Short- and Long-Run Demand and Substitution of Agricultural Inputs

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Short- and long-run Hicksian and Marshallian elasticities are estimated, along with Morishima elasticities of substitution, using a restricted profit function and a series of decomposition equations. Convexity in prices and concavity in quasi-fixed factors of the restricted profit function are simultaneously imposed using Bayesian techniques. The empirical model is disaggregated in the input side, utilizes a Fuss-quadratic flexible functional form, incorporates the impact of agricultural policies, and introduces a new weather index. The methodology is applied to Illinois's agriculture, and implications for agriculture in the Corn Belt and the Northeast are briefly discussed.

Measuring ease of substitutability between production factors is of practical and theoretical importance in economics. Many pessimistic predictions of natural-resource depletion proved to be grossly incorrect because the models used failed to recognize important substitution relationships (Field and Berndt). Concerns over ground- and surface-water quality, food safety, land retirement, and alternative production systems call for quantitative assessments of the effect of changing market conditions or government policies on the demand for agricultural inputs. In U.S. agriculture, it is particularly important to assess policy alternatives targeted to limit the use of fertilizers and pesticides (chemical inputs), which have contributed to the contamination of water resources and to the presence of toxic residues in food. Groundwater contamination is particularly serious in areas with high application rates of nitrogen or mobile pesticides, shallow water tables, and permeable, coarse-textured soils (Miller). About 10% of the nation's 3,000 counties, located chiefly in the Upper Midwest and East, have been identified to have potential for contamination of groundwater by both nitrates and pesticides (Lee).

The failure of many econometric models to incorporate substitution possibilities is due in part to lack of reliable information on price elasticities of input demand. Published empirical estimates of input demand elasticities in U.S. agriculture vary widely (Tables 1 and 2), even excluding earlier estimates based on models not derived from optimizing decisions of economic agents. To a large extent, differences among elasticity estimates are due to differences in model specification, including levels of aggregation over inputs/outputs and firms, functional form, price expectations, and introduction of exogenous variables (e.g., weather, government policy). Also, there are differences in the behavioral assumptions, that is, profit maximization or cost minimization. In addition, models are often inconsistent with economic theory, and frequently long-run equilibrium is implicitly assumed.

Economic theory requires the restricted profit function to be convex in prices *and* concave in quasi-fixed factors. Convexity in prices has been imposed by Shumway and Alexander, Ball, and others. However, unlike this work, previous studies have not imposed convexity in prices and concavity in quasi-fixed factors simultaneously. Both curvature properties are essential, in particular when using decomposition methods. While convexity in prices ensures that short-run Marshallian elasticities are of the "correct" sign, Le Chatelier's principle may be violated if the restricted profit function is not concave in quasi-fixed inputs. For example, some long-run own-price elasticities may be smaller (in absolute value) than corresponding short-run elasticities, and own-price Hicksian elasticities may be larger than corresponding Marshallian elasticities. Among the few

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Table 1. Input Demand Elasticities—Selected Empirical Studies in Agriculture

Author, Year, Country/Region	Type of Input Demand	Functional Form	Number of: Outputs/Var. Inputs/Quasi-fixed Inputs (*Y/X/Z*)	Curvature Imposed	Allowance for Weather and Government Policy
Binswanger, 74, USA	Hicksian, LR[a]	Translog	1/5/0	No	No
Lopez, 80, Canada	Hicksian, LR	G. Leontief	1/4/0	No	No
Ray, 82, USA	Hicksian, LR	Translog	1/5/0	No	No
Brown & Christensen, 82, USA	Hicksian, SR[a], LR	Translog	1/3/2	No	No
Capalbo, 88, USA	Hicksian, LR	Translog	1/4/0	No	No
Capalbo, 88, USA	Hicksian, LR	Translog	2/5/0	No	No
Weaver, 83, ND	Marshallian, SR	Translog	3/5/1	No	Yes
Shumway, 83, TX	Marshallian, SR	N. Quadratic	6/3/2	No	Yes
Lopez, 84, Canada	Marshallian/ Hicksian, LR	G. Leontief	2/4/0	No	No
Antle, 84, USA	Marshallian, LR	Translog	1/4/0	No	No
Capalbo, 88, USA	Marshallian, SR	Translog	1/3/1	No	No
Shumway & Alexander, 88, USA	Marshallian, SR	N. Quadratic	5/4/2	Yes	Yes
Ball, 88, USA	Marshallian, SR	Translog	5/6/1	Yes	No
McIntosh & Shumway, 89, CA	Marshallian, SR	N. Quadratic	10/4/3	Yes	Yes
Burrell, 89, UK	Marshallian, Hicksian, SR	Translog	6/3/3	No	No

[a] LR is long-run; SR is short-run.

decomposition studies in agricultural economics, Lopez (1984) and, recently, Higgins use a long-run profit function to derive long-run Hicksian elasticities. In both cases, the convexity requirement is violated. Hertel uses a restricted profit function to obtain short- and long-run Marshallian elasticities. Convexity in prices is satisfied in Hertel's model using pseudodata, but the issue of concavity in quasi-fixed factors did not arise because Hertel considered only one quasi-fixed factor and assumed constant returns to scale.

This paper provides the methodology to determine theoretically consistent Hicksian and Marshallian input demand functions and elasticities of substitution (ES) in the short and long run. Short-run Marshallian demands are calculated directly using a restricted profit function. Long-run Marshallian and short-run Hicksian demands are derived via decomposition equations, and long-run Hicksian demands are calculated from the corresponding short-run demands by a second transformation. Altogether, this decomposition technique provides a total of four types of demand functions that, if estimated directly, would require estimation of two cost functions and two profit functions. This technique also makes possible the calculation of short-run and long-run elasticities of substitution while maintaining the assumption of profit maximization.

