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A Multicrop Production Model of Irrigated Agriculture, Applied to Water Allocation Policy of the Bureau of Reclamation

Michael R. Moore and Donald H. Negri

Recipients of irrigation water from the Bureau of Reclamation (BuRec) face a future of water conservation. By formally modeling surface water as a fixed, allocatable input to a multioutput firm, this research captures the institutional constraints governing water allocation and, simultaneously, establishes a cohesive approach to analyzing the production effects of BuRec allocation policy. Econometric results show that BuRec-served irrigators' crop supply and land allocation decisions are generally inelastic with respect to the water constraint. Using the elasticities, a policy simulation of a 10% reduction in BuRec water allocation indicates that production response to reduced water supply would affect the national price of three of ten major crops produced by BuRec-served farms.

Key words: fixed, allocatable water; multioutput production; reclamation water policy.

Introduction

To fulfill its primary mission, the U.S. Bureau of Reclamation (BuRec) has steadfastly promoted the development of irrigated agriculture in the American West—on this, both its clients and critics agree. Since 1902, the BuRec has constructed an irrigation infrastructure of 355 water-storage reservoirs, 254 diversion dams, and thousands of miles of transportation canals, pipelines, and tunnels (U.S. Department of the Interior 1988). Over 150,000 farms in the 17 western states receive BuRec-supplied water annually, irrigating roughly 10 million acres of cropland with over 25 million acre-feet of water. The acreage constitutes one-fourth of western irrigated land, while the water use constitutes between 40% and 85% of the annual flow of several major western river systems.

A variety of political and economic forces have coalesced to dictate reform of the BuRec's traditional water resource development mission (Moore; Wahl; Wilkinson). In response to the new policy environment, the BuRec recently adopted a water management mission to replace its development orientation (U.S. Department of the Interior 1987). The new management objectives include removing institutional impediments to irrigation water conservation—including partial deregulation of markets in BuRec-supplied water—and developing procedures for reallocating conserved water to meet urban, recreational, and freshwater fishery demands. Although the mix of market incentives and mandatory regulations remains to be decided, recipients of BuRec irrigation water face a future of water conservation.

This article analyzes the effect on agricultural production of BuRec water allocation policy. To accomplish this, we develop and analyze a multioutput production model of the irrigated agricultural firm, apply the model econometrically using BuRec production data, and simulate production response to a BuRec water conservation policy. The next section of the article develops the production model of the irrigated agricultural firm. Recent research applied a dual approach to modeling multioutput technologies in which fixed, allocatable inputs provide a source of jointness in multioutput decisions (Chambers and Just). Using this general approach, we develop a multioutput profit function with land and surface water as fixed, allocatable inputs. Econometric estimates of supply and land allocation equations are then reported using

Michael R. Moore is a resource economist in the Resources and Technology Division, Economic Research Service, U.S. Department of Agriculture. Donald H. Negri is an assistant professor in the Department of Economics, Willamette University. Senior authorship is not assigned.

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data from 458 irrigation districts that receive BuRec-supplied surface water. Elasticity measures show the effect of the water constraint on land allocation decisions. Finally, we use the elasticities to simulate BuRec-wide production response to a policy-imposed reduction in BuRec water supply. The theoretical model, empirical estimation, and policy simulation combine to create a cohesive, rigorous framework for evaluating the agricultural production impacts of BuRec water-resource policy.

This research makes three general contributions. First, it develops and estimates a positive, behavioral model of irrigated production. Previous research established the inefficiency associated with the heavily regulated system of western water institutions (Burness and Quirk 1979, 1980; Howe, Schurmeier, and Shaw; Kanazawa; Wahl). The regulations imply that surface water is an "institutionally-fixed" input to the producer. As such, researchers commonly adopted a normative programming approach to analysis of irrigated production (e.g., Bernardo et al.). In contrast, by modeling surface water as a fixed, allocatable input to a multioutput firm, this article rigorously incorporates institutional restrictions into a behavioral model.

Second, the article demonstrates an application of an important theoretical model of multioutput production in which fixed, allocatable inputs provide a source of jointness. This model was used several times, but not commonly, in the 1980s (Chambers and Just; Just, Zilberman, and Hochman; Moschini; Shumway, Pope, and Nash). Using the model, explicit allocation equations are derived for the fixed inputs based on a flexible functional form for the crop-specific profit functions. Previously, the allocation equations were stated only in general terms (Beattie and Taylor, p. 208; Shumway, Pope, and Nash, p. 76).

Third, the formal model and empirical application link irrigated production directly to BuRec water allocation policy. By modeling water supply as an exogenous variable, BuRec water allocation can be analyzed quantitatively as a public policy variable. The econometric application creates a geographically complete set of results by covering BuRec activity in the entire western United States. The policy simulation then uses the econometric results to quantitatively analyze the effect on agricultural production of BuRec water conservation policy. The simulation shows that, through the production impacts, BuRec policy decisions can influence the market price of some commodities. The potential for price changes raises the issue of whether BuRec water allocation decisions should be considered solely in terms of federal water policy or broadened to include considerations of national agricultural policy. The latter certainly are appropriate if, by affecting market prices, BuRec water-resource decisions create welfare effects in commodity markets.

A Multioutput Model of the Irrigated Agricultural Firm

While multioutput models of agricultural firms frequently assume that land is fixed at the enterprise level but allocatable among crop production activities, modeling surface water as a fixed, allocatable input is novel in a behavioral model. The rationale for modeling surface water as a fixed input originates in the allocation procedures governing western surface water in general and water deliveries from the BuRec in particular.

An entire body of economic research concludes that water markets or water-right markets generally do not guide western surface water allocation (Bain, Caves, and Margolis; Burness and Quirk 1979, 1980; Howe, Schurmeier, and Shaw; Howitt, Mann, and Vaux). Instead, quantity-based permit systems, typically administered by the states according to the prior appropriation doctrine, establish legal rights to surface water. Once established, legal procedures, legislated policies, and administrative rules greatly impede voluntary transfer of the rights. The surface water right usually becomes attached to the land on which the water is applied initially, with surface water rents reflected implicitly in land prices rather than explicitly in water prices.

Federal reclamation law and BuRec practices exacerbate the rigidities of the states' surface water administrative systems (Ellis and DuMars; Hartman and Seastone; Wahl). The BuRec offers wholesale water supply to irrigation districts from its water projects in each of the 17 western states.[1] Long-term contracts, generally of 40-year duration, establish terms of the delivery agreement with the districts. Although the contracts set water-delivery charges to repay a portion of federal expenditures, the charges reflect administered prices rather than market prices.[2] The combination of contractual quantities and administratively-set prices precludes producers from purchasing the quantity of water demanded at the prevailing price. Further, transfer restrictions on reclamation water rights are especially arduous because the BuRec retains ownership to many of the original water rights and federal reclamation law restricts water use to the original service area of an irrigation district (Ellis and DuMars; Wahl). To model this institutional environment, annual surface water deliveries to farms in an irrigation district should be treated as a fixed, allocatable input rather than a variable input.[3]

Similarly, land should be modeled as a fixed, allocatable input to farms irrigating with surface water in an intermediate-run production period. These farms generally require both off-farm and on-farm water delivery systems that represent largely fixed and sunk capital costs (Bain, Caves, and Margolis). Marginal increases in the land constraint are expensive, while marginal decreases have little salvage value. Thus, land that can be irrigated with existing irrigation infrastructure is the appropriate intermediate-run land constraint.

