# A Dynamic Analysis of the Impact of Water Quality Policies on Irrigation Investment and Crop Choice Decisions

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*Abstract*

A dynamic model is developed to analyze farmers' irrigation investment and crop choice decisions under alternative water quality protection policies. The model is applied to an empirical example in the Oklahoma High Plains. The choices of crops and irrigation systems and the resulting levels of irrigation, income, and nitrogen runoff and percolation are simulated over a ten-year period. An effluent tax on nitrogen runoff and percolation is shown to be effective in reducing nitrate pollution. The efficacy of cost sharing in adopting modern irrigation technologies and restrictions on irrigation water use depends on soil type. A tax on nitrogen use is shown to be the least effective policy.

**Key Words: crop selection, dynamic optimization, irrigation investment, water quality**

Increasing concern over water quality and growing pressures on water supplies in some areas, such as the arid western United States, have shifted the focus of irrigation from expansion to water conservation and its influence on the environment. The availability of high-frequency irrigation systems has made it possible to establish and maintain soil moisture conditions at levels which more closely correspond to crop water requirements. As a result, soil physical properties such as water-holding capacity, formerly considered decisive, are no longer major criteria for determining which soils are irrigable. Lower quality lands (e.g., coarse sands and gravels), which are more erosion-prone and more vulnerable to groundwater pollution, can now be brought into production. This may result in greater erosion hazard and groundwater contamination at the extensive margin. On the other hand, adopting high-frequency irrigation technologies is often cited as a means to conserve water or energy and reduce water and chemical losses in runoff and percolation at the intensive margin. The costs and benefits of modern irrigation technologies to water quality have been a topic of much debate (Lichtenberg).

This paper analyzes farmers' irrigation investment and crop choice decisions on different soils and their effect on water quality. Irrigation investment decisions traditionally have focused on increasing net returns from the current crop mix. However, concerns about water quality and irrigation efficiency have affected the decision making environment. Because of differences in the performance characteristics of irrigation systems (e.g., percolation and runoff ratios and application efficiency), the choice of irrigation system greatly affects the quantity of nutrients and chemicals lost in runoff and percolation. Farmers' crop choice decisions also affect water quality because different crops require different types and amounts of chemicals and are produced on different soils under various tillage practices.

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Farmers' irrigation investment and crop choice decisions are closely related. Lichtenberg found that crops tend to be grown on specific ranges of land quality and the adoption of center pivot systems induced significant changes in cropping patterns. When a new irrigation technology becomes available, farmers may switch to an alternative crop because growing an alternative crop using the new technology may produce more net return. Thus, the adoption of irrigation technology also has an indirect effect on water quality by inducing changes in cropping patterns. Because of differences in water requirements, farmers' crop choice decisions may also affect the adoption of irrigation technologies.

Research on the interaction between farmers' crop choice and irrigation investment decisions and their impact on water quality has been limited. Lichtenberg examined the effects of land quality and technological changes in irrigation on cropping patterns. However, he did not focus on how the interaction between cropping patterns and irrigation technologies affect water quality. Segerson and Wu analyzed the impacts of commodity programs and environmental policies on cropping patterns and groundwater pollution, but they did not incorporate the impact of farmers' irrigation investment decisions. The factors that affect the adoption of modern irrigation technologies have been identified by some studies (Caswell and Zilberman (1985), Negri and Brooks, Casterline et al., Dale et al.). These factors include land quality, water source, relative prices and availability of irrigation inputs, and government program participation. Caswell et al. and Caswell and Zilberman (1986) examined the impacts of pricing policies on the adoption of new irrigation technologies using a static model. Their approach primarily emphasizes timeliness of operations rather than investment analysis and thus does not capture the intertemporal nature of irrigation investment and the time-value aspect of the expected costs and returns over the expected life of the irrigation system. Dynamic models for interseasonal irrigation management include those by Knapp et al., Dinar and Knapp, and Matanga and Marino. However, these studies did not focus on the impacts of economic and policy variables on farmers' crop choice and irrigation investment decisions.

This paper develops a dynamic model for analyzing the interaction between farmers' crop choice and irrigation investment decisions. The advance of irrigation technologies is viewed as a process that involves investment in new irrigation systems, switches between alternative crops, and multi-period decision making. Optimal time paths of irrigation investment and crops are derived under the maximum net present value criterion. The impacts of four commonly discussed policy instruments for controlling agricultural water pollution (cost sharing in adopting modern irrigation technologies; drainage and runoff charges; taxes on nitrogen application; and restricting irrigation water use) on farm income, crop yield, water use, runoff and percolation are analyzed using the model. A numerical example based on the production of three crops (corn, grain sorghum, and winter wheat) on two principal soils (Richfield clay loam and Dalhart fine sandy loam) with four possible irrigation systems (furrow, improved furrow, center pivot, and LEPA) in the Oklahoma High Plains demonstrates the application of the theoretical model. The choices of crops and irrigation systems on the two soils with alternative pump lifts under the four policies are simulated. The impacts of the choices on water use and nitrogen runoff and percolation are evaluated.

## A Dynamic Model of Irrigation Investment and Crop Choice Decisions

Consider a farm with n types of soils. Let $A_j$ be the number of acres of soil type $j$. For simplicity, suppose there are only two crops that can be feasibly grown on the farm and production exhibits constant return to scale on each type of soil for both crops. Let $F_{ij}(h_j(K_{jt})W_{ijt}, C_{ijt})$ be the per-acre production function of crop $i$ ($i=1,2$) on soil type $j$ ($j=1,..., n$), where $W_{ijt}$ is the amount of water applied to crop $i$ on soil type $j$ in year $t$, $h_j(K_{jt})$ is the irrigation application efficiency and is defined as the ratio of effective water (the water utilized by crops) to applied water. It is assumed that $h_j(K_{jt})$ depends on soil type j and the level of irrigation capital $K_{jt}$. Thus, $h_j(K_{jt})W_{ijt}$ is the amount of applied water that is utilized by the crop. $C_{ijt}$ is a vector of other inputs such as fertilizers and pesticides. $F_{ij}(\cdot)$ is assumed to have the regular properties of a neoclassical production function.

In each year, the farmer must decide which crop to grow on each type of soil and whether to improve the existing irrigation technologies. To evaluate irrigation investment, the farmer must compare the conversion costs with the benefits derived over the life of the system. The conversion costs include both the investment cost and the adjustment cost. For example, to convert from gated pipe to a center pivot system, the farmer has to buy an underground mainline, a distribution system (pivot, lateral, and sprinklers), and some valves. In addition, the farmer must remove and dispose of the unused parts.[1] It may be reasonable to assume that the adjustment cost $Z_t$ depends on the level of investment $(I_t)$ and increases from a relatively low-cost modification to complete replacement of the old system, i.e., $Z_t'(I_t)>0$. The benefit from the irrigation investment is a reduction in irrigation operating costs, most notably, fuel, labor and repair costs, and benefits that may arise from switching to a more profitable crop. Irrigation investment may also reduce non-irrigation costs such as tillage costs (Earls and Bernardo).

The long-run problem of the farmer is to choose the time paths of combinations of crops and irrigation technologies to maximize the present value of income from each period over the relevant planning horizon:

$$MAX_{\{s_{jt}, I_{jt}\}} \sum_{t=1}^{T} \sum_{j=1}^{n} \eta_t A_j [s_{jt} \Pi_{1jt} \quad (1)$$
$$+ (1 - s_{jt}) \Pi_{2jt} - y_t I_{jt} - Z_t(I_{jt})]$$

s.t.     $K_{jt+1} = I_{jt} + (1-\delta) K_{jt},$     (2)
         $0 \leq s_{jt} \leq 1,$     (3)

where $\eta_t$ is a discount factor depending on the rate of interest; $s_{jt}$ is the share of crop 1 on soil type $j$ in year $t$; $y_t$ is the price of investment goods in year $t$; $Z_t(I_{jt})$ is the adjustment cost expressed as a function of irrigation investment in year $t$; $\delta$ is the depreciation rate of the irrigation capital; and $\Pi_{ijt}$ $(i=1, 2)$ is the short-run indirect profit function defined as:

$$\Pi_{ijt} = MAX_{\{W_{ijt}, C_{ijt}\}} p_{it} F_{ij}(h_j(K_{jt}) W_{ijt}, C_{ijt}) \quad (4)$$
$$- vc_t(K_{jt}, W_{ijt} - r_t K_{jt} - x_t C_{ijt},$$

where $p_{it}$ is the price of crop $i$ in year $t$, $r_t$ is the price of irrigation capital in year $t$, $vc_t(K_{jt})$ is the

acre-inch application costs in year $t$ which include fuel, labor, lubrication, and repairs costs, and $x_t$ is a vector of other input prices. The amounts of water and other variable inputs used are determined by the maximization problem.

