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Depletion of a Ground Water Source: The Role of Irrigation Technology Adoption

Abstract: Under irrigated conditions agricultural producers are expected to adjust their crop patterns, irrigation systems, and production practices as ground water tables decline and irrigation costs increase. This study provides insight into the efficient path of irrigation technology adoption and the implications associated with this process. It is shown that: (a) the efficient crop pattern is related to the ground water supply condition; (b) declines in the proportion of high water requirement crops produced are rapid with high pumping lift and thin saturated thickness; and (c) declines in saturated thickness appear to have a greater impact on crop pattern and irrigated acreage than do increases in pumping lift. Furthermore, it is shown that the adoption rate of advanced irrigation systems is expected to be higher the more abundant is the ground water source.

INTRODUCTION

Irrigation has played an important role in the development and growth of agriculture in the USA. Irrigated farms contribute proportionally more to crop production than do dryland farms. For instance, in 1982, irrigated farms comprised only 12 percent of all farms, yet they produced nearly one-third of the total value of agricultural products (Moore, Crosswhite and Hostetler, 1987). Irrigation is particularly important to the agricultural economy in the semi-arid area of the High Plains: a large land resource area within the Great Plains region of the USA. This region is one of the most heavily irrigated areas in the USA, comprising some 20 percent of the national irrigated acreage. In the High Plains region, irrigation is essential in agricultural production because rainfall is either unreliable or insufficient. The main water source of irrigation in the High Plains region is the Ogallala aquifer, one of the most extensive and important interstate aquifers in the USA.

In the High Plains region, rapid expansion of irrigation practices using ground water began after World War II. In 1982, about 17 million acres of cropland were under irrigation and the total annual water withdrawal was 21 million acre feet (Moore *et al.*, 1987). Because recharge is insignificant compared to withdrawals, the continued overdraft has resulted in declines of ground water tables from 50 feet to 200 feet in some areas (High Plains Associates, 1982). The per unit energy cost of ground water pumping per foot of lift has increased dramatically since the early 1970s. Sloggett (1985) documented increases in energy costs of 182 percent for electricity to 700 percent for natural gas between 1974 and 1983. The increased pumping lift and decreased well yields, coupled with rising energy costs, have resulted in significant increases in the production cost of irrigated crops.

Given a ground water stock, the rate at which the ground water supply diminishes is determined by the amount of withdrawal, the technology of exploitation, and the input–output price relations. Due to the continued overdraft of ground water in the Texas High Plains region, in which about 30 percent of pre-development storage, on the average, has

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been depleted, this region has become the most critical ground water depletion area in the Ogallala formation (Gutentag *et al.*, 1984).

The objective of this study is to derive dynamically optimal rates of ground water use in agriculture which maximize the net present value of returns to the agricultural producer's ground water stock, land, capital, management, risk and overheads under alternative scenarios. Lubbock County was used as a representative area within the Texas High Plains. In particular, this study includes the determination of dynamically efficient crop patterns, irrigation technologies, and ground water use through time.

METHODS AND PROCEDURES

A dynamic framework whose components included a bio-simulation model of crop growth and a firm-level dynamic programming (DP) model were used to derive optimal decision rules of ground water use over time under alternative scenarios. The bio-simulation crop growth model used was the Erosion/Productivity Impact Calculator (EPIC) developed by Williams, Jones and Dyke (1984). This model was used to simulate data on crop yield–water responses under alternative combinations of cropping practices and irrigation technologies. The crop yield–water data simulated were used to estimate yield–water production functions using regression analysis and were used in the dynamic optimization models (Feng, 1992). The major underlying assumption of the DP models was that irrigators consider the total returns derived from irrigation over a long planning horizon. A 50-year planning horizon was used. These models are capable of determining optimal ground water use, cropping pattern, cropping practice, irrigation technology, and marginal user costs while adjusting ground water availability and extraction cost.

The crops considered in this study were cotton, grain sorghum and corn. These three crops encompass 91 percent of the total irrigated area and 47 percent of the non-irrigated area in Lubbock County. Numerous tillage practices and irrigation technologies exist, but the ones included in the optimization models were those which are widely used or show some acceptance in the study's region. Tillage practices considered in this study included conventional and conservation tillage. Conventional tillage was applied to all crop enterprises, while conservation tillage was only applied to cotton production. The conservation tillage method considered was a terminated wheat and cotton (TWH–CO) rotation. Six irrigation technologies were considered in this study. These included conventional furrow (CF), improved furrow (IF), sprinkler-high pressure (SH), sprinkler-drop (SD), low energy precision application (LEPA), and dryland farming. The optimization models in this study were formulated on a per acre basis with percentages being used to represent the proportion of a crop under a given tillage practice and irrigation technology.