General Model

This section develops estimable crop supply, land allocation, and water allocation equations from a multioutput specification of irrigated agricultural production. Three assumptions guide the representation of multioutput production (Just, Zilberman, and Hochman): (*a*) inputs are allocated to specific crop production activities; (*b*) production is technically nonjoint so that the allocation of inputs uniquely determines crop-specific output levels; and (*c*) land and, in this article, surface water, are fixed, allocatable inputs. Assumptions (*a*) and (*b*) enable formation of separate restricted profit functions for each crop, taking land and water allocations as given. Assumption (*c*) then provides the source of jointness when maximizing multicrop profits (Shumway, Pope, and Nash). These assumptions have two desirable features: they model the essential features of agricultural production, yet provide a tractable approach to the multioutput enterprise.[4]

The notation used throughout this article is: p' $(p'_1\ p'_2 \dots p'_m)$ is a vector of strictly positive crop prices for the m crops; p $(p_1\ p_2 \dots p_m)$ is a vector of relative crop prices normalized by p'_m (with $p_m = 1$); r' $(r'_1\ r'_2 \dots r'_t)$ is a vector of strictly positive variable input prices for the t inputs; r $(r_1\ r_2 \dots r_t)$ is a vector of relative variable input prices normalized by p'_m; y $(y_1\ y_2 \dots y_m)$ is a vector of crop outputs; W is the fixed quantity of water; w $(w_1\ w_2 \dots w_m)$ is a vector of water allocations to production of crop i; N is the fixed quantity of land; n $(n_1\ n_2 \dots n_m)$ is a vector of land allocations to production of crop i; $\pi_i(p'_i, r', w_i, n_i)$ is the restricted profit function of crop i, which holds water and land allocations fixed; and $\Pi(p', r', W, N)$ is the multicrop profit function.

With competitive markets (except for surface water) and regular, nonjoint technologies, individual producers choose the profit-maximizing allocations of surface water and land subject to the water and land constraints. Formally, the multicrop profit function results from maximizing the sum of crop-specific restricted profit functions subject to the constraints:

$$\text{(1)} \qquad \Pi(p', r', W, N) = \underset{\substack{w_1, \dots, w_m \\ n_1, \dots, n_m}}{\text{Max}} \left(\sum_{i=1}^{m} \pi_i(p'_i, r', w_i, n_i) : \sum_{i=1}^{m} w_i = W \text{ and } \sum_{i=1}^{m} n_i = N \right).$$

The $\pi_i(p'_i, r', w_i, n_i)$'s are convex and linear homogeneous in p'_i and r', nondecreasing in p'_i, nonincreasing in r', and nondecreasing in w_i and n_i (Lau 1976). The properties of $\Pi(p', r', W, N)$ follow as convex and linear homogeneous in p' and r', nondecreasing in p', nonincreasing in r', and nondecreasing in W and N (Chambers and Just). A Lagrangian function, denoted L, states the constrained maximization problem as

$$\text{(2)} \qquad L = \sum_{i=1}^{m} \pi_i(p'_i, r', w_i, n_i) + \lambda(W - \sum_{i=1}^{m} w_i) + \mu(N - \sum_{i=1}^{m} n_i),$$

where λ and μ are the shadow prices on the surface water and land constraints, respectively. The necessary conditions for an interior solution are

$$\text{(3)} \qquad \partial L/\partial w_i = \partial \pi_i/\partial w_i - \lambda = 0 \qquad i = 1, \dots, m,$$

$$\text{(4)} \qquad \partial L/\partial n_i = \partial \pi_i/\partial n_i - \mu = 0 \qquad i = 1, \dots, m,$$

$$\text{(5)} \qquad W - \sum_{i=1}^{m} w_i = 0 \qquad \text{and} \qquad N - \sum_{i=1}^{m} n_i = 0.$$

Equations (3) and (4) allocate surface water and land among crops to equate the marginal profit from each crop. The input constraints in (5) are binding assuming an interior solution.

Solving equations (3)–(5) yields the optimal solutions to equation (2), denoted $w_i^*(p', r', W, N)$ and $n_i^*(p', r', W, N)$. These represent the multioutput firm's production equilibrium in water and land allocations.

Inserting the w_i^* and n_i^* into the necessary conditions creates a set of identities for comparative static analysis. The analysis does not yield testable hypotheses about the constraints' roles in land and water allocation. The signs of $\partial w_i^*/\partial W$, $\partial n_i^*/\partial W$, $\partial w_i^*/\partial N$, and $\partial n_i^*/\partial N$ $(i = 1, \dots, m)$ are indeterminate.

The input constraints' roles in the comparative static results relate directly to the plausible signs on the constraints' estimated coefficients in the empirical section. We elaborate further on the results for this reason. The two-crop case clarifies the reasons for the ambiguity of the results and illustrates the relationships underlying land and water allocation decisions. Selected comparative static results for a change in the water constraint are:

(6) $$\frac{\partial n_1^*}{\partial W} = \left(\frac{\partial^2\pi_1}{\partial w_1^2}\frac{\partial^2\pi_2}{\partial w_2 \partial n_2} - \frac{\partial^2\pi_2}{\partial w_2^2}\frac{\partial^2\pi_1}{\partial w_1 \partial n_1}\right) \Big/ H \gtrless 0,$$

(7) $$\frac{\partial n_2^*}{\partial W} = \left(\frac{\partial^2\pi_2}{\partial w_2^2} \frac{\partial^2\pi_1}{\partial w_1 \partial n_1} - \frac{\partial^2\pi_1}{\partial w_1^2}\frac{\partial^2\pi_2}{\partial w_2 \partial n_2}\right) \Big/ H \gtrless 0,$$

(8) $$\frac{\partial w_1^*}{\partial W} = \left(\frac{\partial^2\pi_2}{\partial w_2^2}\frac{\partial^2\pi_1}{\partial n_1^2} + \frac{\partial^2\pi_2}{\partial w_2^2}\frac{\partial^2\pi_2}{\partial n_2^2} - \frac{\partial^2\pi_1}{\partial w_1 \partial n_1}\frac{\partial^2\pi_2}{\partial w_2 \partial n_2} - \left(\frac{\partial^2\pi_2}{\partial w_2 \partial n_2}\right)^2\right) \Big/ H \gtrless 0,$$

and

(9) $$\frac{\partial w_2^*}{\partial W} = \left(\frac{\partial^2\pi_1}{\partial w_1^2}\frac{\partial^2\pi_1}{\partial n_1^2} + \frac{\partial^2\pi_1}{\partial w_1^2}\frac{\partial^2\pi_2}{\partial n_2^2} - \frac{\partial^2\pi_1}{\partial w_1 \partial n_1}\frac{\partial^2\pi_2}{\partial w_2 \partial n_2} - \left(\frac{\partial^2\pi_1}{\partial w_1 \partial n_1}\right)^2\right) \Big/ H \gtrless 0,$$

where H is the determinant of the six-by-six bordered Hessian for the two-crop case.[5] The sufficient conditions dictate only that $\partial^2\pi_1/\partial w_1^2 + \partial^2\pi_2/\partial w_2^2 < 0$, $\partial^2\pi_1/\partial n_1^2 + \partial^2\pi_2/\partial n_2^2 < 0$, and $H > 0$. The second derivatives ($\partial^2\pi_1/\partial w_1^2$, $\partial^2\pi_2/\partial w_2^2$, $\partial^2\pi_1/\partial n_1^2$, and $\partial^2\pi_2/\partial n_2^2$) may be positive, negative, or zero since obtaining a solution to equation (1) does not require concavity of the restricted profit functions in the allocatable fixed inputs.[6] Instead of concavity, the input constraints ensure existence of a solution by providing additional restrictions on the optimization problem. The indeterminacy of (6)–(9) generalizes to more than two crops.

The results in (6)–(9) illustrate the complexity of decisions facing a firm with multiple outputs and two fixed, allocatable inputs. By implication, intuitive approaches to understanding the multioutput agricultural firm may prove misleading. For example, intuition suggests that a firm facing a relatively tight water constraint would allocate more land to cotton production (which has low water requirements) and less land to rice production (which has high water requirements). The comparative static results show a more complex set of tradeoffs.

Examining two identities based on the input constraints provides additional insight into the comparative statics and, again, links the theoretical and empirical sections. The identities, formed by substituting w_i^* for w_i and n_i^* for n_i in the constraints in equation (5), impose physical conservation laws on the allocation decisions. Differentiating the identities with respect to the water constraint yields

(10) $$\sum_{i=1}^{m} [\partial n_i^*/\partial W] \equiv 0 \quad \text{and} \quad \sum_{i=1}^{m} [\partial w_i^*/\partial W] \equiv 1.$$

The first identity in (10) says that crop-specific land reallocations following a change in the water constraint sum to zero since land availability remains unchanged. Thus, if producers increase acreage of some crops in response to a relaxed water constraint, the increases must be offset with a reduction in other crops.[7] The second identity in (10) says that water reallocations completely absorb an increase in the water constraint. The only theoretical restriction on the water reallocations is that they sum to 1. Note that the two-crop case illustrates these identities: equations (6) and (7) sum to 0, and (8) and (9) sum to 1.

