). Figure 1 shows a flow chart of steps involved in the operation of the WISE irrigation scheduler. Figure 2 shows a graphical example output for a daily soil water deficit estimate.

WISE Smartphone Apps

The WISE Apps for iPhone® or Android® smartphones can synchronize with the cloud server to display soil water status information for each individual field (Bartlett et al., 2015). The sequence of smartphone screens in Figure 3 show the following workflow (left to right, top to bottom): (a) login, (b) select a WISE project, (c) select a field within the project, (d) view the soil water deficit or net irrigation requirement (red bar) relative to the management allowed depletion (MAD), (e) add irrigation or precipitation on a specific date, (f) calculate irrigation (inches of water) if equivalent inches of irrigated water is not known, (g- for new users) consult information related to the summary and definitions, and (h) check yesterday's weather and crop growth progress.

New Data Capabilities

Many agricultural applications require geospatial information from models or remote sensing at high resolution. Examples include applications that examine the state of crop health, soil moisture conditions, and/or crop disease impacts as a function of space and time within each field.

Satellite- and drone-based weather/soil sensors can provide coarse resolution soil moisture (Coleman and Niemann, 2013; Ranney et al., 2015; Hoehn et al., 2017) and rainfall data (Kidder et al., 2016) that can be "downscaled" or enhanced to fine-scale resolutions (1-30 m). This is done by using an equilibrium assumption that redistributes the soil moisture toward the natural lay of the land (i.e., that topography of the landscape deduced using geomorphology techniques). That information is then further enhanced using high-resolution remote sensing data (e.g., vegetation indices) and additional assumptions. Results are verified using observations made in highly instrumented regions at very fine scales to provide usable quantitative error estimates. These fine-scale estimates (and corresponding errors) can then be used by numerous applications, including WISE.

In addition to remote sensing geospatial information, numerical weather prediction (NWP) forecasts can be used to forecast conditions into the future (normally out to 7-10 day forecast periods), thus providing temporal "windows" of decision-making opportunities. Predictive numerical weather forecasts are made using complex computer programs run on supercomputers. They can provide predictions on many

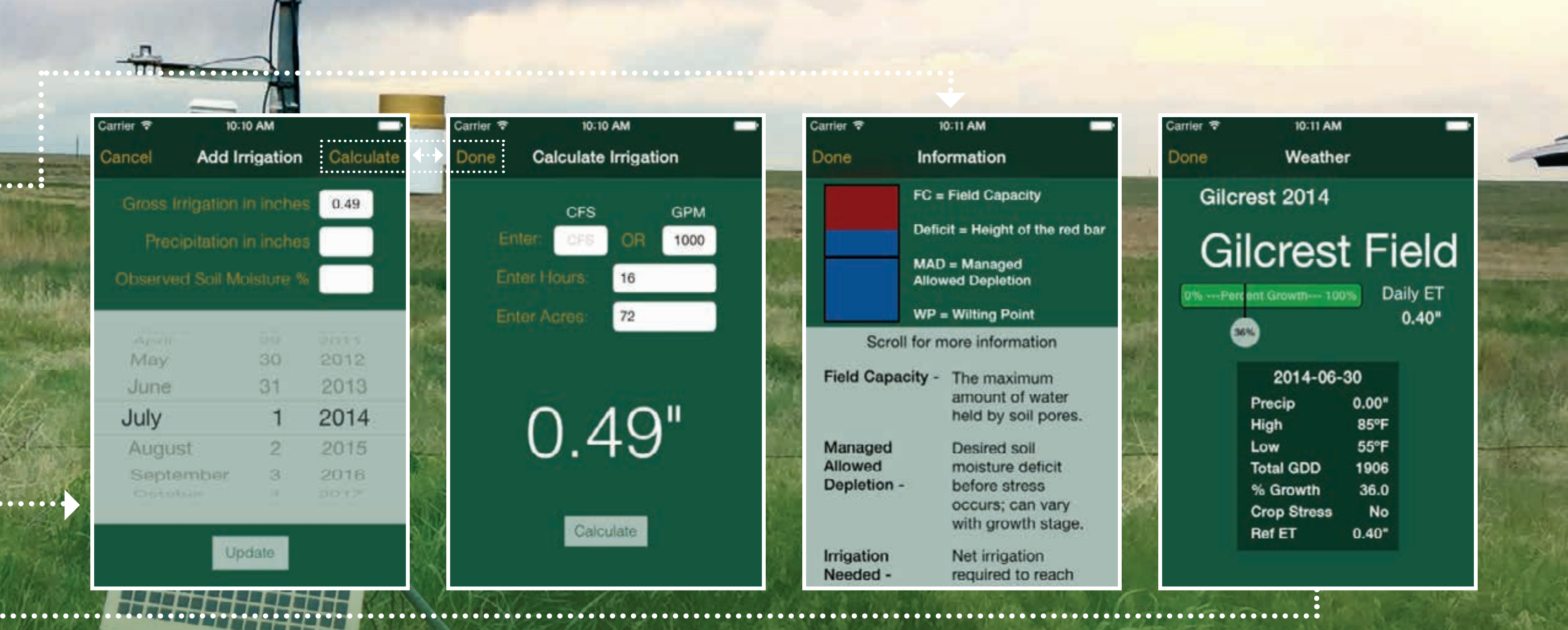


Figure 3. A demonstration sequence of the WISE SmartPhone App interface displays using an example of a crop field near Gilcrest, Colorado. Logins are through eRAMS; likewise, initial set up of WISE projects must be set up in eRAMS using a computer and web browser. Visit http://wise.colostate.edu/ and click on "Get Started" at the bottom of the page to learn how to set up and use the tool.

atmospheric variables including temperature, pressure, wind, and rainfall. The National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), and the National Centers for Environmental Prediction (NCEP, http://www.ncep.noaa.gov/) provide predictive numerical weather forecasts. Use of this type of data is underway at CSU as part of the USDA-NIFA funded Ogallala Water Coordinated Agriculture Project (OWCAP, www.ogallalawater.org). Our OWCAP work includes efforts to account for the dynamic state of the crop within the WISE irrigation tool, which is conditional upon the weather rainfall forecast in near-real time, and identifying the kind of error range that is required for successful recommendations. Our team is using near real-time, cloud-based precipitation forecast data available through a partnership with aWhere, Inc. aWhere also provides and distributes CSU precipitation data and NOAA NWP prognostic information via their globally-scalable information platform (Figure 4). This is an important step for enabling greater fine-scale data usability. Such information is well suited to the WISE smartphone application.

Probabilistic evaluation of forward-looking decision scenarios is possible if these new data sets are applied in predictive sense. For example, if rainfall is forecasted with a particular assigned error probability, those error estimates can be accounted for within a decision-support tool such as WISE to enhance the probability that a decision to irrigate can be successfully delayed without harm to the particular growth-stage of the crop. By comparison, use of high error estimates or more error-prone long-term forecasts for the same scenario may result in a decision tool recommendation to apply water immediately.

We intend to share this predictive capability framework with other irrigation scheduling tools developed for the Ogallala Aquifer Region, including KanSched and DIEM irrigation water management and water-limited crop production tools, within the OWCAP team and potentially more widely. For Kansas State University water tools, visit: https://www.k-state.edu/challenges/water/water-tools.html and for Texas A&M AgriLife Research and Extension's DIEM tool, visit: https://diem.tamu.edu/dashboard/content/static/landing/LandingPage.html.

Integration Software

Another part of the USDA-NIFA funded OWCAP effort includes a new project underway at CSU to integrate near real-time, geospatial remote sensing weather data and numerical prediction products at the 1-7 day forecast interval temporal scale to the irrigation decision-tool framework. The integration of the software and data makes use of the CSU CSIP framework, eRAMS, and a computer programming language called "Python". According to its developers, Python is a language that "lets you work more quickly and integrate your systems more effectively." Because of this, it has become increasingly popular in the academic and scientific worlds, but has often been criticized for its slower computational performance. In recent years, the Pandas package for Python has emerged to provide fast, intuitive tools for data analysis (Pandas URL: http://pandas.pydata.org/). Pandas development is funded by NumFOCUS (see https://www.numfocus.org/open-source-projects/), a non-profit whose mission is to support "high-level programming languages, open code development, and reproducible scientific research."

