What is the use value of the High Plains Aquifer services to agriculture?

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Abstract

The objective of the paper is to provide an estimate of the use value of the High Plains aquifer in agriculture. A region-wide production function for the crop sector is estimated. Using the production response to irrigation we estimate the value of groundwater for agriculture in \$231/acre at 2007 prices.

Keywords: Production function, water, use value.
JEL Classification: Q15, and Q25.

1 Introduction

Agriculture is being challenged, as world population grows and per capita income increases in developing countries, to produce more output with almost all arable land already cultivated. Estimates suggest that by 2050 food demand will be 50% higher than today's values (UnitedNations (1995)). In addition the increasing demand for alternative fuels imposes an increase in the demand for agricultural products. Several ways of increasing production have been developed since the mid-20 century such as increased use of chemicals, fertilizers, machinery and more recently biotechnology among others. Also irrigation systems allowed increasing productivity in land that was not irrigated as well as incorporating into to production land that without irrigation would not be devoted for agricultural production.
The use of water for irrigation is critical in certain regions to sustain agricultural production. The High Plains (HP) aquifer is an underground water reservoir that can provide water for

irrigation of agricultural crops in an area that includes parts of South Dakota, Wyoming, Colorado, Nebraska, Kansas, New Mexico, Oklahoma, and Texas. This region has a semiarid climate that makes crop production highly dependent on irrigation. Scanlon et al. (2007) indicates that changes in land use activities may affect water resources as much as climate change. Irrigation of agricultural crops affects both the dynamics of water and soil properties such as salt contents. The effects appear in the long run and take long time to be reverted. The use of groundwater for irrigation affects the dynamics of the aquifer and more importantly in some regions it also changes the stream-flow.

It has been reported that in some areas of the HP aquifer the water table has dropped to levels that make agricultural production economically infeasible. Depletion of the aquifer might impose a threat to food security as this region contributes substantially to national and international markets. Among other crops 15% of total US wheat, 24% of cotton, 14% of corn and 31% of sorghum were grown in this region in 2008. What then is the social value of the water of the HP aquifer? What is the use value of the services provided by the aquifer to agricultural producers? The main objective of the paper is to provide an estimate of the use value of the High Plains aquifer in agriculture. To accomplish that objective a region-wide production function for the crop sector is estimated. Using the production response to irrigation and the value of production we establish the value of groundwater for agriculture.

2 Literature review

The HP aquifer has a different recharge behavior depending on the region. While the northern area has high recharge that allows for sustainable use of groundwater for irrigation, the southern area has low recharge. Scanlon et al. (2012) indicate that depletion is highly concentrated in a region that represents less than 5% of the HP area. They also establish the difference between the north portion of the HP (NHP) aquifer from the central (CHP) and south (SHP) areas. The NHP presents high recharge assuring a sustainable use of the aquifer while the CHP and the northern part of SHP have a minimum recharge, making the use of water a mining activity.

The estimation of water value in the HP aquifer has been studied mostly within regions following political boundaries rather than the whole aquifer. In an early paper Torell et al. (1990) discusses the market value of water. They approached the value of water as reflected