Normalized Quadratic Functional Form

Unlike conventional input demand functions, fixed-input allocation equations cannot be obtained directly using Hotelling's lemma. Instead, they must be derived from the necessary conditions for multicrop profit maximization. We posit that the restricted profit functions in equation (1) take a normalized quadratic form (Lau 1978; Shumway). Closed-form expressions for w_i^* and n_i^* are tractable using the normalized quadratic because its first derivatives are linear. The allocation equations, now denoted $w_i^*(p, r, W, N)$ and $n_i^*(p, r, W, N)$, depend on relative prices since the normalized quadratic imposes linear homogeneity on the profit function by specifying profit and prices relative to a numeraire price.

To begin deriving the allocation equations, the necessary conditions for multicrop profit maximization corresponding to equations (3)–(5) form a system of $(2m + 2)$ linear equations. Setting the equations corresponding to (3) sequentially equal to $\partial\pi_1/\partial w_1$ removes λ, and doing likewise with the equations corresponding to (4) removes μ. The resulting equations form a linear system of $2m$ equations with $2m$ unknowns, w_i and n_i ($i = 1, \ldots, m$). From this system, closed-form expressions for $w_i^*(p, r, W, N)$ and $n_i^*(p, r, W, N)$ are derived. The solutions are the estimable allocation equations:

(11) $$w_i^*(p, r, W, N) = \alpha_0^i + \sum_{f=1}^{m} \alpha_{1f}^i p_f + \sum_{k=1}^{t} \alpha_{2k}^i r_k + \alpha_3^i W + \alpha_4^i N, \qquad i = 1, \ldots, m$$

and

(12) $$n_i^*(p, r, W, N) = \beta_0^i + \sum_{f=1}^{m} \beta_{1f}^i p_f + \sum_{k=1}^{t} \beta_{2k}^i r_k + \beta_3^i W + \beta_4^i N, \qquad i = 1, \ldots, m,$$

where the αs and βs are simplified coefficients from the parameters of the restricted profit functions. The comparative static relations $\partial w_i^*/\partial W$, $\partial w_i^*/\partial N$, $\partial n_i^*/\partial W$, and $\partial n_i^*/\partial N$, represented by the coefficients on W and N, cannot be signed even with the specific functional form.[8]

With the fixed inputs set at optimal allocations, applying Hotelling's lemma to the multicrop profit function yields crop supply equations. First, state the multicrop profit function in equation (1) as

(13) $$\Pi(p', r', W, N) = \sum_{i=1}^{m} \pi_i(p_i', r', w_i^*(p', r', W, N), n_i^*(p', r', W, N)).$$

The crop supply functions follow directly by using Hotelling's lemma and the envelope theorem (Chambers and Just):

(14) $$\frac{\partial \pi_i(p_i', r', w_i^*, n_i^*)}{\partial p_i'} = y_i(p_i', r', w_i^*, n_i^*), \qquad i = 1, \ldots, m.$$

Corresponding to (14), the supply equations derived from the normalized quadratic specifications are linear in p_i, r, w_i^*, and n_i^*. Substituting into the equations the expressions for $w_i^*(p, r, W, N)$ and $n_i^*(p, r, W, N)$ from equations (11) and (12) results in linear, reduced-form supply equations:[9]

(15) $$y_i(p, r, W, N) = \gamma_0^i + \sum_{f=1}^{m} \gamma_{1f}^i p_f + \sum_{k=1}^{t} \gamma_{2k}^i r_k + \gamma_3^i W + \gamma_4^i N, \qquad i = 1, \ldots, m,$$

where the γs represent the simplified coefficients after the substitution. The crop supply functions slope upward in their own price because restricted profit functions are convex in p_i. However, the signs of the coefficients on W and N (γ_3 and γ_4) again are indeterminate because, in the comparative static results, the qualitative effects of W and N on w_i^* and n_i^* are indeterminate.

Compared to multicrop production economics with variable inputs, the basic difference in the supply and allocation equations is the presence of input constraints as explanatory variables rather than input prices.

Empirical Application

Land allocation equations [equation (12)] are estimated on a regional basis for ten crops, including irrigated corn, wheat, barley, sugar beets, hay (including alfalfa), pasture, fruit and nut orchards, rice, vegetables, and cotton. Irrigated acreage in these crops constitutes 85% of harvested BuRec land in 1987. Regional supply functions [equation (15)] are estimated for eight of the ten crops, with orchards and vegetables excluded because the output units for various orchard and vegetable crops are incompatible. Water allocation equations are not estimated because the data do not include crop-specific water allocations.[10]

Data and Variables

The Bureau of Reclamation operates 120 water projects in the 17 western states, delivering water to 620 irrigation districts. Data on crop output, land allocation, total land in irrigation rotation, water deliveries, and number of full- and part-time farms are from irrigation district reports filed annually with the BuRec beginning in 1979. These reports aggregate the values from all farms served by the district. Pooling cross-sectional data for 458 of the districts with time series from 1979 to 1987 generates 3,507 observations. The appendix describes in detail the sample and variable construction.

BuRec operations are divided into six regions along watershed boundaries of the major western river systems: Pacific Northwest, Mid-Pacific, Lower Colorado, Upper Colorado, Southwest, and Missouri Basin (U.S. Department of the Interior 1988). The model is estimated for each region separately because exploratory analysis indicated that slope coefficients vary substantially across regions.

The land constraint measures acreage to which irrigation water could be applied with existing irrigation infrastructure. The water constraint measures all water delivered by an irrigation district to farms, including BuRec project water and other district water supply sources. District water deliveries approximate the district's legal entitlement to surface water.

District-level values for land allocation and crop output summarize individual production decisions of all farms served by the district. Substantial variation in the number and size of farms across districts required weighting large districts more heavily since they represented more acreage and generally more production decisions than small districts. To address variation in district size, we constructed observations on a per-farm basis and weighted the observation by the number of farms in the district. Thus, district values for land allocation, output, and land and water constraints are divided by the number of farms. The average values are unbiased estimates of the corresponding farm-level values.

State-specific agricultural output and input prices are merged with the irrigation district data. We used expected output prices because producers make land allocation decisions prior to the realization of output price. Input prices include current year market prices for farm labor, electricity, and gasoline. Linear homogeneity of the profit function is imposed by normalizing all prices by the wheat price.

Other independent variables include climate and soil characteristics corresponding to physical conditions in the counties in which the irrigation district operates. Like output prices, the climate variables reflect expected weather conditions. They include proxies for the amount of energy (average growing degree days) and rainfall (average effective rainfall) available for plant growth during the growing season. Soil variables include average soil texture, soil productivity, and soil slope for all cropland in the counties.

Finally, a dummy variable for 1983 captures the effect of 1983's federal payment-in-kind program on crop supply and land allocation. A variable measuring the share of district land farmed by full-time farms serves as a proxy for management intensity within the district.

Econometric Issues

To estimate the supply and land allocation equations, a disturbance term is appended to each equation. The properties of the disturbance terms prescribe the appropriate econometric technique for efficient and consistent estimation. Censored data, aggregation, pooled time-series and cross-sectional observations, and joint production raise four econometric issues, not all of which can be resolved with current econometric techniques.

The first econometric issue concerns censored dependent variables, as every irrigation district does not grow all the crops produced in the region. For example, corn output and land allocation assume zero values for 479 of the 946 observations in the Pacific Northwest. Applying ordinary least squares to non-zero observations leads to biased and inconsistent estimates and eliminates information that can explain the decision to grow a crop. We estimate each supply and land allocation equation separately using tobit regression analysis. Tobit uses all observations and produces unbiased and asymptotically efficient estimates with censored data.