This *prognostic* decision-making irrigation scheduler project aims to build on the foundation of the award-winning WISE irrigation scheduling tool from CSU using the computational power of a computer programming package by Python called Pandas. The goal is to provide a fast, modular application programming interface (API) for agricultural weather data analysis and crop evapotranspiration modeling. Currently in initial stages of development, this modification of an existing irrigation scheduling tool will make it easy to interface with weather station networks and model databases to calculate parameters of agricultural interest using widely accepted algorithms. By using Pandas, incorporation and testing of incremental improvements should be easier and will facilitate use of products by other compatible integrated software systems.

Future Directions and Next Steps

Due to the availability of new data sets and data management capabilities, and the capacity of cloud-based software frameworks, *numerous* near real-time enhancements to the WISE irrigation scheduler data inputs are possible. In the immediate future, we will robustly test the idea that the prognostic NWP precipitation information adds value to the WISE output results. We will also explore the limits of that information to improve decision-making. Selected irrigated fields in northeast Colorado that are near CoAgMet weather stations will be used to test the integration of NWP precipitation forecasts with WISE this year. Later, we will generalize our approach to use additional novel data sets such as the high-resolution soil moisture data sets and available evapotranspiration data sets (either remote sensing-based or model estimated), and other model-generated prognostic weather variables such as humidity and temperature conditions. We also intend to share and test this tool, and collaborate with OWCAP team members based at Kansas State University and Texas A&M who are working to improve other Ogallala-focused decision support systems.

In summary, this work creates a vibrant and shareable test environment for linking irrigation tools to weather and climate to improve decision making systems leading to optimized crop performance and yield. Looking ahead to the future, additional teams and networks-of-teams, along with industry partners, can build upon these multi-disciplinary and multi-faceted modeling capabilities, as demonstrated by the growing cadre of precision agriculture analytics firms that are driven by cloud-based data sets and services (Miller and Mork, 2013; Plume, 2014; Sonka, 2015; Wolfert et al., 2017; Yang, 2014; Jones, 2016).

Acknowledgements

Funding to develop WISE was primarily provided by USDA-NIFA, with additional support from the Colorado Water Conservation Board, Western Sugar Cooperative, the Colorado Agricultural Experiment Station, and the Coca Cola Corporation. WISE is built upon the Environmental Risk Assessment and Management System (eRAMS, https://erams.com/) which in turn is built upon the Cloud Services Integration Platform (CSIP, https://alm.engr.colostate.edu/cb/project/csip), both of which were developed at CSU. CSIP provides for efficient deployment of integrative modeling technology and data management using a Service-oriented Architecture (SoA) in a scientific research environment (David et al., 2016).

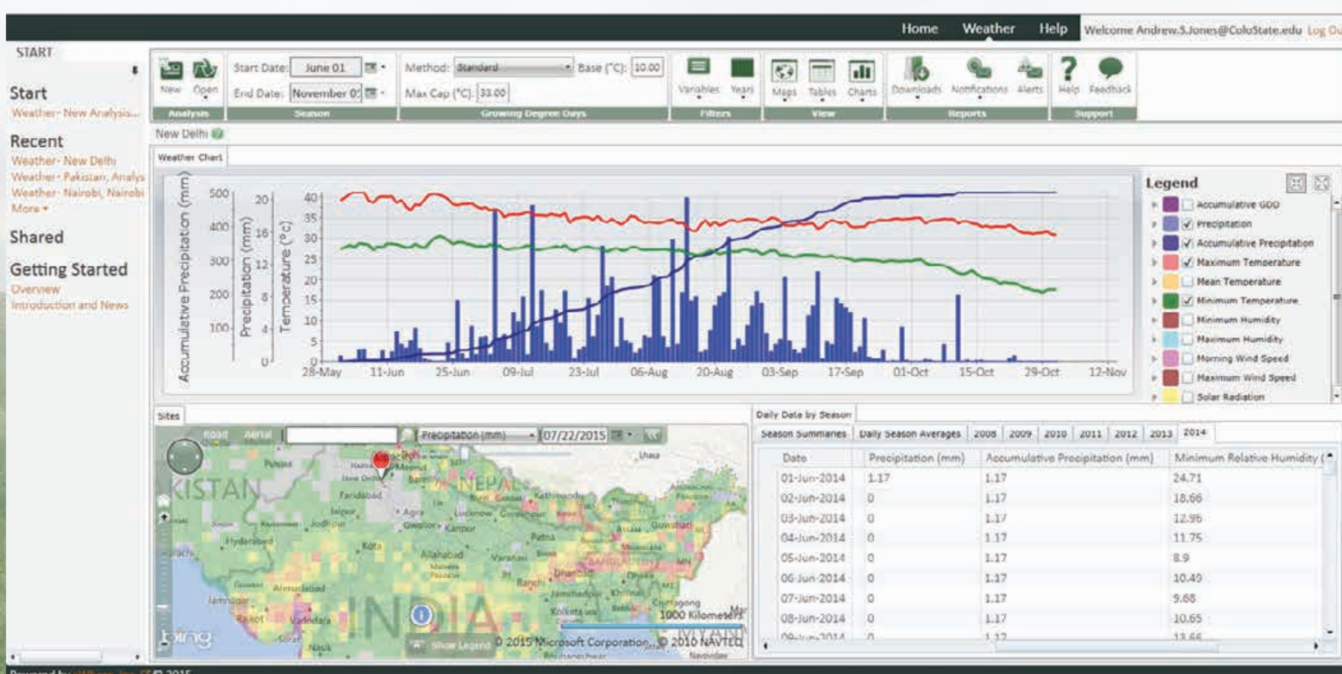


Figure 4. CSU satellite precipitation data, dynamically available in near real-time for global agricultural regions via the aWhere, Inc. platform, which can be readily linked to SmartPhone app databases.

Holyoke, Colorado. Photo by William A. Cotton

Advances in Irrigation Technology

Daran R. Rudnick, University of Nebraska-Lincoln;
José Chávez, Colorado State University;
Jonathan Aguilar, Kansas State University;
Suat Irmak, University of Nebraska-Lincoln;
Jim Bordovsky, Texas A&M AgriLife Research;
Chuck A. Burr, University of Nebraska-Lincoln

Summary

Practicing poor or ineffective irrigation management can have a negative impact on the quality and quantity of water resources, the environment, and financial sustainability. With local and global concerns for future water availability, coupled with the increased competition for freshwater sources across different sectors (agriculture, landscape, domestic, habitat, recreation, and industry), it is imperative that best management practices and new technologies are adopted to improve irrigation efficiency and minimize the degradation of water and soil resources. This article provides a brief overview of advancements in irrigation technologies and information related to their successful adoption and use by producers.

Soil Water Monitoring

One of the most widely recognized methods for scheduling irrigation is monitoring soil water status to maintain the soil water balance within a crop's tolerable deficit range. In general, limitations of soil water monitoring for irrigation management may include determining the number of sensors (or measurements) required and where exactly to install them, representative sensing volume, and response time. Direct measurement of soil water content includes sampling a known volume of soil, oven drying at 221°F, and determining the volume of water loss. This method is time consuming, destructive, and labor intensive. It also may not accurately represent the entire field and is non-continuous in nature, and is therefore impractical for real-time irrigation management.

