Groundwater Depletion and Agricultural Land Use Change in Wichita County, Kansas

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Abstract

Though researchers have documented groundwater and land use changes in the High Plains, few studies have investigated their interactions. This paper examines the relationship between groundwater depletion and agricultural land use change in greater detail than previous studies. Water well measurements and satellite imagery were used to detect changes in groundwater and land cover in Wichita County, Kansas, between 1975 and 2001. Analysis of these changes using GIS indicated that areas experiencing the greatest decline in groundwater were indeed being removed from irrigation, while areas with limited groundwater decline were experiencing fewer land use changes.

Keywords: High Plains, groundwater, land use, remote sensing, kriging.

Introduction

The High Plains, located in the southern part of the Great Plains physiographic region and extending from southern South Dakota to northwestern Texas, is a region dependent on reliable groundwater supplies for the continued existence of agriculture and rural communities in their current form (Kincer 1923; Weeks 1986; Kromm and White 1992b). Despite an abundance of groundwater, burgeoning production of crops and past rates of economic development, urgent sustainability issues exist. Concerns over economic, social, and environmental sustainability are especially evident in areas of high dependency on, and rapid depletion of, groundwater resources.

The High Plains is an area of climatic risk, as evident from the 1930s Dust Bowl and other periods of drought, and an area where rapid drawdown of aquifer levels is occurring (Opie 1993). The combination of climatic risk, groundwater depletion, fluctuating crop and energy prices, and a high dependency on groundwater resources highlights the need for actions toward understanding and creating rural sustainability in the High Plains. The High Plains Ogallala region is ideal for the examination of human/environmental interactions and change because it has experienced, and continues to undergo, significant transformation due to changes in groundwater availability (Harrington, Lu, and Harrington 2002).

Prior to the 1930s, Euro-American land use of the High Plains was dominated by rangeland and dryland wheat production because limited surface water and precipitation were not sufficient for intensive agriculture (Heimes and Luckey 1980; Buller 1982). Irrigated agriculture was restricted to narrow areas along perennial streams (State of Kansas 1912; Sherow 1990). The discovery and subsequent development of the High Plains aquifer system, which occurred soon after the 1930s Dust Bowl, changed historical land use patterns of the High Plains and created an economic environment that became, and remains, dependent on groundwater (Kromm and White 1992a).

Intensive development of groundwater for irrigation has resulted in notable declines of the water table in many areas of the High Plains (Kromm and White 1992b; Opie 1993; Schloss, Buddemeier, and Wilson 2000). The impacts of declining saturated thicknesses, and consequent land use changes, are not uniform because changes in water availability vary significantly throughout the High Plains (Albrecht 1990). Some areas in Texas have eliminated irrigation and have reverted back to dryland agriculture and intensely irrigated areas in Kansas will likely undergo similar change in the next 50 years, whereas some areas in Nebraska are not likely to experience significant change in the near future (Kromm and White 1992b). With diverse social and environmental conditions, the "impact of groundwater depletion on irrigated agriculture is highly variable from place to place" (Kromm and White 1992b, 46).

While previous studies have documented changes in groundwater levels (Schloss, Buddemeier, and Wilson 2000; Woods et al. 2000; Olea and Davis 2002) and agricultural land use change (Thelin et al. 1979; Price et al. 1997) in the High Plains, few studies have explicitly investigated the interactions between groundwater and agricultural land use change. Nellis (1987) and Wu et al. (1999) discussed land use adjustments to aquifer depletion in western Kansas and found that water-intensive crops were located in areas of significant aquifer saturated thickness, and that cropland was changing to grassland where high depth to water and low saturated thickness occurred. Rundquist (1995) build a groundwater index (based on aquifer depth, depletion, percent depletion, and saturated thickness) and found that groundwater availability influences land use change "only under certain circumstances" (87). Qi et al. (2002) investigated the spatial relationship of irrigated land above the High Plains aquifer and found that irrigated land was decreasing where aquifer depletion was the greatest, though no statistics were provided. While these studies have contributed towards understanding of groundwater and land use adjustments, little attention was focused the scale of data and on the accuracy of the models.

