Water Conservation Potential from Irrigation Technology Transitions in the Pacific Northwest

Glenn D. Schaible, C. S. Kim, and Norman K. Whittlesey

The effects of price changes on irrigation technology transitions and potential agricultural water conservation in the Pacific Northwest are analyzed using Parks' (1980) modified multinomial logit model. Results indicate that commodity price effects are statistically significant, but they are relatively small with nonprogram crop price effects greater than program crop price effects. Locational factors are also found to affect technology transitions. In the absence of water policy changes, continued irrigation technology adoption by year 2005 will result in average annual water savings of approximately 404,000 acre-feet in the Pacific Northwest.

Key words: irrigation technology, water conservation, water demand, water policy.

Water resources development, inexpensive energy, and economic policies as well as institutional water resource arrangements have all contributed significantly to agriculture's demand for water resources (Martin; Weatherford and Ingram; Vaux; Just, Lichtenberg, and Zilberman). Irrigated agriculture currently accounts for approximately 83% of water consumption in the 17 western states. However, growing demands for quality water resources by nonagricultural uses, including energy, municipal, commercial and industrial, recreation, fish and wildlife, and Indian and federal reserved rights, has heightened competition for a finite resource supply. Reallocating this scarce water resource may be accomplished with refined water market structures, as well as through resource policy-induced agricultural conservation (Howe; Vaux; Frederick; Bromley).

Removal of institutional barriers associated with Bureau of Reclamation water rights/uses is an important component of the reforms required for the development of market-oriented water transfers (Wahl; Burness and Quirk). However, Bureau of Reclamation water delivered to farms accounts for approximately 60% to 65% of surface water used for irrigation and for only 25% to 30% of total water used for irrigation in the West.[1] In addition, the nature of the "politics of water," due to the common property aspect of water supplies controlled by many irrigation districts, will limit the effectiveness of some water markets (Rosen). Furthermore, upper-basin states, with water-dependent agriculture, are unlikely to provide unlimited support for significant interregional water market transfers. States have become more protective of their resources by broadening the "considerations" in reviewing applications for changes in water rights (MacDonnell). These considerations involve accounting for adverse effects to fish and wildlife, water quality, groundwater recharge, and the regional economy. As a result, significant reallocation of western water resources to either higher valued uses, or uses justified on the basis of equity and/or environmental policy goals, must now be resolved through policies

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[1] Percents were derived using data from the Bureau of Reclamation, *1988 Annual Report*, and the Bureau of the Census, *Farm and Ranch Irrigation Survey (1988)*.

which promote greater agricultural conservation.

Water-conserving irrigation technologies/water management practices are known to be able to significantly increase on-farm irrigation efficiencies by 10–30%, to significantly reduce crop water application requirements, and to reduce energy costs (Sweeten and Jordan; Jensen; Lyle and Bordovsky; Henggeler, Sweeten, and Keese; Homan, Skold, and Heermann; Wyatt). Therefore, as competition for water resources continues to grow, irrigation technology/water management substitutions for water will be required to conserve greater quantities for alternative demands. Caswell, Lichtenberg, and Zilberman confirm that environmental considerations "may become a major incentive for adoption of water-conserving irrigation technologies. . ." (p. 889).

This study is concerned with estimating these conservation/reallocation quantities. The analysis will estimate an irrigation technology transition model in order to assess expected conservation assuming past economic/institutional environments (baseline) continue and the degree to which technology adjustments, given changes in agricultural economic environments, will contribute to conservation/reallocation potential. Given that conservation-oriented water policy changes will induce substitutions of irrigation technology/water management for water beyond baseline estimates, results from the transition model then establish a basis from which to judge potential conservation contributions of water policy changes.

The degree of resource substitution and the potential for agricultural water conservation/reallocation is influenced principally by locational (environmental) and economic variables, such as commodity prices. Locational factors, such as climate, soil types, and topography, play a major role in defining the land quality and crop production character of a region. Several studies have applied multinomial or binomial logit, discrete choice models emphasizing farm-level locational characteristics in estimating descriptive, technology, or cropping pattern adoption models (Caswell and Zilberman; Negri and Brooks; Lichtenberg). Given information on various farm characteristics a priori, such as climatic setting and land quality values, these logit models estimated the likelihood of adopting a particular technology on that farm. However, examination of the influence the agricultural economic environment has had on aggregate irrigation technology transitions has been sparse at best.

Just, Lichtenberg, and Zilberman extend the earlier works of Caswell and Zilberman, and Lichtenberg, estimating an irrigation adoption model to examine the effect farm programs have had on irrigation expansion and groundwater depletion. These authors suggest the need exists to focus more research on structural interactions between resource use and economic variables. Finally, representative, farm-firm level activity models also have been used extensively to examine micromanagement resource adjustments to irrigated agricultural economic environments (Hornbaker and Mapp; High Plains Associates; Bernardo et al.; Ellis, Lacewell, and Reneau). However, these studies generally have used alternative exogenous assumptions to constrain irrigation production technologies.

Previous studies have been site specific, have used only firm-level, cross-sectional data, or are engineering studies based on experimental data. Also, data used in these studies generally have prevented a sufficient disaggregation of technology states. As a result, these studies have been micro oriented and have not examined the influence of prices on aggregate irrigation technology transitions. These studies have not addressed irrigation technology transitions from an aggregate, water conservation/reallocation policy perspective. In addition, previous econometric studies modeled technology adoption assuming only the traditional specification error structure. This study examines the polychotomous character of the technology adoption decision and estimates a modified multinomial logit model, explicitly recognizing the traditional specification error as well as approximation error attributed to having data only on aggregate technology proportions, rather than on micro-level technology transitions (Parks 1980). Finally, emphasizing the influence of the agricultural economic environment on aggregate technology adjustments imposes recognition of the time-dependent nature of technology transitions and an autoregressive error adjustment.

