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Dynamic Adjustment of U.S. Agriculture to Energy Price Changes

David K. Lambert and Jian Gong

Energy prices increased significantly following the first energy price shock of 1973. Agricultural producers found few short run substitution possibilities as relative factor prices changed. Inelastic demands resulted in total expenditures on energy inputs that have closely followed energy price changes over time. A dynamic cost function model is estimated to derive short and long run adjustments within U.S. agriculture between 1948 and 2002 to changes in relative input prices. The objective is to measure the degree of farm responsiveness to energy price changes and if this responsiveness has changed over time. Findings support inelastic demands for all farm inputs. Statistical results support moderate increases in responses to energy and other input price changes in the 1980s. However, demands for all inputs remain inelastic in both the short and long run. Estimation of share equations associated with a dynamic cost function indicates that factor adjustment to input price changes are essentially complete within 1 year.

Key Words: dynamic cost function, energy prices, U.S. agriculture

JEL Classifications: Q11, Q41

Energy markets are important to agriculture. Energy prices affect agricultural production costs directly through fuel and energy use and indirectly through the employment of farm inputs such as fertilizers and chemicals that rely on energy in their manufacturing. Total U.S. direct farm expenditures on fuels and energy totaled \$11.4 billion in 2004, comprising 8.4% of purchased inputs (U.S. Department of Agriculture, Economic Research Service (USDA ERS), Farm Income Dataset). Fertilizer, lime, and pesticide expenditures amounted to \$19.9 billion, or 14.7% of total intermediate input expenses. The combined purchases of these energy-intensive manufactured inputs exceeded \$32 billion in 2004, or about 23% of all purchased inputs.

The demand for direct energy inputs is price inelastic (Miranowski, 2005). Consequently, when energy prices increase, shocks may be absorbed by farmers having limited opportunities to substitute other factors as relative prices change. Total real farm expenditures on energy-related inputs have thus closely followed fuel and energy price changes from 1948 to 2005 (Figure 1). Nominal energy prices were stable during the 1950s and 1960s, though real prices declined over the period. Real expenditures were stable over this period, with increases through the mid 1960s perhaps associated with rapid mechanization of farm production in response to increases in the cost of labor relative to other inputs (Gardner, 2002).

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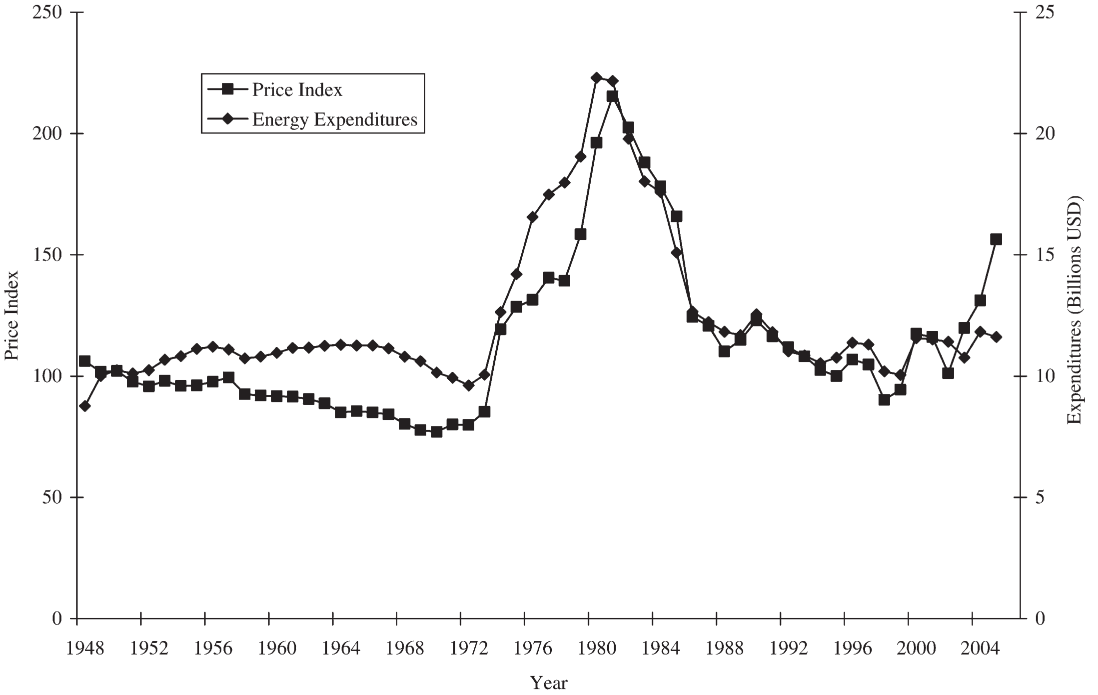

Figure 1. Price Index for Fuels and Related Products and Power (U.S. Department of Commerce, Bureau of Labor Statistics Series WPU05) and U.S. Agricultural Expenditures on Fuel, Oil, and Electricity (USDA ERS) (Both series deflated to 2005 U.S. dollars using the gross domestic product deflator.)

However, prices and volatility increased substantially following the first energy price shock of 1973. Nominal fuel and power prices increased 486% from 1972 to 1981 (U.S. Department of Commerce, Bureau of Labor Statistics, 2004), while U.S. farm expenditures on fuels and power increased 415% over the same 10 years (USDA ERS, Farm Income Dataset, 2004). The correlation between annual prices and expenditures was 0.98 over these 10 years, lending descriptive support to Heady's estimate in 1978 that a 200% increase in energy prices would reduce energy use in agriculture by only 4% (Heady, 1984).

