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Complex water management in modern agriculture: Trends in the water-energy-food nexus over the High Plains Aquifer

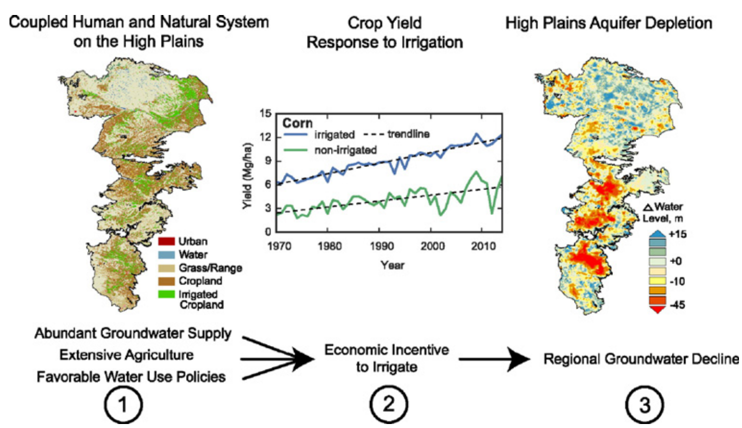
Samuel J. Smidt [a,*], Erin M.K. Haacker [a], Anthony D. Kendall [a], Jillian M. Deines [a,b], Lisi Pei [c,d], Kayla A. Cotterman [a], Haoyang Li [e], Xiao Liu [a], Bruno Basso [a], David W. Hyndman [a]

[a] Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI 48824, USA
[b] Center for Systems Integration and Sustainability, Michigan State University, East Lansing, MI 48824, USA
[c] University Corporation of Atmospheric Research, Boulder, CO 80301, USA
[d] NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI 48108, USA
[e] Department of Economics, Michigan State University, East Lansing, MI 48824, USA

HIGHLIGHTS

- Agricultural water use on the High Plains is largely unsustainable.
- Agricultural water management is framed through the water-energy-food nexus.
- New data integrates five spheres using coupled human and natural systems.
- Farmer profit drives agricultural water use.
- Management strategies must align economic incentives with water conservation.

GRAPHICAL ABSTRACT



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ABSTRACT

In modern agriculture, the interplay between complex physical, agricultural, and socioeconomic water use drivers must be fully understood to successfully manage water supplies on extended timescales. This is particularly evident across large portions of the High Plains Aquifer where groundwater levels have declined at unsustainable rates despite improvements in both the efficiency of water use and water productivity in agricultural practices. Improved technology and land use practices have not mitigated groundwater level declines, thus water management strategies must adapt accordingly or risk further resource loss. In this study, we analyze the water-energy-food nexus over the High Plains Aquifer as a framework to isolate the major drivers that have shaped the history, and will direct the future, of water use in modern agriculture. Based on this analysis, we conclude that future water management strategies can benefit from: (1) prioritizing farmer profit to encourage decision-making that aligns with strategic objectives, (2) management of water as both an input into the water-energy-food nexus and a key incentive for farmers, (3) adaptive frameworks that allow for short-term objectives within long-term goals, (4) innovative strategies that fit within restrictive political frameworks, (5)

* Corresponding author at: Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI 48824, USA.
E-mail address: smidtsam@msu.edu (S.J. Smidt).

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reduced production risks to aid farmer decision-making, and (6) increasing the political desire to conserve valuable water resources. This research sets the foundation to address water management as a function of complex decision-making trends linked to the water-energy-food nexus. Water management strategy recommendations are made based on the objective of balancing farmer profit and conserving water resources to ensure future agricultural production.

1. Introduction

Crop production across the High Plains Aquifer region (High Plains) in the central United States has an annual market value greater than $20 billion—approximately 10% of the entire U.S. crop value (NASS-USDA, 2012). Irrigation is essential to much of this crop production. Irrigated agriculture across the High Plains accounts for 30% of all irrigated acreage in the U.S. (Dennehy et al., 2002), and 97% of High Plains irrigation water is extracted from the High Plains Aquifer (HPA; Maupin and Barber, 2005). Due to extensive irrigation, groundwater levels across large sections of the HPA have been declining for decades, particularly in the southern section where the aquifer is thin and irrigation demand is high (Haacker et al., 2015; McGuire, 2009; Scanlon et al., 2012). Future decades are forecast to bring more widespread groundwater declines, effectively depleting broad regions of the HPA if current practices continue (Haacker et al., 2015). Major reductions in water availability would result in enormous consequences for food and energy production.