The purpose of this paper is to examine the relationship between agricultural land use change and groundwater depletion in greater detail and accuracy than has been attempted previously. While the results of this study may support previous findings, this study provides new replicable methods for integrating different types of data (point and polygon) at a scale that has not previously been attempted.

A single county overlying the High Plains aquifer system, Wichita County, Kansas, with conditions that have led to high proportionate decreases in groundwater and with significant variability in groundwater availability, was chosen for analysis. Changes in groundwater availability and land use here may be indicative of likely future changes in other parts of the region overlying the Ogallala and High Plains Aquifers because impacts of declining water levels are more substantial where limited groundwater exists (Bittinger and Green 1980). The findings of this study will contribute towards a greater understanding of the High Plains and regional sustainability and vulnerability concerns (see, e.g., Wilbanks et al. 1997; Cutter, Golledge, and Graf 2002), as well as integration of available land cover and groundwater data.

Study Area

Wichita County is located on the High Plains of west-central Kansas, encompassing 1862 square kilometers (Figure 1). Historic Euro-American land use was principally cattle grazing and ranching because land was not suited for general agriculture (State Board of Agriculture 1883). The climate is semiarid, but Wichita County is located near the moist continental climate boundary zone where annual precipitation (46 cm) is highly variable (Thornthwaite 1941; Rosenberg 1986; NCDC 2003). Precipitation and access to groundwater are the limiting factors for production agriculture, municipalities, and industries (Prescott et al. 1954; Slagle and Weakly 1976). Irrigation from wells did not begin until 1938, when three wells were drilled and 300 acres were irrigated (USDA 1965). By the turn of the 21st century Wichita County was dependent on groundwater to maintain current levels of productivity.

A 1954 investigation of groundwater resources in Wichita County indicated that under the rates of precipitation, recharge, and groundwater withdrawal at that time, virtually no groundwater was being taken from storage and that there was no danger of lowering the water table below the economic limit of use (Prescott et al. 1954). Twenty years later, a subsequent study reported that groundwater depletion had become excessive, and that "'dry-land' farming probably [would] be practiced once again in large parts of the area in the not-too-distant future" (Slagle and Weakly 1976, 17). By 1980 water availability from the Ogallala Formation had declined by 30 to 50 percent in sections of Wichita County (Dunlap 1980), and by 2000 sections of the aquifer were effectively exhausted (Buchanan and Buddemeier 2001).

Data and Methods

Twenty-five well measurements from the Kansas Geological Survey, capturing a near-complete set of measurements from 1965 to 2001, were used to select the most suitable study periods. Four graphs of well measurements, representing the north to south trend in groundwater depletion (see e.g., Schloss, Buddemeier, and Wilson 2000), were created for locations throughout Wichita County. Observations prior to 1972 were eliminated from consideration because groundwater data sets were less complete and Landsat Multi Spectral Scanner (MSS) and Thematic Mapper (TM) remotely sensed data were not available. Each graph exhibited different amounts of change, but similar trends were found. Following visual analysis of graphs, groundwater change was statistically and cartographically analyzed for three intervals: 1975 to 1985, 1985 to 1992, 1992 to 2001, and a composite interval from 1975 to 2001.

Groundwater Assessment

Well measurements were selected for areas inside Wichita County and within a five-mile buffer around the county. The inclusion of well measurements outside the study area provides for a more accurate localized representation, especially near border areas, where surrounding irrigation wells might affect the water table (Dunlap 1980; Wilson 2002). To reduce the effect of seasonal variations and the cone of depression, January measurements were selected if multiple readings per well per year existed (Dunlap and Spinazola 1981b; Pabst 1988). If January measurements were not available, February and March measurements were used (measurements were not used that occurred April-December). For each interval, well measurements were only used if available in consecutive change detection dates (e.g, 1975 and 1985).

Well measurements were converted to water table surface data using interpolation techniques to provide an accurate but cost effective method to estimate the water table at unsampled locations (Bolstad 2002). Universal kriging (kriging with a trend) was selected as the interpolation technique because it is a minimum error variance algorithm that uses weighted local averages to determine unbiased estimates at unrecorded locations (Burgess and Webster 1980; Bolstad 2002). Kriging has been used in west-central Kansas to determine water table elevations (Dunlap and Spinazola 1981a; Dunlap and Spinazola 1981b) because the technique allows for an estimation of the reliability of map data at unmeasured sites, it is an exact interpolator, it uses information from data points closely surrounding the point to be estimated by incorporating the autocorrelation structure of the data, and it provides a reproducible method of estimating the water-table at unmeasured sites (Olea 1982; Olea and Davis 2002).