The operating cost data used for the crops were the average projected costs for the 1981–1990 period, taken from the *Texas Crop Enterprise Budgets — Texas South Plains District* (Texas Agricultural Extension Services). These budgets included the basic operating costs for dryland and irrigated production, which include fertilizer, seed, herbicide, insecticide, machinery, harvesting costs, and irrigation well costs. The commodity prices used were the ten-year average prices received by farmers for the 1981–90 period as reported in the *Texas Agricultural Statistics* (Texas Department of Agriculture).

The per unit cost of pumping water is a function of pumping lift and well yield. Well yield decreases as the saturated thickness of the aquifer decreases. Therefore, the per unit cost of pumping water is a function of pumping lift and saturated thickness. Also, to evaluate the effect of pumping ground water on the water stock recursive equations, which consider the intertemporal adjustment of water availability, are necessary. All the assumptions and relationships used in deriving the hydrologic equations which describe the dynamics of the per unit cost of pumping water and the aquifer are described in Feng (1992).

Three additional constraints were used in the optimization models. The first constraint was a constraint on operating capital. Operating capital was assumed to be available from two sources. The first source was a fixed value of \$250 per acre in each period of operation. The second source was the portion of the previous year's income which exceeds the average per acre return to land, management, and overhead estimated at \$40 (Texas Agricultural Extension Service). The second constraint was land availability. The third constraint was a pumping capacity constraint at each time period.

SPECIFICATION OF THE DYNAMIC OPTIMIZATION MODEL

The objective function used in the models was that of maximizing the net present value of returns to land, management, ground water stock, risk, and investment in irrigation systems. Net returns are calculated as gross returns minus total costs. The total costs consist of variable costs and fixed costs. The variable costs are the costs directly associated with the level of the control variables, these are the costs of pumping ground water, investment and maintenance costs associated with the cropping practices, and investment and maintenance costs of the various irrigation systems. Given this information, a net return function in time t can be constructed as:

$$(1)\quad NR_t = \Sigma_i \Sigma_j \Sigma_k \Theta_{ijkt} \left\{ P_i Y_{ijkt} \left[WA_{ijkt} \left(WP_{ijkt} \right) \right] - C_{ijk} \left(WP_{ijkt}, X_t, ST_t \right) \right\}$$

where i represents the crops grown; j represents the cropping practices used; k represents the irrigation technologies used; Θ_{ijkt} is the percentage of crop i produced with cropping practice j and irrigated by irrigation technology k in time t; P_i is the price of crop i; WA_{ijkt} and WP_{ijkt} are per acre irrigation water available to the crop and ground water pumped, respectively, for crop i using jth cropping practice and kth irrigation technology at time t; $Y_{ijkt}[.]$ is the per acre yield production function of crop i using the jth cropping practice and the kth irrigation technology at time t; C_{ijk} is the total cost per acre associated with the production of the ith crop using the jth cropping practice and the kth irrigation technology; X_t is the pumping lift at time t; and ST_t is the saturated thickness of the ground water stock at time t.

The objective function to be optimized for the 50-year planning horizon is:

$$(2)\quad \text{Max } NPRV = \Sigma_{t=1}^{50} NR_t (1+r)^{-t}$$

where $NPRV$ is the net present value of returns, and r is the discount rate. The control variables in this optimization problem are WP_{ijkt} and Θ_{ijkt}. Substituting Equation (1) into Equation (2) and adding all the relevant constraints, the empirical dynamic programming model is:

$$(3)\quad \text{Max } NPRV = \Sigma_i \Sigma_j \Sigma_k \Sigma_t \Theta_{ijkt}\left\{P_i Y_{ijkt}\left[WA_{ijkt}\left(WP_{ijkt}\right)\right] - C_{ijk}\left(WP_{ijkt}, X_t, ST_t\right)\right\}(1+r)^{-t}$$

subject to:

$$(4)\quad ST_{t+1} = ST_t - \left[(1-a)\left(\Sigma_i \Sigma_j \Sigma_k \Theta_{ijkt} * WP_{ijkt}\right) - R\right]K / As$$