The second econometric issue concerns aggregation. While the model is derived at the farm level, estimation is based on data aggregated to the district level. Aggregation of farm-level data can lead to heteroskedasticity when the number or size of farms varies across districts. Unlike the linear model, tobit estimates are inconsistent in the presence of heteroskedastic errors (Maddala). We assume the source of heteroskedasticity is the number of farms, which is the denominator in the per-farm values for land allocation, supply, and the land and water constraints. Districts with a large number of farms have smaller error variances than districts with fewer farms. To address the issue, the tobit estimators are weighted by the number of farms operating in the district.[11]

The third issue concerns pooling of time-series and cross-sectional data. Pooling raises the question of whether the error covariance matrix satisfies the classical regression assumptions. The observations may be cross-sectionally correlated, heteroskedastic, and/or time-wise autoregressive. Inefficient estimation and potential bias from other sources of heteroskedasticity are ignored in favor of eliminating the bias associated with censored data.

The fourth econometric issue concerns correlation of disturbance terms across equations. With allocatable inputs imposing joint production, error terms are certain to be contemporaneously correlated across crops. Efficiency requires simultaneous estimation of a system of equations. However, in the general linear model, seemingly unrelated regression does not produce more efficient estimates when the explanatory variables are identical for all equations, as is the case here. Moreover, estimating tobit regressions using a system framework is computationally intractable.

Results

As many as ten land allocation equations and eight supply equations are estimated for each of the BuRec production regions using SHAZAM (White). Since this article primarily focuses on the surface water constraint's role in explaining production decisions, complete results are presented for only three crops in one region. Hay crops, barley, and sugar beets in the Pacific Northwest Region are representative of the performance of the estimation and the role played by the entire set of variables (table 1).[12]

Note first that, for an individual crop, parameter estimates generally are similar in sign and significance for the supply and land allocation equations. This holds true for crops and regions not reported here. The similarity across equations is not surprising given the importance of land inputs in determining crop output.

The price variables perform ineffectively, on balance (table 1). Many price coefficients are statistically significant. Nevertheless, with few exceptions, crop supply equations do not slope upward in their own prices and cross-price effects do not appear to be symmetric. Two factors explain the ineffective performance. First, severe multicollinearity among the 11 possible output and input prices seriously hampered efficient estimation of the coefficients. Second, output prices lagged one year may not adequately capture either the complexity of economic forces affecting land allocation or the lag structure of prices on production. Despite the performance of the price variables, the article's primary empirical interest resides in quantifying the effect of the water constraint on multicrop production. The estimation procedures preserve the unbiasedness and efficiency of the water constraint coefficients since output prices have little correlation with water supply.

Location-specific physical variables function differently in a multicrop model with fixed, allocatable inputs because crops compete for the fixed inputs. The physical variables in the equations measure a location's comparative advantage in producing a crop rather than its absolute advantage. For instance, a positive coefficient on low productivity soil in the barley land allocation equation (table 1) implies that low productivity soil increases acreage allocated to barley because barley is a relatively profitable use of marginal land. It does not imply that low productivity soil will have greater barley production than high productivity soil.

Within this framework, the climate and soil coefficients are generally statistically significant and consistent with an agronomic approach. The performance of the variable "annual growing degree days" (GDD) in the land allocation equations in the Pacific Northwest Region illustrates this. GDD measures the expected length and energy intensity of the growing season. The coefficients on GDD are significant at the .01 level for eight of the nine land allocation equations (including two of the three crops presented in table 1). The signs correspond closely to the length of growing season required by the crops. Land allocated to fruit and nut orchards, sugar beets, grain corn, and vegetables (predominantly potatoes in this region) increases with GDD. These four crops require relatively long growing seasons of four to seven months (Hagan, Haise, and Edminster; Jensen). Coefficients on GDD are negative for wheat, hay crops, pasture, and fallow land allocations. In the Pacific Northwest, spring wheat has a growing season of less than four months during the relatively cool months of early spring to early summer (Bernardo et al.), while hay crops and pasture do not require a long season because they are cut or grazed periodically within the season rather than reaching a single mature stage at season's end (Hagan, Haise, and Edminster). Fallow land naturally requires no growing season. Finally, the GDD coefficient for barley land allocation is not significantly different from zero. Within the Pacific Northwest Region, barley land allocation choices are insensitive to GDD. The general consistency of the physical variables with an agronomic interpretation of the results lends credibility to the data and the analysis.

The input constraints distinguish this model from traditional agricultural production models that include water and land as variable inputs. The constraints perform strongly as determinants of irrigated production decisions. For example, the land constraint is significant at the .01 level in eight of nine land allocation equations and all six supply equations that are estimated with data from the Pacific Northwest Region. Of the nine land allocation equations, the surface water constraint is significant at the .05 level in seven equations and at the .01 level in four of those seven. Of the six crop supply equations, it is significant at the .10 level in five equations and at the .01 level or better in four of those five.

Coefficients on the land constraint in the land allocation equations measure the change in acreage allocated to a crop given a one-acre increase in total land.[13] For example, an additional acre of land would increase allocations to hay crops, barley, and sugar beets by .172, .173, and .087 acres, respectively (table 1). The physical identity [equation (10)] requires that, when all crops are accounted for, changes in land allocation sum to one for a change in the land constraint. In the Pacific Northwest Region, the land constraint coefficients from the nine land allocation equations sum to .815. The difference between the identity summing to one and the coefficients summing to .815 can be attributed to land allocations made to relatively minor crops, which are not estimated.

Coefficients on the water constraint in the land allocation equations measure the change in acreage

Table 1. Tobit Model Estimates—Three Irrigated Crops in Pacific Northwest Region

Independent Variables	Alfalfa Hay and Other Hay		Barley		Sugar Beets	
	Crop Supply (tons)	Land Allocation (acres)	Crop Supply (bu.)	Land Allocation (acres)	Crop Supply (tons)	Land Allocation (acres)
Prices:						
Hay	0.91	0.170	−23.16	−0.248	−38.89	−1.758
($/ton/W)[a]	(1.4)	(1.2)	(−2.2)	(−2.0)	(−10.4)	(−10.2)
Barley	−60.83	−14.645	1,557.10	18.325	507.26	27.431
($/bu./W)	(−1.3)	(−1.5)	(2.1)	(2.1)	(2.2)	(2.5)
Corn	12.17	11.163	−837.47	−9.527	290.55	11.483
($/bu./W)	(0.5)	(1.9)	(−1.9)	(−1.8)	(2.0)	(1.7)
Fruit Index	−0.05	0.003	1.26	0.017	1.15	0.055
(index/W)	(−0.7)	(0.2)	(1.0)	(1.1)	(3.4)	(3.4)
Sugar Beets	−2.71	−1.319	89.13	1.061	−6.30	−0.322
($/ton/W)	(−1.4)	(−3.0)	(2.9)	(2.9)	(−0.9)	(−0.9)
Vegetable Index	−1.66	−0.614	42.78	0.499	−14.00	−0.596
(index/W)	(−2.0)	(−3.4)	(3.2)	(3.2)	(−4.0)	(−3.7)
Wage Rate	−3.82	0.145	−173.91	−1.878	−122.75	−5.818
($/hour/W)	(−0.4)	(0.06)	(−1.0)	(−0.9)	(−2.8)	(−2.8)
Electricity	38.45	10.788	−725.04	−8.869	511.97	22.467
(¢/kwh/W)	(2.8)	(3.5)	(−3.2)	(3.3)	(7.9)	(7.4)
Gasoline	−2.30	−1.552	646.51	5.969	490.84	22.259
($/gal./W)	(−0.04)	(−0.1)	(0.6)	(0.5)	(1.6)	(1.6)
Fixed Quantities:						
Surface Water	0.19	0.035	−2.66	−0.031	−0.19	−0.010
(acre-feet)	(12.6)	(10.5)	(−11.2)	(−10.8)	(−3.0)	(−3.3)
Irrigated Land	0.77	0.172	15.30	0.173	1.75	0.087
(acres)	(14.0)	(14.0)	(16.9)	(16.1)	(6.9)	(7.4)
Physical Variables:						
Growing Deg. Days	−0.01	−0.004	0.06	0.001	0.10	0.004
(days)	(−2.3)	(−3.4)	(0.7)	(1.2)	(4.4)	(3.7)
Effective Rain	−3.17	1.440	427.49	5.795	16.43	0.521
(inches)	(−0.7)	(1.5)	(5.8)	(6.6)	(0.9)	(0.6)
High Prod. Soil	−1.24	−0.130	114.00	0.690	53.51	2.587
(dummy var.)	(−0.4)	(−0.2)	(2.2)	(1.1)	(5.3)	(5.5)
Low Prod. Soil	−16.97	−0.618	335.66	4.303	1.11	0.394
(dummy var.)	(−3.8)	(−0.6)	(4.6)	(4.9)	(0.05)	(0.4)
Sandy Soil	−1.58	2.168	−558.51	−8.020	[b]	[b]
(dummy var.)	(−0.2)	(1.2)	(−4.0)	(−4.8)		
Clayey Soil	−11.74	2.713	−99.55	−2.415	386.37	19.001
(dummy var.)	(−2.6)	(2.7)	(−1.3)	(−2.7)	(6.7)	(7.0)
Soil Slope	1.72	0.064	−78.76	−1.024	−10.23	−0.510
(% slope)	(3.1)	(0.5)	(−8.0)	(−8.7)	(−3.5)	(−3.7)
Other:						
PIK	−5.33	−2.078	106.72	1.077	39.54	1.804
(dummy var.)	(−1.3)	(−2.3)	(1.6)	(1.4)	(2.1)	(2.1)
Full-time Acres	−53.14	−11.226	172.77	2.061	268.67	12.508
(% of acres)	(−8.9)	(−8.4)	(1.8)	(1.8)	(7.2)	(7.2)
Intercept	107.68	23.742	−2,140.40	−25.088	−829.98	−40.740
	(3.5)	(3.4)	(−4.3)	(−4.2)	(−5.7)	(−6.0)
Standard Error of the Estimate	28.22	6.290	441.46	5.268	77.53	3.604