by the difference between irrigated and non-irrigated land prices. They developed two single equation models since some variables where only of interest in one of the two models. They found that irrigated land prices were 30 to 60% higher than non-irrigated land, with differences across the region. Brozović and Islam (2010) estimate the value of groundwater for irrigation in Chase County, NE, also using a difference in land prices. Two models are analyzed. A simple OLS model finds a positive effect of irrigation on sale price.Similarly, a two-stage propensity score model finds that irrigated land has higher price than dryland but it also find that depth to water and climate variables affect the decision of irrigate as well.
Wheeler et al. (2006) evaluates different conservation policies in Texas and Eastern New Mexico. They focused on three policy scenarios: compensating the farmers to stop using the aquifer, limiting water use up to 50% of draw-down from the level it would reach if no conservation policy was applied in a 60 year period, and finally what happens if the draw-down was 75% of that limit. Their results show that the implicit cost of reducing irrigation has different impacts across counties, suggesting that conservation should focus on highly irrigated counties where the cost of conservation is relatively cheap.
The approach of this study to estimate the water value in agriculture is to estimate a production function. Production function estimation is a broad topic that has been deeply studied in the literature. Lau and Yotopoulos (1989) analyzes the use of a meta-production function. The concept of meta-production function is that in a sector or industry there is an underlying relation between inputs and outputs that is common to all the firms in different countries. This concept can be adapted to a county level, assuming that in the agricultural sector of the counties there is an underlying common production function. The authors point out the difficulties that production function estimation involves and how the use of a meta-production function decrease these difficulties. The estimation of production functions for single counties presents some difficulties as pointed by Lau and Yotopoulos (1989). Among those are the lack of variation in the data to estimate the model. The second problem pointed by the authors is that in a single county level analysis it would be difficult to identify the change in production due to technical change and the change that comes from returns to scale. They use different meta-models and test which better estimates the technological change.
Most of the literature that uses meta-production functions are cross-county studies. This type of analysis can be adapted to the cross-county case. Mundlak et al. (2008) discusses the use of panel data and different ways of estimating the county-specific ('within') effects.

Fulginiti and Perrin (1993) estimate a meta-production function to analyze the effects of public policies on prices and how the distorted prices affect technological change. Their model thus incorporates technology as an endogenous variable. They use a modified Cobb-Douglas specification to analyze the policy effects on prices and productivity in agriculture in 18 developing countries. They found that eliminating direct and indirect intervention in agriculture would result in agriculture price increases in almost all countries expect those where subsidies where the dominant policy. Also the elimination of distorting policies would imply a positive change in productivity for most of the countries.

Rezek and Perrin (2004) point out that productivity estimation is a human construction that only consider variables of economic or social interest. Productivity gains are essentially unexplained increases in output. As the production model is extended, unexplained production becomes smaller and therefore the productivity change estimation is lower. They estimate an output distance function for four states in the Great Plains. , including an environmental component. Agricultural productivity is adjusted to incorporate the effects of undesirable output that arise from the use of nitrogen and pesticides.. They first estimate a translog distance function.. They then used that function in a second step to calculate the Malmqvist productivity index. As undesirable outputs increased, the estimated productivity change decreased.

Nishimizu and Page (1982) also uses a deterministic approach to generate the parameters of a translog function. Using a translog instead of a more simple Cobb-Douglas functional form allow them to recover the substitution possibilities.

A deterministic correction to a stochastic estimate is presented in Perelman and Pestieau (1988). In this paper the first step estimate the production function by OLS. Then adjusting the constant term the frontier is *'corrected'* to the point where no error term is positive and only one is zero. That data point corresponds to the efficient firm.

3 Data

To estimate the per-hectare agricultural production function for the HP aquifer region we assume a single crop output, biomass, is produced.. To combine different crops into a single product we summed the biomass produced by all crops including the reported harvest plus non-harvested biomass production implied by estimated harvest indexes for each crop.

Biomass yield was estimated as total biomass produced in the county divided by total planted acres. Production and area data by crop in each county and year are from the surveys of the National Agricultural Statistics Service of the U.S. Department of Agriculture (NASS-USDA) for the 208 counties over the HP aquifer, from 1960 to 2008.

Biomass production requires several inputs, data for which are not generally available at the county level. Agricultural Census data provide expenditures on fertilizer and chemicals approximately every five years. We converted expenditure into a quantity index by dividing by a national price index for each. Then a linear interpolation between census years was made using the following formula

$$Q_{t+i} = \frac{Q_T - Q_t}{T - t} + Q_{t+i-1} \tag{1}$$

where Q_T represents the quantity in the census year that immediately follows Q_{t+i}, Q_t is the quantity in the census previous to year Q_{t+i} and $T - t$ is the number of years between two census years. We interpolate quantities instead of expenditures based on the assumption that farmers have an inelastic demand for these two products. Interpolating expenditures would implicitly assume that expenditures are relatively constant from year to year, implying a unit price elasticity of demand. For early years in some counties, expenditure estimates were not available. In those cases extrapolated quantities backward from the first census year available, using using state-level indexes from ERS, USDA.