The maximization problem (1) can be solved using optimal control or dynamic programming techniques. The current value Hamiltonian function for the maximization problem is

$$H_{jt} = s_{jt} \Pi_{1jt} + (1-s_{jt}) \Pi_{2jt} - y_t I_{jt} - Z_t(I_t)$$
$$+ \lambda_{jt}(I_{jt} - \delta K_{jt}) + \alpha_{jt} s_{jt} + \beta_{jt}(1-s_{jt}), \quad (5)$$

where $\lambda_{jt}$, $\alpha_{jt}$, and $\beta_{jt}$ are the Lagrangian multipliers for the constraints and represent the marginal values of irrigation capital and land allocated to crop 1 and crop 2, respectively. For example, it can be shown that $\lambda_{jt}^* = dJ^*/dK_{jt}$, where $J^*$ is the maximum present value of income from year $t$ to year $T$ with a capital level $K_{jt}$ in year $t$. So, $\lambda_{jt}^*$ can be interpreted as the marginal value or shadow price of the irrigation capital in year $t$. It depends on current and future prices of inputs and outputs.

From the Hamiltonian function, the first-order necessary conditions for the maximization problem can be derived as follows:

$$\frac{\partial H_{jt}}{\partial s_{jt}} = \Pi_{1jt} - \Pi_{2jt} + \alpha_{jt} - \beta_{jt} = 0, \quad (6)$$

$$\frac{\partial H_{jt}}{\partial I_{jt}} = -y_t - Z_t'(I_{jt}) + \lambda_{jt} = 0, \quad (7)$$

$$\frac{\partial H_{jt}}{\partial K_{jt}} = s_{jt} \frac{\partial \Pi_{1jt}}{\partial K_{jt}} + (1 - s_{jt}) \frac{\partial \Pi_{2jt}}{\partial K_{jt}} \quad (8)$$
$$- \delta \lambda_{jt} = \lambda_{jt-1} - \lambda_{jt}.$$

The following Kuhn-Tucker conditions must also be satisfied:

$$\alpha_{jt} s_{jt} = 0, \quad \beta_{jt}(1-s_{jt}) = 0. \quad (9)$$

Equation (6) indicates that if the per acre profit of crop 1, $\Pi_{1jt}$, is greater than that of crop 2, $\Pi_{2jt}$, on soil type $j$ in year $t$, then

$\beta_{jt} = \Pi_{1jt} - \Pi_{2jt} + \alpha_{jt} > 0$. The Kuhn-Tucher conditions (9) implies that $s_{jt} = 1$, that is, the land with soil type $j$ will be used to grow crop 1 in year $t$. Similarly, it can be shown that, if the per acre profit of crop 1 is less than the per acre profit of crop 2, the land with soil type $j$ will be used to grow crop 2 in year $t$. If $\Pi_{1jt} = \Pi_{2jt}$, $s_{jt}$ can be any place between 0 and 1, i.e., either crop 1 or crop 2 can be grown. Note that the crop choice decision is made for a given piece of land with a given soil type in a given year. Over years, the farmer may switch to other crops because of crop rotation practices and changes in input and output prices. Even in a given year, different farmers may grow different crops on the same soil because of government commodity programs and differences in farming tradition, risk preference, financial condition, and other factors. However, the model can not capture these factors.

The above result indicates that each crop will be grown on specific types of land, and the total acreage of crop 1 in year t will be

$$TA_{1t} = \sum_{\{j,\ \Pi_{1jt} \geq \Pi_{2jt}\}} A_j , \tag{10}$$

where $\{j;\ \Pi_{1jt} \geq \Pi_{2jt}\}$ is the set of soil types that are used to grow crop 1 in year $t$. Suppose there is a parametric increase in the price of crop 1 from $p_{1t}$ to $p_{1t}^{*}$ in year $t$. The soil types that will be used to grow crop 1 would become

$$\{\ j;\ \Pi_{1jt} + \frac{\partial \Pi_{1jt}}{\partial p_{1t}}(p_{1t}^{*} - p_{1t}) \geq \Pi_{2jt}\}$$
$$= \{\ j;\ \Pi_{1jt} + y_{1t}^{*}(p_{1t}^{*} - p_{1t}) \geq \Pi_{2jt}\}\ , \tag{11}$$

where $\partial \Pi_{1jt}/\partial p_{1t} = y_{1t}^{*}$ (Hotelling's Lemma) is the per-acre output supply of crop 1 on soil type $j$ in year $t$. It can be shown that

$$\{\ j;\ \Pi_{1jt} \geq \Pi_{2jt}\} \subseteq \{\ j;\ \Pi_{1jt} + y_{1t}^{*}(p_{1t}^{*} - p_{1t}) \geq \Pi_{2jt}\}, \tag{12}$$

Thus, more types of soil will be used to grow crop 1 when the price of crop 1 increases. Similarly, it can be shown that an increase in the price of crop 2 will decrease acreage allocated to crop 1, and that, if crop 1 uses water more intensively than crop 2, an increase in irrigation operating cost would shift land from crop 1 to crop 2. Otherwise, it would shift land from crop 2 to crop 1.

Equations (7) and (8) and the equation of motion for irrigation capital determine the optimal time path of irrigation investment. Equation (7) indicates that the irrigation system should be upgraded until the sum of marginal investment and adjustment costs equals the marginal value of all future incomes. If we substitute (4) into (8) and assume that crop $i$ is grown, we will obtain

$$p_{it}\frac{\partial F_{ij}}{\partial K_{jt}} - W_{ijt}^{*}\frac{\partial vc_{t}}{\partial K_{jt}} = r_t + \delta\lambda_{jt} + (\lambda_{jt-1} - \lambda_{jt}), \tag{13}$$

where $W_{ijt}^{*}$ is the water demand derived from the maximization problem (4). The first term in the left hand side is the marginal value product of the irrigation capital and the second term is the saving in operating costs from using more advanced irrigation technologies. On the right hand side, $r_t$ is the investment cost, $\delta\lambda_{jt}$ represents the depreciation cost, and $(\lambda_{jt} - \lambda_{jt-1})$ is the change in the shadow price of the irrigation capital (or capital loss). So, $r_t + \delta\lambda_{jt} + (\lambda_{jt-1} - \lambda_{jt})$ can be interpreted as the long-run marginal cost of the irrigation capital. Thus, equation (13) indicates that, to maximize the long-run profit, irrigation capital should be kept at the level where the sum of the marginal value product of irrigation capital and the saving in operating cost equals the sum of investment cost, depreciation cost, and capital losses. This rule and the rule derived from equation (8) will be used in the empirical section to determine when a farmer should convert to an improved irrigation technology. Since $\lambda_{jt}$ depends on both the current and the future prices of inputs and outputs, the optimal investment in irrigation in each year is a function of the current stock of irrigation capital and current and future prices.

## Model Application

In addition to high application efficiency and low operating cost, the adoption of modern irrigation technologies also generates some social benefit by reducing runoff and percolation losses. Percolation and runoff losses often contain nitrates and pesticides, which may cause water pollution and impose large social costs. However, without environmental regulations, the farmer would not

take social benefits and costs into account when making production decisions. Four commonly discussed policy options to promote adoption of modern irrigation technologies are (a) a tax on nitrogen runoff and percolation; (b) a nitrogen use tax; (c) cost sharing in adopting modern irrigation technologies; and (d) restricting irrigation water uses. This section analyzes the impacts of these policies on water use, pollution, and adoption decisions using the model presented in the last section.

## The Short-Run Impacts

Denote the stylized pollution generation function (see Opaluch and Segerson and Antle and Just) of crop i on soil type $j$ by $G_{ij}(m_j(K_{jt})W_{ijt}, C_{ijt})$, where $m_j(K_{jt})$ is the fraction of water that is not utilized by the crop and is environmentally damaging: $m_j(K_{jt}) \leq 1-h_j(K_{jt})$. It is assumed that $m'_j(K_{jt})<0$. If an ambient pollution tax $\tau$ is levied, the pollution externalities would be internalized, and the farmer is forced to take the social cost into account when making production decisions. The quasi rent per acre to grow crop i on soil type $j$ becomes

$$\Pi_{ijt}(\tau) = \underset{\{W_{ijt},C_{ijt}\}}{MAX} \quad p_{it}F_{ij}(h_j(K_{jt})W_{ijt},C_{ijt})$$

$$-vc_i(K_{jt})W_{ijt}-r_tK_{jt}-x_tC_{ijt} \qquad (14)$$

$$-\tau G(m_j(K_{jt})W_{ijt},C_{ijt}),$$

where $K_{jt}$ is fixed in the short run. Let $W_{ijt}^*$, $Y_{ijt}^*=F_{ij}(h_j(K_{jt})W_{ijt}^*,C_{ijt}^*)$ and $R_{ijt}^*=G_{ij}(m_j(K_{jt})W_{ijt}^*,C_{ijt}^*)$ denote the water demand, output supply and pollution per acre from the short-run maximization problem. It can be shown that

$\partial W_{ijt}^*/\partial\tau \leq 0$, $\partial Y_{ijt}^*/\partial\tau \leq 0$, $\partial R_{ijt}^*/\partial\tau \leq 0$ and $\partial\Pi(\tau)/\partial\tau \leq 0$. Thus, the pollution taxes would reduce water use and pollution as well as output and income.