Note: The table reports estimated regression coefficients and, in parentheses, *t*-statistics. Maddala (pp. 151–56) describes the relationship between regression coefficients and normalized coefficients in the tobit model. SHAZAM reports both.
[a] W denotes the wheat price ($/bu.), which serves as numeraire.
[b] No estimate is provided because sandy soil was omitted from the regression to facilitate convergence.

Table 2. Land Allocation Elasticities with Respect to Water Constraint

	Bureau of Reclamation Production Region					
Irrigated Crop	Pacific Northwest	Mid-Pacific	Lower Colorado	Upper Colorado	Southwest	Missouri Basin
Alfalfa & Hays	0.58 (10.5)[a]	0.07 (2.4)	0.70 (8.2)	−0.18 (−8.1)	0.27 (2.1)	−0.09 (−2.7)
Barley	−1.08 (−10.8)	−0.43 (−7.9)	−0.05 (−0.4)	0.19 (3.3)	−0.41 (−1.6)	0.15 (2.6)
Grain Corn	1.97 (12.8)	0.08 (2.0)	NA	0.59 (5.0)	−0.93 (−4.3)	−0.24 (−3.4)
Cotton	NA[b]	NE[c]	−0.20 (−1.0)	NA	0.36 (1.3)	NA
Fruits & Nuts	−0.42 (−2.5)	−0.55 (−14.7)	0.32 (3.3)	−0.17 (−1.1)	−0.79 (−2.9)	NA
Pasture	−0.10 (−1.1)	0.14 (4.6)	0.32 (1.9)	−0.05 (−0.8)	0.80 (6.3)	0.25 (5.3)
Rice	NA	1.13 (15.0)	NA	NA	NA	NA
Sugar Beets	−1.20 (−3.3)	0.33 (5.9)	0.04 (0.4)	NA	NA	0.53 (5.0)
Vegetables	0.21 (2.3)	0.07 (1.9)	0.27 (2.5)	0.09 (0.9)	−0.79 (−5.6)	−1.09 (−7.5)
Wheat	−0.01 (−0.2)	−0.20 (−5.1)	0.80 (5.5)	0.38 (5.0)	−0.28 (−1.6)	0.05 (0.7)
Fallow	−0.32 (−2.5)	−0.08 (−2.2)	−2.33 (−12.7)	0.12 (1.1)	0.23 (1.3)	−0.10 (−1.4)

Note: The water constraint elasticity is measured as $\frac{\partial n_i}{\partial W}\cdot\frac{W}{n_i}$ using the tobit model elasticity formula in Maddala.

[a] The numbers in parentheses are *t*-statistics for the regression coefficients on the water constraints from the land allocation equations ($\partial n_i/\partial W$).

[b] NA means that the crop either was not grown in the region or had too few observations for successful estimation.

[c] NE means that the equation was not estimated because the maximum likelihood procedure did not converge.

allocated to a crop given a one acre-foot increase in total available surface water. Accordingly, an additional acre-foot of water would change land allocations to hay crops, barley, and sugar beets by .035, −.031, and −.010 acres, respectively. In combination, the set of water constraint coefficients measures the cropping pattern response to a change in water availability. The results indicate that relaxing the water constraint would induce land reallocation from barley, sugar beets, fruit and nut orchards, and fallow land to hay crops, grain corn, and vegetables. The wheat and pasture coefficients are not statistically different from zero. The physical identity requires that changes in land allocation sum to zero since total land remains unchanged. The nine water constraint coefficients in the region sum to .01.

The water constraint continues to perform strongly as a determinant of production decisions in the other BuRec production regions. In total, 53 land allocation equations and 36 crop supply equations are estimated. Of these, the water constraint is significant at the .05 level in 36 land allocation equations and at the .01 level in 28 of those 36 (table 2). It is significant at the .05 level in 24 of the supply equations and at the .01 level in 20 of those 24. The water constraint's performance in the complete set of land allocation and crop supply equations underscores the importance of water deliveries to irrigation agriculture.

Water constraint elasticities measure the cropping pattern and supply response to a 1% increase in water availability. They largely are inelastic: 47 of 53 elasticities generated from the land allocation equations and 32 of 36 from the supply equations are less than one in absolute value. Table 2 reports the elasticities for the land allocation equations in all six BuRec regions. The supply elasticities generally are similar to the reported land allocation elasticities.[14] Overall, the elasticities suggest that minor reductions in water supply would not produce dramatic adjustments in cropland use and crop supply. The Pacific Northwest Region, with three land allocation elasticities and three supply elasticities in the elastic range, would experience the most significant adjustments.

While theory is silent about the signs on the water constraint coefficients, one perspective for interpreting

Table 3. Simulated Acreage Response to a 10% Water Supply Reduction

	1987 BuRec Land Allocation		Simulated Acreage Response		
Irrigated Crop	Crop Acreage	Percent of BuRec Acres[a]	Acreage Response	Crop Acreage	Percent of BuRec Acres[a]
Alfalfa & Hays	2,208,936	21.2	−49,028	2,159,907	20.7
Barley	514,188	4.9	22,878	537,066	5.1
Grain Corn	835,438	8.0	−409	835,029	8.0
Cotton	829,437	7.9	−2,896	826,541	7.9
Fruits & Nuts	1,020,699	9.8	45,156[b]	1,065,855	10.2
Pasture	821,067	7.9	−5,201	815,866	7.8
Rice	191,660	1.8	−21,658	170,002	1.6
Sugar Beets	354,430	3.4	4,345	358,775	3.4
Vegetables	1,006,095	9.6	−8,209	997,886	9.6
Wheat	756,114	7.2	−5,920	750,194	7.2
Fallow	944,615	9.1	33,962	978,577	9.4

[a] Percentages do not sum to 100 because acreage in miscellaneous crops is not included in the table. Total BuRec land in irrigation rotation was 10,435,165 acres in 1987.
[b] The simulated acreage response for fruit and nut orchards represents 1.3% of 1987 national harvested acreage of the crop. For the remaining crops, the acreage responses comprise less than 1% of national harvested acreage of the crop.

the results is based on the crops' physical water requirements. This perspective says that producers reallocate land from crops with low water requirements to crops with high water requirements as the water constraint relaxes. Water-intensive crops like alfalfa, vegetables, sugar beets, orchards, and grain corn have higher water requirements than wheat, cotton, and barley.[15] Although the comparative static results in (6)–(9) show the importance of intercrop interactions in determining the effect of the water constraint, a single-crop, water-requirement perspective frequently guides intuition.[16]

The empirical results conform to the water-requirement perspective in some, but not all, regions. For each crop, the elasticities and underlying coefficients vary in sign and/or magnitude across regions (table 2), suggesting that producers in different regions face different multicrop profit functions. The coefficients' signs in the Pacific Northwest and Mid-Pacific Regions generally are consistent with the water requirement perspective, while the signs in the Upper Colorado and Missouri Basin Regions generally are inconsistent. Although crop-water requirements are clearly an important factor in determining land allocation decisions when irrigation water is fixed, they do not necessarily dictate the allocations at the margin.