Well measurements were fit to a spherical model for every study interval using a 100% local interpolation method. Kriging parameters were set to identify the five nearest well measurements within a search circle that was divided into quadrants rotated by 45 degrees. The interpolated surfaces were then converted into 1.5 x 1.5 km raster grids.[1]

Wichita County was subsetted from the surrounding seven counties in the interpolated grid because surfaces were initially interpolated beyond the county border. Using the raster calculator in ArcGIS, changes in the water table were calculated and merged into six classes: limited saturated thickness, +1.5 to 0m, -.1 to -2.9, -3 to -5.9, -6 to -8.9, and -9 to -10.7.

Cross validation of the 1975 groundwater interpolation indicated that the model accurately estimated the groundwater table. The mean error (-0.005) and the mean standardized error (-0.004) were close to zero, indicating that the predicted values were unbiased and centered on the true (actual) values. The root-mean square error (20.61) was slightly higher than the average standard error (19.72), indicating that the model was generally accurate, but slightly underestimated data variability. The root mean standardized error (1.065) was close to one, indicating that the model was valid. It was assumed that the remaining three study periods had comparable accuracies because similar modeling procedures were used for interpolation.

Depth to bedrock and depth to water (using data from the period 1940 to 1965) were then used to determine pre-development saturated thicknesses and percent changes in the water table. Using similar interpolation procedures, percent changes in the water table were determined by dividing the change in depth by the pre-development saturated thicknesses. Percent changes in the water table were merged into four classes: limited or no saturated thickness, 16% to -9.9%, -10 to -29.9%, and -30 to -55%.

Land Use

Several studies have investigated changes in irrigated cropland in the High Plains (e.g, Thelin et al. 1979; Williams and Poracsky 1979; Keene and Conley 1980, Thelin 1989; Qi et al. 2002) and Landsat appears to be one of the most suitable data sources (Heimes and Luckey 1980; Thelin and Heimes 1987). This study used a multi-temporal (two season) approach to identify irrigated and non-irrigated cropland using Landsat TM and MSS imagery because discrimination between irrigated and dryland agriculture is higher in multidate studies (Draeger 1977; Kolm 1984; Pax-Lenney and Woodcock 1997; Egbert and Mercier 2000). Landsat images were selected with three criteria: minimal cloud cover (less than 10%), overall quality of image, and availability of two images (from the spring and summer).

Images were geometrically corrected using nine ground control points selected from USGS 1:24000 topographic maps. Image to map registration was performed on the May 2001 image using a first order polynomial transformation and a nearest neighbor resampling technique. Image-to-image registration was then performed for all remaining images using the May 2001 image as the master image. Root mean square (RMS) errors were less than 15m for the TM images and less than 40m for the MSS images (half the pixel size in field of view).

To enable simultaneous digital image processing on multiple images throughout a growing season, spectral bands for each year were stacked into a single data set. MSS bands 1-4 (1975), from spring and summer, were stacked to create a single 8-band image, and TM spectral bands 1-5 and 7 were stacked to form 12-band images (1985, 1992, 2001). After all images were registered and stacked, Wichita County was subsetted from the full path/row image. A supervised classification, using the ISODATA algorithm and maximum likelihood decision rule (ERDAS 2002), was used to detect four classes: irrigated cropland, non-irrigated cropland, fallow, and non-cropland. The 'non-cropland' category included urban areas, drainages, feedlots, and rangeland. A 5x5 neighborhood majority filter smoothing operation was performed to reduce spatial heterogeneity, and to provide a more realistic appearance for the output from the classification process.

Accuracy of land use change analysis is largely dependent on the accuracy of initial land use classifications. Total reported harvested cropland, provided by the United States Department of Agriculture Kansas Farm Facts, was compared with total classified cropland to assess the quantitative classification accuracy (Stern, Doraiswamy, and Cook 2001). Based on these figures, classification accuracies of irrigated cropland, non-irrigated cropland, and total cropland were all above 90% except for the 1975 and 1985 non-irrigated categories, at 88% and 85%, respectively. It is important to note that agricultural data represent estimates and are not exact; therefore, classification accuracy estimates include some error.