$$(5)\quad X_{t+1} = X_t + \left[(1-a)\left(\Sigma_i \Sigma_j \Sigma_k \Theta_{ijkt} * WP_{ijkt}\right) - R\right]K / As$$

$$(6)\quad \Sigma_i \Sigma_j \Sigma_k WP_{ijkt} \leq 28.28 * (ST_t / 210)^2 \text{ for all } t$$

$$(7)\quad \Sigma_i \Sigma_j \Sigma_k \Theta_{ijkt} \leq 1 \text{ for all } t$$

$$(8)\quad \Sigma_i \Sigma_j \Sigma_k C_{ijkt} \leq 250 + \left(NR_{t-1} - 40\right) \text{ for all } t$$

$$(9)\quad \Sigma_i \Sigma_j \Sigma_k C_{ijkt} = FC_{ijk} + HC_{ijkt} + PC_t + PEC_{ijkt}$$

$$(10)\quad PEC_{ijkt} = IC_{ijk} 1/\left[125 - 1.5\left(ST_t - S_o\right)\right]$$

$$(11)\quad PC_t = 0.0014539 * \left(X_t + (3.31 * PSI) * P\right)/(PE)$$

$$(12)\quad X_{t=1} = X_1$$

$$(13)\quad ST_{t=1} = ST_1$$

$$(14)\quad \Theta_{ijkt} \geq 0, WP_{ijkt} \geq 0$$

The two Equations of motion, Equations (4) and (5), update the state variables, saturated thickness (ST_t) and pumping lift (X_t). Equations (6), (7), and (8) are the water pumping capacity, land availability, and capital constraints, respectively. Equation (9) is the cost function, where FC_{ijkt} is the fixed cost component (basic operation costs), HC_{ijkt} is the harvest cost, IC_{ijk} is the irrigation system and crop practice investment costs, PC_t and PEC_{ijkt} are the pumping cost without the impact of saturated thickness and pumping cost induced by the change in saturated thickness. Equations (10) and (11) are the definitions of PEC_{ijkt} and PC_t. Equations (12) and (13) are the initial conditions of the aquifer, and (14) ensures that the values of the decision variables are non-negative.

The dynamically efficient solution to this problem is the one which maximizes the net present value of returns by selecting the rates of ground water pumped for each crop and the combination of crops, cropping practices and irrigation technologies used at each point in time, subject to the constraints. This model was also solved under the assumption of no adoption of new irrigation technologies. This was done by adding two more constraints to the model in equation (3) to (14). These constraints were:

(15) $\Sigma_i \Sigma_j \Theta_{ijkt} \leq D_k \;\; K = 1,2,...,Z$ for $t = 1,2...,50$; and

(16) $\Sigma_i \Sigma_k \Theta_{ijkt} \leq H_j \;\; j = 1,2,...,n$ for $t = 1,2...,50$

where D_k is the observed percentage of acres of irrigated cropland using the kth irrigation technology; and H_j is the observed percentage of acres of irrigated cropland using the jth cropping practice. Both D_k and H_j do not change over time. The difference between the allocation with and without these constraints represents the impact due to irrigation technology adoption.

RESULTS

The results of the DP models include the optimal crop pattern, irrigation technology adoption, and quantity of ground water pumped under the alternative scenarios which include four different ground water supply conditions, and with and without technological change. These scenarios are defined in Table 1. The 'Basic model' is the DP model under the ground water supply condition of 150 feet pumping lift and 130 feet saturated thickness, using average prices, and with irrigation technology adoption with a 2 percent discount rate. The other four scenarios of the model are similar to the Basic model except for the changes indicated in Table 1.

Table 1 *Definitions of the Model Scenarios*

Scenarios	Pumping lift (feet)	Saturated thickness (feet)	Irrigation technology (feet)
Basic	150	130	flexible
BasicP1	130	130	flexible
BasicP2	197	130	flexible
BasicS	150	50	flexible
BasicFT	150	130	fixed

Dynamic Optimal Crop Patterns

The solution of the Basic model is presented in Figure 1. The starting values (the values at time period 1) of the proportion of land by crop represent the current real crop pattern in Lubbock County. As shown in Figure 1, the current crop pattern is far from optimal under the specified ground water supply, capital constraint and price conditions. This is because the crop pattern quickly changes to a different crop combination once water use is optimized. Irrigated cotton increases from 40 percent to 74 percent, dryland cotton decreases from 36 percent to zero, irrigated sorghum drops from 6 percent to zero, and dryland sorghum increases from 13 percent to 23 percent, and irrigated corn decreases from 4.5 percent to zero over the first 40 time periods. The optimal crop pattern, as established in the solution, is kept approximately constant over 35 production periods. After the 35th time period, irrigated cotton declines and dryland cotton increases.

