HOW U.S. AGRICULTURE ADJUSTS TO ENERGY PRICE CHANGES

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Agribusiness and Applied Economics

May 2007

Fargo, North Dakota

North Dakota State University
Graduate School

Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

ABSTRACT

Gong, Jian; M.S.; Department of Agribusiness and Applied Economics; College of Agriculture, Food Systems, and Natural Resources; North Dakota State University; May 2007. How U.S. Agriculture Adjusts to Energy Price Changes. Major Professor: Dr. David Lambert.

The primary objective of this research is to measure the impacts of rising energy prices on U.S. agriculture and to analyze the capability of U.S. agricultural producers to adjust for energy price volatility.

This study compares four different models of producer adjustment: the static model, the simple error correction model, the partial adjustment model, and the fully dynamic model. The first three models are nested within the fully dynamic model using 1948-2002 U.S. agriculture data. Morishima elasticities of substitution and price elasticities are estimated to investigate whether U.S. agriculture's responses to energy prices have changed over time. The elasticity estimates indicate that there are substitutions among production factors in U.S. agricultural production, and the substitution elasticities have increased over the 1948-2002 period. This finding suggests an increasing possibility for farmers to substitute other production inputs for energy to mitigate the effects of changing energy prices.

ACKNOWLEDGMENTS

I would like to thank my adviser, David Lambert, for his guidance and motivation. I appreciate his help during my research. I would like to thank my committee members, Dr. David Lambert, Dr. Robert Hearne, Dr. Dragan Miljkovic, and Dr. Denver D. Tolliver, for their suggestions and comments. Also, I would like to thank the Upper Great Plains Transportation Institute for providing the funds for my thesis research.

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CHAPTER 1

INTRODUCTION

General Problem

Agricultural production requires energy. Agriculture uses energy to produce, process, and transport crop and livestock products. U.S. agriculture's share of energy is low relative to other production sectors, accounting for only 0.7% of total U.S. energy consumption in 2005 (Miranowski, 2005). However, highly mechanized farm production, both for crop and animal products, needs a continuous and stable energy supply throughout the production cycle. Thus, there is much concern that the recent sustained rise in energy prices may have serious impacts on U.S. agricultural production and profitability.

At the farm level, energy can be used either directly or indirectly (Table 1.1). Farmers use energy directly as fuel, natural gas, liquefied petroleum gas, and electricity to operate farm machinery and equipment for preparing fields, planting and harvesting crops, irrigating, applying fertilizers and pesticides, and transporting inputs and outputs to and from domestic or international markets. Energy is used indirectly in agriculture for producing material inputs, such as fertilizers and pesticides. All nitrogenous fertilizers used in the United States require natural gas as a production input, and most pesticides are petroleum-based.

Energy's share of annual agricultural production expenses increases with rising energy prices. In 2005, the annual average domestic crude oil price (Real) reached a record of $44.82 per barrel (EIA, 2006), which was the third highest crude oil price,

Table 1.1. Energy Uses in U.S. Agricultural Production.

Direct Use of Energy	**Primary Energy Source**
Operating farm machinery and large trucks - Field work (tractors, combines, mowers, etc.) - Input purchase and deliveries (large trucks)	Diesel Gasoline
Operating small vehicles (cars and pickup trucks) - Farm management activities	Gasoline
Operating small equipment - Irrigation equipment - Drying of grain or fruit - Ginning cotton - Curing tobacco - Others	Diesel Gasoline Natural gas Electricity
Operating farm building - Lighting for houses, sheds, and barns - Power for farm household appliances	Electricity
Marketing - Transportation (transport to terminal, processor, or port) - Elevating	Diesel Gasoline
Indirect Use of Energy	**Primary Energy Source**
Fertilizer (nitrogen-based)	Natural Gas
Pesticides (insecticides, herbicides)	Petroleum

Source: Economic Research Service (USDA/ERS, 2006b).

causing a significant share (16%) of the total U.S. farm production cost. Direct energy expenditures were $13.7 billion, comprising 6% of total production expenses. Expenditures on fertilizers and pesticides were $21.8 billion (USDA/ERS, 2006a), comprising about 10% of the total farm expenditures. Since 1949, total direct and indirect energy expenditure as a share of total farm production expenses increased from 13% in 1949 to 16% in 2005, with the direct energy share decreasing from 7% in 1949 to 6% in 2005 and the indirect energy share increasing from 6% in1949 to 10% in 2005 (USDA/ERS, 2006a; Figure 1.1).

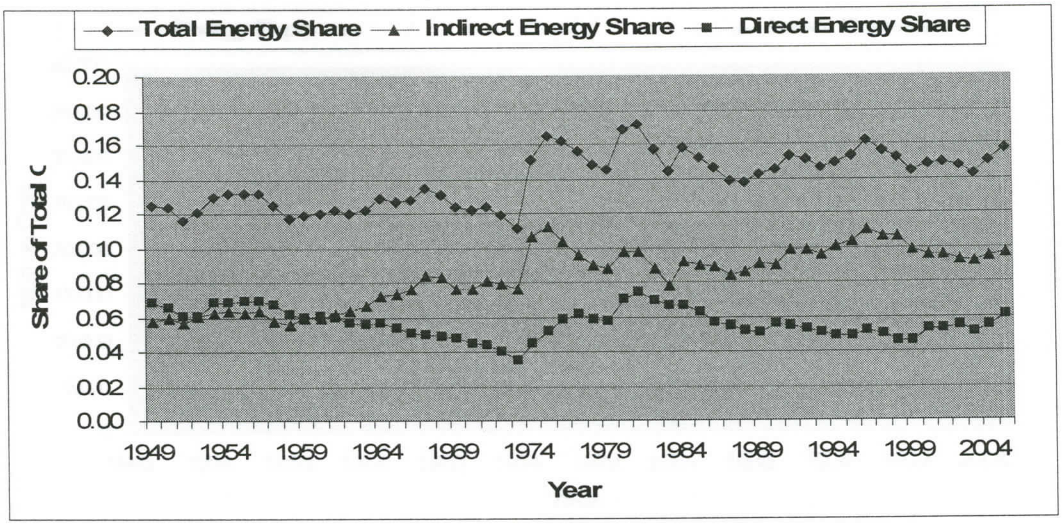

Figure 1.1. The Total, Direct, and Indirect Energy Share of U.S. Total Agriculture Expenses, 1949-2005. Source: Economic Research Service (USDA/ERS, 2006a).

U.S. agriculture's energy expenditures increased much faster than other production input expenditures (Figure 1.2). From 1949 to 2005, U.S. agriculture energy nominal expenditures (Direct and Indirect) increased about 1477% (USDA/ERS, 2006a). Over the same time period, total U.S. agriculture nominal production expenses, labor and capital costs, increased 1157%, 756% and 921% (USDA/ERS, 2006d), respectively. Figure 1.3 shows that the shares of labor and capital in total agriculture expenditures declined, but the share of energy expenditures increased from 1949 to 2005. Compared with labor expenses and capital expenses, energy expenditure's increasing share indicates that an increasing share of U.S. agricultural costs is due to changes in energy markets and prices compared to price changes of the other production inputs.