The variable to represent irrigation in the production function is the ratio of irrigated area to non-irrigated area. Irrigated area is reported for some crops as irrigated area planted but as irrigated area harvested for others. We calculated the irrigation ratio as the highest value of the two total harvested area.

Two other factors considered as inputs to the production function are precipitation and temperature. Daily precipitation by county was constructed as a distance-weighted average of precipitation at the five closest weather stations with daily records available. From these daily data, total precipitation from March to August was calculated. High temperature, measured as degree days (DD) over the season, has been shown as a factor affecting yield (Schlenker and Roberts (2009)). Using the the same sources and methods as for precipitation, we estimated daily high and low temperatures for each county, and from that we estimated the number of hours in various degree intervals during March-August. For this study four degree days variables (DD) were constructed, reflecting the number of days (total hours divided by 24) of temperatures between 5 to 7, 8 to 14, 15 to 32, and 33 to 40 degrees Celsius, respectively. We incorporated DD in the regression as a linear variable following the concept of a damage function as presented by Lichtenberg and Zilberman (1986) and Saha et al. (1997).

Other inputs such labor and capital per hectare where not included given the lack of information at the county level and for the period under analysis.

To obtain the value of irrigation, we require a biomass price index for each county and year, which we calculated as the weighted average of the different crop prices with weights equal to share of production.

4 Econometric Model

Functional forms for expressing a production relationship range from simple but more inflexible to more complex but in general more flexible. In the first group we can include the Cobb-Douglas (2) which is nested in the more flexible Translog (3) representation (Griffin et al. (1987)).

$$y = \alpha \prod_i x_i^{\beta_i} \tag{2}$$

$$\ln y = \alpha + \sum_i \beta_i \ln x_i + \frac{1}{2} \sum_i \sum_j \delta_{ij} \ln x_i \ln x_j \tag{3}$$

where i and j represent the list of variables (fertilizer, chemicals, precipitation, irrigation proportion, time trend) where we have omitted county and time subscripts to simplify the notation. In the Translog model the elasticity of response to irrigation and remaining variables follows the general equation

$$\frac{\partial \ln y}{\partial x_i} = \beta_i + \frac{1}{2} \sum_j \delta_{i,j} \ln x_j \tag{4}$$

The Cobb-Douglas functional form is the most simple but has some limitations. Response elasticity, β_i , is constant, regardless of the intensity of input i or others, precluding the possibility of a yield maximum with negative marginal product beyond some level of input. Given a proportional change in all inputs the marginal rate of technical substitution (MRTS) of the Cobb-Douglas remain constant because it is homothetic. (Griffin et al. (1987)). A related characteristic of the Cobb-Douglas is the constant elasticity of substitution which impose a strong assumption on the production process. The elasticity of substitution express the ratio of change of the production function with respect to two different inputs. In mathematical notation it is

$$\sigma_{ij} = \frac{(f_i/f_j)}{(x_i/x_j)} \frac{d(x_i/x_j)}{d(f_i/f_j)} \tag{5}$$

where $f_i = \partial y/\partial x_i$ and $f_j = \partial y/\partial x_j$. This property of the Cobb-Douglas do not hold in the Translog specification allowing for more flexible representation of the production process.
A production function allows one to understand the response of output to the factors applied in the production process. More formally a production function $f(x)$ gives the maximum output that can be obtained from a set of inputs. If the function is differentiable we can partially differentiate the production function with respect to an input to obtain the marginal productivity of that input. There are some regularity conditions that the production function needs to meet in order to represent a production process. First, it must satisfy the monotonicity assumption which says that if input x is in the input requirement set $V(Y)$ and $x' \geq x$, then x' is in $V(y)$ (Varian (1992)). Second, $f(x)$ must be quasi-concave which is equivalent to the $V(y)$ being convex. This implies that there are non-increasing returns to scale. Third, the set must be closed and bounded to allow for interior solutions. Once the production function is estimated this properties must be checked and if those are not satisfied we should add restrictions in the estimation process.