The empirical model uses a Fuss-quadratic normalized restricted profit function and is disaggregated in the input side to a larger extent than in previous dual models. For example, feeds, seeds, fertilizer, pesticides, fuels, hired labor, and family labor are each a separate category. In addition, the model allows for the impact of agricultural programs and policies on farmers' price expectations, and a new weather index is introduced. The estimated input demand functions are used to provide

Table 2. Own-Price Elasticities of Input Demand, Selected Estimates in Agriculture

Author/Year	Hired Labor	Fertilizer	Chemicals
Binswanger, 74	−0.911	−0.945	
Lopez, 80	−0.897[a]		−0.391
Ray, 82	−0.839	−0.128	
Brown & Christensen, 82	−0.650		−0.188
Capalbo, 88	−0.207[a]		−0.068
Capalbo, 88	−0.492[a]		−0.876
Shumway, 83	−0.43	−0.70	
Weaver, 83	−1.016[a]	−1.377	
Lopez, 84	−0.377/−1.24		
Antle, 84	−1.311		−0.194
Capalbo, 88	−0.594[a]		−0.606
McIntosh & Shumway, 89	−0.593	−0.038	
Burrell, 89		−0.42	

[a] Includes hired and family labor.

an approximate measure of the impact on chemical input use of imposing ad valorem taxes on chemical inputs. This paper reports empirical results for Illinois, which has a large potential for both nitrate and pesticide contamination of groundwater (Lee). However, the methodology developed in this paper may be used on similarly exposed areas in the Corn Belt and the Northeast.

Hicksian and Marshallian Elasticities

Duality theory allows the determination of supply and demand functions without explicit solution of the optimization problem, making possible the use of flexible functional forms with weaker maintained hypotheses than in traditional primal methods, increasing the generality of the inference (Gallant and Golub).[1] Dual models require some behavioral assumptions about the firm and the market where it operates. In agriculture, it is usual to assume that markets are competitive and that the objective of firms is either cost minimization or profit maximization. The type of dual model specified (e.g., cost or profit function) has an important impact on the input demand and output supply elasticities directly derived from the model. If a cost-function approach is used, input demands obtained from the application of Shephard's lemma are characterized as conditional on output level. These Hicksian (or compensated) input demands reflect movements along an isoquant for a given output level (Sakai; Lopez 1984) and are used to calculate elasticities of substitution. When a profit function model is specified, unconditional input demands obtained from application of Hotelling's lemma are known as Marshallian (or uncompensated) demands and include substitution effects along the old isoquant and expansion effects along the expansion path (to the new isoquant). The signs of the Hicksian cross-price input demand elasticities of input pairs are often used to classify inputs into net substitutes (positive) in production or net complements (negative). The corresponding cases for Marshallian elasticities are referred to as gross substitutes/complements.

A version of Le Chatelier's principle requires own-price Marshallian elasticities to be larger in absolute value than the corresponding Hicksian elasticities because the latter hold output constant, while Marshallian elasticities allow both inputs and outputs to adjust to their new equilibrium levels. A procedure similar to the Slutsky decomposition may be applied to obtain a relationship between Marshallian and Hicksian elasticities (Sakai; Lopez 1984; Higgins).

Measures of Substitutability

The degree of substitutability between production factors is measured by the elasticity of substitution (ES). For a production process with two inputs, i and j, the ES (σ_{ij}) is defined by the elasticity of the input quantity ratio with respect to the marginal rate of substitution (MRS) between inputs; σ increases as substitution between inputs becomes easier. Under profit maximization, the MRS is equal to the price ratio. For a two-variable input case there is no ambiguity in the meaning of price change and one elasticity measure suffices since $\sigma_{ij} = \sigma_{ji}$ (Kang and Brown).

When more than two variable inputs are involved in production, there are as many possible definitions of ES as there are possible combinations of elements of the underlying Hessian matrix (Mundlak). Several definitions are used in the literature. The direct elasticity of substitution (DES) is an extension of the ES for two inputs with the condition that output and all the other inputs are held constant. Because of this inflexibility, DES is not commonly used. The Allen-Uzawa partial ES (AUES) can be expressed as the cross-price elasticity of the Hicksian input demand (ϵ_{ij}) divided by the respective cost share. The AUES is an example of the one-factor one-price ES. Its popularity may be due to its appealing symmetry, although the economic interpretation of cross-price elasticities is more direct (Field and Berndt).

The Morishima elasticity of substitution (MES), proposed by Robinson and Morishima, is classified as a two-factor, one-price elasticity of substitution and may be interpreted as the cross-price elasticity of relative (Hicksian) demand because it measures the relative adjustment of factor quantities when a single factor price changes. Intuitively, if inputs i and j are net complements (negative cross-price Hicksian elasticity), an increase in the price, P_j, will lead to a decrease in the quantity employed, X_i. However, since the decrease in P_j also decreases X_j, the own-price effect must be subtracted to obtain the net effect. This is what MES represents.[2]

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[1] In addition, multicollinearity is likely to be less severe among (factor) prices required in the dual approach than among factor quantities used in primal methods, and the exogeneity of prices is more likely to hold.

[2] Koizumi (1976) first suggested this interpretation. He noted that "the Morishima elasticity of substitution of X_j for X_i measures the percentage change in employment in X_i caused by 1% change in the price P_j of X_j after the percentage change in X_j due to the pure demand effect has been partialed out." Note that the MES can be expressed as

$$(MES)_{ij} = \partial\ln(X_i/X_j)/\partial\ln P_j = \partial(\ln X_i - \ln X_j)/\partial\ln P_j = \epsilon_{ij} - \epsilon_{jj}.$$

Kang and Brown recommend the use of the MES because it has the desirable property of being invariant to the separability assumption usually made. They show that the MES is independent from the "unestimated characteristics of the function," while a partial measure, such as the AUES, does not have this property. Thus, it is possible, as Berndt and Wood find empirically, that the AUESs in a three-input model may yield different values than the AUESs for a four-input model, even if the fourth input is separable. Kang and Brown show that the calculation of MES does not even require data for omitted inputs and that values of two different studies are directly comparable.

Moreover, Blackorby and Russell show that the AUES is not a measure of the "ease" of substitutability or curvature of the isoquant; it is meaningless as a quantitative measure; it provides no additional information to that contained in the Hicksian cross-price elasticity, and it cannot be interpreted as a logarithmic derivative of an input quantity ratio with respect to a price ratio (or MRS). The MES, on the other hand, provides an exact measure of the curvature along an isoquant and may be interpreted as a logarithmic derivative of an input quantity ratio with respect to an input price ratio. Consequently, MES is a more appropriate measure of input substitution. Blackorby and Russell also note that the asymmetry of the MES is natural because, while in two-dimensional input space the curvature of an isoquant at a point is an unambiguous idea, in more than two dimensions, curvature may be measured in many directions. For example, the same change in the price ratio, P_i/P_j, may be obtained when P_j changes and P_i is held constant or vice versa. However, each case leads to a different change in the quantity ratio (X_i/X_j).