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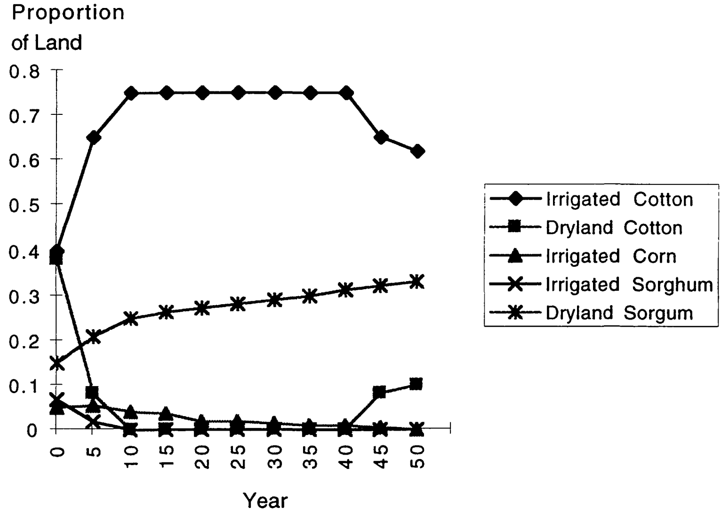

Figure 1 *Optimal Crop Pattern, Basic Model*

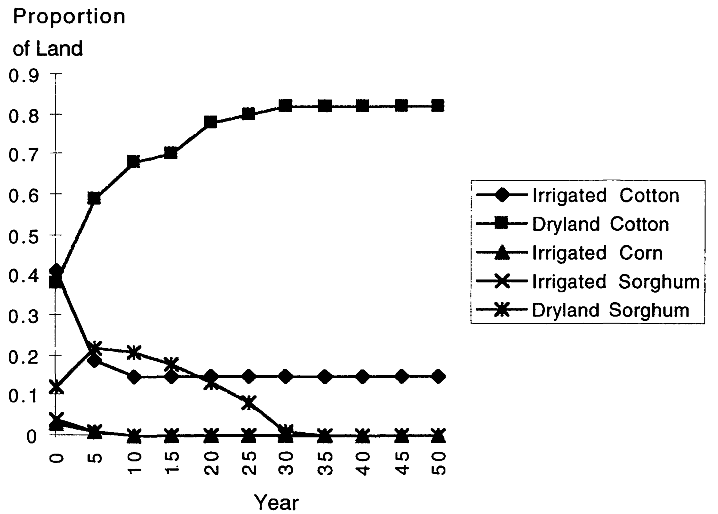

Figure 2 *Optimal Crop Pattern, BasicS Model*

This result suggests that the ground water resource is not utilized efficiently, given the Basic model assumptions. To obtain higher present value of returns from the ground water stock, irrigated production should be further developed. Also, ground water scarcity is not likely to be the factor limiting irrigated production in the next 40 years. This result shows that irrigated cotton is superior to irrigated sorghum and corn. Therefore most of the water is allocated to cotton, less to corn, and none to sorghum. The dynamic efficient crop pattern under the specified condition is approximately three-quarters of irrigated cotton and one-quarter of dryland sorghum.

The solution of the BasicP1 and BasicP2 models in which pumping lift is varied indicated similarities in the optimal crop pattern to that of the Basic model. These models' results showed a trend indicating that the greater the pumping lift, the smaller the irrigated crop percentage. The increased pumping cost due to greater pumping lift may affect irrigated acreage in two ways: (a) increased variable cost of irrigation results in greater production cost, which causes operational capital to become constrained, thus, less cropland can be irrigated; or (b) the increased pumping cost causes irrigated crop production to be less profitable, thus, less money is available for following periods operation and investment on irrigation systems which in turn causes less technological adoption and less percentage of irrigated acreage.