Besides the functional form selected to represent the production process we have to identify an appropriate econometric estimation procedure. The data available conforms an unbalanced panel. The unbalancedness arises from the fact that we do not have complete data for all years in some counties. The most important gap in data is in Texas counties which start to report production and area planted in 1968. From the 208 counties considered there are also two in South Dakota that do not have irrigation area reported and one in Texas that has very few years with reported data. Therefore only 205 counties were included in the estimation.
Three regression models were estimated. In the first model, the data were pooled and Ordinary Least Square (OLS) was used. The second model included a fixed effect (FE) intercept for each county was estimated, and the third model specified a random effect (RE)

for county intercepts These models have the following general representation,

$$y_{it} = \alpha_i + X'_{it}\beta + \varepsilon_{it} \tag{6}$$

where y_{it} is the log of biomass in county i, year t, α_i represents the intercept for county i, X'_{it} is the log of the variable i in year t, and ε_{it} is the error. The difference between these three specifications is how they treat the intercepts α_i for counties. The pooled OLS model assumes that the same intercept applies to all counties, so α is not indexed. The RE model assumes that individual county intercepts are random draws from a distribution. In the RE model both the random effects α_i and ε_{it} are *iid*. In the FE model the individual effects α_i are assumed to be county-specific effects.

Ex-ante, the fixed effect model seems to make more sense since we are not including all the inputs and location specific conditions that might imply differences in the results. But to be sure about which model better represent the biomass production for the HP aquifer the three will be run.

If county effects are fixed then estimators like pooled OLS are inconsistent. So is the RE estimator that treats the unobserved heterogeneity as a random variable distributed independently of the regressors (Cameron and Trivedi (2010)). To determine which of the models better represent the production process we can use the Hausman test to determine whether the coefficients of the time-varying regressors obtained in the FE model are different from the coefficients of the RE model. The test follows the statistic

$$H = (\tilde{\beta}_{t,RE} - \hat{\beta}_{t,FE})' \big[\hat{V}[\hat{\beta}_{t,FE}] - \tilde{V}[\tilde{\beta}_{t,RE}]\big]^{-1} (\tilde{\beta}_{t,RE} - \hat{\beta}_{t,FE}) \tag{7}$$

The test statistic is asymptotically χ^2 distributed under the null hypothesis.

Standard regression analysis assumes that the X variables are fixed, while the Y variable is determined by the functional relationship with the Xs plus a random error term. If the inputs and the expected output are determined simultaneously, OLS estimates may not be appropriate. Mundlak et al. (2008) shows how the simultaneity of the decision process can result in an error term fully transmitted to inputs or that the expected value of the error term is not independent of the exogenous variables. Griliches and Mairesse (1995) present alternatives to the 'transmitted' problem by the use of panel data. They discuss improving the validity of the fixed effect models by the use of the 'within' estimator or by first differencing. Another solution is the use of instrumental variables. One assumption of the linear model is that the exogenous variables are not correlated with the errors. If the process of production determines that some inputs are selected simultaneously with production decision this assumption fails and we have that $E(\varepsilon_{it}|X'_{it}) \neq 0$. Another way to express this is that the exogenous variables in X affect y not only directly but through ε_{it}. To solve this we can use instrumental variables that are variables correlated with the variable of interest but independent of the errors solving the identification problem in some situations.

