Water Depletion, Climate Change, and the Texas High Plains: a model on the future of irrigation dependent agriculture

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Abstract

The High Plains of Texas is an agriculturally productive region of the country producing field crops such as cotton, corn, sorghum, and wheat. Deficit irrigation is leading to declining water levels in the Ogallala Aquifer which poses a threat to the viability of agriculture reliant on water. In addition, changes to historical climate due to climate change are expected to alter agriculture through changing yields and irrigation requirements.

This work utilizes a dynamic mathematical program to model the impact of climate change projections on a region with a limited hydrologic resource over the period 2018-2050. Data on yield and water use under climate projections as well as spatial data on the current aquifer levels are integrated into the regional agricultural model. Adaptation strategies are incorporated to demonstrate a wide range of possible responses to climate change which can affect the impact. In this system, aquifer depletion and crop prices drive transitions away from irrigated agriculture to dryland and in crops grown. Climate change plays a smaller role. Nevertheless, adaptation in the form of water conserving practices are important both to prolong the use of water resources and to lessen the effects of climate change.

Keywords: Ogallala Aquifer, Texas, land use, climate change

Introduction

Irrigated agriculture is prevalent across the state of Texas with approximately 25% of cropland irrigated (Wagner, 2012). The Texas High Plains (THP) is one region that relies heavily on water drawn from the Ogallala aquifer to produce irrigated crops such as corn, cotton, wheat, and sorghum. In total, it was estimated that the THP uses 5.6 million acre feet of water each year to sustain 4.6 million acres of irrigated cropland (Weinheimer et al., 2013). Further, the area is highly productive using this water, yielding approximately 25% of the nation's cotton and 65% of Texas's corn production (Weinheimer et al., 2013) and generating $1.6 billion in crops grown in the THP. Since the introduction of irrigation into agricultural production, its importance for maintaining high yields and buffering against natural disasters such as droughts has been important for both regional and national agriculture production.

Water from the Ogallala aquifer has allowed the THP to be an agriculturally productive region. Despite this, current water use is unsustainable with annual water extraction greater than annual recharge. It was estimated that from 1950 to 2013 the amount of water in the Ogallala aquifer beneath Texas declined 158.2 million acre-feet (McGuire, 2014). Due to the geologic structure of the aquifer, in approximately 15% or more of the area in Texas has experienced decreases in water levels of 25% or more and 5% or more of the area has experienced decrease of 50% or more (McGuire, 2014). Thus, declining water levels pose a threat to future irrigated agricultural productivity in the region.

In addition to declining aquifer levels, global climate change is expected to impact Texas agricultural production in the next 100 years. Already, variable growing conditions have proven to be detrimental to agricultural productivity. The 2011 drought caused major losses across Texas. In total, it was estimated that direct losses due to the drought totaled $3.23 billion for livestock, $2.2 billion for cotton, and $736 million for corn (Guerrero, 2012). In Texas, climate change is expected to increase temperatures and decrease rainfall but also increase the frequency of extreme events such as storms and extreme precipitation events (What Climate Change Means for Texas, 2016). Extreme weather events and changes to historic climate has already been shown to negatively impact agricultural production and future estimates suggest that the effects are only expected to worsen by 2100.

Declining water levels in the Ogallala aquifer as well as climate change is expected to cause changes to agricultural production in the THP. Based on current levels of production, this could impact regional and statewide agricultural output. However, it is unknown how the effects of declining aquifer levels and changing climate will impact the regional agricultural system. This paper aims to use a dynamic mathematical programming model to evaluate the effects of climate change and declining aquifer levels to future agricultural production in the THP. Evaluated jointly, this model will include the hydrologic, agricultural, and economic market which together will determine the economic viability of future production. Finally, including possible adaptation strategies to help maintain agricultural productivity will attempt to show viable solutions and lessen the effects to producers.

Literature Review

Given that the Ogallala aquifer extends under eight states and provides water for a wide range of economic activities, numerous studies have attempted to evaluate the useable life of the Ogallala (Johnson et al., 2009) or quantify its impacts (Hornbeck and Keskin, 2014). A number of studies have evaluated the value of the water including Hornbeck and Keskin (2014) who compared counties with access to the Ogallala to counties without access and quantified differences in agricultural productivity or Almas et al. (2004) who looked at the effect of the aquifer on the regional economy. However, most relevant to this work are linear programming models which attempt to create a realistic model the future of agricultural production in the region.