The purpose of this research is to measure responses to changing energy prices in U.S. agriculture. Given significant changes in energy markets since the first price shock of the early 1970s, we seek econometric support for possible changes in both input use and factor substitution possibilities over the past 50 years. A dynamic dual cost function is used to determine the rate of adjustment to factor price changes in U.S. agriculture and to identify if changes in factor use over the 1948–2002 time period have occurred.

Time series analysis strongly supports a structural break in energy markets coincident with the 1973 oil shocks resulting from supply disruptions associated with the 1973 Yom Kippur War and subsequent cessation of oil shipments by Arab countries of the Organization of the Petroleum Exporting Countries to countries supporting Israel in that conflict (Perron, 1989). Perhaps the first focused look at energy price changes affecting U.S. agriculture was a series of papers published in 1977 (VanArsdall, 1977). Although innovation induced by changes in relative prices was anticipated, most contributors to the discussion stressed the insensitivity of agricultural production to energy price changes.

Numerous authors have addressed the impacts on agriculture of continuing volatility in energy markets over the last 30 years. Hanson, Robinson, and Schluter (1993) used an input-output model to analyze the direct and indirect cost linkages between energy and other sectors of the economy. They confirmed that responses to oil price shocks vary depending on a farm's output mix. Their simulation results showed that agricultural livestock and crop production decreased when oil prices increased. Oil prices of $30, $40, and $50 per barrel resulted in crop production reductions of 4%, 6%, and 8%, respectively. Livestock production was more sensitive to oil price changes, with livestock production reductions of 10%, 20%, and 30%, respectively, corresponding to the increasing per barrel oil prices. Output reductions could increase prices, yet the authors concluded output price effects would not offset increased energy expenditures.

Similar to other sectors in the U.S. economy (Baily and Schultze, 1990), long run adaptations in agriculture may increase input substitution possibilities and lead to greater efficiency in on-farm energy use. Although recent estimates indicate energy demand is still inelastic (Miranowski (2005)) reports a value of −0.60, the industry appears to have adopted innovations to counter high energy prices and volatility.

Studies of input substitution, innovation, and changes in production practices include Edwards, Howitt, and Flaim (1996), who found input substitution, especially substitution of irrigation water and other inputs, to be a significant response to energy price changes. Musser, Lambert, and Daberkow (2006) suggested farm level adaptations to increasing energy costs might be reduced tillage systems, improved drying and irrigation systems, and more careful application of fertilizers. Raulston et al. (2005) found energy price impacts to be dependent on crops grown, with the least negative impact affecting wheat production, whereas impacts on net farm income for cotton producers was greatest due to the reliance of cotton production on energy-intensive irrigation systems. Uri and Herbert (1992) documented the increasing conversion from gasoline to diesel-based power sources since the early 1970s in response to rising energy prices. Debertin, Pagoulatos, and Aoun (1990) confirmed increasing adaptation to changing relative energy prices in U.S. agriculture. Their research revealed that the elasticity of factor substitution in agriculture has changed over time. In particular, energy was a complement for machinery use in the 1950s, yet had become a substitute by the 1970s.

Although time period, input definition, and analytical approaches vary, several authors have derived measures of price and substitution elasticities for energy inputs using static models and aggregate U.S. data. Lambert and Shonkwiler (1995) estimated elasticities of −0.41 for labor, −0.04 for capital, and −0.22 for materials (which included energy) using aggregate U.S. data for 1948–1983. All three factors were Morishima substitutes, meaning as the cost of one input, for example labor, increased, the ratio of other inputs, such as capital and energy, increased relative to labor use. Ray's (1982) analysis of U.S. agriculture between 1939 and 1977 reported inelastic own-price elasticities for labor, capital, fertilizer, feed, seed and livestock, and miscellaneous inputs. With the exception of an own-price elasticity of −1.20 for fertilizer, Huffman and Evenson (1989) also found inelastic demands for factors on U.S. cash grain farms between 1949 and 1974. Shumway, Saez, and Gottret (1988) found inelastic demands in their analysis of U.S. agriculture between 1951 and 1982. They estimated an own-price elasticity for energy between −0.26 and −0.28 using 1982 as a base year. These econometric results support the observed increases in energy expenditures as energy prices increase due to farmers' limited abilities to substitute other inputs.

The next section develops a dynamic cost function to estimate if energy demand has changed in U.S. agriculture following periods of increasing price volatility since 1972. The dynamic specification allows partial annual adjustment to price changes, reflective of the quasi-fixed nature of agricultural investment in capital. Findings indicate the dynamic specification is favored over a static model, yet adjustment to changing relative prices remains inelastic in both the short and the long run.

A Dynamic Model of Production

We hypothesize that short run factor substitution possibilities are limited in commercial agricultural production. Output commitments and existing investments in land and capital largely predetermine factor levels for a variety of planting, cultivation, and harvest activities, irrigation system operations, and heating, feeding, waste management, and other energy-dependent operations associated with livestock production. We expect short run adjustments to be limited, with greater adjustments over time as farmers adjust capital, land, and management inputs in response to changing energy prices.