Specifically, in this article we investigate econometrically, using Parks' (1980) modified multinomial logit model, the influence that agricultural economic variables have on aggregate irrigation technology transitions to water-conserving technologies, while adjusting for locational factors. The model is estimated for the Pacific Northwest states of Idaho, Oregon, and Washington, a region with an increasing sense of scarcity due to growing nonagricultural water demands. We further examine economic implications, in terms of resource reallocation potential, by forecasting technology transitions and estimating agricultural water conservation potential for alternative price scenarios. These relationships are important in identifying potential differences between regional dynamics of water resource adjustments and the conservation/reallocation potential of future conservation-induced water policy changes. Finally, water policy implications are drawn from the research results.

Polychotomous Discrete Irrigation Technology Choice Model

Farm producers, assumed to be rational decision makers, make irrigation technology choices consistent with utility maximizing behavior. Irrigation technology choices, for a particular plot (field), are discrete and mutually exclusive. In other words, choosing one technology for a field excludes the simultaneous use of other technologies on that field. Such discrete choice behavior is assumed to be consistent with a well-defined, additive-separable, perceived utility function and consistent with random utility maximization (McFadden 1974, 1976, 1981; Pudney). Then, irrigators maximize their perceived utility by adopting the ith irrigation technology, wherein:

$$(1) \quad U_i = \underset{T}{\mathrm{Max}}\,[D_i(P, w, \psi) + \epsilon(e_i) > D_j(P, w, \psi) + \epsilon(e_j)]$$

for $i, j = 0, 1, \ldots, T$; $i \neq j$, and where D and ϵ are real valued functions, and $D_i(P, w, \psi) = D[\pi_i(P, w, \psi)]$, $D_j(P, w, \psi) = D[\pi_j(P, w, \psi)]$, and $\pi_j(P, w, \psi)$ is the jth technology-specific perceived profit function, assuming competitive input/output markets and well-defined production technologies (Chambers and Just; Chambers and Foster). The vector sets for P, a vector of output prices; w, a vector of input prices; and ψ, a vector of location (land) and technology attribute/characteristics, represent the nonstochastic, observable values associated with irrigation technology choices and irrigator perceptions of those values that define the relative profitability of alternative technologies. The values e_j represent the element of the technology decision which reflects the vector of values for unobservable, unmeasurable choice attribute/characteristics, plus the unobservable random values associated with irrigator perceptions of observed and unobserved choice factors.

Irrigators maximize their perceived utility by maximizing perceived profits over technology choices (Chambers and Foster; Caswell and Zilberman; Negri and Brooks), such that $\pi_i(P, w, \psi) > \pi_j(P, w, \psi)$ for $i, j = 0, 1, \ldots, T$ and $i \neq j$. The random nature of irrigator perceptions of profits results in a stochastic utility function (McFadden 1974) and, therefore, a probabilistic irrigation technology choice.

Because ϵ in equation (1) is stochastic, the farm-producer decision is expressed as the probability of selecting the ith irrigation technology:

$$(2) \quad P_i = \mathrm{Prob}[D_i(P, w, \psi) - D_j(P, w, \psi) > \epsilon(e_j) - \epsilon(e_i)]$$

for all $i, j = 0, 1, \ldots, T$ and $i \neq j$.

To estimate the probabilities of alternative technologies requires the specification of the functional form of $D_i(P, w, \psi)$ and the distribution of $\epsilon(e_i)$. Specifying these modeling characteristics depends upon the nature of farm-producer technology decisions and consistency of the assumption with respect to $\epsilon(e_j) - \epsilon(e_i)$ and, therefore, $\epsilon(e_j)$ and $\epsilon(e_i)$, with utility-maximizing behavior. Domencich and McFadden demonstrate that if ϵ_j and ϵ_i are independent, identically Weibull-distributed random variables, then their difference is also Weibull distributed and consistent with both the logistic functional form and utility maximization.

With respect to farm-producer decisions, farm producers have the option of choosing from among a multiple of on-farm irrigation technologies. Available technologies include such options as gravity application systems which deliver water across a field by the force of gravity, either through a "field-flooding" technique or the use of more mechanical/management techniques which could include siphon-tube or gated-pipe systems, or surge-flow or cablegation systems. Some of these more management-intensive systems could also include the use of tailwater-reuse pits (the collection and reuse of irrigation water runoff). Sprinkler applications, which deliver water to the field under pressure, include such technologies as gun systems, hand or wheel move systems, permanent systems, and high/low-pressure center-pivot systems. Drip/trickle irrigation, a low-pressure technology, distributes water directly to the plant root zone through water emitters attached to small diameter tubes placed above or below the field's surface. This technology is most often applied to specialty crop production (fruits and nuts, vegetables, etc.).