The anti-pollution taxes also affect crop mix in the short run. Under the taxes, the soil types that would be used to grow crop 1 become

$$\{j;\ \Pi_{1jt} + \frac{\partial\Pi_{1jt}(\tau)}{\partial\tau}\tau \geq \Pi_{2jt} + \frac{\partial\Pi_{2jt}(\tau)}{\partial\tau}\tau\} \qquad (15)$$

$$= \{j;\ \Pi_{1jt} + (R_{2jt}^* - R_{1jt}^*)\tau \geq \Pi_{2jt}\}$$

If growing crop 1 generates more pollution than growing crop 2, i.e., $R_{1jt}^* > R_{2jt}^*$, then $\{j; \Pi_{1jt}+(R_{2jt}^*-R_{1jt}^*)\tau \geq \Pi_{2jt}\} \subseteq \{j; \Pi_{1jt}\geq\Pi_{2jt}\}$. Thus, less land will be used to grow crop 1. Intuitively, when an anti-pollution tax is imposed, the net return to crop 2 would become greater than that to crop 1 after taxes on soils where the net return to crop 1 is only slightly higher than that to crop 2 before the taxes. As a result, these soils would be switched to crop 2.

Similarly, it can be shown that $\partial C_{ijt}^*/\partial x_t \leq 0$, $\partial Y_{ijt}^*/\partial x_t \leq 0$, $\partial R_{ijt}^*/\partial x_t \leq 0$ and $\partial\Pi/\partial x_t \leq 0$. Thus, an increase in nitrogen price due, for example, to a tax would also reduce nitrogen use and pollution as well as output and income. Taxes on nitrogen may also affect crop mix. It would encourage farmers to reallocate land from crops that use nitrogen intensively to crops that use it less intensively.

An alternative to taxes may be positive incentives to adopt modern irrigation technologies that generate less water pollution. If the government shares q percent of the fixed cost of a modern irrigation system, then the quasi rent per acre to grow crop i on soil type j is

$$\Pi_{ijt}(q) = \underset{\{W_{ijt},C_{ijt}\}}{MAX} \quad p_{it}F_{ij}(h_j(K_{jt})W_{ijt},C_{ijt})$$

$$-vc_i(K_{jt})W_{ijt}-(1-q)rK-x_tC_{ijt}. \qquad (16)$$

The first order conditions of this maximization problem are the same as those without cost sharing. Thus, the cost sharing does not change water use and, therefore, runoff and percolation of a given irrigation system. Because it does not change the relative profitability of different crops, cost sharing does not change crop mix in the short run. However, because it promotes adoption of modern irrigation technologies, cost sharing may induce changes in cropping patterns in the long run.

If irrigation water use is limited to $\bar{W}$ inches per acre, the quasi rent per acre to grow crop i on soil type j in year t would be

$$\Pi_{ijt}(\bar{W}) = \underset{\{W_{ijt}, C_{ijt}\}}{MAX} \ p_{it} F_{ij}(h_j(K_{jt}) W_{ijt}, C_{ijt}) \tag{17}$$
$$- vc_i(K_{jt}) W_{ijt} - rK - x_t C_{ijt},$$

subject to $W_{ijt} \leq \bar{W}$. As long as the water use limit is bounding, it will reduce farm income and runoff and percolation. Restricting irrigation water uses may also affect farmers crop choice decisions. It may force farmers to grow crops that use water less intensively. Farmers may even switch from irrigation to dryland production.

## The Long-Run Impacts

The new rule for irrigation investment under the anti-pollution tax becomes

$$p_{it} \frac{\partial F_{ij}}{\partial K_{jt}} - W_{ijt}^* \frac{\partial vc_i}{\partial K_{jt}} - \tau \frac{\partial G_{ij}}{\partial K_{jt}} \tag{18}$$
$$= r_t + \delta \lambda_{jt} + (\lambda_{jt-1} - \lambda_{jt})$$

Irrigation investment generates an increase in output due to high application efficiency and a decrease in acre-inch operating cost. In addition, irrigation investment generates a saving in pollution taxes due to reduced runoff and percolation losses (the third term on the right-hand side). This benefit gives farmers more incentive to adopt modern irrigation technologies. The cost sharing policy induces farmers to adopt modern irrigation technologies by reducing adoption costs. Although both the anti-pollution taxes and the cost sharing promote adoption of modern technologies, the impact of limiting irrigation water use on the adoption of modern irrigation technologies is not clear. Moderate restrictions on water use would encourage the adoption of modern irrigation technologies; however, excessive restrictions would discourage it. When water use is restricted too much, the gain from the increased application efficiency can not compensate the increased system cost. Equation (18) indicates that a nitrogen use tax does not directly affect the adoption decision.

## An Empirical Example

The choices of crops and irrigation systems over the next ten years (1993-2002) in the Oklahoma High Plains are projected based on the theoretical model presented above. Irrigation plays a significant role in the agricultural production of the Oklahoma High Plains. The region produces 63 percent of the state's corn, 87 percent of the state's irrigated grain sorghum, and 78 percent of the state's irrigated wheat (Dale et al.). In response to the declining water levels, many farmers have switched to water conserving irrigation technologies and adopted higher yielding varieties of crops (Mapp et al.). These features make the region an ideal empirical setting for simulating the interaction between farmers' crop choice and irrigation investment decisions.

## Empirical Specification

The simulation is based on the production of three dominant crops (corn, grain sorghum, and wheat) on two principal cropland soils (Richfield clay loam and Dalhart fine sandy loam). Richfield clay loam and Dalhart fine sandy loam soils account for over half of the principal cropland in the region (Mapp et al.). Irrigation systems commonly used in the region are furrow, improved furrow, center pivot, and low energy precision application (LEPA). The most prevalent furrow system in the region is gated pipe. The higher application efficiency of the improved furrow is achieved through practices such as tailwater reuse or the surge-flow technique. Center pivot irrigation provides a considerably higher efficiency of water use particularly on sandy to sandy loam soils. LEPA is a refinement of the center pivot system which employs long drop tubes and specially designed emitters to minimize irrigation losses. It is assumed that a farmer can grow one of the three crops using one of the four possible irrigation systems or dryland production of wheat or grain sorghum on each soil.

The optimal choices of crops and irrigation systems and the resulting yield, water use, and nitrogen runoff and percolation on each soil over the period 1993-2002 are projected by solving the following problem, a discrete form of model (1):

$$MAX_{\{i_{jt},k_{jt}\}} \sum_{t=1993}^{2002} \eta_t [\Pi_{jt}(i_{jt},k_{jt}) - Z(k_{jt-1},k_{jt})], \qquad (19)$$

$$where \quad \Pi_{jt}(i_{jt},k_{jt}) = MAX [p_{it}F_{ij} - W_{ijkt}vc_{kt}$$

$$- N_{ijkt}nw_t - FC_{kt} - OC_{ikt} \qquad (20)$$

$$- \tau(NR_{ij} + NP_{ij})]$$

is the restricted per-acre profit function of crop $i$ on soil type $j$ using irrigation system $k$ in year $t$;[2] $F_{ij}$ is the production function of crop i on soil type $j$; $N_{ijkt}$ is the amount of nitrogen applied; $nw_t$ is the nitrogen price; $FC_{kt}$ is the fixed cost of the irrigation system; $OC_{ikt}$ is the cost of all other inputs; $\tau$ is the rate of tax on nitrogen runoff and percolation; $NR_{ij}$ and $NP_{ij}$ are nitrogen runoff and percolation functions of crop $i$ on soil type $j$, respectively; $Z(k_{jt-1}, k_{jt})$ is the adjustment cost of converting the old system $(k_{jt-1})$ to the new one $(k_{jt})$ in year $t$; $\eta_t$ is the discount factor calculated as $\eta_t = 1/(1+\gamma_{1993})(1+\gamma_{1994})...(1+\gamma_t)$, $\gamma_t$ is the interest rate in year $t$. All other variables are defined as before. For simplicity, it was assumed that the farmer was deciding to buy a new system at the beginning of the simulation period, and that costs of switches between crops are negligible.