Static models, either with or without short run restrictions on some inputs, assume instantaneous adjustment of inputs to changes in the economic environment. However, failure to account for imperfect adjustment to disequilibrium ignores the realities of agricultural production. Empirical models failing to account for intertemporal lags or other errors in adjusting to price changes also introduce estimation problems affecting the validity of hypothesis testing. Estimation difficulties from static models arise from serial correlation, biasing standard errors downward and thus erroneously admitting type II errors in hypothesis testing (Berndt and Christensen, 1974). Anderson and Blundell (1982) credit violations of behavioral properties and of estimation errors to a failure to consider adjustment dynamics. Anderson and Blundell (1982) contend that information search costs and factor and product stickiness should be considered in modeling economic adjustment, leading to their incorporation of distributed lags into singular demand systems. Applying their dynamic model to the data used in Berndt and Christensen (1974), Anderson and Blundell (1982) rejected a static specification in favor of a general dynamic specification of a three factor translog system of share equations.

However, Anderson and Blundell (1982) clearly state their approach was not based on an underlying behavioral model. Their objective was to develop and test a dynamic structure for singular demand systems. Expanding Anderson and Blundell's autoregressive, distributed lag (ADL) model, Giovanni Urga and coauthors in a series of papers (Allen and Urga, 1999; Urga, 1996; Urga and Walters, 2003) develop a cost function consistent with Anderson and Blundell's singular system with distributed lags and error correction.

The basis for the original Urga (1996) article and his subsequent coauthored work is the long run translog cost function:

$$(1)\quad \begin{aligned} \ln C_t^* &= \alpha_0 + \sum\nolimits_{i=1}^{n} \alpha_i \ln w_{it} \\ &+ 0.5 \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{n} \alpha_{ij} \ln w_{it} \ln w_{jt} \\ &+ \sum\nolimits_{i=1}^{n} \alpha_{iy} \ln w_{it} \ln y_t + \sum\nolimits_{i=1}^{n} \alpha_{it} \ln w_{it}\, t \\ &+ \alpha_y \ln y_t + \alpha_{yy} \ln y_t^2 \\ &+ \alpha_{yt} \ln y_t\, t + \alpha_t\, t \end{aligned}$$

Corresponding factor shares result from differentiation of Equation (1) by ln w_{it}:

$$(2)\quad \begin{aligned} S_{it} &= \alpha_i + \sum\nolimits_{j=1}^{n} \alpha_{ij} \ln w_{jt} \\ &+ \alpha_{iy} \ln y_t + \alpha_{it}\, t \end{aligned}$$

Urga (1996) derived a dynamic version of the static share equations consistent with long run equilibrium and a short run error correction mechanism:

$$(3)\quad \Delta S_t = m\Delta S_t^* + K\left(S_{t-1}^* - S_{t-1}\right),$$

where Δ is the first difference operator and ΔS_t is an N by 1 vector of one period changes in the N factor shares, m is a scalar control parameter measuring the rate of adjustment of all factor shares to changes in equilibrium shares, the elements of the N $\times$ N matrix B represent own- and cross-factor effects of short run adjustments to disequilibria, and $K = mI + B$. The elements matrix K measure short run adjustments to discrepancies between equilibrium $\left(S_{t-1}^*\right)$and observed (S_{t-1})shares in the previous period.

Singularity of the system requires dropping one equation from the estimation. As a consequence, the short run parameters of B are not identified, though the long run parameters of S_t are. Urga (1996) introduced a cost function consistent with the share equations to overcome the identification problem, as well as to identify parameters associated with Hicks' neutral technical progress or scale effects. Urga (1996) posits the following disequilibrium cost function consistent with the share equations in Equation (3):

$$(4)\quad \begin{aligned} \ln C_t &= m \ln C_t^* + (1-m) \ln C_{t-1}^* + (1-m) \\ &\times \left(\sum\nolimits_{i=1}^{n} S_{i,t-1} \ln w_{it} - \sum\nolimits_{i=1}^{n} S_{i,t-1}^* \ln w_{i,t-1}\right) \\ &+ \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{n} b_{ij} \left(S_{j,t-1}^* - S_{j,t-1}\right) \ln w_{it} \end{aligned}$$

C is observed and C* is the effective (or equilibrium) cost represented by Equation (1). Elements of the N × N matrix B are represented by b_{ij}. Appending independently and identically distributed additive errors and simultaneous estimation of the cost function Equation (4) and N-1 of the share equations in Equation (3) solves the identification problem while avoiding problems of singularity resulting from the translog form (Urga, 1996).

Nested within Equation (4) is the static model ($m = 1$, $B = 0$), the partial adjustment model ($K = mI + bI$, and $m = b$), and the "simple (non-interrelated) error correction model (Urga and Walters, 2003)," in which $B = (h - m)I$ and, thus, $K = hI$. Likelihood ratios resulting from estimation of each of the four models form the basis for model specification tests.

Data

Data provided by Eldon Ball of the USDA ERS for this research includes an aggregate measure of crop and livestock output quantities and both price and quantity indices for five inputs: labor, capital, land, energy, and intermediate inputs other than energy.[1] Labor includes both self-employed and hired workers. Labor quality adjustments following Gollop and Jorgenson's (1980) procedures are followed. Capital includes depreciable assets and beginning inventories of livestock and crops. The land variable combines land area and values, and adjusts for regional features such as public rangeland in the Western United States. The energy variable includes prices and quantities used of petroleum fuels, natural gas, and electricity. Other intermediate inputs include feed, seed, and livestock purchases, agricultural chemicals, and other miscellaneous inputs such as contract labor services, maintenance and repairs, and irrigation water purchases.[2] Over the 55 years, cost shares averaged 26% for labor, 14% for both capital and land, 4% for energy, and 42% for materials. Additional description of procedures underlying the data set is provided in Ball et al. (1997).