U.S. agriculture energy expenses are sensitive to the volatility of crude oil prices (Figure 1.4). The correlation between nominal crude oil price and U.S. total agricultural energy expenditures is 0.87 over the 1949-2005 period. U.S. total agriculture energy expenditures steadily increased from the 1950s to the beginning of the 1970s because of

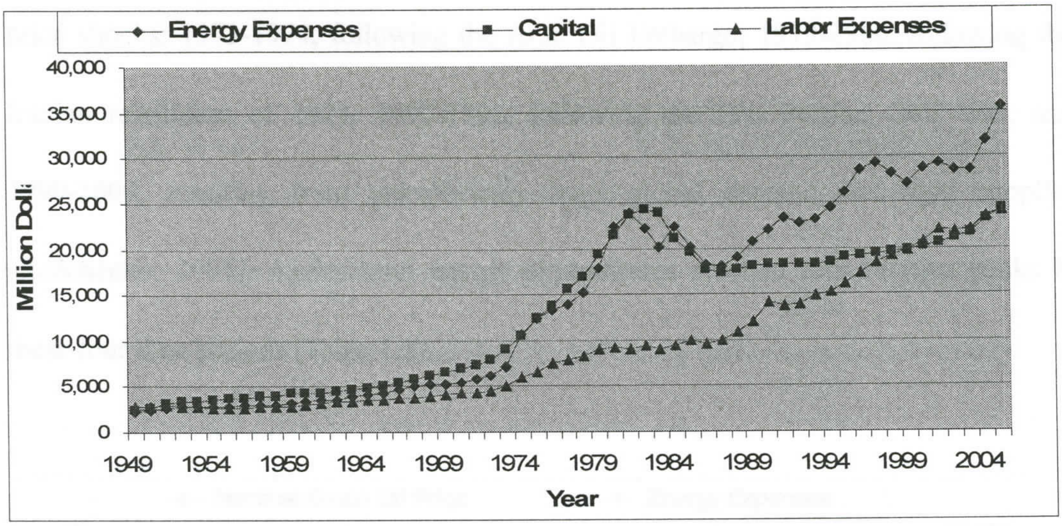

Figure 1.2. The Increasing Trend of Energy Expenses, Labor Expense, and Capital Expense, 1949-2005 (Nominal). Source: Energy Expenses are from Economic Research Service (USDA/ERS, 2006a), Labor Expenses and Capital Expenses are from Economic Research Service (USDA/ERS, 2006d).

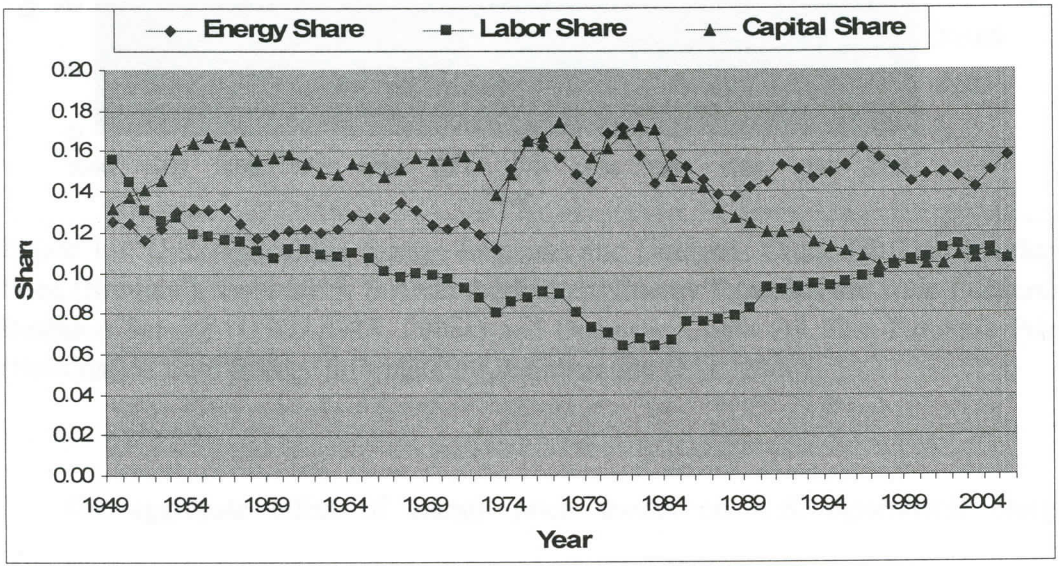

Figure 1.3. Energy Share to Labor Share and to Capital Share in Total Agriculture Expenses, 1949-2005. Source: Energy Expenses are from Economic Research Service (USDA/ERS, 2006a), and Labor Expenses and Capital Expenses are from Economic Research Service (USDA/ERS, 2006d).

relatively increasing reliance on energy-based inputs, as well as low nominal crude oil prices and stable oil supplies. Since 1972, the world has been subjected to four major oil price shocks: 1973-1974, following the Arab Oil Embargo; 1979-1980, following the Iranian revolution of 1979; 1990-1991, following the first Persian Gulf War; and 1999-2000, resulting from unexpectedly large global demand and tight supplies (Radchenko, 2005). Agricultural energy expenditures reached four relative peaks in these four time periods (Table 1.2).

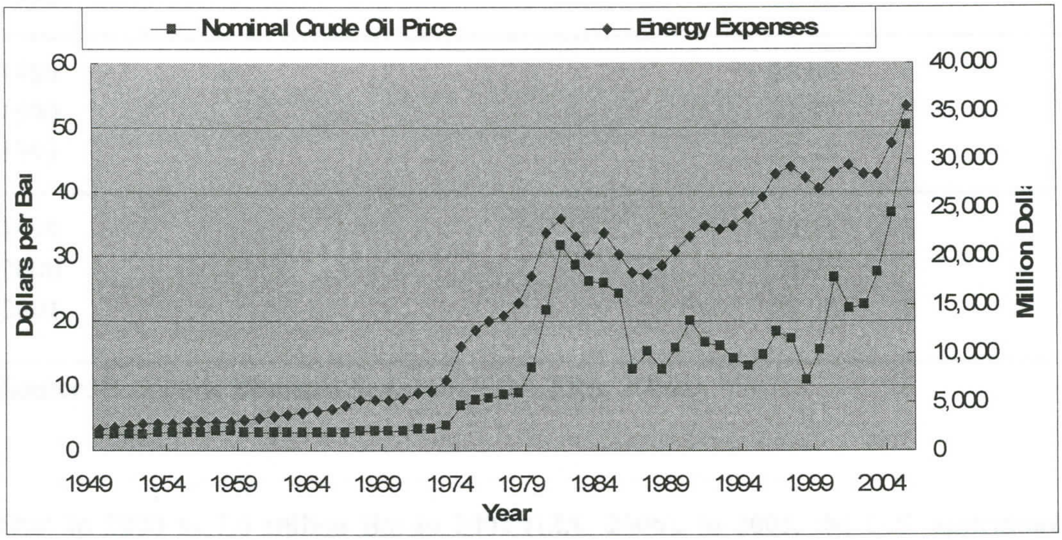

Figure 1.4. U.S. Agriculture Energy Expenses and Domestic Crude Oil First Purchase Price (Nominal), 1949-2005. Source: Agriculture Energy Expenses are from Economic Research Service (USDA/ERS, 2006a) and Domestic Crude Oil First Purchase Price (Nominal) is from Energy Information Administration (EIA, 2006).

The aggregate effect of energy price shocks on U.S. agricultural energy expenditures depends on the relationship between energy prices and demand. Since 2001, the amount of energy used in agriculture declined, while U.S. domestic crude oil prices (Table 1.3) increased. From 2001 to 2005, the U.S. domestic crude oil price has increased about 130%, from \$21.84 per barrel in 2001 to \$50.26 per barrel in 2005. The use of energy by the U.S. agricultural sector decreased about 6%, from 7.4 trillion

Table 1.2. The Impacts of Four Energy Price Shocks on U.S. Agriculture Energy Costs Since the 1970s.