The results of the BasicS model which represents the scenario with poor ground water storage indicated a significantly different crop pattern to those of the previous models, Figure 2. That is, the proportion of irrigated acreage drops, and dryland cotton increases sharply. Thus, these results indicate that the optimal crop pattern is closely related to ground water pumping lift and saturated thickness. The reduction in the percentage of high water requirement crops, such as corn, would be faster in areas with higher pumping lift than in the areas with lower pumping lift, and the total irrigated percentage of cropland is reduced as the pumping lift increases. Declines in saturated thickness appeared to have a greater impact on irrigated production than did increases in pumping lift. Also, the reduction on well yields, due to declines in saturated thickness, result in a reduction in the number of acres that a irrigation system can cover, which in turn causes a great increase in per acre irrigation cost.

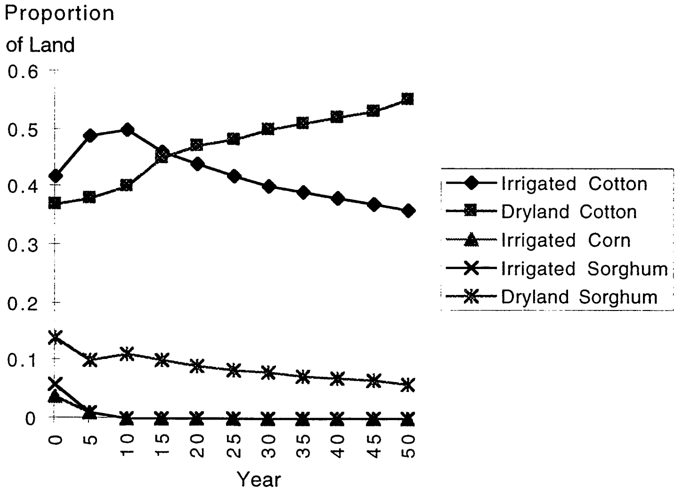

Figure 3 *Optimal Crop Pattern, BasicFT Model*

The results of the BasicFT model indicated that the current crop pattern in Lubbock County is close to the optimal, Figure 3. The differences in the cropping pattern between this model and the Basic model are due to the impact of the irrigation technology adoption assumption. The adoption of irrigation technologies with higher water application efficiency causes an increase in irrigated acreage and the production of crops with high water requirement (as shown in the Basic model). Therefore, the adoption of more efficient irrigation systems does not imply a long-term reduction in ground water use. If the increase in irrigated acreage were large enough to offset the decrease in per acre ground water usage, the net result of irrigation technology adoption would be to increase total water use and, thus, induce a faster depletion of the ground water stock.

Optimal Adoption of Irrigation Technology

The optimal paths of irrigation technology adoption are presented in this section. Among all the irrigation systems and tillage practices included, only three irrigation technologies and one tillage practice, the IF system, the low energy precision application (LEPA) system, dryland farming, and conventional tillage, appeared in the solutions of the DP models under all the scenarios. The LEPA system appeared to be the most efficient irrigation system for all the solutions of the models under all the scenarios. The general trend in the optimal irrigation system adoption under all the scenarios was that LEPA comprised more than 60 percent of cropland for most of the models, the IF system covered less than 5 percent of the cropland for most of the models, and dryland farming covered the remainder.

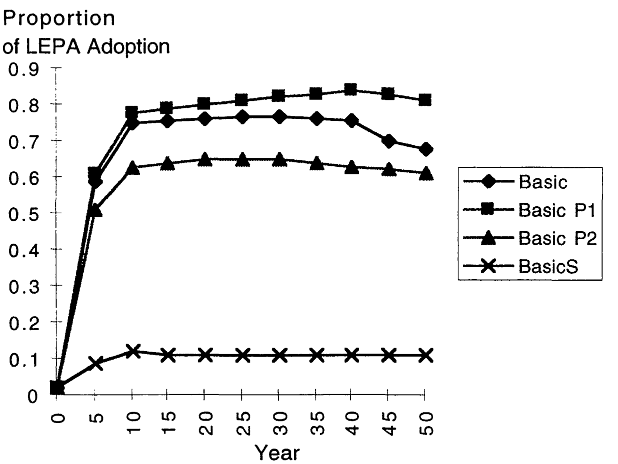

Figure 4 *Optimal LEPA System Adoption Rates at Alternative Water Supply Conditions*