Because of the high correlation between water and nitrogen application (see the next section for a discussion of the data used), the response of crop yield to water and nitrogen uses was specified as a quadratic function of a joint input of water and nitrogen:

$$F_{ij} = a_{ij} + b_{ij} E_{ij} + c_{ij} E_{ij}^2, \qquad (21)$$

where $E_{ij}$ is a joint input of water and nitrogen for crop i on soil type $j$. $E_{ij}$ was measured as inches of effective water applied (i.e., $h_{jk}W_{ijt}$). Nitrogen application associated with each level of effective water was determined as the quantity of $N$ required to avoid $N$ deficits. As was suggested by the analysis in Caswell and Zilberman (1986) and the estimates reported in Hexem and Heady, a quadratic functional form was chosen for the yield response.

The amount of nitrogen lost in runoff or percolation was assumed to depend on the amount of water applied and the system used to apply the water:

$$NR_{ij} \ (or NP_{ij}) = d_{0ij}+d_{1ij}W_{ij}+d_{2ij}W_{ij}^2+d_{3ij}SP \cdot W_{ij}^2$$

$$+ d_{4ij}IF+d_{5ij}CP+d_{6ij}LE \qquad (22)$$

where $NR_{ij}$ and $NP_{ij}$ represent nitrogen runoff and percolation in producing crop $i$ on soil type $j$; $W_{ij}$ is the amount of water applied; $SP$ is a dummy variable for the sprinkler system (the center pivot or LEPA); and $IF$, $CP$, and $LE$ are dummy variables for the improved furrow, center pivot, and LEPA, respectively. The amount of nitrogen used was not included in the equation because of the high correlation between water and nitrogen uses. Thus, the coefficients reflect the influence of both water and nitrogen uses. It is expected that $d_{2ij} \geq 0$ because as the amounts of water and nitrogen increase, nitrogen runoff and percolation will increase at an increasing rate. Likewise, it is expected that $d_{3ij} \leq 0$ because nitrogen runoff and percolation will increase at a lower rate if a sprinkler system is used. Because nitrogen runoff and percolation is expected to increase in response to increases in water and nitrogen applications, only one branch (i.e., the upward sloping side) of the quadratic curve is used to represent the relationship between nitrogen runoff/percolation and water and nitrogen use.

## Data and Assumptions

Equations (21) and (22) were estimated for corn, grain sorghum and wheat on Richfield clay loam and Dalhart fine sandy loam soils using the simulation results of the EPIC-PST model as reported in Mapp et al.. EPIC-PST was developed to simulate the effects of agricultural practices on crop yield and chemical losses by runoff, sediment, and percolation (Sabbagh et al.). A 20-year EPIC-PST simulation run was conducted at different irrigation levels for each combination of crop, soil, and irrigation system. Results of each run indicated by year the crop yield, the amounts of nitrogen and water applied, and nitrogen runoff and percolation.[3] In the EPIC-PST runs, nitrogen applications increase in conjunction with effective irrigation water to avoid $N$ deficits using the automatic $N$ application option of EPIC-PST. Thus, yield increases were achieved by increasing both irrigation and nitrogen application. Equation (21) was estimated using Ordinary Least Squares (see

Table 1). The total number of observations is 480 for corn (20 years, 4 irrigation systems, and 6 irrigation levels) and 400 for grain sorghum and wheat (20 years, 4 irrigation systems, and 5 irrigation levels). The inches of water applied are converted to inches of effective water using application efficiency parameters adapted from Musick et al. and Lyle and Bordovsky. Nitrogen runoff and percolation equations were estimated simultaneously using the Seemingly Unrelated Regression method and the 20-year average data of nitrogen runoff and percolation (see Table 2).

The commodity price projections by the Food and Agricultural Policy Research Institute (FAPRI, 1993*a*) for the 1993-2002 period were used in developing the Oklahoma price projections for corn, grain sorghum and wheat. FAPRI projections are based on a series of assumptions about the general economy, agricultural policies, the weather and technological change. It is assumed that current agricultural policies will continue in the U. S. and other trading nations. Average weather conditions and historical rates of technological change are assumed to prevail during the projection period. Using the historical data on the U. S. and Oklahoma commodity prices from 1970 to 1990 and regression analysis, the relationship between national and Oklahoma prices is established for corn, grain sorghum and wheat. Based on the relationship and the FAPRI projections, the Oklahoma prices of corn, grain sorghum and wheat over the 1993-2002 period are calculated.

Data on acre-inch operating costs for the four irrigation systems were taken from Earls.[4] Operating costs are comprised of four components: fuel cost, lubrication cost, repair cost, and labor cost. With the exception of labor cost, all other cost components change with irrigation system and pump lift. Repair and lubrication were assumed to be constant over the study period. Labor cost is calculated by multiplying the labor requirement per-acre inch by the inches of water used and the Oklahoma farm field worker wage rate. The Oklahoma farm field worker wage rate for the period 1993-2002 is projected based on a wage index series provided by FAPRI and the 1991 Oklahoma farm field worker wage rate (USDA). The principal fuel used in the region for irrigation is natural gas. Thus, annual fuel cost is calculated

by multiplying the energy requirement per-acre inch by the inches of water applied and the natural gas price for irrigation. Using historical data on natural gas prices from 1970-89 as reported by the American Petroleum Institute and regression analysis, the relationship between the natural gas price for irrigation and the U. S. wellhead gas price is established. Based on this relationship and FAPRI projections for the U. S. wellhead price, natural gas prices for irrigation are projected for the 1993-2002 period.

The total investment and conversion costs of the four irrigation systems are calculated using the Oklahoma State University Irrigation Cost Generator (Kletke et al.). The annual fixed cost of an irrigation system includes depreciation, interest, insurance, and taxes. The total investment cost is annualized using straight line depreciation. Following Lichtenberg, interest cost is calculated based upon the average value of the system. The interest rate of prime commercial bank loans projected by FAPRI (1993b) for the 1993-2002 period is used as an estimate. The same interest rate is used in calculating the discount factor $\eta_f$. Annual insurance cost and taxes are assumed to be 1 percent and 0.6 percent, respectively, of the average annual investment (Kletke et al.).

Costs for nitrogen and all other inputs, which include chemicals, seed, labor, fuel, lube, repairs, custom operations, operating capital, and machinery, are obtained from the 1992 Oklahoma Crop Budgets by Oklahoma State University. To generate the costs of these inputs over the 1993-2002 period, the 1992 nitrogen price was adjusted by the 1992-2002 fertilizer price index provided by FAPRI, the costs for other variable inputs were adjusted by the total variable expenses projected by FAPRI (1993b); and the costs for fixed inputs were adjusted by the price index of machinery and equipments (FAPRI, 1993b).

## Baseline Results

The simulation indicates that growing grain sorghum using improved furrow irrigation would be more profitable than any other combination on both Richfield clay loam soil and Dalhart fine sandy loam soil in the next ten years (Table 3). The per-acre income fluctuates between 60 and 130 dollars

**Table 1.** Estimates of Parameters of Yield Response Functions[a]

| parameter | Corn | | Grain Sorghum | | Wheat | |
|---|---|---|---|---|---|---|
| | Richfield cl | Dalhart fsl | Richfield cl | Dalhart fsl | Richfield cl | Dalhart fsl |
| $a_{ij}$ | 108.78 | 123.86 | 65.48 | 57.15 | 8.76 | 9.58 |
| | (7.34)[b] | (5.48) | (5.83) | (6.36) | (3.23) | (3.52) |
| $b_{ij}$ | 9.63 | 5.85 | 9.13 | 8.37 | 8.55 | 8.62 |
| | (1.15) | (0.88) | (0.99) | (1.19) | (0.85) | (0.96) |
| $c_{ij}$ | -0.22 | -0.10 | -0.18 | -0.16 | -0.24 | -0.26 |
| | (0.04) | (0.03) | (0.04) | (0.05) | (0.05) | (0.06) |
| $R^2$ | 0.37 | 0.33 | 0.50 | 0.44 | 0.58 | 0.54 |

[a] $Y_{ij} = a_{ij} + b_{ij} E_{ij} + c_{ij} E_{ij}^2 + e_{ij}$, where $Y_{ij}$ is the yield of crop $i$ on soil type $j$; and $E_{ij}$ is a joint input of water and nitrogen applied to crop $i$ on soil type $j$;

[b] Standard errors are in parentheses.