Energy Price Shocks	U.S. Agriculture Energy Costs
Year	U.S. billion dollars
1972	6.15
1973	7.20
1974	10.76
1978	15.27
1979	17.89
1980	22.43
1989	20.60
1990	21.97
1991	23.23
1999	27.11
2000	28.73
2001	29.38

Source: Economic Research Service (USDA/ERS, 2006a).

Btu[1] in 2000 to 7.0 trillion Btu in 2004 (EIA, 2006). In 2005, the U.S. agricultural sector consumed a total of 7.7 trillion Btu of energy, which was the first time that consumption of energy by the U.S. agricultural sector increased when energy prices increased. Consequently, total U.S. agricultural energy expenses increased by 25% from 2004 to 2005 (USDA/ERS, 2006a). U.S. petroleum import dependency has been growing steadily over the past four decades. In 1970, U.S. petroleum imports accounted for 22% (EIA, 2006) of domestic consumption. By 2005, the import share had grown to

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[1] Btu (British thermal unit) is a measure of the heat content of a fuel and indicates the amount of energy contained in the fuel. Because energy sources vary by form (gas, liquid, or solid) and energy content, the use of Btu's allows the adding of various types of energy using a common benchmark.

about 66% (EIA, 2006). The United States depends on international sources for its energy needs so that U.S. energy prices reflect dependence renders the United States vulnerable to unexpected crude oil price moves in the international energy markets (Hamilton, 1983). Because of energy's 16% share of total farm expenditures in 2005, agriculture appears particularly vulnerable to energy price increases through both petroleum and natural gas markets (Schnepf, 2004).

Table 1.3. U.S. Agriculture Energy Consumption, Energy Expenses, and Domestic Crude Oil First Purchase Price (Nominal) from 2000 to 2005.

Year	Crude Oil Price (Nominal) (Dollars/barrel)	Energy Consumption (Trillion Btu)	Energy Expenses (Billion dollars)
2001	21.84	7.4	29.38
2002	22.51	7.2	28.45
2003	27.56	7.2	28.51
2004	36.77	7.0	31.65
2005	50.26	7.7	35.54

Source: U.S. Agriculture Energy Consumption and Energy Expenses are from Economic Research Service (USDA/ERS, 2006a) and Domestic Crude Oil First Purchase Price (Nominal) is from Energy Information Administration (EIA, 2006).

Direct demand for energy, such as diesel fuel, gasoline, and LP gas, and indirect energy use, such as that embodied in pesticides and fertilizers, is determined mainly by acres planted and harvested, weather conditions, technology, and energy prices. Rising energy prices can increase operating costs of farm machinery and equipment, and irrigation cost. Rising energy prices can also increase the production and application costs of pesticides and fertilizers. Increasing energy costs may reduce farmers' incomes because, in the short run, producers have limited ability to change production and investment decisions and cannot pass along energy price increases to consumers through agricultural product markets. However, farmers may have greater options to respond to energy price changes in the long run.

Specific Problem

The demand for energy inputs in U.S. agriculture is price inelastic in the short run because of asset fixity and long-run production commitments (Miranowski, 2005). Consequently, energy price shocks increase energy costs and may partly result in falling farm net revenues (Table 1.4). Musser (2006, page 1) said: "Energy-intensive farmers are vulnerable to energy price shocks because prices paid by farmers for petroleum products, or direct energy, mirror the national energy markets." In 2006, crude oil prices surpassed $71 per barrel in August and natural gas prices exceeded $16 per million cubic feet (EIA, 2006). Because of the inelastic demand for energy, jumps in oil and natural gas prices cannot be passed on to agricultural product markets in the short-run, further cutting into the agricultural sector's net returns. According to USDA's Economic Research Service (USDA/ERS, 2006c), net farm income experienced a decline of $13.2 billion (or 18%) to $60.6 billion in 2006 compared to 2005. $11.9 billion out of $13.2 billion was due to the increase of total production expenses. Increases in expenditures on manufactured inputs accounted for 20% of the decline of net farm income in 2006 because of higher fuel and fertilizer prices, with the latter resulting from high prices for natural gas (Schnepf, 2007).

In 2005, Miranowski estimated that a 10% increase in energy prices would result in a 6% decrease in energy use in agriculture. But in 1984, Dvoskin and Heady showed that even a 200% increase in energy price would only reduce energy use in agriculture by about 4% in a normative analysis. The difference between these two figures suggests greater substitution may now exist in agricultural production and the elasticities of substitution may have increased.

Table 1.4. The Impacts of Four Energy Price Shocks on U.S. Farm Net Cash Income.

Energy Price Shocks	U.S. Farm Net Cash Income
Year	U.S. billion dollars
1973	35.56
1974	34.38
1975	29.11
1980	33.20
1981	31.56
1990	53.83
1991	51.39
1999	57.93
2000	57.22

Source: Economic Research Service (USDA/ERS, 2006c).

The oil price shocks of the 1970s and 1980s forced the U.S. agricultural sector to become more energy flexible. Since the 1970s, the direct use of energy by agriculture has declined by 26%, while the energy used to produce fertilizers and pesticides has declined by 31% (USDA/ERS, 2006a). Switching from gasoline-powered to more fuel-efficient diesel-powered engines, adopting conservation tillage practices, changing to larger multifunction machines, creating new methods of crop drying and irrigation, increasing use of precision farming, plantings of genetically engineered crops, improving pesticide products and encouraging the production of agriculture-based renewable energy have all contributed to this decline in energy use. Farm energy consumption declined because of the changes in production practices from 9.5 trillion Btu in 1975 to 8.7 trillion Btu in 1989 (EIA, 2006; Figure 1.5).

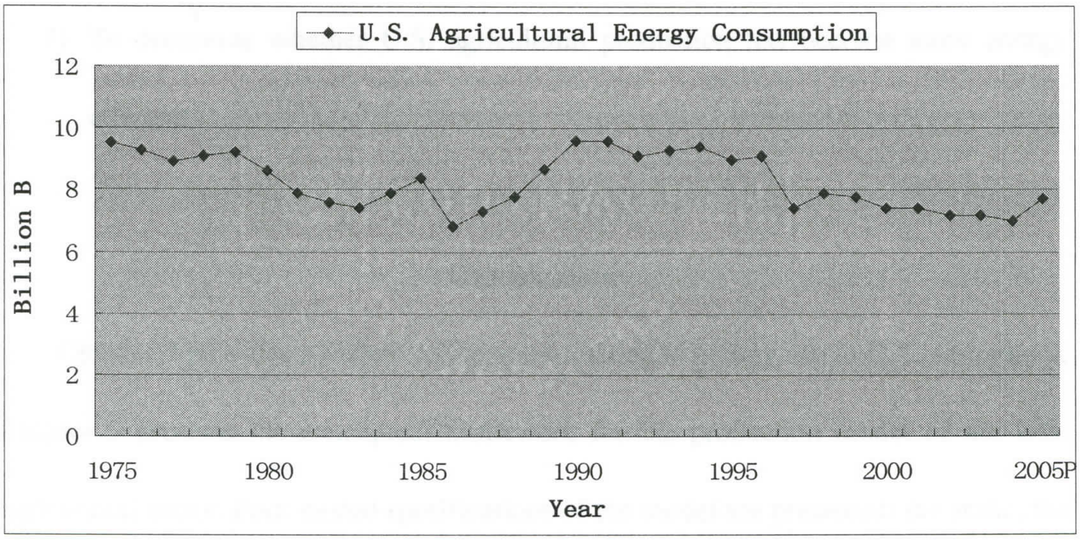

Figure 1.5. U.S. Agricultural Energy Consumption, 1975-2005. Source: Energy Information Administration (EIA, 2006).