The Restricted Profit Function

Early empirical work based on the dual framework implicitly assumes that firms are in static (long-run) equilibrium. Recognition of the short-run fixity of some production inputs makes estimation of a full equilibrium profit (or cost) function inappropriate. As Brown and Christensen observe, in many cases the assumption of full static equilibrium "is suspect and so are the empirical results." In order to relax the assumption of static equilibrium, two basic approaches are available. The first uses full dynamic models within the costs of adjustment framework. By combining techniques of dynamic optimization and the notion of adjustment costs, this approach not only provides estimates of short- and long-run demand functions, but also describes the nature of the adjustment and the time required for the adjustment of the quasi-fixed factors. However, estimation of these dynamic models at the level of disaggregation required to examine input-substitution issues is often not feasible with available data. The second method is based on the use of restricted profit or cost functions. The firm is assumed to be in static (short-run) equilibrium only with variable factors, conditional on levels of the other factors. When the nature of the stock-adjustment process is not the focus of analysis, but rather the characterization of both short- and long-run production structure, models based on the restricted profit (or cost) function are the proper choice (Hazilla and Kopp 1986). The theory of the restricted profit function is well developed (Diewert; Lau 1976). Its framework is general enough to accommodate as special cases cost and revenue functions and all possible intermediate cases (by allowing a subset of inputs and outputs to be variable).

This study assumes profit-maximizing producers operating in competitive markets, and the restricted profit function is used to capture the information about the production structure in both the short and long run.[3] Consider $n + m + s$ "commodities" including n variable net inputs/outputs (netputs), m fixed inputs/outputs, and s exogenous variables such as time or weather. Let $X = (X_1 \ldots X_n)'$ denote the vector of variable netputs with the sign convention $X_i > 0(<0)$ if the ith variable netput is an output (input); $Z = (Z_1 \ldots Z_m)'$ is the vector of non-negative quasi-fixed netputs; $R = (R_1 \ldots R_s)'$ is the vector of exogenous factors; $P = (P_1 \ldots P_n)'$ is the price vector of variable netputs; and $W = (W_1 \ldots W_m)'$ is the price vector of quasi-fixed netputs. The restricted profit function is defined by

$$(1) \qquad \pi(P,Z,R) = \mathrm{MAX}_X[P'X{:}X \in T].$$

The production possibilities set T is assumed to be nonempty, closed, bounded, and convex. In addition, if Z includes only inputs, T is assumed to be a cone (Diewert; Ball). Under the above assumptions on the technology, the restricted profit function is well defined and satisfies the usual reg-

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[3] Recently, Lim and Shumway (1989a) performed nonparametric tests for each of the 48 contiguous states using agricultural production data for the period 1956–82. They found "little departure" of the data from the joint hypothesis of profit maximization and a convex technology in all 48 states. In addition, they found that for about 90% of the states (including Illinois), the data were consistent with constant returns to scale.

ularity conditions (Diewert). In particular, with only the inputs fixed, π is homogeneous of degree one in variable netput prices (P) and quasi-fixed netput quantities (Z). In addition, π must satisfy symmetry (the Hessian matrix must be symmetric), monotonicity, and curvature conditions. Curvature conditions require π to be convex in P for every Z and R, and concave in Z for every P and R. That is, π is a saddle function in (P,Z) for all R. No curvature assumptions are made about R. The unrestricted profit function may be expressed as

$$(2)\quad \pi(P,W,R) = \mathrm{MAX}_Z[\pi(P,Z,R) - W'Z],$$

where $\pi(P,Z,R)$ is defined by equation (1).

Theoretical Consistency

One of the penalties of using flexible functional forms in dual models is that the estimated functions may not be theoretically consistent because the number of parameters is sufficient to allow the elasticity matrix to have any value at any point in the data space (Gallant and Golub). The restricted profit function π is theoretically consistent if it satisfies assumed homogeneity, symmetry, monotonicity, and curvature conditions. Symmetry and homogeneity are usually easier to impose because they translate into equality restrictions on the parameters, which reduces the number of free parameters (the dimensionality of the parameter space). Monotonicity and curvature require inequality restrictions on the parameters, which are more difficult to impose because they reduce the parameter space but not its dimensionality.

Dual methods require more strict curvature conditions than primal methods. As Lau (1978) notes, the production function may not be convex, but the profit function must always be convex in prices when output and input markets are competitive and firms are profit-maximizers. Therefore, a nonconvex profit function is inconsistent with the behavioral assumption of profit maximization. Empirically, consequences of the violation of convexity are that signs of output supply and input demand elasticities are inconsistent with economic theory, and tests of functional structure (e.g., separability) are meaningless because duality theorems do not apply (Hazilla and Kopp 1985; Ball). Imposition of curvature avoids these adverse consequences and provides a gain in statistical efficiency by using a priori information (Gallant and Golub).

Imposition of curvature frequently uses the property of a twice continuously differentiable function that is convex (concave) with respect to a subset of its arguments if and only if its Hessian matrix (**H**) is positive (negative) semidefinite. A necessary and sufficient condition for the Hessian to be positive semidefinite is that all the eigenvalues are non-negative. Alternatively, the Cholesky values must be non-negative. The last condition allows the transformation of the restrictions of positive semidefiniteness of the Hessian matrix into simple inequality restrictions on the parameters, and it is used in the nonlinear programming/maximum-likelihood (NLP) approach to impose curvature. In agricultural economics, Shumway and Alexander, Ball, and others impose concavity on a profit function using this approach. Some of the weaknesses of the approach stem from difficulties in the statistical interpretation of the results and inapplicability of the likelihood-ratio test (Chalfant and White).