Plausible production circumstances require that production functions satisfy regularity conditions such as quasi-concavity. But sometimes production function estimates do not satisfy this theoretical restriction and it has to be imposed. One first attempt to impose some restriction is recognizing that the partial derivatives of a production function reflect marginal product, so that when profit maximization behavior is assumed marginal product equals the price ratio of input to output. When combined with the production function observations on these relationships might solve the concavity problem. This study incorporates such input demand equations for fertilizer and chemicals, providing a system of three equations to be estimated.

A contemporary correlation between errors in different equations is allowed of the form $E(\varepsilon_{ti}\varepsilon_{tj}) = \sigma_{ij}$ (Davidson and MacKinnon (2004)). The resulting system of equations is known as a Seemingly Unrelated Regression model (SUR). To estimate the SUR system and include the instrumental variables a Three-Stage Least Square (3SLS) estimation is required. In short what the 3SLS estimation procedure does is

$$\mathbf{y} = \mathbf{ZB} + \epsilon \tag{8}$$

with $E(\epsilon\epsilon') = \mathbf{\Sigma}$. In the first stage the endogenous variables are instrumented allowing for a generalized least squares estimator to be formed. Matrix $\mathbf{\Sigma}$ is estimated from the second stage residuals and in the third stage the matrix $\mathbf{B}$ is estimated (StataCorp (2011)).

Since we are using a translog specification the elasticities are calculated at each data point (one for each county and year). Then we take the mean to evaluate the overall elasticity. To calculate standard errors for elasticities we used the Delta method. First step consists of recovering the variance covariance matrix of estimated regressions (VCE). Then we construct a vector G that consists of the first partial derivatives of the elasticities with respect to each regressors. Calculating the a matrix GVG as $G' \times VCE \times G$ and taking the square root of it we get the standard error of the elasticity of interest.

5 Empirical results

Preliminary results showed that the production function estimation without constraints did not satisfy regularity conditions. From the estimated function, elasticities were calculated at each data point and averaged over the panel (Table 1). Average elasticities for chemicals in OLS and FE models were negative, an implausible result. Three alternative models were estimated to solve this anomaly. Results show that SUR with fixed effects (SUR+FE), and a three stage least squares SUR regression with fixed effects (3SLS+FE) provide consistent results. Combining SUR with instrumental variables (3SLS) reverses the sign of the estimated time trend and the Degree Day variable for the 33 to 40 °C range (Table 1).

Even though the FE and RE single equation models do not satisfy the conditions of a production function, we tested whether the difference in the B coefficients were statistically significant. Applying Hausman test we found that the null hypothesis of equality is rejected and therefore the random effects coefficients are inconsistent. We also found that the SUR+FE and 3SLS+FE present the lowest Akaike Information Criterion (AIC) indicating that intercepts differ across the aquifer. The differences might come from differences in soil types, crops types, and agronomic practices among others. We do not explore spatial analysis further in this paper but recognize that is a line of work to be done.

By the AIC criterion the model that better explains the production function of biomass in the HP aquifer region is the SUR with fixed effects (SUR+FE) The second model by AIC is the 3SLS+FE. Looking at the values of the elasticities we see that they are quite similar except for the mid-range DD coefficients.

The estimates of elasticity of irrigation response results goes from 0.476 in the OLS case to 0.786 in the RE model. By the AIC criterion we found that the SUR+FE is the model that better fits the data, with an elasticity of irrigation response (IR) of 0.667. This means that changing an acre from dryland to irrigation increases yield by 67%. Considering the standard deviation of IR, the confidence interval at the 95% level shows a range of IR between 55% and 79%. Except the OLS regression all the others econometric specifications show mean values for IR that fall in the range of SUR+FE confidence interval. Thus the estimate of IR is relatively robust.

Evolution of estimated elasticities averaged by state [1] is presented in Figure 1. Two different periods clearly appear, one from 1960 to mid 70s and the other from there to 2007. Since the response to irrigation depends on several variables (Equation 4) there is no a single factor that explains this pattern. It is possible that the land that result in bigger yield response was converted to irrigation first and therefore the effect become lower and more stable.