These technologies differ in their water-application efficiencies, i.e., the ratio of the crop's consumptive water requirement to the quantity of water applied to the field. Irrigation technologies also differ in their unit application costs as well as their effect on crop yields. While for agronomic reasons one technology may be preferable to another, this does not eliminate the technology as a farm-producer option. The water conservation and yield and unit cost effects, however, do result in one technology being relatively more profitable than another. Therefore, the farm-producer decision, together with a Weibull-distributed ϵ, suggests the use of a polychotomous discrete choice model, i.e., a multinomial logit functional form (Caswell and Zilberman; McFadden 1974, 1981).

Following McFadden (1974), choices, or irrigation technology selection probabilities (P_i), are written in terms of the multinomial logit model as:

$$(3) \qquad P_i = \frac{e^{D_i(X)}}{\sum_{j=0}^{J} e^{D_j(X)}}, \qquad i = 0, 1, \ldots, J$$

where $D_j(X)$ is an estimated utility function, U_j, for the farm producer with a probabilistic choice set, P_i, where $i = 0, 1, \ldots, J$; and X represents (simplified for later notational purposes) the aggregate set of relevant prices and location (land) and technology attribute/characteristic vectors, $\{P, w, \psi\}$, such that the farm producer maximizes $U_j = D_j(P, w, \psi) + \epsilon_j$, where ϵ_j are independent random variations identically distributed with the Weibull distribution.

The normalized multinomial logit model is expressed as

$$(4) \qquad p_i = \frac{e^{(d_i)}}{1 + \sum_{j=1}^{J} e^{(d_j)}}$$

for $i = 1, \ldots, J$, and

$$p_0 = \left[1 + \sum_{j=1}^{J} e^{(d_j)}\right]^{-1},$$

where the function d_i, the difference in farm-producer utility between choice sets (P_i) and (P_0), is expressed as the following linear function of the aggregate vector X plus the random error ϵ_i for choice set P_i:

$$(5) \qquad d_i = \beta_{i1}X_1 + \beta_{i2}X_2 + \ldots + \beta_{iK}X_K + \epsilon_i$$

(for $i = 1, \ldots, J$).

Using equations (4) and (5), a multiregional, temporal logit equation for polychotomous irrigation technology decisions is expressed as:

$$(6) \qquad d_{imt} \approx y_{imt} \approx \ln(p_{imt}/p_{0mt}) = \sum_{k=1}^{K} \beta_{ik} X_{kmt} + \epsilon(v_{imt} + u_{imt}),$$

$i = 1, \ldots, J$ (irrigation technology states);
$m = 1, \ldots, M$ (cross sections);
$t = 1, \ldots, T$ (years); and

where y_{imt} represents the normalized choice in terms of the log of the odds of choice p_{imt} to p_{0mt}; X is the aggregate vector of relevant output and input prices, as well as location/technology characteristics; β is the vector of unknown parameters; and v_{imt} and u_{imt} are the specification and approximation random-error terms, respectively (Parks 1980).

Conventional logit analysis assumed that ϵ in equation (1) was equivalent to $\epsilon(v_{imt})$. However, this term is now appropriately recognized as only the specification error component of ϵ (Amemiya and Nold; Parks 1980). Because equation (6) uses observed proportions p_i and not actual selection probabilities P_i, the technology logit equation involves the additional approximation error $u_{imt} = \ln(p_{imt}/p_{0mt}) - \ln(P_{imt}/P_{0mt})$. The errors v_{imt} and u_{imt} are assumed independent (Parks 1980), where for the specification errors $E(v_{imt}) = 0$, and

$$E(v_{imt}v_{jmt}) = E(v_{i\tau}v_{j\gamma})$$
$$= \sigma_{ij} \text{ for } (mt) = \tau = \gamma \text{ for all } i \text{ and } j$$
$$= 0 \text{ for } (mt) = \tau \neq \gamma \text{ for all } i \text{ and } j.$$

The approximation error structure is multivariate normal with the mean vector $E(u_{imt}) = E[\ln(p_{imt}/p_{0mt}) - \ln(P_{imt}/P_{0mt})] = 0$, and the covariance for all i and j for each (mt) diagonal set, $E(u_{imt}/u_{jmt}) = \Omega_{(mt)}$, where:

$$(7) \qquad \Omega_{(mt)} = (1/n)_{mt}$$

$$\begin{bmatrix} 1/P_{0mt} + 1/P_{1mt} & 1/P_{0mt} & \cdots & 1/P_{0mt} \\ 1/P_{0mt} & 1/P_{0mt} + 1/P_{2mt} & \cdots & 1/P_{0mt} \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ 1/P_{0mt} & 1/P_{0mt} & \cdots & 1/P_{0mt} + 1/P_{Jmt} \end{bmatrix}.$$

Based on the use of Zellner and Lee's joint estimation procedure for discrete choice models, the joint multinomial logit equations associated with equation (6) can be expressed in compact notation as:

$$(8) \qquad Y = X\beta + \epsilon,$$

where Y is a $(J \times 1)MT$ vector, β is a $(J \times K) \times 1$ vector such that $\beta = \beta_1', \beta_2', \ldots, \beta_J')'$, and X is a block diagonal matrix such that:

$$(9) \qquad X = \begin{bmatrix} X_{1(mt)} & & & 0 \\ & X_{2(mt)} & & \\ & & \cdot & \\ 0 & & \cdot & \\ & & & X_{J(mt)} \end{bmatrix},$$

and $X_{j(mt)}$ represents the vector of MT observations for the jth logit equation for the $(1 \times K)$ vector of explanatory variables indicated in equation (6). The error structure of equation (8), $\epsilon = (v + u)$, is expressed as $E(\epsilon_{mt}) = 0$ with the covariance matrix for ϵ in block diagonal form as:

$$(10) \qquad E(\epsilon\epsilon') = \begin{bmatrix} \Omega_1 + \Sigma & & & \\ & \Omega_2 + \Sigma & & \\ & & \cdot & \\ & & & \cdot \\ & & & & \Omega_{MT} + \Sigma \end{bmatrix} = \Omega + (I \otimes \Sigma) = V$$

where Σ is estimated by:

$$(11) \qquad \hat{\Sigma} = S - [1/(MT)] \cdot \sum_{g=1}^{MT} \hat{\Omega}_g,$$

and $\hat{\Omega}_g$ is estimated using equation (7), replacing P_i with p_i (Parks 1980). Then, Aitken's estimator, adjusting for heteroskedasticity and cross-equation correlation, for the modified multinomial logit (MML) irrigation technology transition model is given by $b_{MML} = (X' \hat{V}^{-1}X)^{-1}X' \hat{V}^{-1}y$, and the $\text{Var}(b_{MML}) = (X'\hat{V}^{-1}X)^{-1}$.

However, because cross-section, time-series data were used for this study, the estimated cross-choice covariance matrix, $\hat{\Sigma}$, was also corrected for a first-order autoregressive error structure. This correction involved first applying Parks' (1967) cross-section, time-series (CSTS) estimation procedure to the equations indicated in equation (8) to acquire the transformed residuals $e = y^* - (X^*)b_{CSTS}$. Second, the CSTS residuals are used to estimate the unadjusted MML residual covariance matrix in equation (11) as:

$$(12) \qquad S = \left\{\left[1/(MT) \cdot \sum_{g=1}^{MT} e_{ig}e_{jg}\right]\right\}.$$

The estimator, b_{MML}, is both consistent and asymptotically more efficient than the standard multinomial logit estimator (Parks 1980).

Application to the Pacific Northwest

Agriculture in the Pacific Northwest accounts for more than 80% of total water withdrawals [U.S. Geological Survey (USGS)]. Irrigation during initial development stages (early 1900s) emphasized the use of gravity systems. By the early 1970s, technology transitions were evident, with gravity and sprinkler systems accounting for 66% and 34% of regional irrigated acres, respectively (*Irrigation Journal*). Throughout the 1970s and early 1980s, additional technology adjustments consisted primarily of center-pivot sprinkler technology. In 1986 gravity systems accounted for only 42.7%, while sprinkler technology was used on 57.3% of regional irrigated acres (15.6% of which used center-pivot sprinkler technology) (*Irrigation Journal*).[2]

This study examines these transitions to water-conserving technologies, estimating aggregate technology shares as a probabilistic function of locational and time-dependent economic variables. Pooled data for the states of Idaho, Oregon, and Washington, over the period 1974–86, are used to jointly estimate the logit equation (8). Aggregate (grouped) technology shares are estimated using irrigated

[2] Data for 1988, recently available from the *Farm and Ranch Irrigation Survey (1988)* (Bureau of the Census), indicate that gravity systems accounted for approximately 36.1%, while sprinkler systems were used on 62.5% of regional irrigated acres. These data do not exist as an annual series and, therefore, could not be used as part of the data base for the empirical model. However, they do support the general nature of irrigation technology transitions from gravity to sprinkler systems in the Pacific Northwest.

Table 1. Results for the Modified Multinomial Logit Model for the Log of Odds of Irrigation Technology Transitions in the Pacific Northwest

				Log of Deflated Output to Energy Price Ratios for		
Equation:[a]	Constant	*WA**	*ID**	Wheat	Corn	Alfalfa
LN*RAT*10[b]	−4.6365	.4107	−.1446	.1177	−1.2637	1.2499
	(.8719)	(.0844)	(.1031)	(.2794)	(.2245)	(.1575)
LN*RAT*20[c]	−10.8501	.9615	.7433	1.2965	−2.5546	1.8669
	(1.0132)	(.1027)	(.1066)	(.2142)	(.1983)	(.1496)

Joint Equation Estimation $R^2 = .9237$

Covariance Matrix:

$$S = \begin{bmatrix} .0286 & .0398 \\ .0398 & .1031 \end{bmatrix} \qquad \hat{\Sigma} = \begin{bmatrix} .0264 & .0387 \\ .0387 & .0974 \end{bmatrix}$$

[a] Numbers in parentheses are estimated standard errors.
[b] LN*RAT*10 represents the logit equation for the log of the ratio of conventional sprinkler systems (P_1) to gravity systems (P_0).
[c] LN*RAT*20 represents the logit equation for the log of the ratio of center-pivot sprinkler systems (P_2) to gravity systems (P_0).
* Locational variables for Washington (WA) and Idaho (ID). Oregon is the benchmark state.

acreage by technology for each state, published annually in the *Irrigation Journal.*

The dependent variable, $\ln(p_{imt}/p_{0mt})$, represents the log of the odds of the relative shares for irrigation technology classes consisting of gravity systems (p_{0mt}), conventional sprinkler systems (p_{1mt}) (including gun, boom, traveler systems, hand, mechanical, wheel move systems, and towline and sideroll systems), and center-pivot sprinkler systems (p_{2mt}).