The water constraint elasticities should be considered in light of three caveats concerning model specification, data availability, and maintained hypotheses. First, the analysis shows that the water constraint parameters are sensitive to the geographic definition of the regions. This suggests that the slope of the constraint depends on location-specific physical characteristics. Estimating district-specific slopes would abstract from any location-specific effects, but district-specific parameters cannot be estimated without longer time-series data. The coefficients thus are restricted to be equal across districts within BuRec production region boundaries. Second, local patterns of crop rotation practices, water supply variability, land quality variability, BuRec operating rules, weather risk, extension practices, and processing or marketing infrastructure may constitute sources of omitted variable bias. Third, some farms with long growing seasons double crop their land, and some farms have access to groundwater in addition to using BuRec water. These can be interpreted either as departures from maintained hypotheses or as a problem of measuring land allocation and the water constraint properly.

Policy Simulation: A Reduction in BuRec Water Availability

The estimated water constraint elasticities establish a basis for evaluating the impact of water conservation policy on agricultural production from BuRec-served farms. Using the region-specific land allocation elasticities with respect to water quantity (table 2) and 1987 data on land allocation in each BuRec production region, we simulate the effect on a BuRec-wide cropping pattern of a 10% reduction in 1987 water deliveries. The supply reduction equals 2.55 million acre-feet of surface water. The results show the changes in individual crop acreage and in the percentage of total BuRec acres in each crop (table 3). Because the experiment reduces water supply, crops with positive elasticities are allocated fewer acres, while crops with negative elasticities are allocated additional acres. In the Mid-Pacific Region, for example, orchard acreage increases 37,593 acres (from a base of 683,509) and rice acreage decreases 21,658 acres (from a base of 191,660) in response to the water-supply reduction.

The generally small elasticities and, for a given crop, the sign changes across regions combine to produce uniformly low BuRec-wide acreage responses. Although the decline of 49,028 acres in hay crop production is the largest absolute response, it is fairly small relative to its base acreage. In this case, increases of over 10,000 hay acres in the Upper Colorado and Missouri Basin Regions dampen the negative BuRec-wide response. The largest increase in acreage, 45,156 acres, occurs with fruit and nut orchards.[17]

The simulation contains an interesting policy implication concerning the appropriate policy framework for evaluating BuRec water conservation decisions: Is the BuRec important to *both* federal water policy and national agricultural policy in terms of allocative efficiency and welfare effects? The BuRec's control of between 40% and 85% of the annual flow of several major western rivers establishes the agency's importance to federal water policy.[18] Previous research already demonstrates that reallocating water from agriculture to urban, recreational, hydropower, and freshwater fishery purposes would create significant welfare improvements (Howe, Schurmeier, and Shaw; Howitt, Mann, and Vaux; Wahl). Simultaneously, the BuRec services one-fourth of western irrigated agriculture, and western irrigated agriculture accounts for over one-fourth of the market value of national crop production. BuRec operations potentially could affect market prices of up to ten major crops. The possibility of welfare effects in commodity markets must be considered for a full accounting of the economic consequences of BuRec decisions.

Although previous research does not provide detailed numerical information on the necessary reallocation of BuRec water supplies to achieve allocative efficiency, the simulation's 10% reduction in irrigation water supply provides a useful setting for assessing commodity market impacts. Acreage responses of fruits and nuts, rice, and vegetables are sufficiently large relative to national harvested acreage to affect market prices. (The accounting must be in terms of acreage rather than output because, as mentioned earlier, crop supply equations cannot be estimated for fruits, nuts, and vegetables. To relate acreage to output, we assume that acreage response equals supply response in percentage terms.) As percentages of national harvested acreage in the crops, the responses are a 1.31% increase for fruits and nuts, a .93% decrease for rice, and a .34% decrease for vegetables. The price elasticity of demand for fruits, nuts, and vegetables is −.4 (Dunn and Heien) and for rice is −.2 (Lin).[19] With the inelastic price elasticities, the acreage responses translate into proportionately larger price effects: The price of fruit and nuts decreases 3.3%, the price of rice increases 4.6%, and the price of vegetables increases .8%. Thus, by affecting market prices of three important commodities, a 10% reduction in BuRec irrigation water supply would affect the welfare of consumers and producers who otherwise are not related directly to BuRec water allocation.[20]

Summary

This article analyzes irrigated agricultural production on farms served surface water by the Bureau of Reclamation. The institutional environment of western water implies that entitlements to reclamation water deliveries should be treated as a fixed input, that is, as an input allocated by contractual quantity rather than market price. Irrigated production, further, largely occurs as a multicrop enterprise. To capture these traits, we develop a multioutput model of the agricultural firm with surface water and land as fixed, allocatable inputs. By modeling the institutional environment of the multioutput irrigated agricultural firm, the theoretical results, empirical application, and policy simulation produce a cohesive microeconomic analysis of BuRec water supply and conservation.

The empirical evidence—based on estimated equations of up to ten irrigated crops for each of the six BuRec production regions—demonstrates that the surface water constraint performs strongly as a determinant of crop supply and land allocation decisions.

Although BuRec water resource development for irrigation agriculture provided a foundation for western settlement, intersectoral competition for water has triggered a decline in agricultural water use and irrigated acreage that will continue for the foreseeable future. Reducing BuRec irrigation water deliveries, either by voluntary water transfers or mandatory conservation measures, offers one method of achieving Pareto improvements in western water allocation. The article shows, however, that price effects in commodity markets may accompany BuRec water supply reductions. A simulated 10% reduction in water supply generates price changes ranging from .8% to 4.6% for three major crops. Thus, a comprehensive economic analysis of BuRec water supply policy should consider welfare effects in commodity markets in addition to the allocative efficiency of surface water resources.

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Notes

[1] Irrigation districts operate as quasi-public organizations that are managed by a board of directors elected by the retail customers (Leshy). The organizational structure of the districts—operated as nonprofit enterprises with state laws nebulously defining their general public responsibilities—contributes to the institutional rigidities of surface water allocation.

[2] The administrative procedures result in BuRec water prices set below long-run marginal cost of water supply. Two generations of economists have noted the allocative inefficiency of this pricing structure. These include early research contained in the classic volumes by Bain, Caves, and Margolis; Eckstein; Hirshleifer, DeHaven, and Milliman; and Krutilla and Eckstein.

[3] Kanazawa presents econometric evidence to establish the point convincingly that BuRec supplies provide a binding constraint on behavior while BuRec water prices are statistically insignificant in explaining behavior.

[4] Crop-specific profit functions can be defined by assuming technical nonjointness. This makes tractable the derivation of explicit water allocation and land allocation functions using a flexible functional form for the crop-specific profit functions. Equations (1)–(5) and (11)–(12) will make this clear. The technical nonjointness assumption is not required to derive output supply and farm-level input demand functions using standard duality results.