An alternative Bayesian approach was reexamined recently by Kloek and van Dijk, Geweke, and Chalfant and White. No prior information is required beyond the inequality restrictions, which are treated as prior beliefs about the model. The Bayesian approach consists of estimating the parameters without imposing the restrictions. If the restrictions are violated, they are imposed following Geweke. For example, to impose convexity, the prior distribution is the indicator function:

$$p(\theta) = \begin{cases} 1 \text{ if } \theta \in D \\ 0 \text{ otherwise} \end{cases},$$

where θ is the parameter vector, $p(\theta)$ is its prior density function containing all information about θ before the data are examined, and the set D is defined by $D = \{\theta \in \mathfrak{R}^q \mid \text{eigenvalues of } \mathbf{H} \geq 0\}$, where q is the number of free parameters. The mean of the posterior distribution $f(\theta \mid y)$ is a Bayes estimator[4] that minimizes expected loss for a quadratic loss function. In practice, Monte Carlo integration (Kloek and van Dijk; van Dijk and Kloek; Geweke) is used to calculate $E(\theta)$, since analytical procedures are not available and numerical procedures become too complicated beyond three to four dimensions.

Assuming, for example, that the parameter vector follows the multivariate normal distribution with a mean vector θ and known variance-covariance Σ, then the posterior distribution will be a truncated (multivariate) normal such that θ has

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[4] A Bayes estimator can be shown to be consistent and a Best Asymptotic Normal (BAN) estimator under quite general conditions (Mood, Graybill, and Boes).

non-zero values only in D. The procedure involves first estimating the unconstrained $\hat{\theta}$ and its variance-covariance matrix by the usual procedures (e.g., iterative seemingly unrelated regression, ITSUR). Then, random samples are drawn from the multivariate normal distribution and the eigenvalues of **H** are calculated to verify if the particular values of θ lie in D. All draws that yield $\theta \notin D$ (i.e., a Hessian with some negative eigenvalues) are excluded. $E(\theta)$ is calculated from the mean of all values of θ that are in D.

Since Σ is usually unknown, the posterior is no longer multivariate normal. It is necessary to consider a joint prior $P(\theta, \Sigma)$, and a procedure called "importance sampling" is used (Kloek and van Dijk; Geweke). The procedure indicated above is modified by sampling from a multivariate t rather than from a multivariate normal distribution (see details in Geweke and in Chalfant, Gray, and White). In addition to parameters, it is possible to calculate their numerical standard errors that are "analogous to the usual standard error of the estimate of a population mean" (Chalfant, Gray, and White).

Imposition of curvature conditions (convexity or concavity) on the approximating function may be carried out either globally or locally (e.g., at the point of expansion). If convexity conditions are imposed locally, there is no guarantee that the approximating function will be globally convex (an important exception noted by Lau (1978) is the quadratic function). Global convexity/concavity often requires such severe restrictions on parameters of the approximating function that the flexibility of the functional forms is often destroyed, leading to upward bias in the degree of input substitutability (Lau 1978). Thus, the only traditional flexible functional form that satisfies global curvature conditions is the normalized quadratic.

Decomposition Analysis

This section presents a series of decomposition equations required to retrieve all demand functions using the restricted profit function as a starting point. It is based on properties of the Hessian matrices examined first by Lau (1976) and used by Lopez (1984) and by Hertel. Assuming sufficient differentiability of the profit function and using the envelope theorem, the long-run (Marshallian) net supply function is

$$[\partial\pi(P,W,R)/\partial P]_{n\times 1} = X(P,W,R). \tag{3}$$

The first-order condition for long-run (full-equilibrium) profit maximization from (2) is

$$[\partial\pi(P,Z,R)/\partial Z]_{m\times 1} = W, \tag{4}$$

which states that the shadow-price vector is equal to the corresponding vector of rental prices W. From (4), the optimum value for Z, $Z^* = Z(P,W,R)$, is obtained. From (2), using again the envelope theorem,

$$[\partial\pi(P,W,R)/\partial W]_{m\times 1} = -Z(P,W,R). \tag{5}$$

The decomposition equations of the Hessians of the restricted and unrestricted profit functions are obtained by differentiation of the above expressions with respect to P. After some algebra, the Hessian of the (unrestricted) profit function is expressed as a function of the Hessian of the restricted profit function in the neighborhood of the long-run equilibrium as follows:

$$\left[\frac{\partial^2\Pi(P,W,R)}{\partial P^2}\right]_{n\times n} = \left[\frac{\partial^2\Pi(P,Z(P,W,R),R)}{\partial P^2}\right]_{n\times n} - \left[\frac{\partial^2\Pi(P,Z(.),R)}{\partial P\partial Z}\right]_{n\times m}\left[\frac{\partial^2\Pi(P,Z(.),R)}{\partial Z^2}\right]^{-1}_{m\times m}\left[\frac{\partial^2\Pi(P,Z(.),R)}{\partial Z\partial P}\right]_{m\times n}. \tag{6}$$

The Hessian of the restricted profit function may be expressed in terms of the unrestricted profit function:

$$\left[\frac{\partial^2\Pi(P,Z(P,W,R),R)}{\partial P^2}\right] = \left[\frac{\partial^2\Pi(P,W,R)}{\partial P^2}\right] - \left[\frac{\partial^2\Pi(P,W,R)}{\partial P\partial W}\right]\left[\frac{\partial^2\Pi(P,W,R)}{\partial W^2}\right]^{-1}\left[\frac{\partial^2\Pi(P,W,R)}{\partial W\partial P}\right]. \tag{7}$$

It is also useful to express the restricted profit function in terms of a less restricted profit function. The vector of netputs held fixed in the restricted profit function is Z. Denote the fixed netputs in the less restricted profit function by Z^f with prices W^f, and the netputs that become variable by Z^v with prices W^v:

$$(8)\quad \left[\frac{\partial^2\Pi(P,Z^f,Z^v,R)}{\partial P^2}\right] = \left[\frac{\partial^2\Pi(P,W^v,Z^f,R)}{\partial P^2}\right] - \left[\frac{\partial^2\Pi(P,W^v,Z^f,R)}{\partial P\partial W^v}\right]\left[\frac{\partial^2\Pi(P,W^v,Z^f,R)}{\partial(W^v)^2}\right]^{-1}\left[\frac{\partial^2\Pi(P,W^v,Z^f,R)}{\partial W^v\partial P}\right].$$

The long-run Marshallian elasticities are expressed in terms of the corresponding short-run elasticities using equation (6), noting that in the short run only some of the inputs (K) belong to the fixed netput category (Z). Using Hotelling's lemma on (6) yields (in derivative form)

$$(9)\quad \left[\frac{\partial X(P,W,R)}{\partial P}\right]^M_{LR} = \left[\frac{\partial X(P,K,R)}{\partial P}\right]^M_{SR} - \left[\frac{\partial X(.)}{\partial Z}\right]'\left[\frac{\partial^2\pi(P,K(P,W,R),R)}{\partial Z^2}\right]^{-1}\left[\frac{\partial X(.)}{\partial Z}\right].$$

Finally, to calculate the derivatives of the quasi-fixed factors with respect to price in the long run, it is simpler to obtain first $Z^* = (P,W,R)$, as shown in the next section.