Explanatory variables include locational dummy variables and three variables for commodity prices for wheat, corn, and alfalfa hay divided by irrigation energy costs. The three regional dummy variables for Idaho, Oregon, and Washington reflect nominal characterizations of regional "locational" attributes in aggregate that result in differences in regional technology shares. Crop price variables for wheat, corn, and alfalfa were chosen because they reflect regional program versus nonprogram irrigated crop diversity and a significant share of both irrigated program crop and total irrigated acreage (Bureau of the Census). Other crop prices are either significantly correlated with wheat, corn, or alfalfa prices (other hay and alfalfa hay, for example) or acreage for these crops is individually a relatively small share of total irrigated acreage.[3] Electrical costs (¢/kWh) paid by irrigators (Bonneville Power Administration) are used for irrigation energy costs. Crop price data, adjusted to 1984 dollars, are from the U.S. Department of Agriculture (USDA). Indices of prices received for feed grains, food grains, and hay products were used to adjust output prices, and electrical costs were adjusted using an index of prices paid for fuels and energy (USDA).

Estimation Results

Table 1 presents the estimation results for the Pacific Northwest. LN*RAT*10 indicates the estimated parameters for the logit equation for the log (LN) of the ratio (*RAT*) of conventional sprinkler systems (P_1) to gravity systems (P_0), specifically, for $\ln(p_{1mt}/p_{0mt})$. LN*RAT*20 indicates the estimated parameters for the equation for the log of the ratio of center-pivot sprinkler systems (P_2) to gravity systems (P_0), specifically, for $\ln(p_{2mt}/p_{0mt})$. The significance of the price variables and the size of the joint equation estimation R-square value (.9237) indicate that irrigation technology transitions can be explained with price variables.

The coefficients for the price variables may be interpreted as the relative responsiveness

[3] Total regional irrigated corn, wheat, and alfalfa acres account for 36% of total regional irrigated acres. Wheat and corn acres account for 65.4% of total regional irrigated program crop acreage. Remaining regional irrigated crop production includes acres for barley, other hay, sugar beets, Irish potatoes, vegetables, orchards, and an "other crop" category (8.7%, 6.3%, 2.6%, 8.4%, 3.9%, 5.2%, and 28.9%, respectively) (Bureau of the Census). The "other crop" category includes irrigated production for corn silage, dry-edible beans, and such small grains as oats and rye. Crop prices for production of barley, other hay, and the "other crop" category (43.9% of the remaining regional irrigated acreage) are assumed to be strongly correlated with either corn or alfalfa prices.

of the odds of adoption of technology p_i to technology p_0 to changes in deflated relative prices. Therefore, the log-log functional specification results in the coefficients for a price variable being interpreted roughly as a relative price elasticity.

Price coefficients are statistically significant, except for wheat price in equation LN*RAT*10. Relatively small changes in real wheat prices over the study period, 1.2 to 2.1 cents/bushel per year (USDA), due to a government supported price, may be why wheat price is statistically insignificant. However, most price coefficients are not significantly greater than one. These coefficients may indicate that partial price effects on irrigation technology adoption are generally relatively small. In addition, price effects are greater for center-pivot systems relative to gravity systems, than they are for conventional sprinkler systems relative to gravity systems. This is to be expected given greater water-use efficiencies, reduced labor requirements, and the increased range of topography and soils suitability of center-pivot systems, even though investment costs of such systems are often higher than conventional systems (Negri and Hanchar; Sweeten and Jordan).

The nonprogram crop price ratio (alfalfa/energy) has the greatest positive effect on technology transitions for both conventional sprinkler and center-pivot systems. This is probably due to the fact irrigated alfalfa, accounting for the most significant share (nearly 20%) of total irrigated acres in the Pacific Northwest (Bureau of the Census), serves as a critical feedstock input for the regional livestock sector. This result suggests that the transition to more water-conserving technologies in the Pacific Northwest may be influenced more by the economic environment for nonprogram crops than by that for program crops. The negative coefficients for the corn/energy price ratio, while unexpected, probably reflect the fact that deflated corn prices for each state declined over the study period, on average from 4.2 to 8.7 cents/bushel annually (USDA).

Results in table 1 also confirm the conclusions of the previous studies (Caswell and Zilberman; Lichtenberg; Negri and Brooks), that locational factors play an important role in determining irrigation technology adoption. The larger coefficient for Washington in equation LN*RAT*20 indicates that locational factors in Washington influence water-conserving technology adoption to a greater extent than in Oregon or Idaho. However, this probably reflects the fact that a vast majority of irrigation in Washington is more localized within a fairly homogeneous eastern region of the state, characterized by sandy soils and uneven terrain. Furthermore, much of this irrigation exists as part of the Columbia Basin Project, using a publicly financed distribution system to irrigate vast acreages far from the surface water source. Much of this irrigated acreage developed concurrent with center-pivot sprinkler technology. On the other hand, irrigation in Oregon and Idaho is either more geographically dispersed with more privately financed distribution systems or localized, but with a longer history of more intensive riparian development (USGS). This development is characterized by irrigation on heavier soils and on terrain more conducive to the use of on-farm gravity distribution sytems.

In addition, the greater size of the location coefficients for LN*RAT*20 than for LN*RAT*10 suggests locational factors may play a more significant role in technology adoption the more water conserving the technology. This merely reflects the fact that newer, water-conserving technologies are less generic and depend more heavily on management skills in concert with locational factors in defining their adaptability. As a result, the greater "locational" emphasis on the use of more management-intensive sprinkler technology in Washington, due to soils, terrain, and development timing, would seem to preclude an ability to more readily handle adjustments from high-pressure to low-pressure sprinkler technologies. Consequently, assuming no significant water policy changes, the less generic and more location-dependent character of newer technologies means that these results may also suggest a less influential role for prices in future regional technology/water management adoption.