[5] $$H = (\partial^2\pi_2/\partial w_2^2)(\partial^2\pi_1/\partial n_1^2) + (\partial^2\pi_2/\partial w_2^2)(\partial^2\pi_2/\partial n_2^2) + (\partial^2\pi_1/\partial w_1^2)(\partial^2\pi_1/\partial n_1^2) + (\partial^2\pi_1/\partial w_1^2)(\partial^2\pi_2/\partial n_2^2) - 2(\partial^2\pi_1/\partial w_1\partial n_1)(\partial^2\pi_2/\partial w_2\partial n_2) - (\partial^2\pi_1/\partial w_1\partial n_1)(\partial^2\pi_1/\partial w_1\partial n_1) - (\partial^2\pi_2/\partial w_2\partial n_2)(\partial^2\pi_2/\partial w_2\partial n_2).$$

[6] The absence of concavity, however, is not the source of the indeterminate comparative static results. The ambiguity is preserved even when we impose two additional restrictions on the profit functions, both of which represent plausible characterizations of agricultural production. First, strict concavity of the functions imposes negative second derivatives. Second, complementarity of the water and land inputs imposes positive cross-partial derivatives ($\partial^2\pi_1/\partial w_1\partial n_1$ and $\partial^2\pi_2/\partial w_2\partial n_2$). Imposing these restrictions does not eliminate the ambiguity of the comparative static results because the land and water allocations interact through the cross-partial derivatives. If the allocations were independent rather than complementary (i.e., if the cross-partials equalled zero), land allocations would be independent of the water constraint and, assuming concavity, water allocations would be increasing in the water constraint. Without imposing independence, though, theory continues to generate no testable hypotheses.

[7] The land constraint identity in (10) implies that one of the land allocations in (6) and (7) will decrease with an increase in the water constraint (unless both equations equal zero). Imposing concavity and water-land complementarity, $\partial n_1^*/\partial W < 0$ occurs when profitable opportunities exist for land reallocations from crop 1 to crop 2. This tends to occur when: (*a*) the cross-input marginal profitability of allocating land to crop 2 is larger than that for crop 1, and (*b*) the marginal profitability of crop 1 is declining rapidly relative to crop 2's rate of decline.

[8] It also holds that, unlike conventional factor demand functions, the allocation equations in (11) and (12) do not contain symmetric cross-price effects. The logical candidate for symmetry, by analogy, would be $\partial w_i/\partial N = \partial n_i/\partial W$. With two fixed, allocatable inputs, no symmetry conditions hold.

[9] Inserting equation (11) for w_i^* into equation (14) is essential for the empirical section because data on crop-specific water allocations are not observed. It follows, then, that n_i^* also should be replaced by equation (12) to obtain a set of reduced-form supply equations.

[10] In addition to water allocation equations not being estimated because of data limitations, they cannot be identified from parameter estimates of the land allocation and supply equations.

[11] We tried to test for heteroskedasticity by assuming that the error variances are a linear function of the number of farms in the district. Simultaneous estimation of the tobit coefficients and the heteroskedasticity model in a manner described by Maddala (p. 180) failed to converge.

[12] The entire set of crop supply and land allocation equations, estimated by crop and by BuRec production region, are available from the authors upon request.

[13] The stochastic model underlying tobit analysis specifies the relationship between the independent variables and the latent dependent variable (i.e., the desired level of the dependent variable). We observe the latent dependent variable only when it exceeds a threshold level. Thus, coefficients obtained using tobit measure the effect of the explanatory variables on the unobserved latent variable. Multiplying by the probability of the dependent variable exceeding the threshold transforms the coefficients to reflect changes in the observed dependent variable.

[14] The land allocation and supply equations for hay crops are an exception because, in three regions, the signs on the water constraints reverse between the allocation and the supply equations. In the Mid-Pacific, the sign changes from a positive coefficient in the land allocation to a negative coefficient in the supply. The reverse occurs in the Upper Colorado and Missouri Basin. Differences between the supply and land allocation coefficients may be attributable to changes in crop yield, as hay crops provide flexibility in irrigations and cuttings.

[15] The ranking in terms of water requirements is based on predicted water application rates from crop-specific water demand equations (Negri and Brooks). The equations include output and input prices, irrigation technology, topography, and soil and climate characteristics as independent variables. Predicting water application rates at the mean of the independent variables produces an approximate ranking as if all crops faced identical exogenous conditions.

[16] Research applying the water-requirement perspective to a multicrop farm with limited water supplies was conducted using a mathematical programming model (Bernardo et al.).

[17] The simulation results should be interpreted in light of three qualifications. One, the elasticities apply only to marginal changes, while a 10% reduction in water supply is nonmarginal. Two, the model holds land constant. In the long run, reducing water supply likely would cause a reduction in the total land in irrigation rotation. And three,

opportunities to shift to dryland production or to groundwater supply could reduce the production impacts of BuRec water-supply reductions.

[18] The rivers controlled by the BuRec include the Colorado, Snake, and Rio Grande and, in years of low flow, the Sacramento and San Joaquin.

[19] The rice elasticity applies to the domestic market even though rice is exported from the United States. The price elasticity of export demand is ignored because rice exports occur largely as a result of federal export subsidies created in the Food Security Act of 1985.

[20] Of course, the BuRec-wide responses mask the importance of the disaggregated, regional impacts of reduced water deliveries because many regional responses offset each other. Rural economies in many areas of the West rely heavily on farm operations receiving BuRec water. These considerations also weigh heavily in deliberations over BuRec water allocation policy.

References

Bain, J. S., R. E. Caves, and J. Margolis. *Northern California's Water Industry: The Comparative Efficiency of Public Enterprise in Developing a Scarce Natural Resource.* Baltimore: Johns Hopkins University Press, 1966.

Beattie, B. R., and C. R. Taylor. *The Economics of Production.* New York: John Wiley and Sons, Inc., 1985.

Bernardo, D. J., N. K. Whittlesey, K. E. Saxton, and D. L. Bassett. "An Irrigation Model for Management of Limited Water Supplies." *West. J. Agr. Econ.* 12(1987):164–73.

Blaney, H. F., and W. D. Criddle. "Determining Consumptive Use and Irrigation Water Requirements." U.S. Department of Agriculture, Agricultural Research Service, Tech. Bull. No. 1275, 1962.

Burness, H. S., and J. P. Quirk. "Appropriative Water Rights and the Efficient Allocation of Resources." *Amer. Econ. Rev.* 69(1979):25–37.

———. "Water Laws, Water Transfers, and Economic Efficiency." *J. Law and Econ.* 23(1980):111–34.

Chambers, R. G., and R. E. Just. "Estimating Multioutput Technologies." *Amer. J. Agr. Econ.* 71(1989):980–95.

Dunn, J., and D. Heien. "The Demand for Farm Output." *West. J. Agr. Econ.* 10(1985):13–22.

Eckstein, O. *Water-Resource Development.* Cambridge: Harvard University Press, 1958.

Edison Electric Institute. Unpub. data on electricity prices, 1989.

Ellis, W. H., and C. T. DuMars. "The Two-Tiered Market in Western Water." *Nebraska Law Rev.* 57(1978):333–67.

Hagan, R. M., H. R. Haise, and T. W. Edminster, eds. *Irrigation of Agricultural Lands.* Madison: American Society of Agronomy, 1967.

Hartman, L. M., and D. Seastone. *Water Transfers: Economic Efficiency and Alternative Institutions.* Baltimore: Johns Hopkins University Press, 1970.

Hirshleifer, J., J. C. DeHaven, and J. W. Milliman. *Water Supply: Economics, Technology, and Policy.* Chicago: The University of Chicago Press, 1960.

Houck, J. P., and M. E. Ryan. "Supply Analysis for Corn in the United States: The Impact of Changing Government Programs." *Amer. J. Agr. Econ.* 54(1972):184–91.

Howe, C. W., D. R. Schurmeier, and W. D. Shaw. "Innovative Approaches to Water Allocation: The Potential for Water Markets." *Water Resour. Res.* 22(1986):439–44.

Howitt, R. E., D. E. Mann, and H. J. Vaux, Jr. "The Economics of Water Allocation." In *Competition for California Water,* eds., E. Engelbert and A. F. Scheuring. Berkeley: University of California Press, 1982.

