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Merging remote sensing data and national agricultural statistics to model change in irrigated agriculture

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ABSTRACT

Over 22 million hectares (ha) of U.S. croplands are irrigated. Irrigation is an intensified agricultural land use that increases crop yields and the practice affects water and energy cycles at, above, and below the land surface. Until recently, there has been a scarcity of geospatially detailed information about irrigation that is comprehensive, consistent, and timely to support studies tying agricultural land use change to aquifer water use and other factors. This study shows evidence for a recent overall net expansion of 522 thousand ha across the U.S. (2.33%) and 519 thousand ha (8.7%) in irrigated cropped area across the High Plains Aquifer (HPA) from 2002 to 2007. In fact, over 97% of the net national expansion in irrigated agriculture overlays the HPA. We employed a modeling approach implemented at two time intervals (2002 and 2007) for mapping irrigated agriculture across the conterminous U.S. (CONUS). We utilized U.S. Department of Agriculture (USDA) county statistics, satellite imagery, and a national land cover map in the model. The model output, called the Moderate Resolution Imaging Spectroradiometer (MODIS) Irrigated Agriculture Dataset for the U.S. (MIrAD-US), was then used to reveal relatively detailed spatial patterns of irrigation change across the nation and the HPA. Causes for the irrigation increase in the HPA are complex, but factors include crop commodity price increases, the corn ethanol industry, and government policies related to water use. Impacts of more irrigation may include shifts in local and regional climate, further groundwater depletion, and increasing crop yields and farm income.

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1. Introduction

Intensification of agricultural land use through irrigation influences crop yields, boundary layer energy exchange, groundwater recharge, regional climate, and water quality (Adegoke et al., 2003; Matson et al., 1997; Puma and Cook, 2010; Sacks et al., 2009; Scanlon et al., 2007). As of 2007, 22.9 million ha (56.6 million acres) of croplands in the U.S. were irrigated according to the U.S. Census of Agriculture (U.S. Department of Agriculture, 2009a). This represents a modest 2.33% increase in the area of irrigated crops from 2002 (U.S. Department of Agriculture, 2004). However, regional patterns in gains and losses in irrigated area vary significantly from the national picture.

A large proportion of irrigated cropland in the U.S. is fed by groundwater, in fact the USDA estimates nearly 67% of the water used to irrigate is provided by groundwater (U.S. Department of Agriculture, 2009b). In the central Great Plains of the U.S. (portions of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming), over six million ha of irrigated croplands (approximately 26% of the U.S. total), are primarily fed by groundwater extracted from the High Plains Aquifer (HPA), also known as the Ogallala aquifer. The HPA underlies a 451,000 km^2 area and was the most intensively used aquifer in the U.S. in 2000 (Maupin and Barber, 2005). The land cover here is primarily cropland and pasture. Principal irrigated crops include corn (*Zea mays*), soybeans (*Glycine max*), cotton (*Gossypium hirsutum*), alfalfa (*Medicago sativa L.*), grain sorghum (*Sorghum bicolor*), and wheat (*Triticum* spp.) (Dennehy et al., 2002).

Concerns that the widespread practice of irrigation in this region is unsustainable have been expressed since the 1970s (High Plains Study Council, 1982; Peterson and Bernardo, 2003; Sophocleous, 2005). Yet recent studies have indicated expansion in irrigation today (Dennehy et al., 2002; Johnson et al., 2011; Nickerson et al., 2011). This expansion is spatially variable and discontinuous. Since there has been a lack of spatially-detailed data on irrigation status, we see this as a gap needing to be filled. Tracking the locations, geographic area, and timing of agricultural intensification should improve water resource management, advance models of water and energy exchange between the atmosphere and land surface, clarify climate interactions, and reveal effects on ecosystem services (Matson et al., 1997;

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Puma and Cook, 2010; Shiklomanov, 2000; Vörösmarty et al., 2000).

Geospatial irrigation data that is detailed, comprehensive, consistent, and timely is needed to support studies tying agricultural land use change to aquifer water use and other factors. While the USDA publishes county areal irrigation estimates, spatial information is not provided to determine the specific locations of irrigated fields (U.S. Department of Agriculture, 2009a, 2012). Additionally, a handful of studies have produced geospatial irrigation land use data for national, continental, or global domains in the 21st century, but there are none to date that have a regular (e.g. sub-decadal) repeat cycle, allowing for consistent spatially-detailed tracking of irrigation change (Ozdogan and Gutman, 2008; Thenkabail et al., 2009).

This study shows evidence for a recent overall expansion of 519 thousand ha (8.7% increase) in irrigated cropped area across the HPA from 2002 to 2007, and by way of detailed geospatial analysis shows sub-county to regional differences in spatial patterns of irrigation change. For this study, we employed a modeling approach implemented at two time intervals (2002 and 2007) for mapping irrigated agriculture across the conterminous U.S. (CONUS). We then utilized this methodology to determine relatively detailed spatial patterns of irrigation change across the HPA. Subsequent change analysis incorporated national-level geospatial models called the Moderate Resolution Imaging Spectroradiometer (MODIS) Irrigated Agriculture Dataset for the U.S. (MIrAD-US) computed for two eras, 2002 (Pervez and Brown, 2010) and 2007. This article summarizes 2007 model results, the change in irrigation from 2002 to 2007 and presents a discussion of possible causes and effects related to the changes in land use associated with irrigated agriculture between 2002 and 2007 within the HPA.