Results

Model Specification Tests

The fully dynamic model places no restrictions on the scalar m and the elements of the B matrix. Restrictions on m and B correspond to the static, the partial adjustment, and the error correction model, as well as various permutations of the short run error correction mechanism embedded in the B matrix. The cost function Equation (4) and four (i.e., N − 1) of the share Equations (3) were estimated using nonlinear seemingly unrelated regression procedures in EViews. Model specification tests are based on likelihood ratios. In all three comparisons with the fully dynamic model, the null was strongly rejected. Likelihood ratio test values for the static, the partial adjustment, and the error correction model were 219.4, 253.7, and 103.4, respectively, all surpassing the critical value of 37.6 at the 99% level for the (average of) 20 restrictions imposed on the three restricted models.

Statistical properties of the static and the fully dynamic models are reported in Table 1. The Jarque-Bera test for normally distributed errors for the five estimated equations failed to reject normality for four out of five of the equations. Normality of residuals for the land share equation was strongly rejected. Serial correlation was not statistically significant in the fully dynamic specification, though could not be rejected in the static model. The Box-Pierce Portmanteau test for both first and

[1] State and U.S. output and input indices are available from the ERS. Requests for price indices corresponding to the output and input indices can be addressed to Dr. Ball. Data used in the current research is available at the following website: http://www.ageconomics.ksu.edu/DesktopDefault.aspx?tabid=660.

[2] The objective of the current research is to estimate changes in relative factor use as direct energy prices change. Although most material inputs use energy in their manufacture, only direct impacts of energy (e.g., fuels and electricity) price and quantity changes on farm costs and factor demands are isolated in this research.

second order serial correlation of residuals and the Lagrange Multiplier tests both reject the hypothesis that there is serial correlation in the residuals of the estimating equations of the fully dynamic model.

Monotonicity of the cost function requires each estimated share to be nonnegative. Estimated share values were positive for all 54 observations, supporting a monotonically increasing cost function in factor prices. Concavity[3] was rejected for most of the observations. Twenty-seven of the 55 years had at least one (out of five) violations of the negativity conditions based on estimates of the Allen Elasticities of Substitution. Concavity was violated for 11% of the 275 total observations (55 years $\times$ five share equations per year). For the remaining concavity conditions, 40 years had at least one violation of the 2×2 matrix condition (29% of the total observations violated the 2×2 condition), 42 years had at least one violation of the 3×3 matrix condition (53% violation of the total observations), and 36 years had at least one violation relative to the 4×4 matrix (a total of 65% of the 275 observations violated concavity). Due to imposed homogeneity, the 5×5 matrix of Allen Elasticities of Substitution was singular in all years. We assume that the same reasons underlying Urga and Walters' (2003) finding of violations of concavity apply to the agricultural data: (1) asymmetries in shares; (2) small substitution elasticities; and (3) volatility in input prices.

[3] Urga and Walters (2003) provide the necessary conditions for concavity: at each data point, (1) all five own Allen-Uzawa elasticities of substitution (σ_{ii}^A) are negative; (2) the determinants of all 10 matrices of $\begin{bmatrix} \sigma_{ii}^A & \sigma_{ij}^A \\ \sigma_{ji}^A & \sigma_{jj}^A \end{bmatrix}$ are positive; (3) the determinants of the 10 matrices of $\begin{bmatrix} \sigma_{ii}^A & \sigma_{ij}^A & \sigma_{ik}^A \\ \sigma_{ji}^A & \sigma_{jj}^A & \sigma_{jk}^A \\ \sigma_{ki}^A & \sigma_{kj}^A & \sigma_{kk}^A \end{bmatrix}$ are negative; (4) the determinants of the five matrices of $\begin{bmatrix} \sigma_{ii}^A & \sigma_{ij}^A & \sigma_{ik}^A & \sigma_{il}^A \\ \sigma_{ji}^A & \sigma_{jj}^A & \sigma_{jk}^A & \sigma_{jl}^A \\ \sigma_{ki}^A & \sigma_{kj}^A & \sigma_{kk}^A & \sigma_{kl}^A \\ \sigma_{li}^A & \sigma_{lj}^A & \sigma_{lk}^A & \sigma_{ll}^A \end{bmatrix}$ are positive; and (5) the 5×5 matrix of all substitution elasticities is singular.

Following Urga and Walters (2003), hypotheses concerning the short run adjustment parameters $\{b_{ij}\}$ were tested. Results are reported in Table 1. Hypotheses of symmetry of the B matrix (i.e., $b_{ij} = b_{ji}$) and that B is a diagonal adjustment matrix with either identical or share specific adjustment parameters were all strongly rejected. These results indicate that adjustments in factor shares are interdependent across inputs. These results are consistent with the Morishima elasticity results discussed below.