**Table 2.** Estimates of Parameters of Nitrogen Runoff and Percolation Functions[a]

| Variable | Corn | | | | G. Sorghum | | | | Wheat | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Richfield CL | | Dalhart FSL | | Richfield CL | | Dalhart FSL | | Richfield CL | | Dalhart FSL | |
| | Runoff | Percol. | Runoff | Percol. | Runoff | Percol. | Runoff | Percol. | Runoff | Percol. | Runoff | Percol. |
| Const | 16 1284*** | 0.3004 | 17.0860*** | 1.0925 | 11.0456*** | 0.4382 | 14.0822*** | 3.2757*** | 15.5631*** | 0.1991 | 18.0877*** | 0.8232 |
| | (2.2718)[b] | (1.0509) | (3.5281) | (1.4615) | (0.6230) | (0.2907) | (0.5401) | (0.5798) | (1.9058) | (0.1558) | (2.6929) | (0.7472) |
| $W_{ij}$ | -0.3644 | -0.0993 | 0.8076 | 0.1711 | -0.2063*** | -0.0836* | 0.0646** | 0.0953*** | -1.8676*** | -0.0954** | -1.7758*** | -0.3227* |
| | (0.3324) | (0.1538) | (0.4914) | (0.2036) | (0.0884) | (0.0413) | (0.0273) | (0.0293) | (0.4348) | (0.0355) | (0.5456) | (0.1514) |
| $W_{ij}^2$ | 0.0269** | 0.0059 | -0.0114 | 0.0066 | 0.0100* | 0.0045*** | | | 0.1082*** | 0.0070*** | 0.1014*** | 0.0270** |
| | (0.0116) | (0.0054) | (0.0152) | (0.0063) | (0.0030) | (0.0014) | | | (0.0235) | (0.0019) | (0.0245) | (0.0068) |
| $SP \cdot W_{ij}^2$ | -0.0150*** | -0.0008 | -0.0123* | -0.0015 | 0.0018 | -0.0011* | | | -0.0257** | -0.00001 | -0.0260 | -0.0054 |
| | (0.0030) | (0.0014) | (0.0060) | (0.0025) | (0.0013) | (0.0006) | | | (0.0085) | (0.0007) | (0.0164) | (0.0046) |
| IF | -4.1478*** | 0.4023* | 1.5306 | -1.1387** | -1.8622*** | 0.6184*** | -0.1626 | -2.0667*** | -0.3932 | 0.1677** | -0.8117 | 0.5478** |
| | (0.4384) | (0.2028) | (0.9996) | (0.4141) | (0.2050) | (0.0956) | (0.3958) | (0.4249) | (0.8303) | (0.0679) | (0.9041) | (0.2509) |
| CP | -10.6833*** | 0.1018 | -19.2839*** | -4.9830*** | -8.6216*** | 0.0099 | -12.7718*** | -4.1308*** | -2.7105** | 0.0893 | -3.1844* | 0.3761 |
| | (0.7815) | (0.3615) | (3.1550) | (1.3069) | (0.3582) | (0.1672) | (0.4341) | (0.4660) | (1.2411) | (0.1015) | (1.6697) | (0.4633) |
| LE | -10.8682*** | 0.1735 | -19.3656*** | -3.3785*** | -8.7359*** | 0.0352 | -13.0298*** | -3 9490*** | -2.5236* | 0.0387 | -3.3717** | 0.3836 |
| | (0.7088) | (0.3279) | (1.8459) | (0.7647) | (0.3197) | (0.1492) | (0.4128) | (0.4432) | (1.1938) | (0.0976) | (1.5314) | (0.4249) |
| System Weighted $R^2$ | 0 99 | | 0.99 | | 0.99 | | 0 99 | | 0 90 | | 0.98 | |

[a] $NR_{ij}$ (or $NP_{ij}$) $= d_{0ij} + d_{1ij} W_{ij} + d_{2ij} W_{ij}^2 + d_{3ij} SP \cdot W_{ij}^2 + d_{4ij} IF + d_{5ij} CP + d_{6ij} LE$, where $NR_{ij}$ and $NP_{ij}$ represent nitrogen runoff and percolation in producing crop $i$ on soil type $j$; $W_{ij}$ is the amount of water (nitrogen) applied; $SP$ is a dummy variable for the sprinkler system (the center pivot or LEPA); and $IF$, $CP$, and $LE$ are dummy variables for the improved furrow, center pivot, and LEPA systems, respectively. Three asterisks indicate statistical significance at the 1% level; two asterisks indicate statistical significance at the 5% level, and an asterisk indicates statistical significance at the 10% level.

[b] Standard errors are in parentheses.

Table 3. The Simulated Choices of Crops and Irrigation Systems Under Alternative Policies[*]

| Year | Baseline | Taxes on Nitrogen Runoff & Percolation | | Taxes on Nitrogen | | Limitations on Irrigation Water Use | | | Cost Sharing in Adop Sprinkler & LEP | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $1/lb. | $5/lb. | 50 percent | 100 percent | 15"/A | 10"/A | 5"/A | 5 percent | 20 per |
| | | *--------------------On Dalhart Fine Sandy Loam Soil, 300 feet pump lift----------------------* | | | | | | | | |
| 1993 | *S, IF* | *C, LE* | *S, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 1994 | *S, IF* | *C, LE* | *S, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 1995 | *S, IF* | *C, LE* | *C, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 1996 | *S, IF* | *C, LE* | *C, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 1997 | *S, IF* | *C, LE* | *S, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 1998 | *S, IF* | *S, LE* | *S, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 1999 | *S, IF* | *S, LE* | *S, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 2000 | *S, IF* | *C, LE* | *S, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 2001 | *S, IF* | *C, LE* | *S, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| 2002 | *S, IF* | *C, LE* | *C, LE* | *S, IF* | *S, IF* | *C, LE* | *C, LE* | *S, DRY* | *C, LE* | *C, LE* |
| | | *-----------------------On Richfield Clay Loam Soil, 300 feet pump lift----------------------* | | | | | | | | |
| 1993 | *S, IF* | *S, IF* | *S, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 1994 | *S, IF* | *S, IF* | *C, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 1995 | *S, IF* | *S, IF* | *C, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 1996 | *S, IF* | *S, IF* | *C, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 1997 | *S, IF* | *S, IF* | *C, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 1998 | *S, IF* | *S, IF* | *S, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 1999 | *S, IF* | *S, IF* | *S, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 2000 | *S, IF* | *S, IF* | *C, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 2001 | *S, IF* | *S, IF* | *C, LE* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |
| 2002 | *S, IF* | *S, IF* | *C, LE* | *S, IF* | *S, IF"* | *S, IF* | *S, IF* | *S, IF* | *S, IF* | *C, LE* |

[*] *C*=Corn; *S*=Grain Sorghum; *IF*=Improved Furrow; *LE*=the LEPA System; *DRY*=Dryland Production.

on Richfield clay loam soil and between 15 and 80 dollars on Dalhart fine sandy loam soil, with a decreasing trend on both of the soils (Figure 1). The result reflects that prices of inputs such as fuel, labor, and chemicals are projected to increase much faster than output prices. For example, FAPRI projections indicate that the variable costs of producing grain sorghum will increase by 28 percent from 1993 to 2002, while the price of grain sorghum will increase only 10 percent over the same period (FAPRI, 1993*a* and 1993*b*). Because of the rapidly increasing irrigation operating costs, irrigation level is projected to decrease from 21.7 to 18.3 inches on Richfield clay loam soil and from 23.9 to 19.3 inches on Dalhart fine sandy loam soil (Figure 2). Irrigation level is higher on Dalhart fine sandy loam soil than on Richfield clay loam soil because of the lower application efficiency and higher runoff and percolation ratios on Dalhart fine sandy loam soil. Nitrogen runoff and percolation are projected to decrease on both of the soils

because of the decreasing irrigation level and nitrogen use. As expected, more nitrogen would be lost in runoff and percolation on Dalhart fine sandy loam soil than on Richfield clay loam soil (Figures 3 and 4). It is estimated that the average nitrogen runoff and percolation per acre in the next ten years will be 9.0 and 1.2 pounds on Richfield clay loam soil and 15.3 and 3.2 pounds on Dalhart fine sandy loam soil.