If the Hessian $\partial^2\pi(.)/\partial Z^2$ is negative semidefinite, it follows that $[\partial X_i/\partial P_i]^{LR} \geq \partial[X_i/\partial P_i]^{SR}$, which illustrates that Le Chatelier's principle will be satisfied if the restricted profit function is convex in P and concave in Z. In terms of elasticities, the above show that long-run own-price elasticities are larger (in absolute value) than the corresponding short-run elasticities. The Hicksian short-run input demand elasticities[5] are obtained from (8), noting that in this case the fixed netputs vector Z includes all outputs (Y) and some inputs (K). Thus, $Z = [Y',K']'$. In this case, the restricted profit function becomes $\pi(P,Z,R) = -Cost(P,Y,K,R)$. From (8) and (3), the matrix of derivatives of the short-run Hicksian input demand with respect to price is

$$(10)\quad \left[\frac{\partial X(P,Y,K,R)}{\partial P}\right]^H_{SR} = \left[\frac{\partial X(P,W^Y,K,R)}{\partial P}\right]^M_{SR} - \left[\frac{\partial X(.)}{\partial W^Y}\right]'\left[\frac{\partial^2\pi(P,W^Y,K,R)}{\partial(W^Y)^2}\right]^{-1}\left[\frac{\partial X(.)}{\partial W^Y}\right].$$

In this expression, the first term of the right-hand side is the familiar substitution effect and the second the expansion effect. Since $\partial^2\pi(.)/\partial(W^Y)^2$ is positive semidefinite, then $[\partial X_i/\partial P_i]^H \leq \partial X_i/\partial P_i]^M$, which is another manifestation of Le Chatelier's principle. Finally, an expression similar to (10) is used to express the long-run Hicksian demand, and the corresponding long-run Marshallian demand is obtained using an expression analogous to (9).

The Empirical Model

The empirical model uses the Fuss-quadratic normalized restricted profit function (Fuss; Diewert and Ostensoe). This flexible functional form is capable of satisfying curvature globally. Imposing symmetry and linear homogeneity in P and Z, it may be expressed as

$$(11)\quad \tilde{\Pi}(\tilde{P},\tilde{Z},R) = \frac{\Pi(P,Z,R)}{P_1Z_1} = a_0 + (a'b'c')\begin{bmatrix}\tilde{P}\\ \tilde{Z}\\ R\end{bmatrix} + \tfrac{1}{2}(\tilde{P}'\tilde{Z}'R')\begin{bmatrix}B & E & F\\ E' & C & G\\ F' & G' & D\end{bmatrix}\begin{bmatrix}\tilde{P}\\ \tilde{Z}\\ R\end{bmatrix},$$

where $\tilde{P} = (P_2/P_1 \ldots P_N/P_1)'$, $\tilde{Z} = (Z_2/Z_1 \ldots Z_M/Z_1)'$, $R = (R_1 \ldots R_s)'$; a_0 is a scalar parameter; and a, b, and c are vectors of constants of the same dimension as $\tilde{P}$, $\tilde{Z}$, and R, respectively. B, C, and D are symmetric matrices of parameters of the appropriate dimensions, e.g., B is $(n - 1) \times (n - 1)$. Similarly E, F, and G are matrices of unknown parameters. Because no interaction is expected between exogenous factors and quasi-fixed factors, G is a null matrix and D is diagonal. Using the envelope theorem, the vector of short-run net sup-

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[5] Similarly, a long-run Hicksian demand may be obtained from the unrestricted profit function (Lopez 1984).

ply functions divided by Z_1, i.e., $\tilde{X} = (X_2/Z_1 \ldots X_n/Z_1)'$, is

$$(12) \qquad \tilde{X}(\tilde{P},\tilde{Z},R) = \nabla_{\tilde{P}}\tilde{\pi}(\tilde{P},\tilde{Z},R) = a + B'\tilde{P} + E\,\tilde{Z} + F\,R,$$

which provides $n - 1$ equations. The numeraire equation is obtained from

$$(13) \qquad \frac{X_1}{Z_1} = \tilde{\pi}(\tilde{P},\tilde{Z},R) - \tilde{P}'\tilde{X} = \frac{\pi(P,Z,R)}{P_1 Z_1} - \sum_{i=2}^{n} \tilde{P}_i\tilde{X}_i; \text{ and}$$

$$(14) \qquad \frac{X_1}{Z_1} = a_0 + b'\tilde{Z} + c'R - \frac{1}{2}\tilde{P}'B\,\tilde{P} + \frac{1}{2}\tilde{Z}'C\tilde{Z} + \frac{1}{2}R'D\,R.$$

Short-run Marshallian elasticities are obtained directly by calculating first the derivatives of the $\tilde{X}$'s. Other elasticities are derived from the decomposition equations. Long-run elasticities require the optimum $\tilde{Z}$ vector, which is obtained by solving for $\tilde{Z}$ in the expression

$$(15) \qquad \tilde{W} = W/P_1 = \nabla_{\tilde{Z}}\tilde{\pi}(\tilde{P},\tilde{Z},R) = b + E'\tilde{P} + C\,\tilde{Z}.$$

The derivatives of $\tilde{Z}$ with respect to $\tilde{W}$ and $\tilde{P}$ are obtained from (15), resulting in $\partial\tilde{Z}/\partial\tilde{P} = -C^{-1}E$ and $\partial\tilde{Z}/\partial\tilde{W} = C^{-1}$. This allows the calculation of long-run elasticities for the quasi-fixed factors. Long-run elasticities for variable factors are obtained from the decomposition equations.