Objectives

The overall objectives of this thesis are to measure the impacts of changing energy prices on U.S. agriculture and to analyze how U.S. agriculture adjusts to energy price changes. The following specific objectives are identified:

1) To identify the factors which significantly influence U.S. agricultural

expenditures;

2) To identify the capacity for U.S. farmers to adjust in the short and long run to changing input prices;
3) To estimate the substitution and price elasticities among the production inputs in U.S. agriculture and evaluate the elasticity changes among production inputs over time;
4) To determine whether structural changes have affected factor demands over time.
5) To determine whether U.S. agricultural production has become more energy efficient.

Organization

Chapter 2 provides a review of literature relating to energy use in U.S. agriculture. Chapter 3 presents the conceptual framework for the production model of the U.S. agricultural sector. Four nested specifications of the model are presented: the static, the simple error correction, the partial adjustment and the fully dynamic model. Chapter 4 presents results of the model estimation. Conclusions, implications, and limitations of this thesis will be offered in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

Numerous authors have investigated the relationships between energy price and different sectors of the U.S. economy. Results have varied by industry and by approach. This chapter offers a review and discussion of this research.

The Impacts of Rising Energy Prices on Agriculture

Early studies often concentrated on individual farms, ignoring the effects of rising energy prices on the agricultural industry. Doering (1977) demonstrated that rising energy prices increased fertilizer and irrigation costs as direct effects, and transportation costs as indirect effects. He concluded that energy prices could have only a "minor" role in affecting the structure of agricultural production. He predicted sect oral adjustments to cope with rising energy prices including the development of new technologies that would have the ultimate effect of reducing petroleum and natural gas requirements, increased management and information requirements, and adjustments in food production because of the effects of rising energy prices on the input, processing, marketing, and food preparation sectors.

Aggregate impacts of increasing energy prices on the agricultural sector were also addressed following the first energy price shock of 1973. Connor (1977, pg. 675) wrote "...energy use in agriculture has become a topic of increasing concern to agriculturalists and various policy makers." He stated that aggregate adjustments to changing energy prices and supplies were more likely to be price-related than supply-related because the reducing energy inputs would affect the amount of food produced and hence food prices. Micro-adjustments would be used by individual farmers in response to rising energy prices, including energy conservation, reducing energy usage and waste, changing agriculture production structures, and seeking more economical energy substitutes, etc.

Dvoskin and Heady (1978) estimated that doubling energy prices would cause only a 4% reduction in total energy use, 24% decline in electricity use, 5% decrease in the use of natural gas, and 7% decrease in fertilizers use in agricultural production by using a normative analysis of U.S. agriculture extending 10 years into the future based on 1985, which could provide a time span long enough to allow farmers to respond to the changing energy situation. This cost minimization procedure was subject to a set of primary restraints corresponding to land, energy supplies by regions and production requirements by locations, etc. They demonstrated that the measurement of the impacts of an energy crisis were not limited to on-farm production, but also would impact food processing and transportation. Heady (1984) found that energy demand in agriculture is highly inelastic in field operations and for biological technologies such as fertilizer and pesticides use. He assumed that the without an equal relative increase in commodity prices, increases in energy prices should also increase the price of inputs embodying energy.

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 agricultural production techniques were energy-intensive, but energy intensity and the response to crude oil price shocks vary depending on product mix. Higher energy prices lead to a fall in output. There is some increase in output price, but not enough to offset the increase in cost. Their simulation results showed that agricultural livestock and crop production decreased when the oil price increased. When oil prices were assumed to be \$30, \$40 and \$50, crops production declined by 4%, 6% and 8%, and livestock production decreased by 10%, 20% and 30%.

Miranowski (2005) indicated that agricultural energy demand varied widely by region and by different types of crop and livestock farms. He demonstrated that higher energy prices will not only mean adjustments in production, but also higher production costs and decreased returns, at least in the short run. His results were consistent with earlier findings of inelastic demand for energy. He used an econometric model to estimate that the own price elasticity for energy was –0.60 based on 1991-2002 U.S. agricultural data, indicating inelastic demand yet also suggesting greater responsiveness to energy price changes than those reported earlier by Dvoskin and Heady (1978).

Substitution Among Energy Types and Among Production Inputs

Input use will vary as relative prices and production technologies change. Input-output relationships in agriculture also vary depending on soil types, technology, weather, and other factors affecting the complex biological, chemical, and physical relationships underlying agricultural production. Input substitution means that the decreased (increased) use of one input may be compensated for by increased (decreased) use of another input.

Griffin and Gregory (1976) reported Allen-Uzawa elasticities of substitution for capital to energy in the manufacturing sectors of Belgium, Denmark, France, West Germany, Italy, the Netherlands, Norway, the United Kingdom, and the United States. The Allen-Uzawa elasticity of substitution between factors measures the percentage change in the ratio of inputs resulting from 1% change in the ratio of their prices. In these seven countries, capital was a substitute for energy, and the Allen elasticities of capital for energy averaged over one, meaning that a 1% increase of the relative energy price would result in more than 1% increase in capital use relative to energy. The substitution relationship between energy and capital in the manufacturing sector of these nine countries was elastic.

Denny, May and Pinto (1978) used a non-homothetic,[2] generalized Leontief cost function to generate demand equations for labor, capital, energy, and materials to derive the elasticities of substitution in the U.S. and Canadian manufacturing sectors in 1965. In the U.S. manufacturing sector, the elasticities of substitution for energy to labor, to capital, and to material were 0.64, -3.22, and 0.74, respectively. Based on these results, energy and labor, and energy and materials were substitutes, but energy and capital were complements. The corresponding values for the Canadian manufacturing sector were 4.89, -11.91, and 0.12. Energy and labor, and energy and materials were

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[2] Homogeneous functions (whatever the degree) are special cases of a more general class of functions known as homothetic functions (Shephard, 1953). A function (F) is homothetic if it is itself a monotonic transformation of a homogeneous function.

substitutes, but energy and capital were complements. In general, this pattern of substitution possibilities in Canada is similar to that found in the United States, although the levels are very different.

Hamilton (1983) found that seemingly small disruptions in the supplies of primary commodities such as energy could be the source of fluctuations in aggregate employment and can exert surprisingly large effects on real output. In a later paper, Hamilton (1988) showed that the role of specialization in employment and the business cycle can be rigorously grounded in a fully specified general equilibrium model with rationally formed expectations.

Uri (1996) investigated the effect of changes in the price of crude oil on agricultural employment in the U.S. between 1947 and 1995. He used Granger causality to establish an empirical relationship between agricultural employment and crude oil price changes. He studied the structural stability of the functional relationship between agricultural employment and the price of crude oil, percentage changes in expected net farm income, realized technological innovation, and the wage rate. He found that at least 3-year period was required before the measurable impacts of a percentage change in the real price of crude oil on agricultural employment are exhausted. He also suggested that the increase in the real price of crude oil on average has accounted for an annual decrease in agricultural employment (i.e. on-farm workers) of approximately 0.21% over the 1947-1995 periods.

Shankar, Piesse and Thirtle (2003) used panel data methods, Generalized Method of Moments (GMM), and instrumented exogeneity tests to analyze the relationship between relative input prices on capital formation and chemical use in the Hungarian agricultural sector. They reported that Morishima elasicities of substitution of energy to labor, capital and material were 3.01, 0.56 and –1.35, respectively. Thus, energy was a substitute for labor and capital. The Morishima elasticity of substitution measures the changes in the ratio of two factors in response to a 1% change in the price of one input.