The simulations indicate that the ratio of incomes from using a sprinkler system and a furrow system will increase as pump lift increases from 100 to 300 feet. This suggests that modern irrigation technologies have more comparative advantages on land with high pump lift. Given the irrigation system, irrigation level and crop yield would be lower on land with higher pump lift because higher operating cost associated with higher pump lift discourages irrigation water use. Thus, land with a higher water table and, therefore, more vulnerability

**Figure 1.** Per-Acre Income Levels Under Alternative Policies
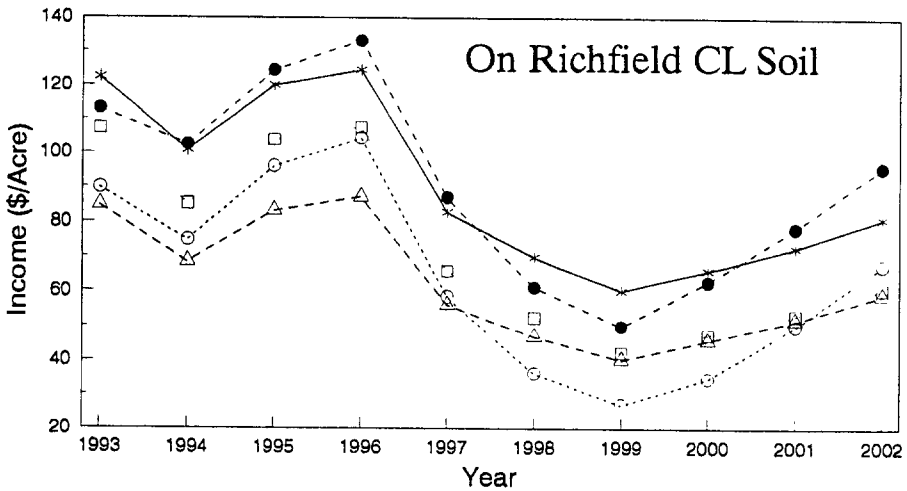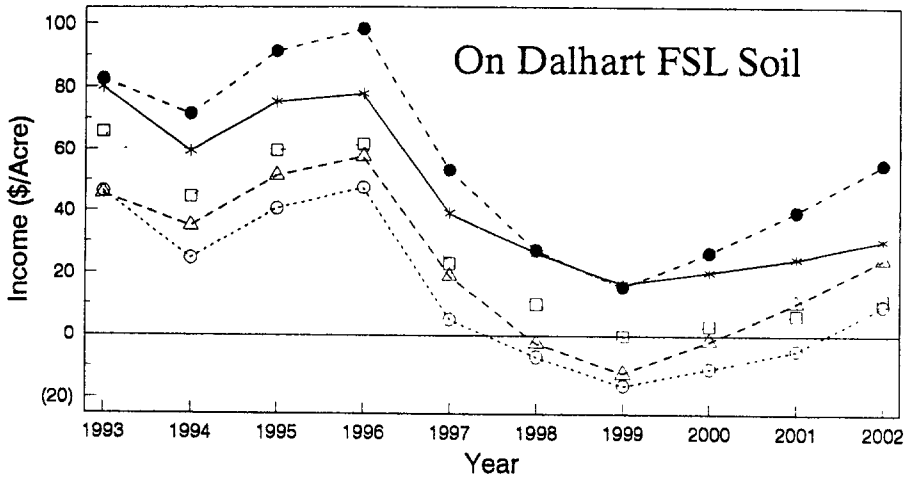


Base    N R&P Tax ($5/lb)  N Tax (50%)  Water Use Lt. (10"/A)  Cost Sharing (20%)

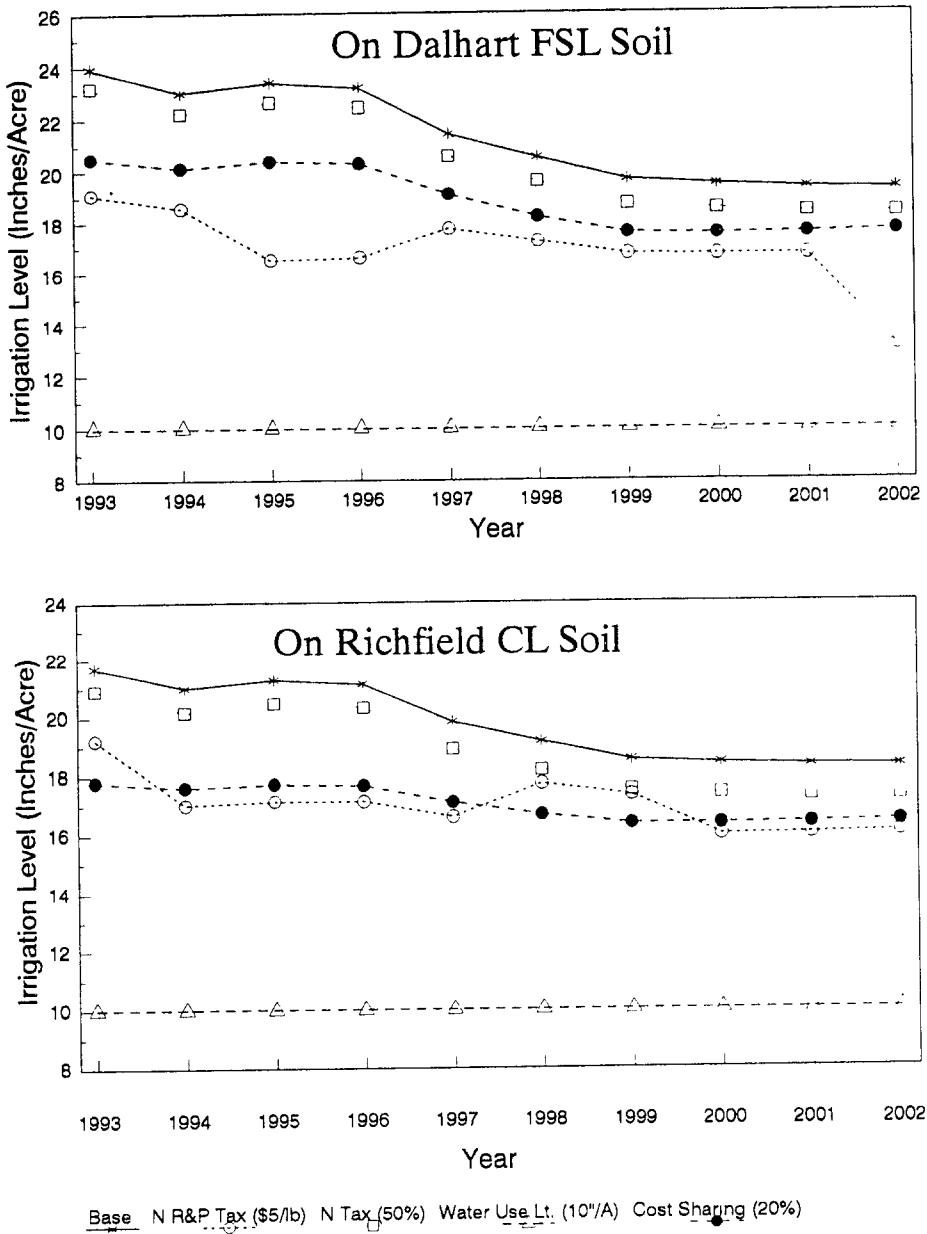**Figure 2.** Irrigation Levels Under Alternative Policies

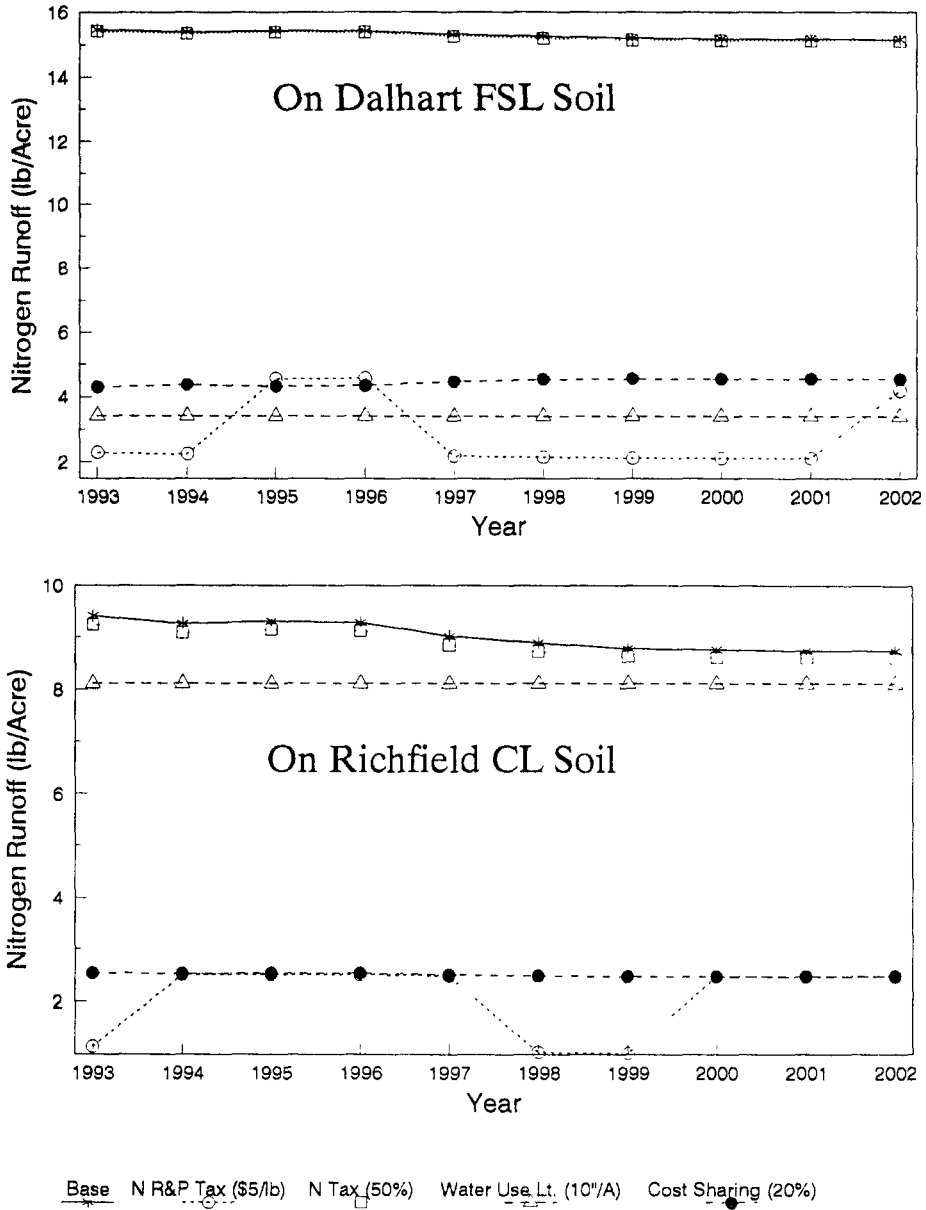**Figure 3.** Nitrogen Runoff Levels Under Alternative Policies