Irrigation water value (IWV) by state in 2007 is estimated as

$$IWV = \frac{TBM}{TPA} \times AvgP \times IR \tag{9}$$

where TBM is total biomass produced by state, TPA is total planted area in the state, AvgP is the weighted average price index of the state, and IR is the response of yield to irrigation (Table 2). We present the results by state instead of by county to simplify the analysis. Two different irrigation response coefficients are used to estimate the irrigation water value. One is the response over the whole period of analysis (1960-2007) ranging from \$116 to \$324/ac [2]. The other is the response by state in 2007 allowing to see a more present value of irrigation since the response at the end of the period is lower than overall, where the range falls to \$114-312/ac. The estimated average value for the whole aquifer was \$231 for the average irrigation response over time (confidence interval between \$189 and 273), and \$214/ac for 2007 irrigation response.

An important part of the value variation comes from the differences in yields that reflects the different crop combination in each state. The portion of the aquifer over South Dakota is the one that shows the highest response to irrigation overall the period and for 2007. This might be explained by the fact that in average is the state where the irrigation is less adopted. Texas and New Mexico are the States where the response is lower but are also the states where the area irrigated is more stable over time.

Values of irrigation shown in Table 2 for 2007 are larger than the difference between irrigated and non-irrigated land rents in these states. The state level information include the whole states and not only the HP aquifer portion. Even when our results might be larger we are just considering extra revenue from increased yield (Figure 2).

[1] Reference to states refers to just the counties in the state that are over the HP aquifer.

[2] We present results in dollars per acre even when for estimation purposes we uses values of production and input in a per hectare basis. It just makes the number simpler to compare with those currently used in the U.S.

6 Summary and Conclusions

The High Plains aquifer has been providing water for agricultural production for more than 50 years. In some regions the irrigated area has been stable over that period but in some other portions irrigated acreage has been increasing. At this point the southern portion is experiencing a drop in the water table that imposes a threat to irrigated crop production.

Using a production function approach we estimated the yield response to irrigation on the aquifer cropland area. Our estimate is that changing an acre from dryland to irrigated cropland will increase the yield by an average of 67% across time and counties, with a confidence interval ranging between 55 and 79%. Estimating the value of irrigation as the increased yield times the price of that yield we found that water provides an extra revenue that ranges between $189 and 273 per acre over the confidence interval around the mean. At the state level the values vary between $116 and 324 per acre, showing the regional differences across the aquifer region. When discussing alternative uses for the HP aquifer water, these results can help in the decision of how to allocate water to different activities across time. Even though the population living in the region right over the aquifer might not be large there are other populated areas that might compete for the resource in the future.

A deeper spatial analysis is the next step in future research work to better capture the regional differences. These differences arise from aquifer geological differences, crop farming choices, and environmental conditions across the region. Fixed effects models performed better among the models presented, suggesting that there are some spatial differences across counties and indicating that spatial analysis can be useful to improve estimates. How to balance the use of a scarce resource between food production, direct human consumption, and environmental allocation is a difficult task. In this paper we approximated the use value in agriculture as a contribution to the discussion.