Henry Thompson (2004, pg.150) said, "The economic outcome of decisions regarding energy policy often hinges on substitution between energy and other factors of production." In the 1950s and 1960s, relatively low and stable crude oil prices and increasingly mechanized on-farm production practices resulted in the substitution of energy and capital for labor. Agriculture appeared to follow Berndt and Wood's findings (1975) that energy was a substitute for labor but a complement with capital for the U.S. manufacturing sector over the period 1947-1971.

Miranowski (2005) reported that own price elasticity for energy was –0.60, and substitution elasticities of energy to land, labor and capital were 0.35, 0.59 and 1.13, respectively, in U.S. agriculture. Land, labor and capital could substitute for energy when energy prices rise relative to other input prices.

Lambert (2005) applied a cost function and an error correction model to analyze the short and long run responsiveness of U.S. agriculture to energy price changes by using 1948-2002 U.S. agriculture data. He found that demand was inelastic for all inputs and the Morishima elasticities of substitution of energy and labor and energy and materials were 0.19 and 0.41. Consistent with many of the earlier studies, energy and labor and energy and materials were substitutes in agricultural production. He found that the demand for energy became more elastic between 1983 and 1992 with own-price elasticity of demand changing from –0.08 to –0.32 between the two years.

In addition to substituting among inputs, limited substitution may occur among different energy types. With increasing fuel costs, farmers sought to improve energy flexibility and find cheaper forms of energy or increasing use of non-energy inputs in production. Uri (1982) analyzed the U.S. transportation sector for substitution possibilities and found that substitution among energy types was limited to motor gasoline and diesel fuel. The same kind of substitution was also available in the U.S. agricultural sector. Uri (1992) estimated the demand for diesel fuel and coined the word "dieselization" to describe the substitution of diesel for gasoline by farmers in the United States. In his 1988 paper, he found that the substitution of diesel fuel for gasoline was significant in agriculture. He indicated that, although substitution among energy types did occur, the extent of this substitution was relatively small.

Translog Cost Function Model

The translog cost function is one of the most commonly used flexible functional forms. Guilkey and Lovell (1980) demonstrated that a flexible functional form may be used as a global representation of technologies and consumer preferences in applied general equilibrium analysis and the translog could be used to test hypotheses on functional separability, substitution possibilities and demand elasticities. Viton (1981), Pindyck and Rotemberg (1983), and Ray (1982) have used translog forms to analyze production relationships. We use this functional form to reveal the relationships among the production inputs in U.S. agriculture.

Anderson and Blundell (1982) believed that dynamic specifications should be considered when modeling factor demand equations given the constraints of partial adjustments in the short run. However, dynamically misspecified models would result in serially correlated residuals, which happened in many earlier empirical demand studies. Anderson and Blundell further developed parameter restrictions associated with the singular system of equation arising from the translog specification, with special reference to dynamic relationships. Starting with the static equilibrium model, they developed and tested a first difference model, a basic time series model, an error correction model and a partial adjustment model.

Following Anderson and Blundell's work, Urga (1996), Allen and Urga (1999), and Urga and Walters (2003) estimated a cost function, jointly with a set of consistent share equations to solve the parameter identification problem proposed by Anderson and Blundell's. Urga and his co-authors linked the dynamic derived demand equations with a dynamic cost function by deriving representation of the cost function. Urga demonstrated how his approach allows specification testing of alternative adjustment processes. He and his co-authors used this framework to analyze the inter-fuel substitution in U.S. industrial energy demand and in the non-energy business sector of the UK economy.

Elasticity estimates may vary over time as farmers adapt to changing relative input prices. In the short run, input substitution possibilities may be constrained. In the long run, farmers may be more responsive to changing energy prices. Thus, short-run demands are expected to be more inelastic than the long-run estimates since a longer time frame allows new technologies to arise and substation possibilities to increase (the Le Chatelier principle). The difference between the short-run and long-run elasticities and elasticity changes in different time period will be compared to evaluate U.S. agricultural adjustment changing energy prices over time.

CHAPTER 3

CONCEPTUAL MODEL

Dual and primal approaches have been applied to model agricultural production relationships. Direct estimation of the production function is more effective in the case of endogenous output levels. The dual cost function summarizes all of the economically relevant information about the process of transforming inputs to output (Gronberg and Jansen, 2005). The U.S. agricultural sector competes with other sectors, such as industry and transportation, for factors of production and this leads to exogenous determination of factor prices. The cost function represents the minimum cost of producing a given quantity of output subject to available technology and given input prices. If relative factor prices change, the cost-minimizing choice of inputs would likely change. In this paper, we study the impacts of rising energy prices on U.S. agriculture. Therefore, the dual cost function approach is preferred over the production function in order to detect responses to changing factor prices.

Factor demands can be obtained from the cost function by using Shephard's Lemma. Input demands are functions of factor prices and output level. We assert that farmers produce output (y) by hiring the optimal inputs of labor, capital, land, energy and material in perfectly competitive markets to minimize the cost of production. We specify the cost function as:

$$C\,(w, y) = \min_x\,[w\,x \mid y \leq f(x)] \tag{1}$$

Where w represents exogenous input prices, x is a vector of variable input levels, and y is output. Output is an aggregation of crop and livestock product and agricultural services.

The cost function and its analysis are due largely to the famous work of Paul Samuelson (1947) and Ronald Shephard (1953). Its general properties are the following:

1) Non-negativity: $C\ (w, y) > 0$ for $w > 0$ and $y > 0$
2) Monotonicity in y: if $y' \geq y$, then $C\ (w, y') \geq C\ (w, y)$
3) Monotonicity in w: if $w' \geq w$, then $C\ (w', y) \geq C\ (w, y)$
4) Homogeneity of degree one in prices: $C\ (\lambda w, y) = \lambda C(w, y)$
5) Concavity: $C\ (w, y)$ is concave in w.

We use the translog cost function form in our empirical analysis. According to Thirtle (2003, pg.186), "the translog is an obvious choice since it does not constrain the elasticities of substitution to be constant and it is interpretable as a second order approximation." The translog cost function models the influence of input prices on total cost and input demands. Estimation usually occurs over the total cost function and derived factor-demand functions. We construct a general form of the long-run translog cost function for output levels and five inputs as

$$\ln C^*_t = \alpha_0 + \sum_{i=1}^{N} \alpha_i \ln P_{it} + \alpha_y \ln y_t + \alpha_t t + 1/2 \sum_{i=j}^{N} \alpha_{ij} \ln P_{it} \ln P_{jt}$$

$$+ 1/2 \sum_{i \neq j}^{N} \alpha_{ij} \ln P_{it} \ln P_{jt} + \sum_{i=1}^{N} \alpha_{iy} \ln P_{it} \ln y_t$$

$$+ \sum_{i=1}^{N} \alpha_{it} t \ln P_{it} + 1/2 \alpha_{yy} \ln y_t \ln y_t$$

$$+ \alpha_{yt} t \ln y_t + 1/2 \alpha_{tt} t^2 + \varepsilon_t \tag{2}$$

where C^*_t is the optimal total cost at time t, y is output, P_{it} represents the ith input price (labor, capital, land, energy and other materials) at time t, and α 's are coefficients to be estimated.