Short and Long-Run Elasticities

The le Chatelier principle dictates that the rate of input adjustment to changing prices can be no less in the short than in the long run. A necessary condition for the le Chatelier principle to hold is for the short run elasticities to be smaller in absolute value than the long run elasticities, indicating the presence of friction in adjusting to changing relative prices. The long run adjustment parameter m indicates the speed of adjustment. Support for the le Chatelier principle applying to each factor is provided if $[\alpha_{ii}(m - 1)] > 0$ (Urga, 1996). All parameters associated with the own-price quadratic terms in the cost function (i.e., the α_{ii} terms) are significantly greater than zero (Table 2). The estimate for m, 1.007, is greater than one, thus supporting the le Chatelier principle in U.S. agriculture between 1948 and 2002. However, support of the le Chatelier effect is weak, as the Wald test results of the hypothesis that $m = 1$ could not be rejected (Table 1).

Consequently, long run demands are more elastic than the short run estimates (Table 3), but not by much. These results are consistent with Allen and Urga's (1999) analysis of interfuel substitution in U.S. industrial energy demand. Their estimated value of m was 1.006, also not significantly different from one. They concluded that adjustment to long run equilibrium in the composition of fuels consumed was almost instantaneous in their annual model. A similar interpretation of the results in Table 3 indicates that, in U.S. agriculture, factor adjustment to changing input prices was similarly instantaneous, or at least occurred within a year of a factor price shock.

Table 1. Test Results for the Static and the Fully Dynamic Models

Test	Static Model	Fully Dynamic Model
R_{cost}^2, R_l^2, R_c^2, R_d^2, R_e^2	0.998, 0.70, 0.78, 0.92, 0.85	0.999, 0.85, 0.95, 0.92, 0.71
Log likelihood	876.697	986.402
Likelihood ratio (χ^2)	219.40 (0.000)	NA
$AR(1)_{cost,}$ $AR(2)_{cost}$ χ^2 test		
Total cost	0.275 (0.041), 0.356 (0.009)	−0.083 (0.554), −0.205 (0.154)
Labor share	0.512 (0.003), 0.346 (0.009)	0.078 (0.588), 0.040 (0.779)
Capital share	0.803 (0.000), 0.132 (0.359)	0.053 (0.707), −0.061 (0.662)
Land share	−0.059 (0.685), −0.036 (0.787)	−0.067 (0.639), −0.145 (0.310)
Energy share	0.739 (0.000), −0.021(0.880)	−0.201 (0.158), −0.102 (0.473)
Serial correlation Lagrangian Multiplier F-test		
Total cost	0.309 (0.736)	1.755 (0.183)
Labor share	3.386 (0.042)	0.233 (0.793)
Capital share	0.640 (0.532)	0.903 (0.412)
Land share	0.209 (0.812)	0.722 (0.491)
Energy share	0.279 (0.757)	1.675 (0.197)
Residual Normality Test		
Total cost	40.141 (0.000)	0.647 (0.724)
Labor share	5.270 (0.072)	5.344 (0.069)
Capital share	3.115 (0.211)	1.790 (0.409)
Land share	77.701 (0.000)	102.749 (0.000)
Energy share	25.018 (0.000)	12.765 (0.002)
Wald ($m = 1$) χ_1^2 (p)		0.006 (0.939)
LR ($K = mI + B$, $B = B'$) χ_6^2		3783 (0.000)
LR ($K = mI + b_{ii}I$) χ_{12}^2		182.865 (0.000)
LR ($K = mI + BI$) χ_{15}^2		8.931 (0.030)
LR ($m = b$) χ_{16}^2		38.628 (0.000)

Notes: Values in parentheses are the probabilities of observing the specified test statistic under the indicated distribution.
LR ($K = mI + B$, $B = B'$) refers to a likelihood ratio test for parameter symmetry, distributed χ_6^2 under the null hypothesis that $b_{ij} = b_{ji}$. p-value is in the parentheses.
LR ($K = mI + biiI$) refers to a likelihood ratio test for diagonal adjustment matrix, distributed χ_{12}^2 under the null hypothesis that b_{ij} off diagonal elements of B are zero.
LR ($K = mI + BI$) refers to a likelihood ratio test for a scalar adjustment matrix, distributed χ_{15}^2 under the null hypothesis that $b_{ll} = b_{kk} = b_{dd} = b_{ee}$.
LR ($m = b$) refers to a likelihood ratio test for a partial adjustment mechanism, distributed χ_{16}^2 under the null hypothesis.

The rows of the B matrix indicate changes in individual shares resulting from short-run disequilibria between effective and observed factor shares. Consider the effects of short run disequilibria on energy shares (i.e., the coefficients b_{el}, b_{ek}, b_{ed}, b_{ee}, and b_{em}).[4] Errors between effective and observed energy shares in the previous period enter the differenced energy share equation (Equation (3)) with an estimated effect of $b_{ee} = -1.009$. If effective energy shares in period $t - 1$ exceeded actual shares, for example, the change in energy shares between period $t - 1$ and t will be reduced, ceteris paribus, by this short run error times -1.009. Signs of all of the diagonal terms in the B matrix are similarly negative, indicating "overshooting" in period $t - 1$ depresses own-share adjustments in period t.

The off-diagonal terms indicate interdependence of the error correction mechanism. For example, planned capital shares exceeding actual shares in period $t - 1$ will depress adjustment in capital shares in period t ($b_{kk} = -0.961$).

[4] Following Urga and Walters (2003), the short run error correction mechanism for each share is homogenous (i.e., $\sum_j b_{ij} = 0$).