Linear homogeneity is imposed by normalization and symmetry by sharing of parameters. Monotonicity is verified when the predicted X's have the correct sign (i.e., negative for variable inputs and positive for outputs). In order to satisfy the curvature conditions, the restricted profit function must be a saddle function, convex in prices and concave in the quasi-fixed inputs. The Fuss-quadratic normalized profit function $\tilde{\pi}$ is globally convex in prices if and only if (iff) the Hessian $\nabla_{\tilde{P}\tilde{P}}{}^2\,\tilde{\pi}(\tilde{P},\tilde{Z},R) = B$ is positive semidefinite, and $\tilde{\pi}$ is globally concave in Z iff C is negative semidefinite. Curvature conditions are imposed following the Bayesian (statistical) approach. The initial (unconstrained) parameter estimates are obtained by the iterative seemingly unrelated regression (ITSUR) technique, which is asymptotically equivalent to maximum-likelihood estimation. Given that homogeneity and symmetry are maintained and monotonicity is verified, the mean of the posterior density, that is, the mean vector of those replications that satisfy the curvature conditions (non-negative eigenvalues for B, nonpositive for C), provides the estimate of the parameter vector. A total of 14,000 replications are carried out for the estimation. After the parameters are obtained, the model may be used to carry out policy simulations, such as examining the effect of imposing taxes (on fertilizer and pesticides) on input use, output supply, and farm income.

The desire to specify a highly disaggregated model in terms of outputs and/or inputs is often hampered by multicollinearity and degrees of freedom limitations. Thus, separability and nonjointness assumptions are usually maintained. In some cases separability assumptions are not tested. More often, researchers maintain some separability assumptions in their models and they test (and usually reject) separability at a higher level of aggregation than that of their models. For this study, we draw on recent empirical evidence (Lim and Shumway 1989b) that finds consistent aggregation of all outputs in a single category is justified in 11 of the 48 contiguous states, including Illinois. The model is specified as part of a two-stage optimization (Fuss). The output submodel is a revenue function that includes five output categories. The input submodel includes aggregate output and nine input categories: hired labor (numeraire), feed, seeds, fertilizer, pesticides, fuels, capital and related services, operator/family labor, and land (including buildings). Operator/family labor and land are considered as quasi-fixed inputs. In addition, the model includes time as a proxy for disembodied technical change, a weather index discussed in the next section, and a government policy variable to account for diversion payments.

Previous studies (e.g., Shumway and Alexander; Huy, Elterich, and Gempesaw) have documented considerable regional differences in the agricultural production structure. Recent empirical studies (Polson; Lim and Shumway 1989b) have found that the production structure, in particular separability, varies even among states in the same production region. As a result, aggregate studies of U.S. agriculture, and even regional studies, may suffer from unknown specification bias. Consequently, current research is focusing on states (or counties) as data become available. The estimated model consists of eight equations (12) and (14) with additive disturbances appended to reflect errors in optimization. After imposing symmetry and linear homogeneity, 61 parameters are estimated (that is, θ is a 61-dimensional vector). After the parameters are estimated, short-run Marshallian elasticities are calculated and the decomposition equations are used to obtain Marshallian long-run and Hicksian short-run/long-run elasticities. Finally, MES is obtained by using $(MES)_{ij} = \epsilon_{ij} - \epsilon_{jj}$.

Data

The model is estimated using annual data for the state of Illinois for the period 1950–86. The data set used was compiled by Evenson and updated by McIntosh using various U.S. Department of Agriculture publications. For this study, a fuel data series is added and other minor changes introduced. Fuel expenditures are obtained from *Economic Indicators of the Farm Sector* (EIFIS) and prices are from *Agricultural Prices*. For those years that state-level fuel prices are not available, regional (Corn Belt) or U.S. prices are used as proxies. All aggregation is made using Tornqvist indices.

Producers are assumed to make their production plans based on subjective evaluations of future output prices and government programs. Lagged output prices are used as proxies based on results by McIntosh and Shumway, which show that one-period lags of output prices are better predictors of output price than other ARIMA models or futures-based models. The concepts of effective support price (ESP) and effective diversion payments (EDP) (Houck et al.; Ryan and Abel) are used following McIntosh and Shumway. Since announced government programs may affect farmers' decisions even when the ESP is below the expected output price (Shumway, McIntosh, and Polson), a weighted average of expected market prices and ESP is calculated using Romain's technique, in which the weights depend on the relative magnitudes of ESP, expected market prices, and loan rates.

While weather has been recognized as a very important factor in the supply of agricultural commodities, few empirical studies using the dual framework have incorporated weather into their models. Shumway used the Stallings index, which is the ratio of actual to calculated yields based on a linear trend. A drawback of the Stallings index is that it is not directly related to weather variables. More recently, Shumway and Alexander, and McIntosh and Shumway have incorporated weather variables (such as rainfall and temperature in critical planting and growing months) in their dual models. However, they report statistically insignificant weather coefficients. One difficulty with this direct approach is that many weather variables would need to be introduced to the model to capture the effect of weather on agricultural output, consuming scarce degrees of freedom. This study introduces into the model a weather index, R_2, that synthesizes the weather information relevant to each specific crop. The index is defined as the ratio of actual to normal yields and is calculated for each major crop as a function of the weather variables V_i:

$$(16)\quad R_2 = \frac{Y_{actual}}{Y_{normal}} = 1 + \frac{1}{Y_{normal}}\left(\sum_{i=1}^{n} \beta_i V_i\right).$$

The coefficients β_i are calculated using Thompson's multiple-regression technique (Thompson 1970, 1986) to capture the effect of weather on yields using state-level yield (USDA) and weather (Teigen and Singer) data. Following Thompson, relevant weather variables for the Corn Belt are preseason precipitation; June, July, and August rainfall; June, July, and August temperature (all in deviation form); and their squares.

Empirical Results

Table 3 compares the short-run Marshallian own-price elasticity for the variable inputs in 1986, with and without imposing curvature conditions. In general, the theoretically consistent own-price elasticities are larger in absolute value than the corresponding unrestricted elasticities; differences range from 9% for hired labor to 64% for pesticides.