The results of optimal LEPA system adoption for different ground water supply conditions, that is, the solutions for the models of Basic, BasicP1, BasicP2, and BasicS are presented in Figure 4. As shown in Figure 4, under the given cost and capital constraint current usage of LEPA in Lubbock County, 3.6 percent of total irrigated production, is far from optimal. To achieve higher returns to water, land, management, risk, and overhead, more LEPA should be adopted. Notice, however, that the optimal level of adoption of LEPA varies with the ground water supply condition. The optimal path of LEPA system adoption shows that the more abundant is the ground water storage, the higher the LEPA system adoption and the higher the proportion of irrigated production. The results also show that the proportion of irrigated acreage becomes closer to the proportion of LEPA system usage over time. This indicates that if operational capital is not binding, the LEPA system should be used in all irrigated acreage. With respect to the discount rate impact on irrigation technology adoption, it was found that LEPA system adoption is the same under the 2, 5, and 8 percent discount levels during the first 10 production periods. After the 10th production period, LEPA system adoption is lower under the 5 and 8 percent discount rates, than under the 2 percent discount rate, and there is not much difference in the adoption of the LEPA system under the 5 and the 8 percent discount rates.

Optimal Net Present Value of Returns

The per acre net present values of returns of the model under the five scenarios were: Basic, $2713.70; BasicP1, $3230.40; BasicP2, $2250.40; BasicS, $819.10; and BasicFT $1775.80. As can be noticed, the net present value of returns is sensitive to the ground water supply condition. The highest net present value of returns among the different groundwater supply scenarios was $3230.40 for the BasicP1 model. The lowest net present value was $819.10 for the BasicS model. The reduction in the net present value of returns, as the scarcity on ground water increases, is contributed by both the increased ground water pumping cost, and the constraint imposed on irrigation technology adoption and irrigated acreage by the scarcity of ground water.

CONCLUSIONS AND POLICY IMPLICATIONS

Texas High Plains producers are expected to adjust their crop pattern, irrigation systems, and production practices as the ground water level declines and irrigation cost increases. This study provides insight into the efficient path of this adjustment process and implications associated with this process. It was found that the efficient crop pattern is related to the ground water supply condition. The declines in the proportion of high water requirement crops, such as corn, is fast with high pumping lift and thin saturated thickness. The declines in saturated thickness appear to have greater impact on crop pattern and irrigated acreage than do the increases in pumping lift. Thus, most of the ground water is allocated to irrigated cotton and less to non-irrigated corn and sorghum under all scenarios.

Irrigated acreage is not likely to decline within 20 to 30 years in the study region, if the adoption of irrigation technology follows the optimal path, except in areas underlying with thin saturated thickness (approaching 50 feet). The observed declines in irrigated acres in the Texas High Plains are mainly due to the utilization of low efficient irrigation systems, which combined with low crop prices result in low profitability. Declining ground water levels and depletion of the Ogallala aquifer are not the primary causes of the recent declines in irrigated acres, because these would increase if more efficient irrigation technology was used. Given that the total ground water withdrawals and total irrigated acres increase with the adoption of more efficient irrigation technologies, irrigation technology adoption could lead to substantial increases in the net present value of returns, but will not lead to ground water conservation. Public policies aimed at reducing total ground water withdrawals may not achieve their goal through increasing irrigation efficiency, since increases in profitability of irrigation bring about increases in irrigated acreage, and the increase in irrigated acreage will offset the reduction in per acre water use due to increased efficiency.

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DISCUSSION OPENING — Chamhuri Siwar *(University Kegangsaan, Malaysia)*

This highly technical paper is about adjustments in irrigation technology adoption that would maximize the net present value of returns under alternative scenarios given the ground water stock, land, capital, management and risk. Adjustments in optional crop patterns are made under four different ground water supply conditions, with and without technological change.

The result shows that producers respond to changing ground water level and increasing irrigation costs by adjusting their cropping pattern, irrigation systems and production practices.

The writer contends that the ground water supply conditions affect the efficient crop patterns but seems to contradict that contention with another statement that 'declining ground water levels...are not the primary causes of recent decline in irrigated acres'.

It seems that producers' response to prices (costs) may be the more dominant factor. Increasing pumping costs greatly affect irrigated acreage by eating into the profitability of investments on irrigation systems. The producer's objective to maximize net return alters his technology adoption and hence his cropping pattern, preferring the low energy precision application (LEPA) system under all scenarios. The net present value of returns is foremost affected by the increased ground water pumping cost, it seems, and is constrained by scarcity of ground water which affects irrigation technology adoption.

Two questions may be asked regarding the policy implications of the study. First, how would irrigation technology adoption adjust if ground water level reached its critical stage, where it may be no longer economical to pump water? What may be the impact on cropping patterns? Second, how will the social benefit–cost of ground water conservation compare with the social benefit–cost of increasing irrigated acreage?