"Indirect" soil water monitoring sensors that have been developed and marketed for irrigation management provide better alternatives. Indirect soil water monitoring involves measuring a surrogate reference that can be calculated back to estimate soil moisture, via time domain reflectometry, neutron attenuation, capacitance, or electrical resistance, and other methods. Therefore, these sensors can be affected by outside factors, such as temperature, salinity, soil type, etc., which can impact their accuracy. Although most of these sensor technologies have been around for decades, considerable improvements have occurred recently in data processing, displaying of measurements, and user friendliness, related in part to advancements in telemetry capability and user interfaces. Such advancements, coupled with consultation by sensor providers, crop consultants and/or university faculty, have increased the use of these technologies for irrigation management decisions.

Another notable advancement in soil water monitoring is the development of sensors that spatially (and remotely) monitor soil water status, such as the cosmic ray probe (Hydroinnova, Albuquerque, New Mexico) and passive microwave reflectometry (divirod, Boulder, Colorado). Spatial water

Photo by Daran Rudnick

Figure 1. Mobile sensing platform at the University of Nebraska-Lincoln West Central Research and Extension Center (UNL-WCREC) in North Platte, Nebraska. Sensors include: four Apogee infrared radiometers (Apogee Instruments, Inc. Logan, Utah), two Holland Scientific crop circle sensors (Holland Scientific, Lincoln, Nebraska), two spectral reflectance sensors (Decagon Devices, Inc., Pullman, Washington), two GoPro cameras (GoPro, Inc., San Meteo, California), and one Apogee quantum sensor (Apogee Instruments, Inc., Logan Utah).

monitoring can help identify differences in crop water availability across the field, so that irrigations can be triggered based on field-level economic thresholds and/or the use of variable rate irrigation. Furthermore, spatial soil water status can help inform other agronomic practices, such as planting date and depth, hybrid type and population density, and nutrient management. One limitation of these technologies is that their measurement depths are focused near the soil surface. Depending on crop type and other management practices, deeper measurements are required to account for crop water availability, especially for late-season irrigation decisions, when crop roots occupy more of the soil profile. To capture both spatial and profile soil water status, producers can elect to use separate technologies or deploy a sensor network of profile units, such as John Deere Field Connect (Deere & Company, Moline, Illinois), Aqua-Check (AquaCheck Ltd., Durbanville, South Africa), AquaSpy (AquaSpy Co., San Diego, California), IRROmesh (Irrometer Co., Riverside, California), among others.

Plant and Canopy Sensors

If crops do not have adequate available water in the soil profile, they will not be able to extract enough water to meet transpiration demand, and as a result, crop canopy temperature can increase and stem diameter can decrease throughout the day. Therefore, monitoring crop status through direct or indirect measurement of transpiration can indicate whether irrigation is required or not.

Sensors that monitor the effects of reduced transpiration on crop status are becoming more widely used. For example, crop

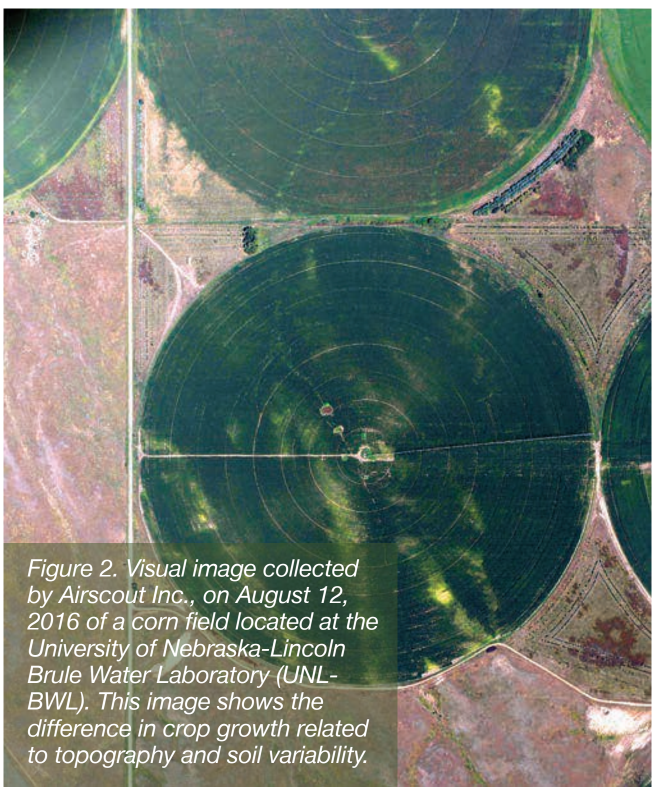


Figure 2. Visual image collected by Airscout Inc., on August 12, 2016 of a corn field located at the University of Nebraska-Lincoln Brule Water Laboratory (UNL-BWL). This image shows the difference in crop growth related to topography and soil variability.

canopy temperature can be measured using stationary and/or mounted infrared radiometers (IRTs). Stationary measurements provide diurnal changes in temperature, which can be compared against baseline temperatures for various crops to detect when and how long the crop was under stress. Similar to most soil water sensors, stationary IRTs do not provide spatial information in crop status that might be attributed to variable fields. However, these sensors can be mounted on mobile platforms (Figure 1) as well as on pivots (O'Shaughnessy et al., 2015). One limitation of IRTs is that they require some calibration to account for sensor body temperature, surface thermal emissivity, and background effects. Data from calibrated IRTs can be paired with reference crop evapotranspiration (ETref) to estimate actual crop transpiration rates. Alfalfa or grass based ETref values can be computed from agricultural weather stations or from modified atmometers (ETgag®).

Crop transpiration can also be measured using Sap flow sensors, such as Dynagage (Dynamax Inc., Houston, Texas); however, due to cost and the complexity of the equipment these sensors have not been widely used in row crop production practices. Another technology to detect crop water stress consists of monitoring micro-variations in stem diameter (Phytech Ltd., Israel). The sensors are clamped to the plant stem and wirelessly communicate to a base logger. The accuracy in detecting micro-variations in stem diameter due to water stress rather than growth in row crops has yet to be assessed.

Imagery

Several platforms exist for collecting multispectral imagery, including satellite, aerial, and unmanned aircraft (i.e., drones). These platforms range in temporal and spatial frequency of measurements, as well as the resolution of the imagery itself. There are several types of imagery that can be collected, including visual (RGB), near-infrared (NIR), mid infrared (MIR) and thermal infrared (TIR), as well as indices based on combinations of the aforementioned platforms. Imagery has been widely used for field scouting to detect spatial differences in crop and soil conditions that might be attributed to non-uniform pest pressure, salinity, water logging, nutrient and/or water requirements, compaction, residue cover, and other factors. An example of an aerial image (Airscout, Inc., Montee, Illinois) showing differences in crop growth due to spatial differences in topography and soil type is shown in Figure 2. Several companies and research groups are working on developing tools that can use imagery to automatically prescribe agronomic recommendations, such as scheduling irrigation and nitrogen fertilizer applications. The use of remote sensing images and related products that can be derived from collecting these images is expected to increase in the near future, due to faster processing and distribution capabilities using cloud servers and smart phones.

Big Data Management and Decision Support

The promise of big data in technology development is the rapid aggregation of information from a variety of sources, including crops, geographical information, real-time weather data, and other systems, to determine patterns helpful for evaluating water and energy use. With the "internet of

Figure 3. An individual sprinkler controlled variable rate irrigation (VRI) system (Zimmatic by Lindsay, Corp, Omaha, Nebraska) installed at the University of Nebraska-Lincoln's West Central Research and Extension Center Brule Water Laboratory (UNL-BWL) near Brule, Nebraska.

Photo by Daran Rudnick

things" creating cascades of data from various sensors on a 24/7 basis, the information generated is overwhelming in volume and variability and must be transformed through decision support systems (DSS) that can help us visualize and understand huge data sets.