Digital Orthophoto Quarter Quadrangles (DOQQs) were used to check the spatial classification accuracy. Using a stratified random sampling algorithm, 252 were used to compare the 1991 DOQQs to the 1992 classified image. The Kappa value (0.65) was low due to several factors: the DOQQs and classified images were taken during different growing seasons (1991 and 1992) and from different times during the year (April/July and September, respectively). Despite the low Kappa value, the method was still useful for testing the accuracy of the 'non-cropland' class because its spectral characteristics do not change noticeably year to year or throughout the growing season, as compared to irrigated cropland. The Kappa value for the 'non-cropland' class was 0.98. Considering that all other categories were types of cropland, the accuracy of the Kappa values of the non-cropland implies that overall there was a good differentiation between crop and non-crop areas.

Data must be the same scale to accurately detect change over time. Because MSS (60x60m) and TM (30x30m) imagery have different resolutions, TM data from 1985 and 2001 were rescaled to 60x60m to allow for comparisons between 1975 to 1985 and 1975 to 2001. The 1992 to 2001 comparison was done based on 30x30 m pixels. ArcGIS 8.2 was used to overlay changes in agricultural land use. To reduce classes and to enhance the changes in agricultural practice, the initial 16 categories of change were merged and recoded into four classes: into irrigation, out of irrigation, other, and no change. Finally, all land use change classifications were rescaled to 1.5 km for comparison with groundwater changes within land use change cells. Cells were summarized using a 25x25m and a 50x50m majority algorithm, for the MSS and TM images, respectively.

Groundwater and Land Use Change

After changes in groundwater and agricultural land use were individually quantified, ArcGIS 8.2 was used to overlay the changes in both groundwater and land use. Data were displayed in a matrix form and a chi square (χ^2) contingency analysis was used to investigate the statistical relationship between observed and expected values of groundwater depletion and land use change.

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{k}\frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}} \qquad (1)$$

The expected frequency of cell $_{ij}$ was determined with the following formula:

$$E_{ij} = \frac{R_i C_j}{N} \qquad (2)$$

where (R) is the sum of the observed counts of land use change cells within each interval of groundwater change, (C) is the sum of the observed counts of cells within each land use change column, and (N) is the grand total of all observed frequencies.

Results

Depth to groundwater varied throughout Wichita County, but the water table was generally deeper in the north and shallower in the south for each study period. The greatest depth to groundwater occurred in 2001 in the north, measuring 46m below the surface, while the shallowest measurement was located in the south in 1975, at 27m below the surface.

Results of the groundwater change analysis indicated that changes in the water table varied in time, location, and quantity (Figures 2 and 3). The greatest amount of depletion occurred between 1975 and 1985, where water levels declined 3 to 6m (10-30%) throughout the county, except areas in the southern section of the county where there was no significant change. Depletion slowed substantially from 1985 to 1992 and again from 1992 to 2001, as the water table decreased by 0 to 3m (5 to 15%) in each year. During the entire study period (1975 to 2001), 6 to 11m (20 to 40%) of depletion occurred in the north, while southern sections of the county experienced a 0 to 3m decline.

Land use classifications of satellite imagery revealed differences in agricultural practices across the county. Most irrigated land occurred in the north, whereas dryland agriculture occurred predominantly in the south. The overall trend in agricultural land use change was a decrease in irrigated cropland and an increase in non-irrigated cropland; few changes occurred in the 'non-cropland' classes (Figures 4 and 5).

The greatest decrease in irrigated land occurred between 1975 and 1985, when a net 4.6% of the total land area was taken out of irrigation (11.9% out of irrigation, 7.3% into irrigation). The more noticeable changes in irrigated agriculture occurred in the northern section of Wichita County, whereas changes in the south were more subtle (Figure 6). During the next two study periods (1985 to 1992 and 1992 to 2001) there was little net change in irrigated cropland.