Table 2. Parameter Estimates of the Fully Dynamic Model

m	1.007 (0.039)*	b_{ll}	−0.847 (0.083)*
α_0	220.464 (260.872)	b_{lk}	0.937 (0.317)*
α_l	−1.360 (0.393)*	b_{ld}	−2.392 (1.190)*
α_k	−0.075 (0.250)	b_{le}	2.995 (2.045)
α_d	1.077 (0.544)*	b_{kl}	0.967 (0.566)
α_e	−0.480 (0.195)*	b_{kk}	−0.961 (0.040)*
α_{ll}	0.132 (0.011)*	b_{kd}	−3.129 (1.101)*
α_{lk}	−0.049 (0.006)*	b_{ke}	7.094 (2.228)*
α_{ld}	−0.038 (0.003)*	b_{dl}	−0.375 (0.153)*
α_{le}	−0.020 (0.005)*	b_{dk}	−0.519 (0.213)*
α_{kk}	0.107 (0.005)*	b_{dd}	−0.010 (0.107)
α_{kd}	−0.020 (0.002)*	b_{de}	0.794 (0.514)
α_{ke}	0.008 (0.003)*	b_{el}	−1.068 (0.829)
α_{dd}	0.095 (0.004)*	b_{ek}	0.623 (1.019)
α_{de}	−0.009 (0.001)*	b_{ed}	1.650 (1.266)
α_{ee}	0.032 (0.004)*	b_{ee}	−1.009 (0.040)*
α_{ly}	0.141 (0.033)*	b_{ml}	2.525 (1.430)
α_{ky}	0.018 (0.021)	b_{mk}	1.880 (1.843)
α_{dy}	−0.053 (0.047)	b_{md}	6.676 (3.092)*
α_{ey}	0.040 (0.016)*	b_{me}	−17.309 (5.876)
α_{lt}	−0.007 (0.002)*	α_y	−35.935 (45.499)
α_{kt}	−0.001 (0.001)	α_t	0.630 (0.838)
α_{dt}	−0.0002 (0.00)	α_{yy}	3.123 (3.968)
α_{et}	0.0003 (0.00)	α_{yt}	−0.056 (0.073)
		α_{tt}	0.001 (0.001)

Note: Standard errors in parentheses.
* Indicates significance at the 5% level.

However, this period $t - 1$ disequilibrium in capital share adjustment will have a positive influence on the adjustment in energy shares ($b_{ek} = 0.623$) in period t.

With the exception of energy own-price elasticity of demand, estimated own-price elasticities are more elastic under the dynamic than under the misspecified static model (Table 3). Factor adjustment under the static model assumes equilibrium is reached in each period. The dynamic model admits both the possibility of partial adjustment to changing prices as well as short run adjustments resulting from the error correction mechanism. In our case, the adjustment parameter m was not significantly different from unity. Elasticity differences between the static and the fully dynamic model therefore arise from the error correction mechanism embedded in the share equations. Failure to consider the error correction mechanism in factor demands results in a misspecified model in this case, as well as generally leads to biased estimates of own- and cross-price elasticities of demand.

Formal tests for structural breaks within the sample period were precluded by the large number of parameters in the fully dynamic model. We therefore estimated changes in demand elasticities by estimating own-and cross-price elasticities of demand for different subperiods. Own-price elasticity results are reported in Table 4. Included in the table are the results of the hypothesis test that the change in elasticity from one decade to the next was not significantly different from zero. The change was significantly different than zero for three of the decade-to-decade elasticity changes for labor, all four of the changes for capital, three of the changes for land, and for the latter two decade-to-decade changes for energy (the elasticity estimate for 1981–1990 (1991–2002) was significantly different than the estimate for 1971–1980 (1981–1990)).

Of special interest are changes in response to energy price changes, measured by η_{ee}. Energy demand was more inelastic in the first two decades than it was following the first energy price shock of the early 1970s. Elasticities increased from −0.109 to −0.169 between the 1960s and the 1970s, though the change was not statistically significant. Even greater responsiveness to energy price changes appeared during the 1980s, with own-price elasticity increasing to −0.303, a statistically significant increase in elasticity from the 1971–1980 period. Elasticity again returned to earlier levels in the 1991–2002 period, becoming more inelastic (−0.185). The decrease in elasticity from the previous decade was statistically significant. However, it is worth noting that in all of the subperiods, the own-price elasticities of demand are less than the −0.60 estimate reported by Miranowski (2005). It is also worth noting that own-price demands for energy are inelastic over the entire period, supporting claims that farmers do not have many options for input substitution in the presence of energy price shocks.

Factor Substitution

Morishima elasticities of factor substitution (MES) for the full period are reported in Table 5.