Table 4 and 5 present the short-run Marshallian, short-run Hicksian, and long-run Hicksian elasticities for the last observation (1986). As expected, own-price elasticities are negative for inputs and positive for outputs, and Le Chatelier's principle is satisfied in both the long-run/short-run and the Marshallian/Hicksian cases. All elasticities are in the inelastic range except for hired labor. The results of Table 4 show that in the short-run, except for feeds, the difference between Marshallian and Hicksian own-price elasticities is very small, due to a small short-run expansion effect. This effect is

Table 3. Own-Price Short-Run Marshallian Elasticities, Illinois, 1986, with/without a Theoretical Consistent Restricted Profit Function

	With	Without	Difference (%)
Hired labor	−2.076	−1.884	9.2
Feeds	−0.242	−0.134	44.6
Seeds	−0.291	−0.255	12.4
Fertilizer	−0.078	−0.065	16.7
Pesticides	−0.104	−0.037	64.4
Fuels	−0.048	−0.039	18.8
Capital	−0.601	−0.487	19.0
Output	0.061	0.032	47.5

Table 4. Marshallian/Hicksian Short-Run Elasticities of Input Demand, Illinois, 1986

	Hired Labor	Feeds	Seeds	Fertilizer	Pesticides	Fuel	Capital
H. Labor							
Marshallian	−2.076	−0.166	0.154	−0.091	−0.149	−0.282	2.878
Hicksian	−2.035	−0.308	0.146	−0.117	−0.136	−0.291	2.741
Feeds							
Marshallian	−0.028	−0.242	0.029	0.027	0.017	0.013	0.027
Hicksian	−0.052	−0.159	0.033	0.042	0.010	0.018	0.108
Seeds							
Marshallian	0.135	0.149	−0.291	−0.051	−0.075	−0.025	0.113
Hicksian	0.128	0.173	−0.290	−0.046	−0.077	−0.024	0.136
Fertilizer							
Marshallian	−0.041	0.071	−0.026	−0.078	0.072	−0.017	−0.057
Hicksian	−0.052	0.111	−0.024	−0.070	0.068	−0.015	−0.018
Pesticides							
Marshallian	−0.100	0.069	−0.057	0.107	−0.104	0.111	0.030
Hicksian	−0.091	0.039	−0.059	0.102	−0.101	0.109	0.001
Fuels							
Marshallian	−0.233	0.061	−0.024	−0.032	0.138	−0.048	0.088
Hicksian	−0.240	0.088	−0.022	−0.027	0.135	−0.047	0.114
Capital							
Marshallian	0.423	0.024	0.019	−0.019	0.007	0.016	−0.601
Hicksian	0.403	0.093	0.023	−0.006	0.000	0.020	−0.533

larger in the long run. Compared to the results of this paper, Lopez (1984) finds moderate long-run expansion effects in Canadian agriculture, while Higgins finds large expansion effects for Irish agriculture.

Focusing on chemical inputs (Table 6), the estimated own-price short-run elasticities for fertilizer lie at the lower end of the range of previous econometric estimates using dual models (e.g., Binswanger; Burrell), but they are higher than a more recent estimate by McIntosh and Shumway for California. Long-run Marshallian estimates are more in line with previous estimates. The results are consistent with the estimates for nitrogen fertilizers for Illinois for 1980/89 by Vroomen and Larson using a direct approach and are also similar to estimates for the United Kingdom and West Germany based on LP techniques (Burell). The demand for pesticides is also quite inelastic and there is little published information on elasticities derived from dual methods to compare our results with. Earlier research (Miranowski) reports own-price elasticities of −0.19 for herbicides and −0.62 for insecticides used in the production of corn, based on 1966 cross-sectional data.

The intensification of agricultural production, made possible by fertilizers and pesticides, has also led to contamination of ground- and surface-water resources and contributes to the presence of toxic residues in food. Environmental concerns have generated interest about alternatives to limit the use of inorganic fertilizers as well as pesticides. The simplest alternative, and easiest to control, is the imposition of ad valorem taxes on those products.[6] The effectiveness of such taxes depends on the responsiveness of fertilizer and pesticides demand to increases in their prices. The results of this study show that such response is quite small. For example,[7] a 10% reduction in fertilizer use would require a 128% tax in the short run and a 65% tax in the long run. To reduce fertilizer use to the point that excess nutrient[8] (available for leaching or runoff) is negligible would require a tax of more than 300% in the short run and near 200% in the long run.[9] In the case of pesticides (mainly herbicides), a 10% reduction in use would require a 96% tax in the short run and a 26% tax in the long run. Thus, even moderate reductions in fertilizer or pesticide use would require substantial taxes. On the other hand, taxes have a significant

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[6] Sweden, Austria, and Finland currently impose a 25% tax on nitrogen and phosphorous fertilizers (OECD). Iowa has a very small tax on nitrogen fertilizers for the purpose of raising revenue for research and extension activities related to groundwater protection.

[7] The results presented in this paragraph are only approximate since point elasticities are assumed to be approximately applicable. In addition, feedback output effects from the markets of agricultural products are beyond the scope of this paper.

[8] Following Huang and Lantin, excess nutrient is defined as the difference between the amount of nutrient applied from all sources (on an acre of cropland) and the amount removed at the end of the growing season in the grain and stalks. For example, they estimate the amount of nitrogen required to achieve zero excess in the production of corn to be about 110 lbs/a per year. The average amount of nitrogen used on corn in 1986 was 155 lb/a in Illinois (Vroomen).

[9] These figures can be compared to results for the European Community (EC), where the per acre application of fertilizer is more than twice that of the U.S. According to Henrichmeyer, a 400% to 500% tax on nitrogen would be required in the EC to achieve a noticeable effect.