Visual comparisons of groundwater and land use changes between 1975 and 2001 indicated a strong spatial relationship between groundwater depletion and land use change (Figures 2, 3, and 6). Areas of the county undergoing the greatest amount of groundwater depletion were transitioning away from irrigated cropland, whereas areas experiencing less groundwater depletion had fewer land use changes. Between 1975 and 1985 the greatest decrease in irrigated land occurred in the north, the same general area where groundwater had undergone the greatest depletion. For the next two study periods the severity of groundwater depletion and land taken out of irrigation were less.

The χ^2 statistical tests supported the visual comparisons and revealed that a significant difference between the observed land use changes and land use changes that might be expected under conditions of no relationship between groundwater depletion and land use change (Tables 1 and 2). The relationship was the strongest in the 'out of irrigation' class, especially during the periods of heaviest decline. The only study year when the 'out of irrigation class' was not related to groundwater depletion occurred when depletion (as a percent) was the least. In contrast, the strongest relationship between groundwater and land use change in the 'into irrigation' class occurred when groundwater depletion was less severe. There was essentially no relationship in the 'no change' land use change class.

Discussion

Although study years using satellite imagery were limited to 1975 through 2001, it should be noted that Wichita County also had significant groundwater depletion between 1965 and 1975. Average annual decline in the water table was the fastest between 1965 and 1985 and slowed during the next two study periods (1985 to 1992 and 1992 to 2001). The pattern of decreasing rates of groundwater decline between 1965 and 2001 can be attributed to the interaction of a number factors: groundwater was more abundant and available prior to heavy withdrawals, groundwater becomes more expensive to pump as the depth increases, irrigation systems were becoming more water efficient, and the aquifer was becoming exhausted.

Results of the land use/land cover classification indicated differences in agricultural practices across the county. There was significantly more irrigation in the north and more dryland farming in the south in every study period. While the north to south division became less significant from 1975 to 2001, as irrigated cropland decreased and non-irrigated cropland increased, the overall pattern remained distinct. Land use along the drainages of Ladder Creek and White Woman Creek changed the least, remaining as non-cropland, as sloping land is generally less suitable for cropland. It appears that dryland farming, which requires less capital investments of resources and time than irrigated agriculture, has been more sustainable through periods of transition.

Between 1975 and 2001 irrigation practices also changed throughout Wichita County. A manual count of center pivots from the classified imagery revealed that in 1975 there were relatively few center pivots in Wichita County. The number of center pivots increased from 8 in 1985 to 16 in 1992, and to 155 in 2001. The increase in center pivots is the result of a transition to more water efficient irrigation techniques that conserve water and reduce the quantity of water necessary for irrigation, thus reducing costs.

Conclusions

Few studies have actually documented the relationship between groundwater and land use change in the High Plains, although relationships have been asserted for a number of years. This study used new methods to integrate different scales and types of data to examine the relationship between groundwater and land use change. Results indicated that there is indeed an identifiable relationship between groundwater depletion and agricultural land use change on the edge of the

High Plains Aquifer, which has limited groundwater resources and will be more likely to experience change. This study also appears to be the first detailed and localized study that has investigated the relationship between groundwater change (in meters and as a percent) and land use change. These detailed findings, based on an intensive local study, are consistent with other studies that have shown that water intensive crops are located above significant aquifer saturated thickness and that irrigated land had decreased where aquifer depletion was the greatest (Nellis 1987, Rundquist 1995, and Wu et al. 1999).

Future research can build upon the findings of this study by applying similar methods to regions experiencing different depletion rates and by expanding the study area to regional scales (see Wilbanks and Kates 1999). Is there a critical threshold in depth to water, depth change, or percent change that is necessary to trigger land use change? Although previous research has investigated the relationship between Conservation Reserve Program (CRP) enrollment and aquifer thickness (Wu et al. 1999), research has not yet identified the spatial relationship among land enrolled or retired in CRP, depth of the water table, change in the water table, and percent change in the saturated thickness. Future research may also expand upon the factors behind local and regional change by focusing on climate variation and hazards, human vulnerability, polich effects, sustainability, and qualitative forces behind individual and societal decisions. Although Wichita County is a single case, the existing rural and agricultural changes are likely be representative of other counties in Kansas and the High Plains, and may provide an early indication of future changes.

Notes:

[1] While conversion into a smaller grid cells would yield a more precise portrayal of the water table, the surface would be less accurate (the average minimum distance between wells was 5.4 km).