Finally, the predictive efficiency of the estimated logit equations was also tested using Theil's U-coefficient. The relatively small U-coefficient values (table 2) indicate that the estimated equations performed reasonably well and are reasonably valid relationships. The high R^2 for the joint equation estimation, statistically significant coefficients, and small U-coefficients all seem to suggest, at least for the Pacific Northwest, that the MML irrigation technology model can be useful as a predictor of the effects of exogenous economic changes.

Table 2. Theil's *U*-Coefficients

State/Region	For Predicted Proportions		
	p_0	p_1	p_2
Idaho	.0416	.0520	.1304
Oregon	.0520	.0596	.1245
Washington	.1067	.0594	.1137
Pacific Northwest	.0628	.0580	.1191

Note: Values equal to zero indicate the simulated results are perfect. Values equal to one indicate no relationship (Chan).

Simulation Analysis

In 1988 nearly 12.3 million acre-feet of water were applied to produce a variety of crops in the Pacific Northwest. Table 3 indicates actual aggregate water-use coefficients of alternative irrigation systems. These coefficients reflect current average water-use efficiencies given real-world application difficulties, constraints, and mismanagement. While these coefficients are similar for Idaho and Oregon (for overall systems), Idaho uses the greatest quantity of water (6.1 million acre-feet) within the region. Average per-acre application for all irrigation systems was 1.9 acre-feet in Idaho and Oregon, compared to 2.3 acre-feet for Washington (Bureau of the Census). In all three states, per-acre application rates were lower for sprinkler irrigation systems than for gravity flow systems. Continued adoption of sprinkler irrigation systems (especially center-pivot systems) will result in agricultural water conservation through increased water-use efficiency.

Simulation analysis is conducted to provide information on agricultural water conservation assuming continued technology adoption,

Table 3. Water Application Rates in the Pacific Northwest

State/Region	Irrigation Technology		
	All Systems	Gravity Systems	All Sprinkler Systems
	Acre-Feet/Acre		
Idaho	1.9	2.2	1.7
Oregon	1.9	2.1	1.6
Washington	2.3	2.6	2.1
Pacific Northwest	2.0	2.3	1.8

Source: Bureau of the Census, *Farm and Ranch Irrigation Survey (1988).*

Table 4. Annual Average Real (Deflated) Price Changes for the Period 1974-86

State	Corn ($/bu.)	Wheat ($/bu.)	Alfalfa ($/ton)	Energy (¢/kWh)
Idaho	−.042	.017	3.03	.002
Oregon	−.087	.021	4.20	.002
Washington	−.066	.012	2.10	.001

Note: Computed from data in *Agricultural Prices: Annual Summaries 1973–1988,* USDA.

however, in the absence of water policy changes. The analysis indicates the degree of change to be expected, from the 12.3 million acre-feet of regional agricultural water use, under varying price assumption scenarios. The estimated coefficients from table 1 [for equation (6)] along with equation (4) are used to simulate the effects on technology proportions for alternative price scenarios for the period 1986–2005. Then, the technology proportions for each price scenario are further evaluated by comparing their water conservation potential.

Four annual price scenarios were used to simulate technology proportions. Annual price ratios for the estimated logit equations (table 1) for the period 1987–2005 were computed using historical average real (deflated) price changes over the period 1974–86 (table 4). For Scenario I, wheat price rises annually by the historical average annual price change, while prices for corn, alfalfa, and energy are held constant at 1986 levels. Scenario II is similar to Scenario I but with a 30% increase in wheat's historical average annual price change. Scenario III, which closely proxies a baseline scenario, involves annual price increases for wheat, alfalfa, and energy by their historical average annual price change, while corn price is held at the 1986 level. And Scenario IV is similar to Scenario III but with the historical average annual price change increased by 30%.

Results of the technology share simulations are presented in table 5. These results indicate that rather modest technology transitions would continue with program crop (wheat) price increases (Scenario I), with declines in gravity and conventional sprinkler systems and slight increases in center-pivot sprinkler systems for all three states. Center-pivot sprinkler systems would increase from 1.3–1.5% from 1986–2005, with average annual real price increases for wheat ranging from 1.2 to 2.1 cents per bushel. With a 30% increase in the average annual price change for wheat (Scenario II), center-pivot sprinkler systems would increase from 1.7–1.9%. These results seem to suggest that price increases for program crops in the Pacific Northwest have minimal effects on irrigation technology transitions.[4]

The combined effect of price increases for wheat, alfalfa, and energy, however, are more significant. If annual prices for wheat, alfalfa, and energy increase by their historical average annual price change (Scenario III), the decline in gravity-irrigated acreage would range from 8% in Washington to 15.9% in Idaho from 1986–2005. Increases in sprinkler-irrigated acreage during this time would range from 5.1% and 2.9% for conventional and center-pivot systems, respectively, in Washington to 10.1% and 5.8% for conventional and center-pivot systems, respectively, for Idaho. Increasing the average annual price changes by 30% (Scenario IV) results in a slight increase in these technology transitions. Sprinkler irrigated acreage would increase by an additional 1.71%, 2.27%, and 3.22% for Washington, Oregon, and Idaho, respectively. These relatively minor increases probably reflect the effects of institutional barriers to resource adjustments common to western irrigated agriculture. In other words, they reflect the conservation disincentives inherent with beneficial use criteria, i.e., "use it, or lose it," and the lack of institutional arrangements for conserved water rights. Rather than risk losing water rights, these institutions (or the lack of them) promote stability with irrigators' initial investments, i.e., technology in place tends to remain in use. However, results for Scenarios III and IV do seem to suggest that nonprogram crop price changes have a more significant effect on technology transitions in the Pacific Northwest than do program crop price changes.[5] This is due to the larger share of the region's cropping pattern accounted for by nonprogram crops, which is invariably influenced by their regional comparative economic advantage.