At the core of agricultural water management challenges is the water-energy-food nexus. Acting within this nexus across the HPA are the individuals and institutions that adapt to address the realities of groundwater depletion. These include creating and adopting new technologies, developing and planting different cultivars, shifting cropping patterns, implementing new policies, expanding monitoring, and pushing toward more efficient use of limited resources. These strategies have been designed around the objectives of increasing crop yields, decreasing production costs, improving or maintaining soil fertility, and reducing environmental impacts (Edwards, 1989; Stuart et al., 2015). They can be generalized into two broad focus areas: (1) water conservation to both use less water and be more efficient in application, and (2) water productivity to maximize the return on water use. Water conservation research has focused on strategies such as deficit irrigation (Fereres and Soriano, 2007; Geerts and Raes, 2009), irrigation technologies (Colaizzi et al., 2009; Howell, 2001), rainfed agriculture (Rockström et al., 2010; Rosegrant et al., 2002), and land management practices (Bossio and Geheb, 2008; Bossio et al., 2010). Water productivity research has focused on improved seed genetics (Hu and Xiong, 2014; Passioura, 2006), variable rate irrigation (Basso et al., 2013; Evans et al., 2013), and intraseason water management through irrigation scheduling and soil moisture monitoring (Aguilar et al., 2015), vegetation indices (Basso et al., 2004), and tillage practices (Derpsch et al., 2010). Despite this increased emphasis toward groundwater conservation among researchers, and new technologies and strategies that can greatly improve water productivity, groundwater supplies across the HPA continue to decline at unsustainable rates (Haacker et al., 2015; Scanlon et al., 2012).

Historically, water management strategies have targeted water use drivers within three major domains: (1) physical (e.g., climate, geology), (2) agricultural (e.g., crop type, tillage practices), and (3) socioeconomic (e.g., groundwater doctrines, market values) (Pimentel et al., 1997). However, water use drivers in modern agriculture are too complicated to be regulated individually within these separate domains. For example, changes in precipitation patterns have direct implications on irrigation scheduling and applications (Lorite et al., 2015), improved technologies allow for innovative and heterogeneous farming practices (Steven and Clark, 2013; Zhang and Kovacs, 2012), and crop prices respond to changes in global market demands (Rosegrant et al., 2008). Furthermore, drivers within these domains each influence short- and long-term water use decisions in ways that have not been addressed in static water management strategies (e.g., climate variability, government incentives, and annual crop insurance plans). Moreover, water use drivers across these domains are inherently linked, making it impossible to implement temporally relevant water management strategies in one domain without impacting another.

There are clear gaps in current water management strategies across the High Plains, as evidenced by the increase in both crop production and water use despite the reality of groundwater depletion (NASS-USDA, 2012). Nowhere is agricultural water management more prevalent than in the water-energy-food nexus of the HPA, making the region ideal to learn how complex management domains influence water use and decision-making. This study provides a comprehensive overview of the major drivers of water use across the HPA through a novel synthesis of data and an in-depth review of the relevant literature. We examine drivers in the physical, agricultural, and socioeconomic domains in contrast to the historical approach. Furthermore, within each domain, we analyze water use trends and examine how these drivers interact to influence water use decisions. We then synthesize across domains to present a framework for maintaining long-term aquifer supplies through improved agricultural water management strategies across the water-energy-food nexus.

2. Methods

This study synthesizes extensive agricultural databases along with the relevant water management literature across the HPA. When used, specific processing techniques are discussed within corresponding sections. Sections 3, 4, and 5 compile individual water use drivers or driver categories into major domains, where each subsection represents a major driver set or focus area. Subsections are selected according to the most significant topics for water supply or water use across the region, as a complete synthesis of these drivers is necessary to formulate water management suggestions and highlight areas where water resources are exploited. All drivers at every spatial and temporal scale may not be included, as our subsection lists are representative of and relevant to large scale management schemes. We derive our conclusions based on the trends found within and across each domain, and we make management suggestions based on the goals of maintaining farmer profit and achieving long-term aquifer sustainability.

3. The physical domain

The physical domain defines the limits of the water-energy-food nexus. For example, food production requires both energy and water. If water is limited, so will be the ability to increase crop yields. Thus, balancing components within the nexus to find the combination where production is highest and resource expenditures are lowest over time is critical for sustainable agriculture. A required step to reach this ideal nexus status is to assess total water availability and supply through time. Here, we analyze the major physical drivers that impact water availability and supply, and we highlight the trends that have the most influence on long-term sustainability goals.