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	Into Irrigation	Out of Irrigation	Fallow	No Change	Total	Critical Value
1975 - 1985	6.41	53.68	11.47	3.92	75.48	16.92
1985 - 1992	18.35	14.04	23.53	12.71	68.63	12.59
1992 - 2001	24.02	16.61	17.40	0.18	58.21	12.59
1975 - 2001	10.05	58.04	18.69	5.99	92.77	21.03

Table 1: Chi-square statistics for Groundwater depletion (in meters) and land use change

	Into Irrigation	Out of Irrigation	Fallow	No Change	Total	Critical Value
1975 - 1985	13.58	48.24	12.10	2.64	76.56	16.92
1985 - 1992	17.89	20.80	21.66	4.44	64.78	12.59
1992 - 2001	30.18	12.37	4.53	13.48	60.57	12.59
1975 - 2001	14.78	89.92	57.21	2.81	164.72	19.92

Table 2: Chi-square statistics for groundwater depletion (as a percent) and land use change

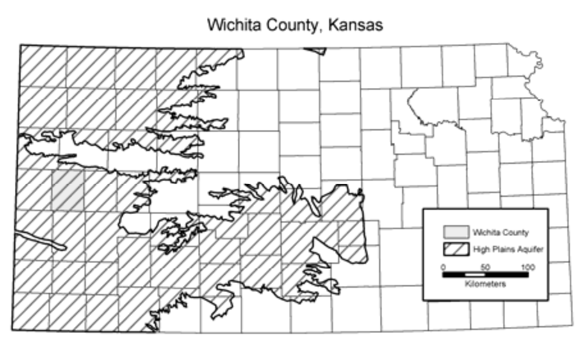

Figure 1: Map of Wichita County Kansas and High Plains Aquifer.

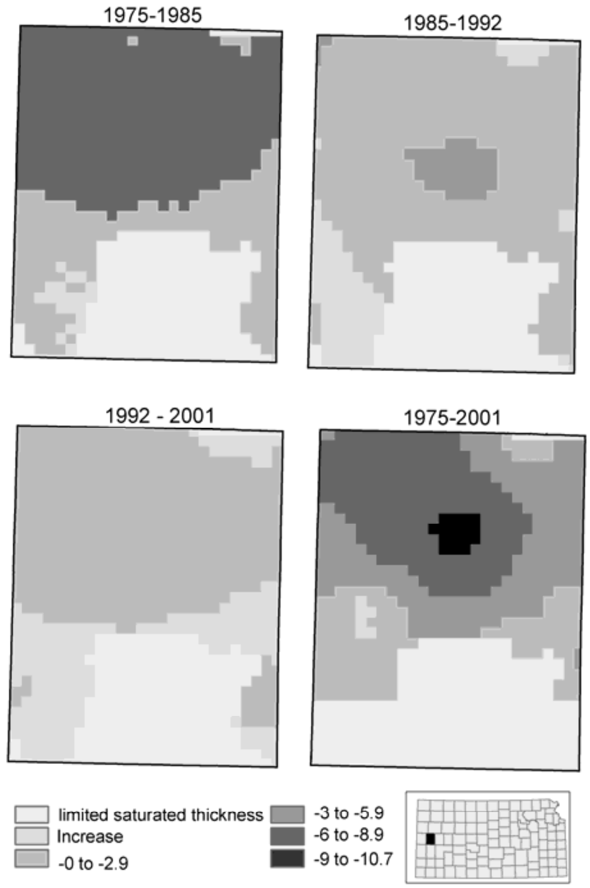

Figure 2: Groundwater change (in meters)