Finally, these results provide some evidence of the potential price effects of commodity support programs on regional irrigation technology transitions. At least for the Pacific Northwest, increases in commodity program support prices (specifically for wheat) would have minimal effects on any "land-augmenting" irrigation technology adoption. While this evidence differs from previous research (Lichtenberg; Just, Lichtenberg, and Zilberman), it is not surprising. Both studies emphasize relative profitability of irrigated program crops as critical determinants of land-augmenting technology adoption. However, program crop prices affect profitability for a much smaller portion of irrigated crop production in the Pacific Northwest than in western Nebraska. Irrigated program crop acreage accounts for only 25.3% of total irrigated acreage in the Pacific Northwest, and approximately 73% of water for irrigation comes from surface sources (Bureau of the Census). In addition, purchased water costs for off-farm water sources for the Pacific Northwest are relatively low, averaging less than $22 per acre.[6]

Agricultural water use associated with technology transitions for the Pacific Northwest is estimated by applying 1988-level irrigated acres (Bureau of the Census) and water-use rates (table 3) to the projected technology shares from the model simulation results (table 5). The quantity of annual agricultural water conservation by 2005 due to continued irrigation technology adoption is the difference in water use for 1986 and 2005. Annual water conservation estimates by 2005 for each state (and the Pacific Northwest) and MML model scenario are presented in table 6.

Annual water conservation by the year 2005 for the Pacific Northwest will amount to approximately 404,000 acre-feet, assuming that historical average annual price changes continue (Scenario III). This level of water conservation amounts to 3.3% of 1988 water use. If the average annual price change increased by 30% (Scenario IV), agricultural water conservation would amount to 3.9% of 1988 agricultural water use. This level of water conservation is relatively modest. The additional

[4] Irrigated program crop acreage accounts for only 25.3% of total irrigated acres in the Pacific Northwest (Bureau of the Census). Irrigated wheat acreage accounts for the largest portion (57%) of this irrigated program crop acreage and nearly 15% of total irrigated acres. Only irrigated alfalfa acreage exceeds irrigated wheat acreage relative to total irrigated acreage.

[5] Irrigated alfalfa acreage accounts for nearly 20% of total irrigated acres in the Pacific Northwest and represents the largest single nonprogram crop, accounting for 26% of nonprogram crop acreage (Bureau of the Census).

[6] Purchased water costs for Bureau of Reclamation water in the Pacific Northwest averaged $13.31 per acre in 1986 (McGuckin, Moore, and Negri), while the *Farm and Ranch Irrigation Survey (1988)* (Bureau of the Census) indicates that purchased water costs from off-farm sources averaged $22 per acre for the Pacific Northwest.

Table 5. Simulation Results for Alternative Price Scenarios Using the Estimated Multinomial Logit Model

	Technology States[a]											
	Scenario I			Scenario II			Scenario III			Scenario IV		
State/Year	P_0	P_1	P_2	P_0	P_1	P_2	P_0	P_1	P_2	P_0	P_1	P_2
Idaho												
1986	.4907	.3888	.1204	.4907	.3888	.1204	.4907	.3888	.1204	.4907	.3888	.1204
1995	.4859	.3872	.1268	.4845	.3867	.1288	.4029	.4471	.1500	.3813	.4606	.1581
2005	.4807	.3853	.1339	.4778	.3842	.1380	.3313	.4902	.1785	.2991	.5078	.1931
% Change 1986–2005	−1.00	−.35	1.35	−1.29	−.46	1.76	−15.94	10.14	5.80	−19.16	11.90	7.26
Oregon												
1986	.3344	.5483	.1172	.3344	.5483	.1172	.3344	.5483	.1172	.3344	.5483	.1172
1995	.3305	.5453	.1243	.3293	.5443	.1264	.2652	.5993	.1355	.2489	.6105	.1406
2005	.3262	.5418	.1320	.3238	.5398	.1364	.2124	.6340	.1536	.1897	.6471	.1632
% Change 1986–2005	−.82	−.65	1.48	−1.06	−.85	1.92	−12.20	8.57	3.63	−14.47	9.87	4.60
Washington												
1986	.2865	.5214	.1919	.2865	.5214	.1919	.2865	.5214	.1919	.2865	.5214	.1919
1995	.2837	.5182	.1981	.2828	.5172	.2000	.2434	.5505	.2060	.2325	.5574	.2101
2005	.2805	.5145	.2049	.2788	.5125	.2088	.2067	.5725	.2208	.1896	.5816	.2288
% Change 1986–2005	−.60	−.69	1.30	−.77	−.89	1.69	−7.98	5.10	2.88	−9.69	6.01	3.68

Note: Scenario I—Wheat prices increase annually by the historical average annual price change for wheat (table 4), while prices for corn, alfalfa, and energy are held constant at 1986 levels.
Scenario II—Wheat prices rise annually by a 30% increase in the historical average annual price change for wheat, while all other prices are held constant at 1986 levels.
Scenario III—Prices are increased annually for wheat, alfalfa, and energy by their historical average annual price change, while corn price is held constant at 1986 levels. This scenario closely approximates a baseline scenario.
Scenario IV—Similar to Scenario III, but with a 30% increase in the historical average annual price change for wheat, alfalfa, and energy.