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	Translog					
Elasticities[1]	OLS	FE	RE	SUR+FE	3SLS	3SLS+FE
Fertilizer	0.512	0.253	0.295	0.268	0.432	0.276
	(0.032)	(0.011)	(0.011)	(0.007)	(0.008)	(0.008)
Chemicals	-0.102	-0.039	-0.056	0.057	0.030	0.031
	(0.026)	(0.012)	(0.012)	(0.008)	(0.009)	(0.009)
Precipitation	0.373	0.130	0.155	0.174	0.417	0.163
	(0.033)	(0.012)	(0.012)	(0.011)	(0.014)	(0.011)
Irrigation	0.476	0.780	0.786	0.667	0.548	0.634
	(0.130)	(0.075)	(0.076)	(0.061)	(0.065)	(0.068)
Time	0.001	0.006	0.005	0.002	-0.002	0.004
	(0.001)	(0.001)	(0.001)	(0.000)	(0.0005)	(0.001)
Coefficients						
lDD-5 to 7	1.654	0.599	0.700	0.343	1.163	0.540
	(0.173)	(0.029)	(0.030)	(0.025)	(0.027)	(0.027)
lDD8 to 14	0.815	0.356	0.387	0.169	0.521	0.286
	(0.226)	(0.033)	(0.034)	(0.028))	(0.037)	(0.031)
lDD15 to 32	1.989	1.145	1.116	0.640	1.227	1.085
	(0.281)	(0.088)	(0.088)	(0.074)	(0.075)	(0.082)
lDD33 to 40	0.018	-0.035	-0.037	-0.030	0.018	-0.028
	(0.020)	(0.004)	(0.004)	(0.004)	(0.005)	(0.004)
AIC	–	1514	–	-30607	-23399	-29414

Table 1: Elasticities for Translog specifications

[1] Standard errors in parenthesis

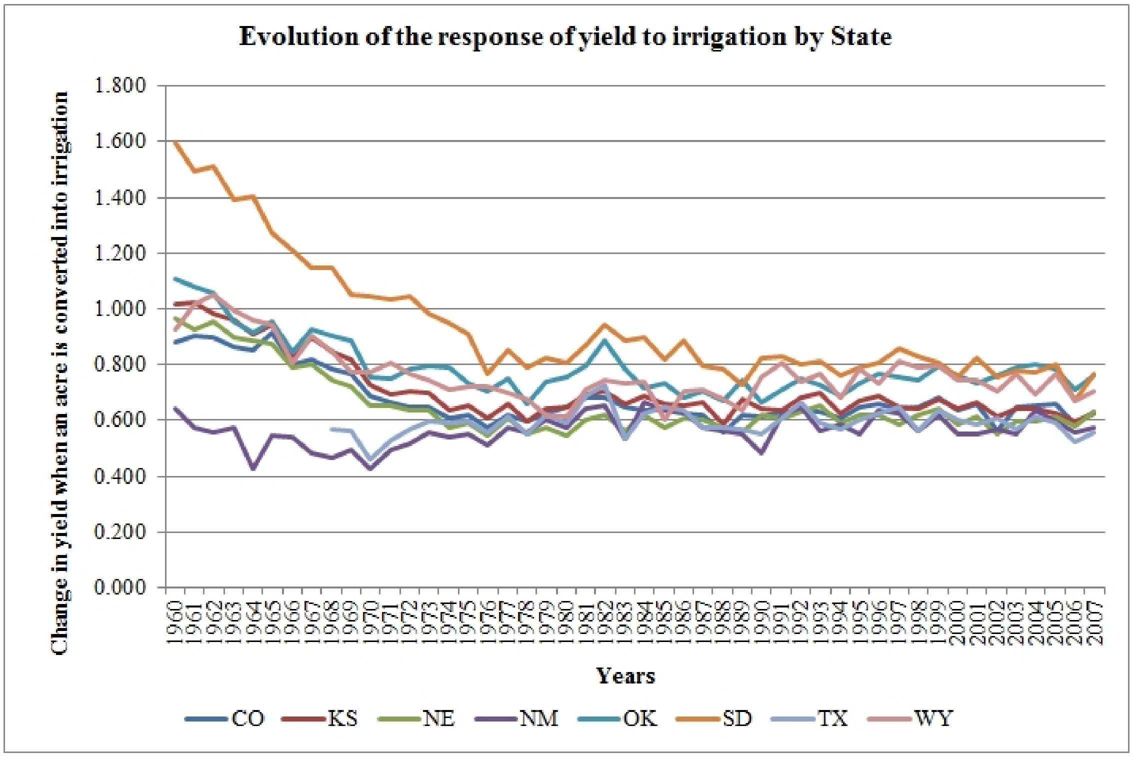

Figure 1: Evolution of the response to irrigation by State.