Table 3. Price Elasticities of Demand

Elasticity	Static	Dynamic (Long Run)	Dynamic (Short Run)
η_{ll}	−0.129 (0.076)	−0.230 (0.041)	−0.227 (0.042)
η_{lk}	−0.134 (0.052)	−0.048 (0.023)	−0.049 (0.025)
η_{ld}	−0.011 (0.026)	−0.008 (0.011)	−0.009 (0.013)
η_{le}	−0.013 (0.018)	−0.036 (0.019)	−0.037 (0.021)
η_{lm}	0.287 (0.086)	0.322 (0.039)	0.321 (0.040)
η_{kl}	−0.242 (0.094)	−0.086 (0.041)	−0.089 (0.041)
η_{kk}	0.144 (0.078)	−0.103 (0.036)	−0.098 (0.037)
η_{kd}	0.045 (0.034)	−0.003 (0.014)	−0.004 (0.016)
η_{ke}	0.018 (0.029)	−0.017 (0.023)	−0.018 (0.023)
η_{km}	0.035 (0.131)	0.210 (0.058)	0.209 (0.061)
η_{dl}	−0.020 (0.047)	−0.014 (0.020)	−0.016 (0.022)
η_{dk}	0.046 (0.035)	−0.004 (0.014)	−0.004 (0.015)
η_{dd}	−0.131 (0.034)	−0.181 (0.030)	−0.176 (0.032)
η_{de}	0.004 (0.012)	−0.022 (0.010)	−0.023 (0.011)
η_{dm}	0.101 (0.069)	0.220 (0.039)	0.219 (0.042)
η_{el}	−0.079 (0.115)	−0.228 (0.119)	−0.231 (0.121)
η_{ek}	0.062 (0.100)	−0.060 (0.079)	−0.061 (0.080)
η_{ed}	0.015 (0.040)	−0.076 (0.036)	−0.078 (0.037)
η_{ee}	−0.250 (0.123)	−0.181 (0.107)	−0.176 (0.108)
η_{em}	0.252 (0.052)	0.546 (0.117)	0.546 (0.118)
η_{ml}	0.174 (0.052)	0.195 (0.024)	0.195 (0.025)
η_{mk}	0.012 (0.044)	0.071 (0.020)	0.070 (0.022)
η_{md}	0.033 (0.023)	0.073 (0.013)	0.072 (0.014)
η_{me}	0.024 (0.005)	0.052 (0.011)	0.053 (0.013)
η_{mm}	−0.243 (0.098)	−0.391 (0.038)	−0.390 (0.038)

Note: Standard errors are in parentheses.

Given the similarity of long and short run elasticities, only the long run values are reported. All factors are Morishima substitutes over the 1948–2002 period: as the price of factor *i* increases, the use of all other factors increases relative to factor *i*. In general, changes in the prices of labor, capital, land, or energy lead to small proportional increases in the use of other factors. For example, a 1% increase in energy prices leads to increases in the ratio of labor, capital, land, and materials to energy use of 0.145, 0.164, 0.159, and 0.233%, respectively.

Greater factor substitution occurs when material prices change. Morishima elasticities result from either an increase in the quantity of other factors used or a decrease in material use, or some combination of both effects. Based on the own- and cross-price elasticities of demand reported in Table 5, it would appear that the Morishima substitution effects with respect to a materials price change result from proportionately greater decreases in materials use than increases in the substitute factors.

Subperiod estimates of the MES are reported in Table 6. There is no evident trend in three of the factor elasticity estimates (labor, land, and materials). Changes do appear to be in the MES estimates for capital and energy prices. At the beginning of the time period (1948–1960), labor, land, energy, and materials were all Morishima complements with capital. Increases in capital prices were accompanied by decreases in the ratio of other factors relative to capital use. This post World War II period was characterized by rapid mechanization in agriculture as labor was attracted to off-farm employment by a rising urban-rural wage differential (Gardner, 2002). Thus, the Morishima complementary relationships may reflect the increasing capital requirement during the period to offset labor leakage from agriculture. From 1961 on, other inputs are Morishima substitutes for capital when capital prices change.

Table 4. Own-Price Elasticities of Demand

	η_{ll}	η_{kk}	η_{dd}	η_{ee}	η_{mm}
			Static Model		
1948–2002	−0.129	0.144	−0.131	−0.250	−0.243
	(0.076)	(0.078)	(0.034)	(0.123)	(0.098)
			Fully Dynamic Model		
1948–2002	−0.230	−0.103	−0.181	−0.181	−0.391
	(0.041)	(0.036)	(0.030)	(0.107)	(0.038)
1948–1960	−0.263	0.096	−0.224	−0.119	−0.403
	(0.035)	(0.047)	(0.027)	(0.116)	(0.040)
1961–1970	−0.261	−0.040*	−0.096*	−0.109	−0.395
	(0.036)	(0.038)	(0.034)	(0.118)	(0.039)
1971–1980	−0.190*	−0.299*	−0.253*	−0.169	−0.383
	(0.047)	(0.023)	(0.026)	(0.109)	(0.037)
1981–1990	−0.125*	−0.252*	−0.150*	−0.303*	−0.391
	(0.054)	(0.026)	(0.032)	(0.090)	(0.038)
1991–2002	−0.221*	−0.320*	−0.132	−0.185*	−0.379
	(0.042)	(0.021)	(0.032)	(0.107)	(0.036)

Note: Standard errors are in parentheses.
* Indicates elasticity change from previous period is significantly different than zero at the 95% level.

Results in Table 6 indicate an increasing propensity over time to substitute other factors when energy prices increase. The MES estimates showed limited substitution among other factors for the first two subperiods, 1948–1970. The MES estimates increased during the 1970s, coinciding with the increases in energy prices during the first price shock of 1973. Changes in farming practices and other technological changes (for example, the dieselization of agriculture mentioned by Uri and Herbert (1992)) may have enabled the greater MES substitution estimates of the 1980s. Reductions in the MES estimates for the 1991–2002 period may reflect changes of the 1980s were adopted throughout agriculture, and a new level of equilibrium in farming practices and input use had been achieved.