For instance, a suite of in-field and remote sensors generating a very large amount of data can be integrated (on a server or cloud) to generate better products than what could be provided by one or few sensors alone. Data are stored, processed, analyzed remotely, and are condensed to provide user-friendly information and guidelines to assist decision-making. Multiple water management scenarios can be run, with viable and sustainable alternatives presented to users in a way that makes it easier to visualize and interpret the potential impacts of making different decisions.

As part of the DSS, for example, distributed irrigation, groundwater and open channel sensor data can be uploaded continuously at a certain frequency (i.e., every 5, 10, or 30 minutes) including: surface/air/soil temperature, soil water status, relative humidity, wind speed, solar radiation, rainfall precipitation, water flow rates, canal water depths, bulk soil water electric conductivity, well water quality, airborne/satellite imagery, etc. When integrated, this data gives users a deep understanding of the irrigated agricultural system, providing detailed information on how, where, and when processes are occurring. With enough data, the DSS can build predictive models to accurately forecast production conditions. Then farmers can use the data to determine the best use of water for their crops in nearly real-time to improve irrigation efficiency, crop water productivity, and to enhance farm resilience to climate change. Products produced by the DSS can also be used in conjunction with in other algorithms (e.g., at the user end through smart phone apps) as input to generate or derive other useful decisions in the field.

Irrigation Systems

Variable rate irrigation (VRI) allows for applying different depths or rates of water radially and/or along the length of the system to accommodate spatial differences in crop water demands, soil conditions, and/or other constraints. VRI requires accurate characterization of crop and soil conditions. There are two types of VRI: sector/speed control and zone control. Zone control VRI systems have the ability to control down to a single sprinkler through advancements in control panel and communication equipment as well as with electronically controlled solenoid valves. An example of a Zimmatic by Lindsay individually-controlled sprinkler VRI system (Lindsay Corp., Omaha, Nebraska) is shown in Figure 3. Potential economic gains can be obtained through the integration of a variable frequency drive (VFD), to vary the pump electric motor rotations per minute (rpm) when operating a different number of nozzles per location using VRI.

In order to achieve uniform application of water depth in the field using VRI, the stop/advance pattern of conventional center pivots and lateral move systems may result in a different amount of water applied by location. Knowing the system movement pattern and having VRI is useful in decreasing water application errors (Chávez et al., 2010). In addition, recent advancements in injection systems, such as Agri-Inject's Reflex System (Agri-Inject Inc., Yuma, Colorado), allow for variable rate fertilizer (VRF) application. Variable rate systems have the potential to decrease water withdrawal, energy use, and applied fertilizer and, if targeted correctly with regard to crop and soil conditions, can increase return on investment.

Another notable advancement in irrigation systems is the re-engineered mobile drip irrigation (MDI) system. MDI was designed to integrate the potential water application efficiency of drip irrigation into center pivot irrigation systems. The MDI system consists of drip lines that have emitters every 6 inches, installed on drops every 2.5 or 5 ft along the length of the pivot, which are dragged behind the system. Potential advantages of MDI include reductions in evaporative losses, wind drift and wheel tracks, etc.; potential limitations include additional hardware management, switching directions of the system, emitter clogging, etc.

Additional Information

A considerable range of information and tools are available that can be effectively used to improve crop water management and farm profitability, some considered to be "new", while others are considered "old" or maybe even "obvious". Some basic yet very important information for irrigation management that producers should not overlook includes: historical records (crop rotations, yield data, compaction issues), soil properties (NRCS soil survey, ECa mapping), topography (digital elevation maps (DEMs), LiDAR), field conditions (residue cover, pest pressure, nutrient availability), visual observations (drainage ways, streams, roads), and data generated from the direct and/or indirect methods described earlier in this article.

The degree in which irrigation technology will improve an operation will depend upon the accuracy or "success" of use to justify the cost, installation, and maintenance of the equipment. Improper selection, installation, maintenance, calibration, and interpretation of data collected from different sensor technologies or platforms can result in users not trusting and even abandoning these tools. Therefore, it is imperative that users have access to excellent guidance in selecting, installing, calibrating, and managing the right technology for their operation and intended use.

The mention of trade names or commercial products is for the information of the reader and does not constitute an endorsement or recommendation for use by the authors.

Ogallala Region Livestock Systems

Brent Auvermann, Texas A&M AgriLife Research and Extension Center at Amarillo;

Chuck West, Texas Tech University

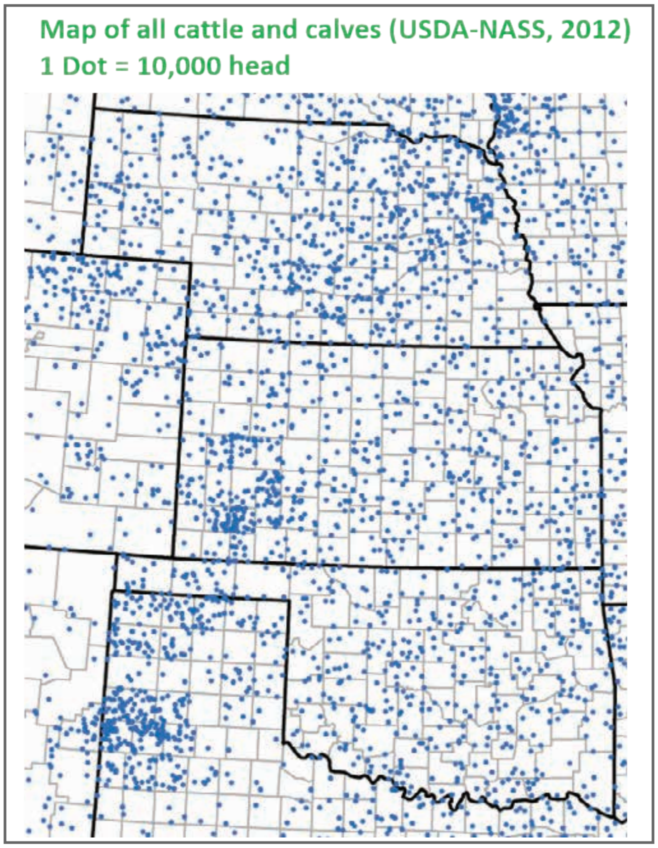
Photos courtesy of Texas A&M AgriLife Research

Water from the Ogallala Aquifer combines with excellent soils and sun-drenched growing seasons to produce large quantities of valuable animal feeds. Meat and milk production in the region adds value to the crops produced and diversify farm income. Industrial plants in the OAR that process raw meat and milk for human consumption provide rural employment and further enhance value of farm output. In the southern Ogallala Aquifer Region (OAR), an area that extends from Kansas southward, covering an area of 97,000 square miles, livestock production and processing contributes to 70-80% of the total annual agricultural economic output ($47 billion).

Livestock production in the southern OAR consists of four primary types: confined dairy production, confined swine production, confined beef fattening, and cow/calf and stocker production on grasslands. Confined feeding operations also exist for poultry, but confined dairy, beef, and swine production account for most of the livestock value. Dairy operations are not widespread across the OAR but are important in eastern New Mexico, Texas Panhandle, and southwest Kansas. Large beef-feeding operations in the region finish over 10 million head of cattle per year and are most concentrated in areas where aquifer water supplies are high enough to support abundant corn production, such as in the Texas Panhandle and southwest Kansas (see map of cattle and calves). The value of the water that supports livestock production exceeds $5,000 per acre-foot (as seen in the table). Feeding operations co-locate with corn production, thanks to the least-cost factors stemming from corn's high caloric value in diets, high yields for the amount of water applied, and low shipping costs.

Despite advances in water conservation (improvements in irrigation equipment, recycling water used to clean livestock facilities, crop genetics, etc.), corn production needs for water to produce maximum yield can be difficult to fulfill due to reductions in pumping capacity in the southern OAR. Correspondingly, interest and acres in sorghum are on the rise, because sorghum's high starch grain, like corn, can provide most of the energy needs in animal diets but requires less water than corn to reach maximum yield. The prospects of grain sorghum replacing corn in the OAR, however, are limited by two facts: (1) sorghum yields only about 70% of the amount of grain per acre as corn at medium to high water supply, and (2) the feed conversion efficiency in livestock when fed sorghum grain is about 10% lower than for corn. In Texas, if seasonal water use (irrigation + effective rainfall + change in soil water content) is less than 17 inches, grain sorghum will more likely out-yield corn; above 17 inches, corn will likely yield more than grain sorghum.