Base    N R&P Tax ($5/lb)    N Tax (50%)    Water Use Lt. (10"/A)    Cost Sharing (20%)
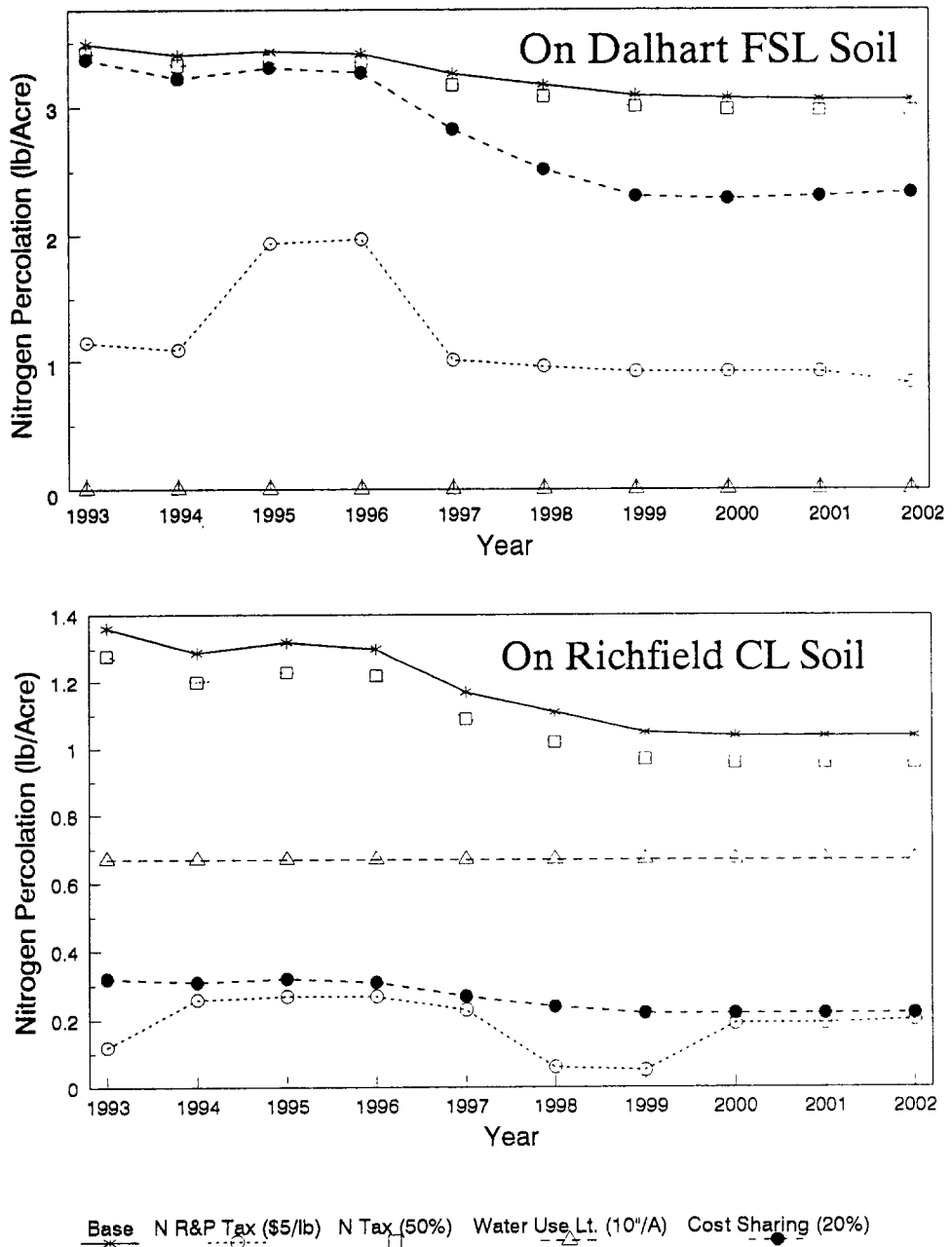
**Figure 4.** Nitrogen Percolation Levels Under Alternative Policies

to groundwater pollution is more likely to be used for water intensive crops using furrow irrigation. In the policy simulations discussed below, a 300-foot pump lift was assumed.

## A Tax on Nitrogen Runoff and Percolation

The tax was shown to be very effective in reducing water pollution from nitrogen runoff and percolation. First, it reduces irrigation level and nitrogen use. Second, and maybe more importantly, it encourages the adoption of modern irrigation technologies. For example, if five dollars are charged to each pound of nitrogen lost in runoff or percolation, irrigation level would be reduced by 14 and 21 percent on Richfield clay loam soil and Dalhart fine sandy loam soil, respectively. LEPA would become the most profitable system on both of the soils. Because of the high application efficiency and low operating costs of the LEPA system, producers would switch to corn in some years on both of the soils. The average nitrogen runoff and percolation in the 1993-2002 period would be reduced by 77 and 85 percent on Richfield clay loam soil and 81 and 64 percent on Dalhart fine sandy loam soil, respectively. The simulation indicates that under the tax the reduction in nitrogen runoff and percolation resulting from reduced water and nitrogen use is much smaller than that from the switch to LEPA. For example, on Dalhart fine sandy loam soil, the average nitrogen runoff in the 1993-2002 period would be reduced by only 0.28 pound per acre without switching to LEPA. Thus, of the total reduction in nitrogen runoff (12.4 pounds), over 97 percent is due to the switch to the LEPA system.

The switches between corn and sorghum result in some kinks on the curves under the tax in Figures 2 through 4. Because corn uses more nitrogen than sorghum, it generates more nitrogen runoff and percolation than grain sorghum. As a result, the irrigation level for corn is lower than that for grain sorghum under the tax. Because more nitrogen would be lost in runoff and percolation on Dalhart fine sandy loam soil than on Richfield clay loam soil, per-acre income would be reduced more on Dalhart fine sandy loam soil (70 percent) than on Richfield clay loam soil (29) under the tax.

## A Nitrogen Use Tax

The nitrogen use tax is shown to be less effective in reducing water pollution than a tax on nitrogen runoff and percolation. There are two reasons for this result. First, a nitrogen use tax does not promote the adoption of modern irrigation technologies. Under the tax, improved furrow will still be used to grow grain sorghum on both of the soils. Second, water and nitrogen applications are not responsive to changes in nitrogen price. For example, increasing nitrogen price by 50 percent reduces water and nitrogen application by only 5 and 3 percent on Richfield clay loam soil and 4 and 2 percent on Dalhart fine sandy loam soil in the 1993-2002 period.[5] As a result, average nitrogen runoff and percolation would be reduced by only 2 and 7 percent on Richfield clay loam soil and 0.35 and 2.62 percent on Dalhart fine sandy loam soil, respectively. The effect is smaller on Dalhart fine sandy loam soil because nitrogen runoff and percolation are more sensitive to irrigation method on coarser and more permeable soils. Under the 50 percent nitrogen use tax, per-acre income would be reduced by 19 percent on Richfield clay loam soil and 37 percent on Dalhart fine sandy loam soil in the 1993-2002 period.