	IR[1] (1960-2007)	Yield 2007 (Metric Tons/ac)	Value ($)	IR[2] (2007)	Value ($)
Colorado	0.678	3.238	212	0.631	197
Kansas	0.711	3.012	213	0.624	187
Nebraska	0.654	4.772	324	0.630	312
New Mexico	0.565	2.303	116	0.572	117
Oklahoma	0.791	2.278	180	0.758	173
South Dakota	0.939	1.730	170	0.769	139
Texas	0.592	1.948	121	0.556	114
Wyoming	0.766	2.773	199	0.704	183
HP aquifer	**0.667**	**3.395**	**231**	**0.619**	**214**

Table 2: Irrigation water value by state in 2007

[1] Irrigation response overall period of analysis.
[2] Irrigation response in 2007.

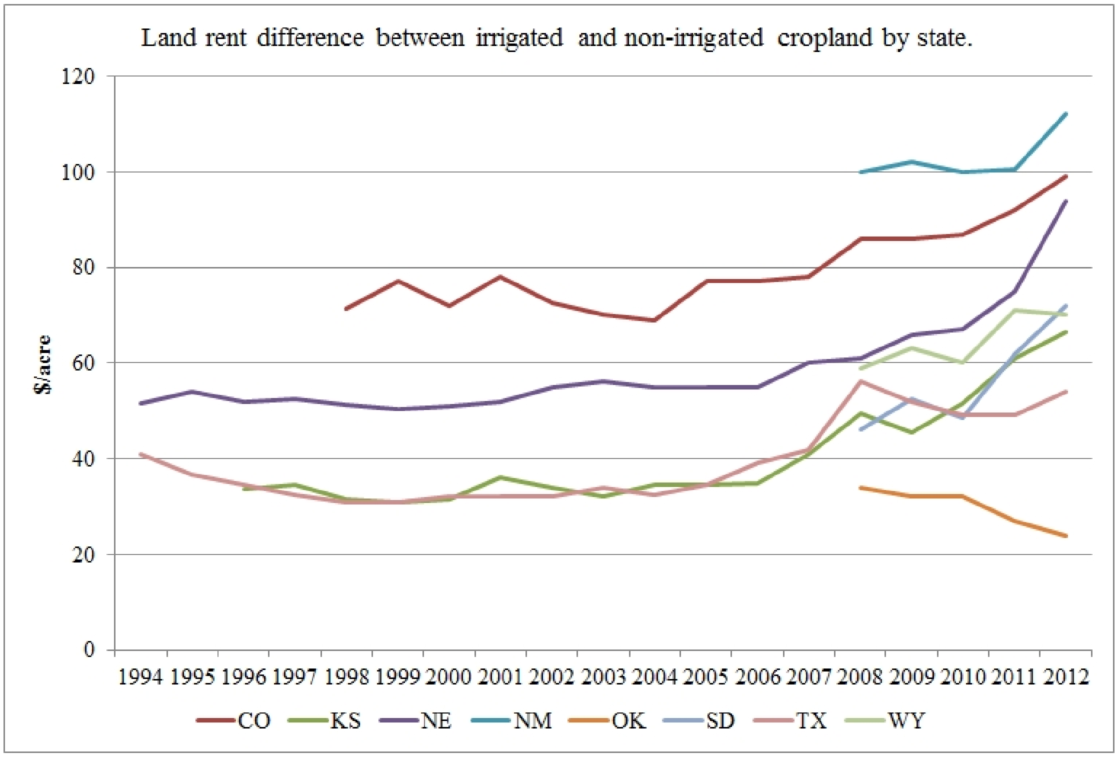

Figure 2: Land rent difference between irrigated and non-irrigated cropland by state. Source: USDA-NASS Quick Stats Lite.