Where well output is low, forage sorghum can be grown to provide a partial replacement for corn with sorghum in



Cattle and calves in the Southern High Plains.

beef and dairy diets. Forage sorghum maximum yields take 25-30% less water to reach compared to maximum corn silage yields, with similar amounts of water used per ton of forage produced. The nutritional quality of forage sorghum is limited relative to corn because it contains less energy-dense grain. Breeders have incorporated a trait called brown midrib (BMR) into forage sorghum to unlock more digestible energy from the sorghum fiber and promote cattle productivity. Properly matching the variety of forage sorghum with a farm's water supply and animal nutritional needs is a practical strategy for profitable cattle production.

Diversified Economies, Crops, and Grasslands Support Livestock

In the last decade, there has been a large growth in the number of ethanol plants in the OAR, whose main feedstock is corn (and to a lesser extent, sorghum) grain. During ethanol production, the residual solids fraction that remains after starch extraction (distiller's grains and solubles) is a readily available, high-protein, and high-fat feed ingredient that is used for up to 35% of the dry matter in some cattle-feeding operations to balance diets. Livestock production also uses processing co-products derived from cotton, soybean, wheat, and peanuts.

Forage crops for cattle in addition to corn and sorghum commonly include wheat and triticale. Wheat and triticale are commonly grazed during winter by beef calves after weaning but before moving to the fattening phase in feedlots, and by female dairy heifers before entering the milking herd. Forage crops are also produced for hay, meaning that the crop is cut, lays in the field for 2-3 days, and is harvested dry into bales. Hay is used for feeding cattle that are not on a fattening ration, such as beef cows during winter when grazing is inadequate. Hay is also commonly sold to cattle and horse enterprises that are short on feed.

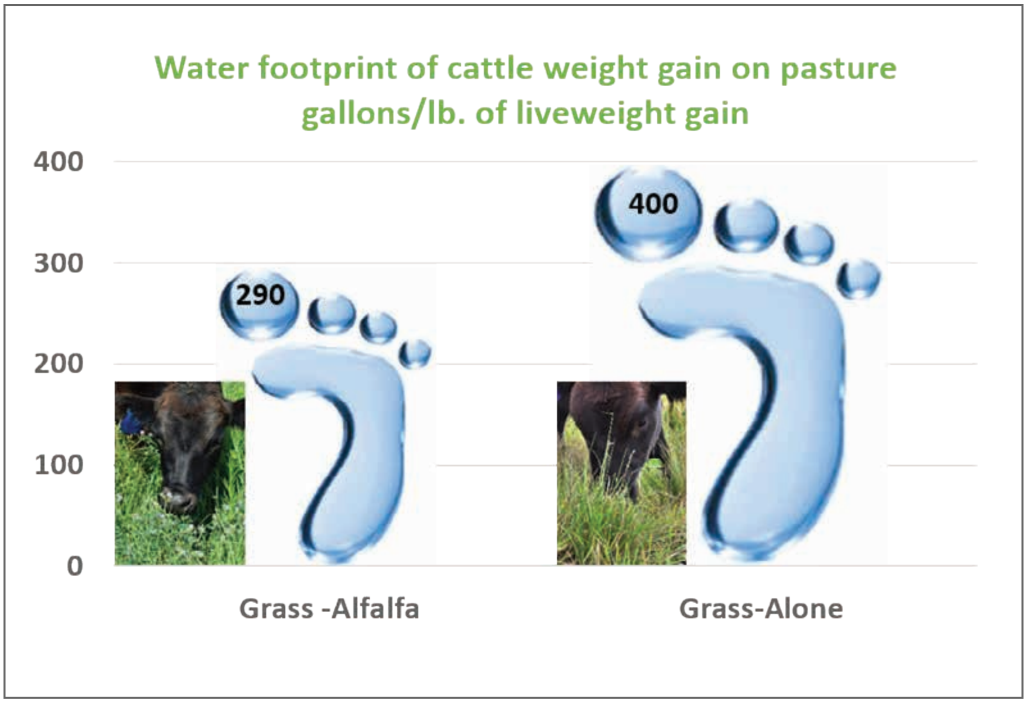
Grasslands contribute to the agricultural economy and environmental functioning of the OAR. Soils that are too erosive, steep, shallow, or have poor water-holding capacity are maintained with permanent grassland vegetation. Besides grasses, such land, usually referred to as rangeland, often includes herbaceous plants with flowers (forbs), some woody shrubs, and sparse trees. Such areas are not irrigated, and with the semi-arid conditions typifying the OAR, their vegetation is of low productivity. Other grasslands often occur in the dry corners of fields that are irrigated with center-pivot systems and along borders of playa lakes. Grasslands widely support herds of beef cows, which are one of the sources of calves that enter the feedyards for meat production. Many of the cattle in OAR feedyards come from distant states, mostly in the South and Midwest.

Many farms diversify their cropping operations by also managing beef cow/calf herds on their non-cultivated land, thereby spreading financial risk over more commodities. Grasslands also provide habitat for various wildlife species, some of which are threatened with extinction, and for plant populations whose flowers support insects that are important pollinators. Landowners also diversify income by leasing grasslands which have been managed for hunting game. Grasslands interspersed among irrigated crop fields provide catchment area for precipitation, some of which percolates to recharge the aquifer, and provides land area for extracting energy from petroleum, wind, and the sun.

Water Footprint

The concept of a "water footprint," (Wackernagel and Rees, 1998) the amount of water used in the production and processing of a commodity, can be used to assess how much water can be conserved by implementing a new practice. Estimates of the water footprints of beef and dairy production over the entire OAR have not yet been made, but we can draw from studies on specific sectors of production in considering how to prevent the exhaustion of the Ogallala Aquifer.

Most of the water used in livestock production is called "indirect" water (as seen in the table), which is the water used to grow the feedstuffs from irrigation and rainfall. In an analysis of the life cycle of beef cattle in the southern OAR, Rotz et al. (2015) calculated 371 gallons of irrigation water used per pound of weight gain, but did not



management is another type of direct water use for confined livestock. Beef feedyards in the southern OAR generally handle manure in its solid form, but some dairies and most swine facilities use water to remove manure from the production area. In nearly all cases, wastewater is recycled from lagoons and/or runoff holding ponds for use in flushing manure alleys (Harner et al., 2013). In an open-lot dairy in central Texas, conversion from fresh groundwater to recycled waste water for flushing manure

include "direct" water consumption by the cattle, which ranges from 3.2 gallons per pound of gain in feedyard-only production (i.e., no grazing phase after weaning) to 13.5 gallons per pound of gain on native grass (Heflin, 2016). Recent research in the Texas South Plains on yearling beef cattle grazing Old World bluestem grass in the summer revealed a water footprint of 400 gallons of irrigation, plus drinking water per pound of liveweight gain (Baxter et al., 2017). Including alfalfa in the grazing rotation reduced the water footprint to 290 gallons per pound, as seen in the water footprint graph. The improved nutritional quality of forage resulting from including alfalfa increased the efficiency of feed conversion, so that less water was required to produce a pound of gain. Such examples indicate the importance of proper balancing of animal diets to maximize efficiency of water input used in feed production that is ultimately used for animal production.

Besides the use of water for livestock drinking, waste

reduced fresh water consumption by up to 80% (Sweeten and Wolfe, 1993). Groundwater may also be used in beef cattle feeding for controlling fugitive dust and thus reducing nuisance complaints. Direct water use in feedyards during the April-October dusty season approximately doubles compared to the winter season when using sprinkler systems (Bonifacio et al., 2011). Open-lot dairies, however, are seldom equipped with sprinkler dust-control systems. Evaporative cooling is an important type of direct water use in dairies and swine facilities.