## Limitations on Irrigation Water Use

Restrictions on irrigation level reduce nitrogen runoff and percolation by reducing water and nitrogen application and possibly by promoting adoption of modern irrigation technologies. The simulation indicates that on Richfield clay loam soil it is still more profitable to grow grain sorghum using improved furrow under any limitation on irrigation water use. In this case, nitrogen runoff and percolation are reduced simply by reducing irrigation level and nitrogen use. For example, if irrigation level is limited to 10 inches per acre on Richfield clay loam soil, nitrogen runoff and percolation would be reduced by 10 and 43 percent, respectively. Per-acre income would be reduced by 31 percent. On Dalhart fine sandy loam soil, growing corn using LEPA would become more profitable if irrigation level is limited to any level between 15 and 10 inches per acre. In this case, nitrogen runoff and percolation are reduced by the adoption of LEPA and the lower irrigation level. Because corn uses more nitrogen than grain

sorghum, more nitrogen would be applied even when the irrigation level is limited to 10 inches per acre. Nevertheless, because of the adoption of LEPA, nitrogen percolation would be reduced to negligible levels, and nitrogen runoff would be reduced by 78 percent over the ten year period.

The simulations indicate that moderate restrictions on irrigation water use would encourage the adoption of modern irrigation technologies, while excessive restrictions would discourage the use of modern systems. This is due to the fact that when LEPA is used to pump a limited amount of water, the grain from the increased application efficiency can not compensate for the increased irrigation fixed cost.

## Cost Sharing in Adopting Modern Irrigation Technologies

This option reduces nitrogen runoff and percolation by promoting the adoption of modern irrigation technologies, but does not reduce nitrogen runoff and percolation by a given system. Thus, if the percentage of the fixed cost shared is not set high enough to induce the adoption, the policy is completely ineffective in reducing nitrogen losses. For example, it the government shares only 5 percent of the fixed cost of the center pivot or LEPA, farmers would still use the improved furrow on Richfield clay loam soil over the 10-year period. Irrigation level and nitrogen runoff and percolation would not be affected. However, if 20 percent of the fixed cost is shared, growing corn using LEPA would become more profitable on Richfield clay loam soil. Irrigation level would be reduced by 14 percent over the 1993-2002 period, and average nitrogen runoff and percolation would be reduced by 72 and 77 percent, respectively. The per-acre income under this policy would increase by nearly 1 percent. On Dalhart fine sandy loam soil, a cost sharing of 5 percent would induce conversion from a furrow system to LEPA. Because of the high application efficiency of LEPA, the irrigation level would be reduced by 11 percent over the 10-year period. Nitrogen runoff would be reduced by 71 percent. Also, growing corn would become more profitable than growing grain sorghum. Because more nitrogen would be applied to corn than to grain sorghum, and Dalhart fine sandy loam soil has

moderately high permeability, average nitrogen percolation would be reduced by only 15 percent over the next ten years.

## Summary and Conclusions

The adoption of modern irrigation technologies is viewed as a process that involves irrigation investment, crop mix adjustment, and multi-period decision making. Solution of the theoretical model indicates that irrigation investment should be made until the sum of marginal investment and adjustment costs equals the marginal values of all future incomes, and that irrigation capital should be kept at the level where the sum of the marginal value product of irrigation capital and the saving in operating cost equals the sum of the investment cost, depreciation cost, and capital losses.

A numerical example based on the production of three major crops on two principal soils with four possible irrigation systems in the Oklahoma High Plains demonstrates the application of the theoretical model. The choices of crops and irrigation systems and the resulting levels of income, irrigation, and nitrogen runoff and percolation on the two soils are simulated over the 1993-2002 period. The results indicate that growing grain sorghum using improved furrow is the most profitable system on both Richfield clay loam and Dalhart fine sandy loam soils. Per-acre income and irrigation level are projected to decrease on both of the soils, reflecting increasing production costs and relatively stable output prices. Average annual nitrogen runoff and percolation per acre would be 9.0 and 1.2 pounds per acre on Richfield clay loam soil and 15.3 and 3.2 pounds per acre on Dalhart fine sandy loam soil over the 10-year period.

Four commonly discussed policies to reduce agricultural water pollution were simulated: (a) a tax on nitrogen runoff and percolation; (b) a nitrogen use tax; (c) restrictions on irrigation water use; and (d) cost sharing in adopting modern irrigation technologies. The results indicate that a tax on nitrogen runoff and percolation would be very effective in reducing water pollution. The tax reduces nitrogen runoff and percolation both by promoting adoption of modern irrigation technologies and by reducing water and nitrogen use. A nitrogen use tax is less effective in reducing

nitrogen losses because it does not promote the adoption of modern irrigation technologies and water and nitrogen use is not responsive to changes in nitrogen price. The cost sharing policy reduces nitrogen runoff and percolation by inducing adoption of modern technologies, but does not reduce water and nitrogen application used in conjunction with a given system. As a result, it may not be effective on highly permeable soils. Excessive restrictions on irrigation water use may actually discourage the adoption of modern irrigation technologies. Thus, caution must be exercised in implementing a water use limit.

The impacts of the policies on farm income and water use also differ. If the objective is to save water as well as to reduce runoff and percolation in a region facing serious water shortage, water use restrictions or a tax on nitrogen runoff and percolation may be preferred. If the objective is to promote the adoption of modern irrigation systems and at the same time maintain farmers income, the cost sharing policy may be the best choice. Political implications also differ across these policies. Irrigation water use regulations or taxes would encounter objection from farmers, while cost sharing might not be a viable alternative for an administration facing a large budget deficit.

In general, policies that lead to the adoption of modern irrigation technologies are more effective in reducing nitrogen runoff and percolation than policies that do not. Thus, dynamic incentives should be a major consideration in the design of water quality policies. Priority should be given to those policies that encourage the adoption of modern irrigation technologies. Public research aimed at improving the design and reducing the fixed cost of the modern systems may also be worthwhile. Moreover, because crop mix adjustments usually accompany adoption, extension and educational activities that assist producers in modifying production plans may hasten adoption and help control agricultural water pollution.

Although the analysis is focused on the intensive marginal effect, the results also have implications regarding the extensive effect. If production with modern irrigation technologies becomes more profitable than dryland production on a soil that used to be non-irrigable, irrigation would be eventually expanded to the soil. Thus, the modelling framework could be restructured to address decisions concerning irrigation expansion as well.

The model presented in this paper abstracts from several important facets of adoption decisions. For example, farming tradition, risk preference, cash flow, and financial conditions all affect irrigation investment decisions, but are not explicitly represented in the analysis. It is assumed that irrigation system and crop choices are determined by maximizing net present values of all future incomes and are made for a given piece of land with a given soil type. Important extensions include (a) incorporating cross-farm heterogeneity such as risk preference and aggregating to the regional level to allow multi-crop choices on each soil; and (b) accounting for farm financial conditions and the impact of variability of net returns on farmers' irrigation investment decisions.

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**Endnotes**

1. The total cost of the converted system (the cost of reused parts plus new investment minus the salvage value of the unused parts) is usually higher than a complete new system. The difference plus the cost of removing and disposing of the unused parts are the major components of the adjustment cost.

2. $i_{il}$=1, 2, 3 represents corn, grain sorghum, and wheat respectively; $j$=1, 2 represents Richfield clay loam and Dalhart fine sandy loam soils, respectively; $k_{il}$ =0, 1, 2, 3, and 4 represents dryland production, furrow, improved furrow, center pivot, and LEPA, respectively.

3. The simulated crop yields were validated by comparing the simulated yields with the observed yields for production on Richfield clay loam soils at the Panhandle Research Station, Goodwell, Oklahoma. Overall, the simulated yields are about 5% higher than the observed for the three crops. The differences may reflect yield reductions from insects and other factors not represented in EPIC-PST (Mapp et al., 1991, pp. 9-11).

4. The most prevalent furrow and improved furrow systems in the Oklahoma High Plains are the gated pipe and surge flow systems. Therefore, they are selected to represent the two irrigation methods in calculating the fixed and operating costs.

5. The response of nitrogen use to own-price changes estimated in this study is smaller than those estimated by Ray (1982) and Shumway (1983) for two reasons. First, the own-price elasticity of nitrogen use by irrigated crops is expected to be smaller than the elasticity of nitrogen use by both non-irrigated and irrigated crops. Second, water was modeled as a complementary input to nitrogen in this study. A reduction in nitrogen use is accompanied by a reduction in water use. This makes nitrogen use less responsive to own-price changes.