Table 5. Hicksian Long-Run Elasticities of Input Demand, Illinois, 1986

	With Respect to the Price of							
	Hired Labor	Feeds	Seeds	Fertilizer	Pesticides	Fuels	Capital	Land
Hired labor	−11.45	0.090	0.150	−0.062	−0.287	−0.264	3.383	8.442
Feeds	0.015	−0.191	0.033	0.038	0.022	0.016	0.056	0.011
Seeds	0.132	0.171	−0.290	−0.047	−0.076	−0.024	0.133	0.001
Fertilizer	−0.028	0.100	−0.024	−0.072	0.072	−0.015	−0.037	0.004
Pesticides	−0.191	0.086	−0.058	0.108	−0.119	0.113	0.078	−0.016
Fuels	−0.218	0.077	−0.022	−0.028	0.139	−0.048	0.097	0.004
Capital	0.497	0.049	0.022	−0.012	0.017	0.017	−0.605	0.015
Land	−0.044	0.021	0.000	0.003	−0.008	0.001	0.034	−0.007

impact on farm income. A simple calculation shows that in the short run, the tax necessary to achieve a 10% reduction in fertilizer use would cause a 41% drop in farm income, while the tax required to decrease pesticide use by 10% would reduce income by 17%.

The signs of the cross-price input-demand elasticities are often used to classify inputs into net (gross) substitutes in production when the Hicksian (Marshallian) elasticity is positive or into net (gross) complements if negative. It is found that for Illinois, the classification into net and gross substitutes/complements coincides for all pairs. In the short run, all pairs are weak net and gross substitutes/complements except for the pair hired labor/capital, although this weakness is moderated in the long run. Nearly 60% of all pairs are short-run substitutes and about 70% are long-run substitutes. It is interesting that in both the short run and the long run, pesticides behave as net and gross substitutes for feeds, fertilizer, fuel, and capital, and fertilizer is a net and gross substitute for feeds and pesticides. The substitutabilities between pesticides, and fuels and capital may be related to alternative tillage practices, while substitutabilities between feeds and fertilizers, pesticides, and other inputs may be due to the presence of *purchased* feeds.

Table 7 presents the short- and long-run Morishima elasticities of substitution (MES) for 1986. For most inputs, differences in MES between the short run and the long run are small except for some of the input pairs that involve hired labor or capital. The estimates also show more than 90% of the input pairs exhibit short-run Morishima substitutability, while only 60% of the input pairs behave as net (Allen) substitutes. This behavior is similar to that noted by Ball and Chambers in a different context.

Table 6. Own-Price Elasticities of Chemical Inputs, Illinois, 1986

	Short-Run Hicksian	Short-Run Marshallian	Long-Run Hicksian	Long-Run Marshallian
Fertilizer	−0.070	−0.078	−0.072	−0.155
Pesticides	−0.101	−0.104	−0.119	−0.382

Strong Morishima substitutability is found for the pair hired labor/capital for both the short and long run. In addition, the large degree of asymmetry for that pair suggests that any policy that causes similar percent decreases in the price of capital or increases in the price of hired labor will induce very different increases in the capital/hired-labor ratio. For example, an increase of 10% in the price of hired labor will lead to an 11% increase in the long-run capital/labor ratio. However, a 10% decrease in the price of capital will lead to a 148% increase in the capital/labor ratio. All other pairs show much weaker Morishima complementarity in both the short and long run. For example, an increase of 10% in the price of pesticides will increase the fertilizer/pesticide ratio by only about 2%.

The inherent asymmetry of the Morishima elasticities is very pronounced in the short and long run. Only four input pairs exhibit a small/moderate degree of asymmetry. They are fertilizer/feeds, pesticides/fuels, capital/seeds, and feeds/pesticides. The asymmetry in the pair fuels/capital, noted by Taylor and Gupta for southeastern agriculture, is even more pronounced for Illinois.

Concluding Comments

The main contribution of this study is that it provides a procedure whereby, based on estimation of a theoretically consistent restricted profit function and using a series of decomposition equations, all demand functions (Hicksian and Marshallian in the short run and the long run) and the elasticities of substitution are readily calculated without estimat-

Table 7. Short- and Long-Run Morishima Elasticities of Substitution, Illinois, 1986

	Hired Labor	Feeds	Seeds	Fertilizer	Pesticides	Fuels	Capital
Hired Labor							
SR[a]	0.00	1.72	2.18	1.92	1.90	1.74	4.77
LR[a]	0.00	11.5	11.6	11.4	11.2	11.2	14.8
Feeds							
SR	0.11	0.00	0.19	0.20	0.17	0.18	0.27
LR	0.21	0.00	0.22	0.23	0.21	0.21	0.25
Seeds							
SR	0.42	0.46	0.00	0.24	0.21	0.27	0.43
LR	0.92	0.46	0.00	0.24	0.21	0.27	0.42
Fertilizer							
SR	0.02	0.18	0.05	0.00	0.14	0.06	0.05
LR	0.04	0.17	0.05	0.00	0.14	0.06	0.04
Pesticides							
SR	0.01	0.14	0.04	0.20	0.00	0.21	0.10
LR	−0.07	0.21	0.06	0.23	0.00	0.23	0.20
Fuels							
SR	−0.19	0.13	0.02	0.02	0.18	0.00	0.16
LR	−0.17	0.12	0.03	0.02	0.19	0.00	0.14
Capital							
SR	0.94	0.63	0.56	0.53	0.53	0.55	0.00
LR	1.10	0.65	0.63	0.59	0.62	0.62	0.00

[a] SR is short-run; LR is long-run.

ing the cost function. Unlike previous work, this study imposes simultaneous convexity in prices and concavity in quasi-fixed factors. Both curvature properties are essential in the use of decomposition methods to avoid violations of Le Chatelier's principle. In addition to the short-run and long-run Hicksian and Marshallian elasticities, both Allen-Uzawa and Morishima ES can be calculated, although the theoretical evidence favors the use of the Morishima elasticities. Thus, the proposed methodology provides a wealth of information, facilitating analysis of the flexibility of production systems. The model is disaggregated in the input side to obtain information (e.g., pesticides) not readily available from this type of model, and a new weather index is introduced.

More empirical work is needed using dual models with a fair amount of disaggregation in the input side. While these efforts are facilitated by the use of two-stage modeling, some separability and homotheticity assumptions still need to be established. The task can be simplified by drawing on nonparametric results such as Lim and Shumway's. Provided the estimated model is theoretically consistent, all elasticities will be of the correct sign and Le Chatelier's principle will be satisfied. For the case of Illinois, the producers' responsiveness to price changes for fertilizer and pesticides is small, in particular in the short run, implying that the impact of taxes imposed on these inputs of the size imposed in some countries in Western Europe (25%) will be negligible in the short run and small in the long run.

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