[a] P_0 = gravity systems; P_1 = conventional sprinkler systems; P_2 = center-pivot sprinkler systems.

Table 6. Annual Water Conservation in Year 2005 from Irrigation Technology Adoption in the Pacific Northwest

	Using MML Simulation Results from:			
	Scenario I	Scenario II	Scenario III	Scenario IV
	(1,000 acre-feet)			
Idaho	15.9	20.0	252.9	304.1
Oregon	5.8	7.6	89.4	106.1
Washington	4.3	5.0	61.3	74.6
Pacific Northwest	26.0	32.6	403.6	484.8

water conservation expected from increasing only wheat prices will also be relatively small. Finally, results in table 6 indicate that the majority of agricultural water conservation (62.7%) will occur in Idaho (Scenario III). This is to be expected, given that in 1988 50.8% of regional irrigated production occurred in Idaho (3.2 million of 6.3 million acres) (Bureau of the Census). In addition, a larger share of irrigated production in Idaho (41%) is based on gravity technology, while only 31% of irrigated production in Oregon and Washington is based on gravity technology. Furthermore, 2.6 million acres of Idaho's irrigated crop acreage produces lower valued crops, relative to 1.3 and 1.1 million acres for Oregon and Washington, respectively. Therefore, profitability is regionally more critical in Idaho.

Research Summary and Policy Suggestions

Results from this study indicate that commodity prices affect irrigation technology adjustments. However, while the price parameters for the Pacific Northwest are statistically significant, most are relatively small, with prices for nonprogram crops having a greater influence on irrigation technology transitions than prices for program crops. Locational factors, such as climate, topography, soils, and development timing, also affected Pacific Northwest irrigation technology adjustments. Nonetheless, economic variables will be important when evaluating potential agricultural water conservation from future irrigation technology transitions.

The results indicate that irrigation technology transitions in the Pacific Northwest have been and will continue to be (in the absence of water policy changes) relatively slow. Assuming that real prices for wheat, alfalfa, and energy increase annually by their historical average annual real price change, gravity irrigated acreage declines by as much as 15.9% in Idaho to 8% in Washington by year 2005 (Scenario III). Conventional and center-pivot sprinkler systems will increase by 10.1% and 5.8%, respectively, in Idaho, and by 5.1% and 2.9%, respectively, in Washington. These shifts will result in annual water savings by year 2005 of nearly 404,000 acre-feet for the Pacific Northwest. Increasing the average annual real price changes by 30%, however, results in only a slight increase in technology shifts, ranging from 1.7% to 3.2% across states. These technology shifts increase water savings from 3.3% to 3.9% of 1988 agricultural water use. Finally, results indicate that irrigation technology transitions due to changes in real prices for wheat are relatively insignificant.

However, considering that the estimated technology transitions and the implied conservation are indicative of past irrigation efficiencies, future conservation may be greater because future irrigation technologies will be more efficient. Recent studies examining the economics and risk aspects of water-conserving technologies and water management strategies, including improved furrow irrigation systems, low-pressure center pivots, low-energy precision application (LEPA) systems, and irrigation scheduling, indicate potentially significant savings in water use and increased on-farm returns (Lee, Ellis, and Lacewell; Bernardo et al.; Homan, Skold, and Heermann; Harris and Mapp; Hornbaker and Mapp). Adoption of these technologies has varied throughout the West, with adoption being particularly slow in the Pacific Northwest.

In 1988, less than 19% of irrigated acreage in the Pacific Northwest involved the use of such water-conserving technologies as LEPA, surge-flow, or cablegation systems, etc. (Bureau of the Census). Even fewer acres involved the use of such water management techniques as soil moisture sensing or commercial irrigation scheduling services. Therefore, the future adoption of newer water-conserving technologies/management practices means that the water conservation estimates in this article are probably conservative. Future application of this study's research approach in regions where these technologies have become more dominant should reveal their conservation potential.

Finally, the historically slow pace of irrigation technology adoption in the Pacific Northwest should not be considered all that unusual. The availability of major surface water sources (the Columbia and Snake River basins) and the institutionally protected status of agricultural water use, both legally (legal preference for agricultural uses) and economically (see footnote 6), has resulted in the perception by many irrigators of unconstrained water resource supplies. The lack of adequate market forces to transmit information to the agricultural sector on the increasing scarcity value of western water resources has resulted in market indicators (relative prices) playing a reduced role in the past in promoting water-use efficiency/conservation in agriculture.

The results of this study indicate that locational and economic parameters do influence irrigator technology transitions to water-conserving technologies. However, within an economic environment of relatively low real crop price increases and perceived unconstrained water supplies, transition to water-conserving technologies is relatively slow. This means, that in the absence of policy-induced changes, relatively small conserved quantities can be expected to be available in the future to meet increasing nonagricultural demands. Therefore, due to the stability of irrigation technology in the Pacific Northwest, conservation incentive-oriented water policies, either subsidies or institutional changes (rights to conserved water, for example), will be needed to promote adoption of water-conserving technologies to acquire more significant gains in agricultural water conservation for reallocation.

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