Early linear programming models developed in 1980s relied on modeling a representative farm or other smaller scale enterprise and incorporated declining water levels, increasing pumping costs, and declining irrigated acreage in the region (Short, 1980; Warren et al. 1982). However, Feng (1992) provides what many cite as the first dynamic optimization specification to model the Ogallala aquifer in Texas. This model includes variables for irrigation and cropping practices to show optimal water allocation over a 50-year time horizon for Lubbock County. In particular, equations for pumping cost as a function of lift and water-yield responses characterize water use and production costs and are still integral to models developed today. Over time, the mathematical models started including more realistic and varied water use scenarios (Johnson, 2003; Das, 2010), geographic regions (Wheeler, 2008), and geospatial data (Wang, 2012).

Methodology

This paper uses a multi-period nonlinear programming model to maximize the net present value of potential sources of agricultural revenue for the region subject to resource availability and other constraints. As described above, the model includes specifications for both cropland and rangeland agriculture. In each period the model will choose the production which will maximize net revenue. The model applies to Dallam, Hartley, and Sherman counties over the period of 2015-2050. Specification seen below is reproduced from Wang (2012). The objective function is:

Maximize $$NPV = \sum_{t=1}^{T}(1+r)^{-(t-1)}\, NR_t \tag{1}$$

Where: $$NR = \Sigma_z \Sigma_i\, \Sigma_l [P_{it}\, Y_{ilt} ACR_{zilt} - C_{zilt}] + \sum_z NB_t\, (PASTLAND_{zt}) \tag{2}$$

Defined as:

NPV	net present value of net returns,
r	discount rate,
NR_t	net return at time t, defined as the difference between total revenue and total cost in time t,
P_{it}	price of crop i at time t,
Y_{ilt}	yield of crop i in land type l in time t,
ACR_{zilt}	acreage in zone z of crop i in land type l in time t,
C_{zilt}	variable and fixed cost of production in zone z of crop i in land type l in time t,
NB_t	net benefit of livestock in time t,
$PASTLAND_{zt}$	acreage of pasture land for livestock in zone z and time t,
z	subscript denoting saturated thickness zone,
i	subscript denoting crop,
l	subscript denoting land type (dryland or irrigated),
t	subscript denoting time.

One component of increasing production costs comes from additional pumping costs because each unit of water is being pumped from further down in the aquifer. This difference is captured by the pumping lift, and can be conceptualized as:

$$LIFT_{zt} = LIFT_{z0} + \frac{\left(Recharge + (WATUSE_{zt} * ACR_{zilt})\right)}{AREA_{zilt} * Yield} \tag{3}$$

$LIFTz_0$	Lift for each zone in the first time period,
$WATUSE_{zt}$	Total water used for each crop in each time period,
$AREA_z$	Total land available,
$Yield$	Specific yield of water which gives the amount of water available based on saturated thickness,
$Recharge$	recharge from precipitation,

A constraint is imposed to represent yield as a function of water use:

$$Y_{ilt} = f(WATUSE_{zt}) \tag{4}$$

One key component to the production in any time period is the amount of water available must be more than the amount used. The amount of water pumped is a function of the water used multiplied by the acreage in each county and zone. The amount of water available is given in the geospatial data layers and set at the first time period for each county and zone.

$$\Sigma_t WATUSE_{zt} = TOTWATR_{z0} \tag{5}$$

where:

$TOTWATR_{z0}$	total water available in a given zone at the start of the model

One concern is that the model will shift rapidly among available production practices which, in addition to costs, removes any practical difficulties with changing production practices such as the time learning new systems. To ensure that future crop and production mixes are similar to current levels and do not shift abruptly, a historical crop mix approach as given in McCarl (1982) and Onal and McCarl (1989) is used. The crop mix equation is given as:

$$ACR_{zilt} = \Sigma_j CROPMIX_{zljt} * histcrop_{zilj} \quad (6)$$

where:

$CROPMIX_{zljt}$	amount of land placed under historic crop mix constraint for a given zone, landtype, historic crop mix, and time, with constraint relaxing over time,
$histcrop_{zilj}$	proportion of crop in cropmix for a zone, crop, landtype, and historic crop mix,
j	subscript indicating historic crop mix.