The most critical challenge to livestock industries in the OAR is the decline in groundwater supplies to support high yields of corn, since that is the commodity with the largest input into meat and dairy production. Even with advances in reducing the water footprint of corn, alternative, low water-demanding feeds with improved nutritional quality will be needed to replace some of the expected decline in local corn production.

Economic values of beef, dairy, and swine production in the southern OAR, from the northern border of Kansas southward (adapted from bulletins by Guerrero et al., 2012, 2013).

Economic Measure	Beef	Dairy	Swine	Total
Total economic output ($BB/year)	$29.80	$4.33	$3.66	$37.79
Throughput or inventory (MM head/year)	10.3	0.453	10.6	21.353
Direct water use (% of total ag water use, TAWU)	1.0	0.3	0.2	1.5
Direct + regional indirect water use (% of TAWU)	28.6	14.8	13.7	57.1
Value of direct + regional indirect water use ($/ac-ft)	$5,654	$1,632	$5,176	$5,176

An Integrated Modeling Framework for Investigating Water Management Practices in the Ogallala Aquifer Region

Isaya Kisekka leading a DSSAT workshop.

Photo by Amy Kremen

Prasanna Gowda, USDA-ARS - Grazinglands Research Laboratory;

Ryan Bailey, Colorado State University;

Isaya Kisekka, University of California-Davis;

Xiaomao Lin, Kansas State University;

Meagan Schipanski, Colorado State University

As groundwater availability declines across much of the Ogallala Aquifer Region (OAR) in the coming decades, different technologies, crops, and crop rotations will be needed, including the transition to rain-fed (dryland) cropping systems. However, to date we have lacked an effective means of assessing possible water, land use, soil, and agronomic scenarios that might extend the life of our shared groundwater resources. As part of our U.S. Department of Agriculture—National Institute of Food and Agriculture (USDA-NIFA) funded Coordinated Agricultural Project, we are working to integrate scientific knowledge across disciplines to develop a comprehensive modeling framework that can be used to evaluate the effect of alternative crop, soil, and water management strategies on groundwater demand and availability in the OAR under temporal and spatial climate variability, with an overarching goal of sustaining food production systems, rural communities, and ecosystem services in the region.

Model Testing with Scenarios

Figure 1 illustrates a schematic of the proposed integrated modeling framework for agricultural water management in the Ogallala Aquifer Region. This modeling framework consists of the Decision Support System for Agrotechnology Transfer (DSSAT) cropping system model, linked to the Soil Water Assessment Tool (SWAT), for watershed hydrology and MODFLOW (for groundwater hydrology) with an aim of retaining the strength of each model, i.e. watershed hydrology for SWAT, crop growth, and root zone hydrology for DSSAT, and groundwater hydrology and groundwater/surface water interactions for MODFLOW. Model applications to both historical conditions (1955-2015) and future conditions (2015-2060) will be represented. The SWAT-DSSAT-MODFLOW model is represented in the center, with DSSAT linked to SWAT and coupling occurring between SWAT-DSSAT and MODFLOW. Deep percolation calculated by DSSAT for cultivated fields and stream stage calculated by SWAT for sub-basin channels are mapped to MODFLOW, which simulates water table elevation and groundwater flow rates. It then maps volumes of pumped groundwater, water table elevation, and exchange rates between sub-basins channels and the aquifer back to SWAT and DSSAT. Pumped groundwater is converted to irrigation capacity and used to constrain irrigation schedules in DSSAT. Water table elevations are given to SWAT, as high water tables can affect soil hydrologic processes and exchange rates are provided to SWAT channels. The Unsaturated-Zone Flow (UZF) package of MODFLOW is employed since many regions of the OAR have deep water tables and therefore the groundwater travel time through the vadose zone to the water table can be significant.

The data required for model simulations are summarized in in Figure 1, and include land surface topography (digital elevation models; DEMs), soil maps and aquifer data (e.g. hydraulic conductivity, specific yield that vary in space), climate data, land use and crop types, and location and extraction rate for groundwater wells. SWAT and DSSAT will calculate evapotranspiration (ET) during the 1955-2000 simulation period. Between 2000 and 2015, however, ET will be specified according to results from algorithms that use output from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). The algorithms use remotely sensed data from MODIS leaf area index (LAI), land cover, albedo, enhanced vegetation index) to compute both plant transpiration and soil evaporation on a daily basis.

Model output for the historical simulation period will be compared against water table elevation (at many locations), stream discharge at U.S. Geological Survey (USGS) gaging sites, and county-aggregated crop yield, with model calibration performed to achieve acceptable residuals between observed and simulated values. Model parameters likely to be modified during this procedure include aquifer hydraulic conductivity, specific yield, and various land surface parameters. Before inclusion in the integrated modeling framework, the DSSAT model will be calibrated using experimental data from research sites in Colorado, Nebraska, Kansas, and Texas.

Using a set of scenarios, the tested model will evaluate the effect of alternative crop, soil, and water management strategies on groundwater demand and availability in the OAR under historic (1955-2015) and projected climate conditions in the coming decades (through 2060). It is critical to have finer spatial resolution of projected climate information to feed the suite of crop and hydrological simulations because climate projections from General Circulation Models (GCMs) are coarsely resolved and are usually only able to simulate the major features of the Earth's climate. There are a few factors that could contribute to the uncertainty in downscaled climate variables: the choice of greenhouse emission scenarios; selection of GCMs which can minimize both hindcast and projection uncertainties in the OAR; systematic debiasing algorithms; and lateral boundary settings in the dynamic downscaling modeling. With the dynamic downscaling completed by the Weather Research & Forecasting Model (WRF), models will provide primary climate variables including daily maximum and minimum temperatures, 24-hour precipitation, solar radiation, and wind speed components at up to 3 km resolution in the OAR for the 2015 to 2060-time period. Downscaled climatic data will be evaluated against measured data from regional weather networks within the OAR.

Applying the model to study areas throughout the OAR, various management strategies, such as limited irrigation, conversion to dryland, and implementation of novel irrigation technologies, will be assessed in terms of crop yield, available groundwater, and groundwater depletion trends. Scenarios will vary groundwater pumping rates, ranging from current pumping rates (status quo) to rates required for new irrigation strategies or as constrained by the saturated thickness of the aquifer. In particular, DSSAT will be used to simulate multi-year outcomes of crop management strategies such as crop rotations, deficit irrigation scheduling as limited by irrigation capacity, and institutional constraints. Irrigation scheduling scenarios also will be subjected to limitations imposed by diminished well capacities. We anticipate that the integrated modeling framework described herein will provide important guidance for groundwater management groups seeking to evaluate the potential water use and agricultural production impacts of management and policy options. In addition, this framework could be applied to other irrigated groundwater systems worldwide.