Conclusions

Static models of agricultural production fail to account for lags that may occur between changes in the economic environment faced by farmers and their ability to make new investments or alter production practices. Dynamic models retain this flexibility of partial adjustment and can provide estimates of the overall rates of adjustment as prices and other environmental factors change. In an application to U.S. agriculture between 1948 and 2002, specification tests ruled out a static representation of production in favor of a fully dynamic model of U.S. agriculture.

The long run adjustment parameter *m* indicated that adjustments to changing input prices occur quickly, within the 1 year time period of our annual data. However, the fully dynamic

Table 5. Long Run Morishima Elasticities of Substitution, 1948–2002

Changes in the Price of:	Labor	Capital	Land	Energy	Materials
Labor	—	0.144	0.216	0.002	0.425
Capital	0.055	—	0.099	0.043	0.174
Land	0.173	0.178	—	0.105	0.254
Energy	0.145	0.164	0.159	—	0.233
Materials	0.713	0.601	0.611	0.937	—

Note: Column 1 indicates source of price change.

Table 6. Subperiod Estimates of the Long Run Morishima Elasticities of Substitution

	Labor	Capital	Land	Energy	Materials
		Change in Labor Price			
1948–1960		0.119	0.319	0.042	0.502
1961–1970		0.182	0.249	0.029	0.497
1971–1980		0.199	0.183	−0.077	0.356
1981–1990		0.066	0.033	−0.085	0.257
1991–2002		0.272	0.175	−0.013	0.410
		Change in Capital Price			
1948–1960	−0.148		−0.121	−0.207	−0.063
1961–1970	0.006		0.002	−0.053	0.096
1971–1980	0.308		0.399	0.318	0.455
1981–1990	0.193		0.291	0.277	0.374
1991–2002	0.371		0.409	0.366	0.499
		Change in Land Price			
1948–1960	0.252	0.189		0.142	0.305
1961–1970	0.091	0.060		−0.019	0.149
1971–1980	0.248	0.325		0.196	0.351
1981–1990	0.087	0.177		0.102	0.215
1991–2002	0.108	0.178		0.046	0.197
		Change in Energy Price			
1948–1960	0.092	0.081	0.099		0.169
1961–1970	0.080	0.082	0.074		0.158
1971–1980	0.122	0.172	0.155		0.220
1981–1990	0.250	0.309	0.285		0.364
1991–2002	0.146	0.193	0.157		0.237
		Change in Materials Price			
1948–1960	0.717	0.524	0.616	0.142	
1961–1970	0.724	0.576	0.577	0.945	
1971–1980	0.705	0.685	0.645	0.944	
1981–1990	0.680	0.657	0.600	0.916	
1991–2002	0.718	0.700	0.602	0.944	

model differs from both the static and the other dynamic formulations by the interdependence among factor shares adjusting to short run disequilibria. Including producer adjustments to the short run disequilibria resulted in generally greater own- and cross-price elasticities than in the static formulation, with the notable exception of the energy input share. Although failure to satisfy concavity at each observation is a concern, the fully dynamic model did reduce biases resulting from serial correlation in the static model.

Factor demands in U.S. agriculture are price inelastic. As prices of labor, capital, land, energy, or materials increase, total expenditures in the affected factors increase. Elasticities of substitution indicate all factors are Morishima substitutes, so substitution of other factors does occur in response to increases in the price of one factor. Substitution elasticities are low, however, reflecting fixity in input use due possibly to short run commitments to an output mix, predetermined factor usage due to established farming practices, and lumpy investments in farm equipment.

Although demands for energy remain inelastic, the results indicate demand elasticity for energy did increase slightly in the years following the first price shocks of the 1970s. The own-price elasticity of energy demand became slightly more elastic in the 1980s, changing from an average of −0.11 during 1948–1970 to −0.30 during the 1980s. Energy demand returned to levels similar to the levels of the 1970s in the years between 1991 and 2002.

The conclusions are surprisingly consistent with the papers presented over 30 years ago at the 1977 American Agricultural Economics Association meetings (VanArsdall, 1977). The aggregate production data does not reflect great potential to shift away from energy (or any other inputs) when prices change. Although minor adjustments may be possible, past farm investments in energy using inputs, such as tractors, combines, irrigation infrastructure, and drying equipment, preclude rapid adjustment to energy price changes. The decision to replace equipment, for example, with more fuel efficient models, even if possible, is based on a wide range of production and cost considerations other than just the potential for fuel savings. Optimal replacement decisions may require full depreciation of energy using inputs prior to their replacement by more efficient models. Numerical confirmation of this conclusion is provided in the Morishima elasticities of substitution reported in Table 6. Although capital usage relative to energy does increase in response to changing energy prices, indicating substitutability of capital for energy is possible, the elasticity is relativity small indicating the quasi-fixity of capital stock. Precommitment to cultural practices and output mix may underlie the overall low values of the MES estimates with respect to changes in energy prices. It is worthwhile to note, however, that substitutability of each of the other four factors occurs when energy prices change.

Interestingly, adding bioenergy among the set of agricultural outputs, an increasingly popular adaptation to the changing economic and political environment, may provide a mechanism to offset energy cost increases with higher prices for energy crops and, indirectly, other crop outputs. Future research may indicate that the current rise in commodity prices will fuel investment in more energy-efficient capital and farm production practices. Greater substitution elasticities reported here following the high fuel prices of the early 1980s may indicate an historical precedent for increasing future investments in energy saving farm practices.

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