The cost function is assumed to be homogeneous of degree 1 in input prices, meaning a one percent increase in the price of all inputs results in a one-percent increase in total cost. Factors shares must sum to one and requires symmetry in the cross-price terms. These conditions require imposing the following parameter restrictions:

$$\sum_{i=1}^{N} \alpha_i = 1$$

$$\sum_{i=1}^{N} \alpha_{ij} = \sum_{j=1}^{N} \alpha_{ij} = \sum_{i=1}^{N} \alpha_{iy} = \sum_{i=1}^{N} \alpha_{it} = 0$$

$$\alpha_{ij} = \alpha_{ji} \tag{3}$$

Using Shepherd's Lemma, differentiating the translog cost function with respect to the logarithms of input prices yields the share equations:

$$\frac{\partial \ln C_t^*}{\partial \ln P_{it}} = \frac{P_{it} X_{it}}{C_t} = S_{it}^* = \alpha_i + \sum_{i=1}^{N} \alpha_{ij} \ln P_{jt} + \alpha_{iy} \ln y_t + \alpha_{it} t + \varepsilon_{it} \qquad i = L, K, D, E, M \qquad (4)$$

The Allen-Uzawa partial elasticity of substitution (σ) (Allen, 1938) and the price elasticity of demand (η) estimate the sensitivity of input demands to changing input prices. The long-run (superscript l) Allen-Uzawa partial elasticity of substitution can be calculated as:

$$\sigma^l_{ii} = \frac{\alpha_{ii} + S_i^2 - S_i}{S_i^2} \quad \text{and} \quad \sigma^l_{ij} = \frac{\alpha_{ij} + S_i S_j}{S_i S_j} \qquad \text{for } i \neq j \qquad (5)$$

From equation (4), the price elasticities can be estimated by:

$$\eta^l_{ii} == S_i \sigma^l_{ii} \quad \text{and} \quad \eta^l_{ij} = S_j \sigma^l_{ij} \qquad (6)$$

The translog cost function does not constrain the production structure to be homothetic, nor does it impose any restrictions on the elasticities of substitution. However, these restrictions can be tested statistically. A cost function corresponds to a homothetic production function if the cost function can be expressed as a separable function in output and the input factor prices. A homothetic cost function is further restricted to be linearly homogeneous with respect to output if the elasticity of cost with respect to output is constant. The required restriction for the translog cost function to be homothetic is $\alpha_{iy} = 0$ (Kant and Nautiyal, 1997). The requirements for output homogeneity of the translog cost function are $\alpha_{yy} = 0$ and $\alpha_{iy} = 0$. Symmetry of the

Allen-Uzawa elasticities of substitution ($\sigma_{ij} = \sigma_{ji}$) is guaranteed by the symmetry of the estimated parameters (Urga, 2003).

Specification of Dynamic Model

Let the optimal level of the share of a factor at time t be S_{it}^{*}. Then a dynamic first-order autoregressive distributed lag (ADL(1,1)) process for the short-run (actual) shares S_{it} can be specified as follows (Urga, 2003):

$$S_t = D_1 S_t^{*} + D_2 S_{t-1} + D_3 S_{t-1}^{*} \tag{7}$$

where D_1, D_2 and D_3 represent the N × N adjustment matrices.

We can rewrite equation (7) as a general error correction model (Anderson and Blundell, 1982):

$$\Delta S_t = G \Delta S_t^{*} + K(S_{t-1}^{*} - S_{t-1}) \tag{8}$$

where Δ means the first difference, $\Delta S_{it} = S_{it} - S_{i,t-1}$ and $\Delta S_{it}^{*} = S_{it}^{*} - S_{i,t-1}^{*}$. In the translog model, the summing-up constraint on the dependent variables leads to a singularity problem. Anderson and Blundell (1982) solve the singularity problem in the dynamic formulation by deriving the following conditions:

$$i'G = mi' \qquad and \qquad i'K = hi' \tag{9}$$

where i is a N × 1 unit vector and m and h are scalars. In fact, singularity of the equation system implies that the contemporaneous disturbance covariance matrix is also singular in the share context (Berndt and Savin, 1975). Barten (1969) showed that when constrained disturbances are serially independent, maximum likelihood estimation of the parameters in the singular system can be obtained by dropping one equation:

$$\Delta S_t^n = G^n \Delta S_t^{*n} + K^n (S_{t-1}^{*n} - S_{t-1}^n) \tag{10}$$

where ΔS_t^n, ΔS_t^{*n}, S_{t-1}^{*n} and S_{t-1}^n are the vectors ΔS_t, ΔS_t^*, S_{t-1}^* and S_{t-1} with the nth row deleted. G^n and K^n are now (N - 1) × (N - 1) matrices.

Singularity of the contemporaneous disturbance covariance matrix raises issues concerning the identification of the parameters of the autoregressive process (Berndt and Savin, 1975). Without imposing adding-up restrictions, the specification of the model is conditional on the equation deleted. As a result, the maximum likelihood estimates of the parameters and the likelihood ratio tests are no longer invariant to the equation deleted. The elements of G^n and K^n, which play the role of the reduced form (short-run) coefficients, are not identified without imposing further restrictions. Here we impose some restrictions on the adjustment parameters, which allow us to identify short-run responses, by specifying a general cost function which contains both equilibrium and disequilibrium terms. Following Stagni (1994) and Allen and Urga (1999), we specify the following dynamic cost function:

$$\ln C_t = m \ln C_t^* + (1\text{-}m) \ln C_{t-1}^* + (1\text{-}m)\left(\sum_i^N S_{i,t-1} \ln P_{it} - \sum_i^N S_{i,t-1}^* \ln P_{i,t-1}\right)$$

$$+\sum_{i}^{N}\sum_{j}^{N} b_{ij}\,(S^{*}_{j,t-1} - S_{j,t-1})\ln P_{it} + \varepsilon_t \tag{11}$$

where b_{ij} are the elements of the D_2 matrix of Equation (7), C represents the equilibrium cost and C* is the effective cost. In this cost function, the identification problem is confined to the parameters b_{ij}, which are the elements of K in equation (8).

The vector of dynamic factor shares consistent with equation (11) is:

$$S_t = m\,S^{*}_t + (1-m)\,S_{t-1} + B(S^{*}_{t-1} - S_{t-1}) + \varepsilon_t \tag{12}$$

Urga (1996) rewrites the share equations more compactly as:

$$\Delta S_t = m\Delta S^{*}_t + K(S^{*}_{t-1} - S_{t-1}) \tag{13}$$

where K = mI+B. Equation (14) represents a partially generalized error correction mechanism. A single estimating equation is:

$$\Delta S_{it} = m\Delta S^{*}_{it} + \sum_{j=1}^{N} K^{n}_{ij}\ (S^{*}_{j,t-1} - S_{j,t-1}) \tag{14}$$

Following Urga and Walters (2003), we simultaneously estimate the cost function (11) and the set of factor demand equations (13) to solve the singularity problem. Symmetry and linear homogeneity restrictions are imposed.

The fully dynamic model, equation (11), nests other adjustment models. If B is a diagonal matrix, equations (11) and (13) are a simple (non-interrelated) error correction model (as in Allen, 1994), which means K in equation (13) is also diagonal. The restrictions in equation (9), B = K-mI (and K = hI), indicate that the adjustment coefficients are equal for all inputs. If parameters m and h are equal, the autoregressive coefficients in each equation must be identical. Then equations (9) and (12) turn out to be a partial adjustment mechanism. This simple (non-interrelated) error correction model can be written as following:

$$\ln C_t = m\ln C_t^* + (1\text{-}m)\ln C_{t-1}^* + (1\text{-}m)\left(\sum_i^N S_{i,t-1}\ln P_{it} - \sum_i^N S_{i,t-1}^* \ln p_{i,t-1}\right)$$

$$+ (h\text{-}m)\,(S_{j,t-1}^* - S_{j,t-1})\ln P_{it} + \varepsilon_t \qquad (15)$$

The share equations for this error correction model are:

$$\Delta S_{it} = m S_{it}^* + h\,(S_{j,t-1}^* - S_{j,t-1}) \qquad (16)$$

The partial adjustment model is:

$$\ln C_t = m\ln C_t^* + (1\text{-}m)\ln C_{t-1}^* + (1\text{-}m)\left(\sum_i^N S_{i,t-1} * \ln P_{it} - \sum_i^N S_{i,t-1}^* \ln p_{i,t-1}\right) + \varepsilon_t \qquad (17)$$

The share equation for this partial adjustment model is:

$$\Delta S_{it} = m S_{it}^* + m(S_{j,t-1}^* - S_{j,t-1}) \qquad (18)$$

Equation (17) allows calculation of the short-run (superscript s) price elasticities as:

$$\eta^s_{ii} = \frac{m\alpha_{ii}}{S_i} + S_i - 1 \quad \text{and} \quad \eta^s_{ij} = \frac{m\alpha_{ij}}{S_i} + S_j \qquad (19)$$

where $m*\alpha_{ij} = \dfrac{\partial S_i}{\partial \ln P_j}$ and $S_j = \dfrac{\partial \ln C_t}{\partial \ln P_j}$.