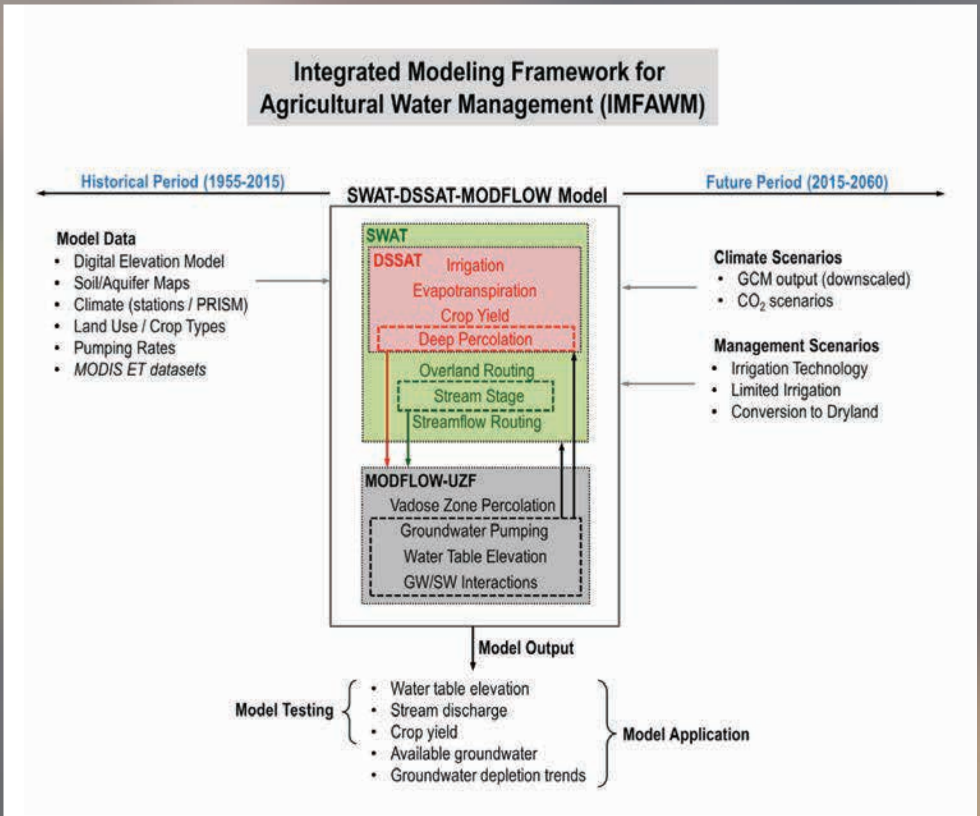


Figure 1. A schematic of an integrated modeling framework for agricultural water management in the Ogallala Aquifer Region.

Linking Soil Health to Water Conservation in the Ogallala Aquifer Region

Amanda Cano, Texas Tech University and Wind Erosion and Water Conservation Research - USDA-ARS;
Agustín Núñez, Colorado State University;
Veronica Acosta-Martinez, Wind Erosion and Water Conservation Research - USDA-ARS;
Meagan Schipanski, Colorado State University;
Rajan Ghimire, New Mexico State University;
Chuck Rice, Kansas State University

Overview

"Soil health" is a term commonly used to reference ecological parameters and other soil measurements considered in aggregate. This article covers the background and processes that drive soil health along with a description of the research of the Ogallala Water Coordinated Agriculture Project (OWCAP). Specifically, team members are focused on the important role that soil health plays during the transition from irrigated to dryland production.

A healthy soil can improve crop yields, nutrient cycling, resistance to erosion, and water storage. In the Ogallala Aquifer Region (OAR), high irrigation demand, low recharge rates, and extreme climate variability are threatening or have exhausted the aquifer resource. Reduced well outputs and prolonged drought events have led to dust storms reminiscent of the 1930s Dust Bowl Era. Some areas have lost irrigable water, forcing a transition from irrigated to dryland production. To date, emphasis on management practices in order to deal with water limitation in the OAR has largely focused on how and when to limit irrigation and shifting to crops (and crop varieties) with lower water demands. For the foreseeable future, especially as more producers transition from irrigated to dryland cropping systems, encouraging improvements in soil health and water conservation will be a key priority for the region.

It is estimated that one gram of soil may contain as many as one billion bacterial cells belonging to thousands of individual species, one million fungal species, and thousands to millions of algae and protozoa species. All of these microbial groups complement each other's contribution to healthy soil function, with the soil microbiome regulating 80–90% of important processes including decomposition, nutrient cycling, detoxification of soil and water, and disease suppression. For example, fungi may help increase soil particle aggregation and structure while increasing water and nutrient uptake through mycorrhizal associations on root surfaces (Rillig et al., 2004). Actinobacteria are also important for the decomposition of complex substrates, including lignin. Other bacterial popula-

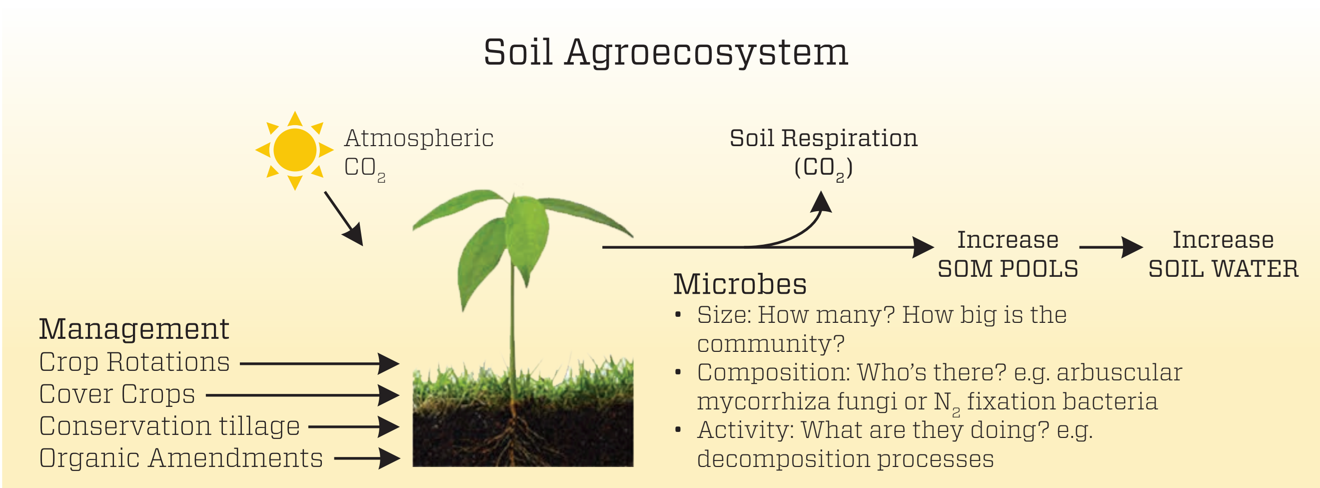


Figure 1. The coupled metabolisms of soil microorganisms during the decomposition of carbon (C) inputs builds soil organic matter (SOM) and releases carbon dioxide (CO_2). In agroecosystems, SOM is the manifestation of a dynamic equilibrium of C inputs and C outputs from decomposition, leaching, and soil erosion.

tions, including *Clostridium, Azotobacter* and *Rhizobium* are involved in fixing nitrogen.

Soil organic matter (SOM) is another critical component required for soil health, as it provides the environment which sustains the soil microbiome and stores water. SOM is composed of materials that range in their extent of decomposition, including plant and animal residues. How much SOM builds or is stabilized in agroecosystems also depends on several factors including initial SOM content, soil management practices, and environmental conditions. The soil microbiome itself, through the metabolism of micro-organisms, is also fundamental to the accumulation of SOM.

In the OAR, rainfed production typically leads to less plant biomass production relative to irrigated production. Low rainfall in the region, coupled with high evaporative demand, leads to soil carbon levels that are 20–50% lower on average relative to Midwestern U.S. soils. When soil carbon is low, the composition of soil microbial community shifts to one that functions under carbon-limited conditions; this can lower overall soil microbial community diversity and further decrease SOM content.

In limited irrigation and dryland systems, prioritizing conservation tillage practices that help keep the soil covered and fed with plant residues (in other words, which maintain or improve soil carbon/organic matter levels) is expected to improve the soil microbiome's adaptation to climate variability (including prolonged drought), to increase water use efficiency (Figure 2) and crop yield. For example, reducing tillage can conserve labile (readily decomposable) residues, creating a more consistent soil environment that supports microbial activity. The integration of crop-livestock systems and the incorporation of diverse crop rotations including cover crops can also help build SOM.