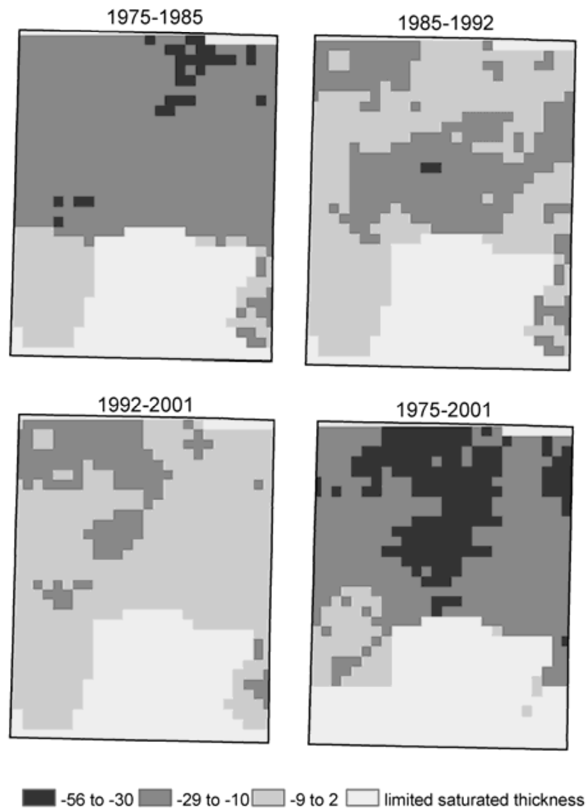

Figure 3: Groundwater change (as a percent)

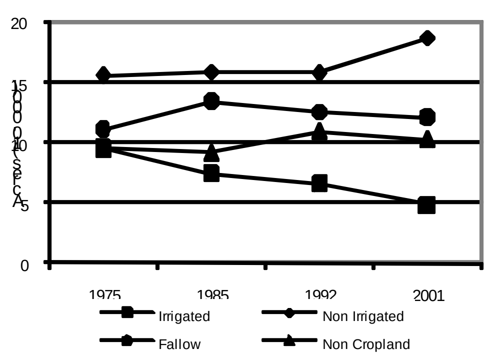

Figure 4: Land Use Change

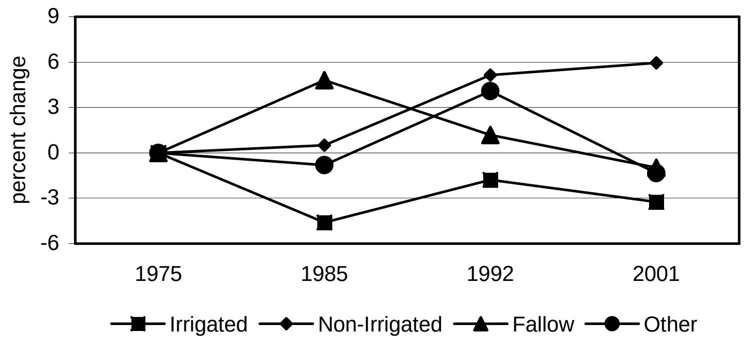

Figure 5: Land Use Change (as a percent)

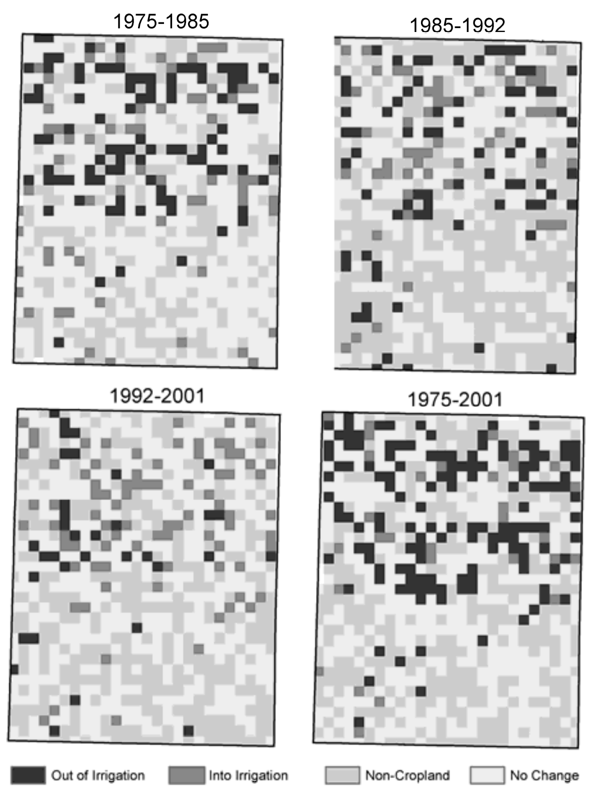

Figure 6: Agricultural land use change