There are two uncertainties left to be tested empirically: concavity and whether short-run demands are more inelastic than the long-run estimates (Le Chatelier principle). A necessary condition for the latter to be satisfied is that the short-run own-price elasticities are smaller than the long-run own-price elasticities, or $\alpha_{ii}(m\text{-}1)>0$ when we use equation (19).

CHAPTER 4

ESTIMATION RESULTS

Data Description

Price and quantity indexes of output and inputs used in U.S. agricultural production covering the period from 1948 to 2002 were provided by V. Elden Ball of the Economic Research Service. Data descriptions are provided in Ball et al. (1997). We used a single measure of output, and inputs were disaggregated into labor, capital, land, energy, and materials.

Ball et al. (1997) used the Fisher index[3] to calculate the price and quantity indexes of output and inputs. Output included the quantities of commodities sold and consumed by farmers plus inventory changes during the calendar year. The prices and quantities of labor were adjusted by gender, age, education, and employment classes. Capital included equipment and structures, and inventories. The quantities and average value per acre of land were based on National Agricultural Statistics Service data for each state (USDA/NASS, 2007). The energy input included petroleum fuels, natural gas, and electricity. Materials included feed, seed and livestock, purchased agricultural chemicals, and other purchased inputs.

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[3] The Fisher index is a geometric mean of the Laspeyres and Paasche indexes (i.e., the quantity index Q_F equals $(Q_L Q_P)^{½}$). The Laspeyres quantity index is calculated as $Q_L(p^0, p^1, x^0, x^1) = p^0 x^1 / p^0 x^0$. The Paasche quantity index is calculated as $Q_P(p^0, p^1, x^0, x^1) = p^1 x^1 / p^1 x^0$. p is a vector of prices, and x is the corresponding vector of quantities.

Estimation Procedure

After dropping one share equation, the estimating system consists of the translog cost function and four input share equations. Estimation is conducted using nonlinear seemingly unrelated regression. Seemingly unrelated regression is a technique for analyzing a system of multiple equations with cross-equation parameter restrictions and correlated error terms. Joint estimation allows imposing cross-equation restrictions. The method of Fully Information Maximum Likelihood is used to re-compute the covariance matrix from the parameters at each iteration. Maximum likelihood estimation is a popular statistical method used to make inferences about parameters of the underlying probability distribution from a given data set. Maximum likelihood reflects parameters from a given distribution that are "most likely", given the data. The possibility of lost information from single equation estimation may be avoided because the equation errors will be correlated. Eviews is used to estimate the coefficients of the models.

The hypotheses of homogeneity, symmetry of the α_{ij} parameters, and adding-up restrictions can be tested by the likelihood ratio test. The likelihood ratio is equal to double the difference between the logarithmic values of likelihood functions of the unrestricted and the restricted models. This ratio has a χ^2 (Chi-square) value with degree of freedom equal to the number of independent restrictions imposed.

Results of Regression Analysis

Four models were estimated: the static model (the general long-run translog cost function), the partial adjustment model, the error correction model (ECM), and the fully dynamic model. The first three models were nested within equation (11). Table 4.1 contains the parameter estimates for all 4 models.

Table 4.2 contains the test results for all four models. Log likelihood ratio results show that the fully dynamic model is better specified than the other three models at the 99% level. The normality test refers to the Jarque-Bera test[4] for the residual of the four models. For the fully dynamic model, four out of five the equation residual estimates are normally distributed. These normality test results also indicate the goodness-of-fit of the fully dynamic model is better than the other models.

The AR (n) test (Chi-square) refers to the Box-Pierce Portmanteau test[5] for n^th^ order serial correlation of residuals. The Lagrangian Multiplier (LM) test is another way to test the serial autocorrelation of residuals. Both tests fail to reject the hypothesis that there is no serial correlation in the residuals in the fully dynamic model.

Based on the test results above, the fully dynamic model appears to be a better specification than the other three models.

For the fully dynamic model, input demand functions need to be positive to satisfy the monotonicity condition as well as the law of demand. The positivity of the input demand functions is checked and found to be true for all annual observations. Twenty-eight of forty-nine estimated parameters are significant at a 5% confidence level (Table 4.1). In all five cases, the share of expenditures on labor, capital, land, energy, and material are positively and significantly related to changes in their

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[4] Jarque-Bera test is a goodness-of-fit measure of departure from normality, based on the sample kurtosis and skewness in statistics.

[5] Box-Pierce Portmanteau test is a test for auto-correlated errors. The Box-Pierce statistic is computed as the weighted sum of squares of a sequence of autocorrelations. If the errors of the model are white noise, then the Box-Pierce statistic is distributed approximately as a chi-square distribution with h – v degrees of freedom, where h is the number of lags used in the statistic and v is the number of fitted parameters other than a constant term.

Table 4.1. Parameter Estimates for Four Models and Their Share Equations (Standard deviation (S.D.) in parentheses).

Parameters	Static Model	Partial Adjustment model	ECM	Fully Dynamic Model
h scalar			0.428 (0.053)*	
m scalar		0.880 (0.031)*	1.060 (0.046)*	1.007 (0.039)*
α_0 overall intercept	928.865 (283.342)	925.437 (306.891)*	408.581 (272.871)	220.464(260.872)
α_l labor intercept	1.118 (1.131)*	1.034 (1.150)	-0.685 (0.779)	-1.360 (0.393)*
α_k capital intercept	-0.970 (0.845)*	-0.838 (0.843)	-0.587 (0.605)	-0.075 (0.250)
α_d land intercept	2.232 (0.695)*	0.832 (0.784)	0.665 (0.476)	1.077 (0.544)*
α_e energy intercept	-0.397 (0.261)	-0.448 (0.233)	-0.346 (0.208)	-0.480 (0.195)*
α_y output intercept	-159.355 (49.470)*	-159.081 (53.565)*	-68.872 (47.640)	-35.935 (45.499)
α_t overall time trend	2.827 (0.926)*	2.789 (1.003)*	1.222 (0.894)	0.630 (0.838)
α_{ll} labor-labor	0.157 (0.020)*	0.154 (0.021)*	0.108 (0.021)*	0.132 (0.011)*
α_{lk} labor-capital	-0.071 (0.013)*	-0.072 (0.013)*	-0.053 (0.012)*	-0.049 (0.006)*
α_{ld} labor-land	-0.038 (0.007)*	-0.041 (0.007)*	-0.033 (0.006)*	-0.038 (0.003)*
α_{le} labor-energy	-0.014 (0.005)*	-0.015 (0.004)*	-0.017 (0.006)*	-0.020 (0.005)*
α_{kk} capital-capital	0.142 (0.011)*	0.149 (0.012)*	0.115 (0.012)*	0.107 (0.005)*
α_{kd} capital-land	-0.013 (0.005)*	-0.014 (0.005)*	-0.018 (0.004)*	-0.020 (0.002)*
α_{ke} capital-energy	-0.003 (0.004)	0.008 (0.004)*	-0.005 (0.004)	0.008 (0.003)*
α_{dd} land-land	0.102 (0.005)*	0.098 (0.005)*	0.089 (0.004)*	0.095 (0.004)*
α_{de} land-energy	0.005 (0.002)*	-0.006 (0.001)*	-0.006 (0.002)*	-0.009 (0.001)*
α_{ee} energy-energy	0.029 (0.005)*	0.031 (0.005)*	0.028 (0.005)*	0.032 (0.004)*
α_{lt} land-time	-0.003 (0.002)	-0.003 (0.002)	-0.005 (0.001)*	-0.007 (0.002)*
α_{kt} capital-time	-0.001 (0.001)	-0.001 (0.001)	-0.0002 (0.00)	-0.001 (0.001)
α_{dt} land-time	0.002 (0.001)*	0.0004 (0.00)	0.0002 (0.00)	-0.0002 (0.00)
α_{et} energy-time	-0.0003 (0.00)	-0.0002 (0.00)	-0.0001 (0.00)	0.0003 (0.00)
α_{yy} squared output	13.871 (4.319)*	13.874 (4.675)*	6.001 (4.159)	3.123 (3.968)
α_{yt} output-time	-0.247 (0.081)*	-0.244 (0.088)*	-0.107 (0.078)	-0.056 (0.073)