In the OAR, as producers shift away from irrigated production (predominantly corn) to planting more dryland wheat, sorghum-based rotations and/or other "alternative" crops including forages, a new carbon (C) balance will be reached in soil relative to changes in C inputs and outputs. Typically, it can take several years to realize the benefits of shifts towards soil health-oriented management. Even small improvements in SOM can be very meaningful: an increase in 1% SOM can improve a soil's water holding capacity by more than 20,000 gallons/acre (U.S. Natural Resources Conservation Service, 2013). Early changes in SOM can be identified and evaluated by measuring and analyzing different SOM fractions (those that are readily decomposable and those that are resistant) and microbial activity. With a proper selection of crop rotation, tillage, and other relevant management practices, it is possible to maintain a healthy soil for limited irrigation or dryland production systems for future generations.

Integrating Information to Assess and Improve Soil Health for Water-Limited Production

The team of researchers brought together by the USDA-NIFA funded Ogallala Water Coordinated Agriculture Project (OWCAP) are researching a diverse set of soil health indicators relevant to producers facing increasingly

Dr. Amanda Cano collecting soil samples in a non-irrigated cotton field in Lubbock, Texas.

Photo by Diana Vargas

Dr. Rajan Ghimire in one of his mixed cover crop research plots at New Mexico State University's Agricultural Research Center at Clovis, New Mexico.

Photo by Amy Kremen

water-limited conditions. This kind of soil health assessment data will yield valuable information about diverse soil types and climatic zones important for agricultural activities across the OAR. Our integrated research findings will help inform producers interested in efficient, water conservation-oriented management practices.

At the Agricultural Science Center and surrounding farms in Clovis, New Mexico, Dr. Rajan Ghimire's research group is evaluating conservation tillage systems, cover crops, and crop residue management practices aimed at minimizing soil organic carbon loss and improving soil health and water conservation in dryland and limited-irrigation cropping systems suited to water availability in that region.

In Lubbock, Texas, Drs. Veronica Acosta-Martinez with the USDA-ARS and Amanda Cano with Texas Tech University are conducting research on the soil microbial community as indicators of soil health affected by management selections and climate variability across the OAR. By correlating the soil microbial community's size (biomass), composition, and activity in nutrient cycling with certain management practices, field management choices that are more effective at promoting soil health can be identified.

At Kansas State University, Dr. Chuck Rice is assessing soil organic matter, soil aggregation, and microbial community structure in undisturbed prairie and no-till and tilled annual cropping systems. In less disturbed (prairie, no-till) systems, soil organic matter and nutrients increase, creating an environment which supports soil micro-organisms, especially fungi, which in turn increases soil aggregation. Such soil has greater water holding capacity, because the improved soil structure permits greater rainfall infiltration while reducing erosion and evaporation.

At Colorado State University, Dr. Meagan Schipanski and Ph.D. student Agustín Núñez are working with producers to evaluate fields converted from irrigation crops to dryland management at different time points across the OAR. Soil samples from each field will be taken from inside the former irrigated pivot area as well as from pivot corners that had been maintained under dryland production. This information will be integrated with data from an ongoing experiment at a CSU field research station to better understand the processes behind soil health changes during the transition from irrigated to dryland production.

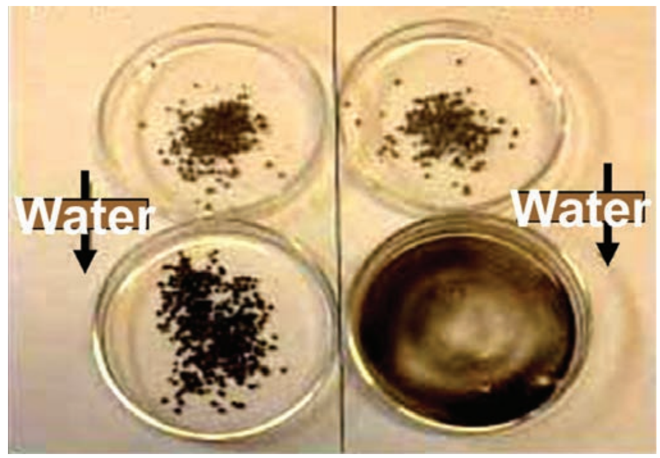


Photo by G. Wilson

Soil aggregates with a normal amount of fungi present (left) and soil with reduced fungal populations (right). During soil wet-up, aggregates with reduced fungal populations lose their structure; this soil is more prone to erosion.

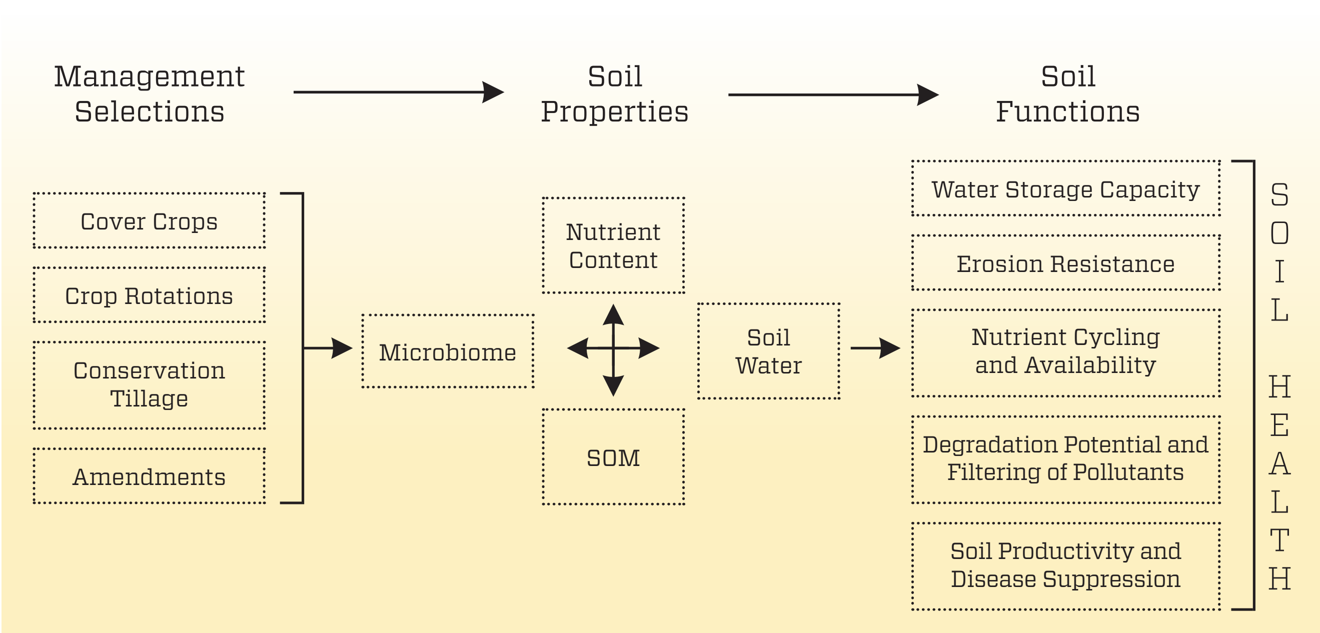


Figure 3. Management strategies affect soil properties, which in turn impact overall soil health.

Collaborators

OgallalaWater.org

OPTIMIZING WATER USE TO SUSTAIN FOOD SYSTEMS

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K-STATE Research and Extension

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OKLAHOMA STATE UNIVERSITY EXTENSION

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USDA

USDA United States Department of Agriculture National Institute of Food and Agriculture

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Colorado State University
CSU Water Center and the Colorado Water Institute
1033 Campus Delivery
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Water from springs at the head of Whitetail Creek, Keith County, Nebraska. The water issues from the upper part of the Broadwater Formation (Pliocene) just below the contact with the sands of the Nebraska Sand Hills, all parts of the High Plains Aquifer in Nebraska.

Photo courtesy of R.F. Diffendal, Jr., University of Nebraska.