Land availability is also constrained based on current geospatial data. The land in acreage and pasture land must be less than or equal to total land available.

$$ACR_{zilt} + PASTLAND_{zt} \leq AREA_z \quad (7)$$

Data

Integrating hydrologic data to characterize the Ogallala aquifer and quantify water availability at every point in the study area is a cornerstone of this analysis. Given that water in the Ogallala aquifer in this region does not move large distances horizontally, water is largely confined to its current location. Saturated thickness characterizes the water available at any location in the Texas High Plains and is available from the United States Geological Survey (USGS). In addition, specific yield information is also available from USGS studies which describes for a given amount of saturated thickness the amount of water that can be extracted. In order to conceptualize the water availability, each county was divided into zones of saturated thickness. In total, acreage in a county was divided into six zones that corresponding to saturated thickness of: 25 feet or less, 25-75 feet, 76-125 feet, 126-175 feet, 176-225 feet, 225 feet or more. This allowed for analysis at the county level and water availability in any county to be heterogeneous.

In addition to hydrologic geospatial data, geospatial data on current land use was gathered from the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS). Current land use was able to characterize how many acres of various crops are currently in production in a given county. This data served as a starting point for the analysis. The following land types were included: corn, cotton, sorghum, wheat, hay, alfalfa, grass, and idle land.

Agricultural production data was gathered from USDA Quickstats. Specifically, inputs to the model included historic crop acreage and yield. This information was then used to build the historic crop mix constraints as described in the methodology section. Additionally, crop and livestock production budgets were gathered from Texas A&M Extension. These budgets provided fixed and variable cost of production information for each possible output so that the model can accurately account for costs of production.

As the water availability in the Ogallala aquifer declines, the cost of pumping water is expected to increase as a function of the lift (distance in feet water is below the surface). The pumping equation given below is modeled after equations taken from Guerrero et al. (2010), Amosson et al. (2011), and personal correspondence with Dr. Steven Amosson. The final formula given calculates the amount of million cubic feet of natural gas required to lift one acre-inch of water from a specified lift (in feet).

$$\frac{Mcf}{Acre - Inch} = \frac{GPM * PL + \left(\frac{2.31\,ft}{psi} * OP\right)}{3960 * E_p * E_{GH}} * \frac{2545\,BTU}{HP - HR} * \frac{Mcf}{1{,}000{,}000\,BTU} * \frac{1}{E_E} * \frac{450}{GPM} \qquad (8)$$

Where:

E_E	engine efficiency, assumed to be 21%
GPM	gallons per minute, assumed to be 600 for the system
E_p	pump efficiency, assumed to be 60%
E_{GH}	gearhead efficiency assumed to be 95%
PL	pumping lift in feet
psi	pounds per square inch
OP	operating pressure of the system and assumed to be a weighted average based on available system reported PSI and frequency of use. Weighted average used: 16.85

Finally, climate change data which shows future expected yield and water use changes was gathered from Beach et al. (2015) for each crop. Beach et al. use a water-yield response function modeled in Environmental Policy Integrated Climate (EPIC) under two climate models and show the associated change in yield and water use for the Texas High Plains (2015). EPIC data used two climate projections (Model for Interdisciplinary Research on Climate (MIROC) and the Integrated Global System Model (IGSM)) under a reference and policy scenario which are similar to the representative concentration pathways (RCP) and assume that emissions are either unrestricted or capped.

Preliminary Results

Preliminary results suggest that irrigated acreage declines over the time period of analysis as water availability declines and costs of pumping water increase. There is a shift towards less water intensive crops and production practices as was expected. Further, changes to yield and water use due to climate change is a less important factor than declining aquifer levels in the choice between irrigated versus dryland production, among crops, and between crops versus rangeland agriculture.

Conclusion

Agricultural production in the High Plains of Texas is an important facet of the regional economy and total agricultural production in Texas. Declining water levels in the Ogallala aquifer as well as climate change is expected to have an impact on agricultural productivity over the next 100 years. This study demonstrates that while agricultural output in the THP will change from what we see today, the area will remain productive although experience a decline in reliance on pumped water from the Ogallala aquifer. Finally, this work also shows the importance of adopting adaptation strategies or changing current production in order to lessen the effects of climate change and react to lower aquifer levels. Future studies can further incorporate adaptation scenarios, updated and more detailed hydrologic information, as well as scenarios for water management into the model in order to make more precise future predictions.

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