2. Background

The first wells installed in the HPA for irrigating crops were dug in the late 1930s, followed by large increases in drilling especially in the 1950s, 1960s, and 1970s (Nebraska Department of Natural Resources, 2012b). Although the establishment of new irrigation wells appeared to stabilize in the 1980s and 1990s, it appears that expansion of irrigation is occurring again in this century. In Nebraska alone, over 60,000 registered irrigation wells tapped into the HPA between 1972 and 2011 (Nebraska Department of Natural Resources, 2012b). In 2000, total groundwater withdrawals from the HPA were estimated at 17,500 Mgal/day and the majority (97%) of the total water withdrawn was used for irrigation (Maupin and Barber, 2005).

The states of Nebraska, Texas, and Kansas used 88% of the HPA total water withdrawals in 2000 almost entirely for irrigated agriculture (Maupin and Barber, 2005). Approximately two thirds of the aquifer's total water storage capacity underlies the state of Nebraska (Johnson et al., 2011). Furthermore, Nebraska is currently the most intensively irrigated state in the country, surpassing California with the highest number of irrigated ha in 2007 (U.S. Department of Agriculture, 2009a).

In many areas, groundwater withdrawals from the HPA already exceed recharge, causing substantial declines in groundwater levels (Dennehy et al., 2002). Some of the largest groundwater level declines have occurred in southwest Kansas and the panhandle of Texas (see Fig. 2 in McGuire (2011)). Following the large expansion in irrigation in the decades leading up to 1980, decreasing groundwater resources across the HPA and increasing energy costs led to concerns about the sustainability of water use. Multiple studies were initiated; the most comprehensive water policy analysis conducted to date was the High Plains Ogallala Regional Aquifer Study (referred to here as the High Plains Study) completed in 1982 (High Plains Study Council, 1982). The High Plains Study predicted future reductions in irrigated land area and related water use (under its baseline scenario involving no major changes in state water-use regulations), but rather than seeing reductions in the amount of irrigation supplied by the HPA, the most recent decade has seen an expansion in irrigation land use. An expansion in irrigated fields does not necessarily mean a comparable increase in water or energy use, since efficiencies have been gained by technological changes in water delivery mechanisms and management practices (Evans and Sadler, 2008).

3. Data and methods

In a prior study, we implemented a geospatial model (Pervez and Brown, 2010) to create a U.S. map of irrigated lands for the year 2002. For the current study, we implemented the model using the same input data types from our prior study but tuned for circa 2007, the target time period. Herein, we provide a brief description of the input data sets and the geospatial model specific to the modeling year. A detailed description of the input data for the model is provided by Pervez and Brown (2010). The method incorporated the following three primary data inputs:

1. USDA county-level irrigation area statistics for 2007 (U.S. Department of Agriculture, 2009a).
2. Annual peak MODIS Normalized Difference Vegetation Index (NDVI) (a proxy for maximum vegetation vigor) for 2007.
3. A land cover mask for agricultural lands derived from NLCD 2006 (Fry et al., 2011).

And the success of the modeling relied on the following three assumptions:

1. Irrigated crops commonly exhibit higher annual peak NDVI values than non-irrigated crops in the same local area.
2. The growing season peak NDVI, at any time it occurs, will vary for each crop and for each geographic region of the U.S.
3. The difference in NDVI between irrigated and non-irrigated crops will be enhanced under non-optimal precipitation conditions (e.g., drought).

3.1. Input data

3.1.1. County irrigation statistics

The USDA Census of Agriculture publishes estimates of irrigated area (in acres) for each of the 3114 counties in the conterminous U.S. every five years and we used these county statistics of irrigated areas for 2002 and 2007 (U.S. Department of Agriculture, 2009a). The Census of Agriculture estimates were derived from data collected from over three million farmers and ranchers primarily through mailout and mailback method supplemented with electronic data reporting, telephone interview and personal enumeration with response rate of 85.2% for the 2007 Census. The collected data go through intensive quality checking before being used in an extensive process to compute adjusted estimates for the entire country. USDA National Agricultural Statistics Service (NASS) reported the reliability of the 2007 estimates as relative Root Mean Square Error (RMSE) of 0.25% which has improved from the RMSE of 0.64% for 2002 Census estimates (U.S. Department of Agriculture, 2009a).

3.1.2. MODIS annual peak NDVI

We computed the annual peak (or maximum) NDVI for 2007 from an annual time series of MODIS composited NDVI. The 2007 NDVI source was part of the CONUS 250-m resolution MODIS time