Jensen, M. E. "Plant and Irrigation Water Requirements." In *Sprinkler Irrigation,* eds., C. H. Pair, W. H. Hinz, D. Reid, and K. R. Frost. Washington DC: Sprinkler Irrigation Association, 1969.

Just, R. E., D. Zilberman, and E. Hochman. "Estimation of Multicrop Production Functions." *Amer. J. Agr. Econ.* 65(1983):770–80.

Kanazawa, M. T. "The Economic Efficiency of the Water Supply Policies of the Bureau of Reclamation: A Reconsideration." Work. Pap., Dep. of Econ., Carleton College, 1988.

Krutilla, J. V., and O. Eckstein. *Multiple Purpose River Development.* Baltimore: Johns Hopkins University Press, 1958.

Lau, L. J. "Applications of Profit Functions." *Production Economics: A Dual Approach to Theory and Applications,* Vol. 1, eds., M. Fuss and D. McFadden, Chap. I.3. Amsterdam: North-Holland, 1978.

———. "A Characterization of the Normalized Restricted Profit Function." *J. Econ. Theory* 12(1976):131–63.

Leshy, J. D. "Irrigation Districts in a Changing West—An Overview." *Arizona State Law J.* (1982):345–76.

Lin, W. Economic Research Service, USDA. Personal communication, 1989.

Maddala, G. S. *Limited-Dependent and Qualitative Variables in Econometrics.* Cambridge: Cambridge University Press, 1983.

Moore, M. R. "The Bureau of Reclamation's New Mandate for Irrigation Water Conservation: Purposes and Policy Alternatives." *Water Resour. Res.* 27(1991):145–55.

Moschini, G. "Normal Inputs and Joint Production with Allocatable Fixed Factors." *Amer. J. Agr. Econ.* 71(1989): 1021–24.

Negri, D. H., and D. H. Brooks. "Decomposing Ground Water Demand." Unpub. manuscript, Economic Research Service, USDA, Washington DC, 1989.

Shumway, C. R. "Supply, Demand, and Technology in a Multiproduct Industry: Texas Field Crops." *Amer. J. Agr. Econ.* 65(1983):748–60.

Shumway, C. R., R. D. Pope, and E. K. Nash. "Allocatable Fixed Inputs and Jointness in Agricultural Production: Implications for Economic Modeling." *Amer. J. Agr. Econ.* 66(1984):72–78.
U.S. Department of Agriculture, National Agricultural Statistics Service. *Annual Price Summary* (1978–87), various issues. Washington DC.
U.S. Department of Agriculture, Soil Conservation Service. *Land-Capability Classification.* Agr. Handbook No. 210. Washington DC, 1973.
———. "National Resources Inventory" (magnetic tape), 1982.
U.S. Department of Commerce, National Climatic Data Center. "Documentation for Magnetic Tape Version of the Climatography of the United States, No. 20." Tape Series TD-9641, March 1986.
U.S. Department of Energy, Energy Information Administration. "Energy Price and Expenditure Report." DOE/EIA-0376, 1983 and 1986 issues.
U.S. Department of the Interior, Bureau of Reclamation. *Assessment '87: A New Direction for the Bureau of Reclamation.* Washington DC: Bureau of Reclamation, 1987.
———. *1987 Summary Statistics, Vol. 1: Water, Land, and Related Data.* Denver: Bureau of Reclamation, 1988.
Wahl, R. W. *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation.* Washington DC: Resources for the Future, 1989.
White, K. J. "A General Computer Program for Econometric Methods—SHAZAM." *Econometrica* 56(1988):239–40.
Wilkinson, C. F. "Western Water Law in Transition." *University of Colorado Law Rev.* 56(1985):317–45.

Appendix

Data for land allocation and crop supply come from "Crop Production and Water Utilization Data," an annual survey of irrigation districts served by the BuRec. The data, aggregated to the project level, are summarized in *Summary Statistics, Vol. I: Water, Land, and Related Data,* an annual BuRec publication. The population of 620 irrigation districts is not used in the current analysis because of missing data problems. The number of observations per BuRec region are: Pacific Northwest, 946; Mid-Pacific, 1,306; Lower Colorado, 191; Upper Colorado, 414; Southwest, 146; and Missouri Basin, 504.

The land constraint measures total land that can be irrigated with existing irrigation infrastructure. It is recorded as "total area in irrigation rotation" on the survey. Crop-specific land allocation and supply (the dependent variables) also are taken directly from the survey tape.

The water constraint measures the total water delivered by the irrigation district to farms. It includes both BuRec project water and non-BuRec water obtained by the district and excludes operational spills, transportation losses, and non-agricultural deliveries made by the district. The data do not distinguish which districts contain farms that pump groundwater.

Expected output prices and variable input prices are relative prices normalized by the wheat price [U.S. Department of Agriculture (USDA), National Agricultural Statistics Service; U.S. Department of Energy; Edison Electric Institute]. With the exception of vegetable price, all output market prices and variable input prices are state-level data. Vegetable price is a national index of vegetable prices. For crops covered by federal commodity programs, the price variable is the higher of one-year lagged market price or weighted support price (Houck and Ryan). For the remaining crops, the price variable is one-year lagged market price.

Climatological data are derived from the magnetic tape, "Climatography of the U.S., No. 20," a monthly summary of climatological observations from the NOAA cooperative network (U.S. Department of Commerce, National Climatic Data Center). Matching each county with the nearest cooperative weather station generates county-specific climate. Climate data pertaining to irrigation districts are computed as a weighted average of county-level data since districts often span more than one county. The weights are the irrigation district acres within the counties.

The estimated equations include two variables that proxy for evapotranspiration. Since climate, not weather, determines land allocation, the variables represent climate conditions for the growing season. Annual weather conditions that influence crop yields are not included in the estimation. The climate variables are: (*a*) cumulative effective rainfall (in inches) for the growing season, and (*b*) cumulative growing degree days (GDD) for the growing season, using a base of 60 degrees. Effective rainfall measures the fraction of monthly rainfall that contributes to plant growth (Blaney and Criddle). The mean daily temperature minus 60 degrees, if the mean exceeds 60, or zero otherwise, defines the number of GDD for each day. Expected GDD and effective rainfall are accumulated over the growing season.

Because the growing season varies by climatic region, the monthly values of the climatic variables accumulate between January and September when the following conditions are satisfied. If the average minimum daily temperature never falls below freezing for the entire month, then the climate variables accumulate the full value of the monthly observations. If the average minimum daily temperature falls below freezing between one and five times, then the variables accumulate only half the monthly values, as if the season began or ended in mid-month. Months with more than five freezes are excluded completely from the growing season.

Topography, soil productivity, and soil texture variables are taken from the "National Resources Inventory" (NRI) (USDA, Soil Conservation Service 1982), which contains county-level data. For each county, the NRI sampled the physical characteristics of all non-federal rural land at several randomly selected points. Within county observations, soil texture, soil slope, and land capability class are quantified and averaged. The average includes only cropland observations. Like the climate variables, soil and land characteristics pertaining to the district are a weighted average of county-level data for the counties spanned by the district.

County observations of soil texture are classified on a five-point scale, where 1 = sand, 2 = sandy loam, 3 = loam, 4 = clay loam, and 5 = clay. The numerical averages for the counties are classified into three dummy variables: sandy soil (texture $\leq$ 2.3), loamy soil (2.3 < texture < 3.6), and clayey soil (texture $\geq$ 3.6). The sand and clay dummy variables capture the soil-texture effect relative to loam.

The land capability classification system used in the NRI classifies soils based on their ability to produce commonly cultivated crops (USDA, Soil Conservation Service 1973). Land capability classes, identified 1 through 8, indicate progressively more limitations that restrict agricultural land use. For example, soils that are erosive, saline, shallow, stony, or wet limit land productivity. County observations on land capability are averaged and then classified into dummy variables following a procedure similar to the soil texture dummies. Land capability classifications less than 2.5 defined high productivity soils, while classifications greater than 3.5 defined low productivity soils. Finally, a topography variable, soil slope, measures the average cropland slope (in percentage) for the county.