Table 4.1. (continued)

Parameters	Static Model	Partial Adjustment model	ECM	Fully Dynamic Model
α_{tt} overall squared time	0.004 (0.002)*	0.004 (0.002)*	0.002 (0.001)	0.001 (0.001)
b_{ll} labor-labor				-0.847 (0.083)*
b_{lk} labor-capital				0.937 (0.317)*
b_{ld} labor-land				-2.392 (1.190)*
b_{le} labor-energe				2.995 (2.045)
b_{kl} capital-labor				0.967 (0.566)
b_{kk} capital-capital				-0.961 (0.040)*
b_{kd} capital-land				-3.129 (1.101)*
b_{ke} capital-energy				7.094(2.228)*
b_{dl} land-labor				-0.375 (0.153)*
b_{dk} land-capital				-0.519 (0.213)*
b_{dd} land-land				-0.010 (0.107)
b_{de} land-energy				0.794 (0.514)
b_{el} energy-labor				-1.068 (0.829)
b_{ek} energy-capital				0.623 (1.019)
b_{ed} energy-land				1.650 (1.266)
b_{ee} energy-energy				-1.009 (0.040)*
b_{ml} material-labor				2.525 (1.430)
b_{mk} material-capital				1.880 (1.843)
b_{md} material-land				6.676 (3.092)*
b_{me} material-energy				-17.309 (5.876)*

* Significant at 5% level.

Table 4.2. Test Results for Four Models.

	Static Model	Partial Adjustment model	ECM	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	0.998,0.74,-0.52,0.92,0.58	0.998,0.39,0.85,0.90,0.71	0.999,0.85,0.95,0.92,0.71
Log likelihood	876.697	859.542	934.676	986.402
Likelihood Ratio (χ^2)	219.40(76.15)	253.72(76.15)	103.44(76.15)	-
$AR(1)_{cost}$, $AR(2)_{cost}$ χ^2(p)	0.275(0.041), 0.356(0.009)	0.248(0.069), 0.328(0.018)	0.161(0.254), 0.099(0.455)	-0.083(0.554),-0.205(0.154)
$AR(1)_l$, $AR(2)_l$ χ^2(p)	0.512(0.003), 0.346(0.009)	0.515(0.000), 0.319(0.021)	0.277(0.046), 0.325(0.016)	0.078(0.588), 0.040(0.779)
$AR(1)_c$, $AR(2)_c$ χ^2(p)	0.803(0.000), 0.132(0.359)	0.780(0.000), 0.158(0.275)	0.497(0.000), 0.345(0.012)	0.053(0.707),-0.061(0.662)
$AR(1)_d$, $AR(2)_d$ χ^2(p)	-0.059(0.685),-0.036(0.787)	-0.098(0.499),-0.048(0.738)	-0.466(0.001),-0.314(0.021)	-0.067(0.639),-0.145(0.310)
$AR(1)_e$, $AR(2)_e$ χ^2(p)	0.739(0.000),-0.021(0.880)	0.541(0.000), 0.119(0.410)	0.085(0.556), 0.062(0.671)	-0.201(0.158),-0.102(0.473)
Serial correlation LM test (F-stat)				
Total cost (t_c)	0.309(0.736)	2.049(0.140)	0.806(0.453)	1.755(0.183)
Labor share (S-l)	3.386(0.042)	6.421(0.003)	4.038(0.024)	0.233(0.793)
Capital share (S_c)	0.640(0.532)	0.330(0.721)	2.373(0.104)	0.903(0.412)
Land share (S_d)	0.209(0.812)	2.057(0.139)	1.231(0.301)	0.722(0.491)
Energy share (S_e)	0.279(0.757)	0.295(0.746)	0.231(0.795)	1.675(0.197)
$Normality_{cost}$ χ_2^2(p)	40.141(0.000)	48.860(0.000)	16.341(0.000)	0.647(0.724)
$Normality_{S\_l}$ χ_2^2(p)	5.270(0.072)	9.793(0.007)	9.372(0.009)	5.344(0.069)
$Normality_{S\_k}$ χ_2^2(p)	3.115(0.211)	3.621(0.164)	1.646(0.439)	1.790(0.409)
$Normality_{S\_d}$ χ_2^2(p)	77.701(0.000)	22.411(0.000)	39.076(0.000)	102.749(0.000)
$Normality_{S\_e}$ χ_2^2(p)	25.018(0.000)	23.382(0.000)	3.903(0.142)	12.765(0.002)
Wald (m=1) χ_1^2(p)		15.361(0.000)	1.754(0.185)	0.006(0.939)
LR (K=mI+B, B=B') χ_6^2(p)				37.783(0.000)
LR (K=mI+b				

Note: 1) *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. 2) *LR (K=mI+b*

respective price changes.

In the fully dynamic model, the estimated coefficient *m* is not significantly different from 1.0. We cannot reject the hypothesis that adjustment to price changes occurs within a single period. Following Urga, a value of 1.0 for the adjustment parameter *m* suggests the short-run and long-run elasticities do not significantly differ from each other. Further, we rejected the alternative specifications of the share adjustment mechanism embodied in the B matrix. Specially, we rejected a symmetric B matrix, a diagonal B matrix, a scalar B matrix, and a partial adjustment mechanism.

Elasticity Estimates

Allen-Uzawa Elasticity of Substitution (AUES)

The Allen-Uzawa measure is a one-price-one-input elasticity of substitution measure (Thirtle, 2003). It is used to estimate the effect of the change in one input's price on the use of another input. Two inputs are Allen substitutes if an increase in the price of one leads to an increase in the utilization of the other. On the other hand, two inputs are Allen complements if an increase in the price of one leads to decreased utilization of the other. The AUES measures substitutability relationships among the five production inputs in this research.

The Allen-Uzawa elasticities of substitution are tabulated in Table 4.3. AUES estimates for energy in most cases are larger in absolute value than the other input comparisons. This suggests that the energy use in U.S. agriculture is relatively more sensitive to the prices of other inputs. All AUES estimates involving energy are in excess of 0.55 in absolute value except energy and capital (0.42), which is still larger than most of the non-energy AUES in absolute value. This sensitivity between energy and the other production inputs indicates that changes in the prices of non-energy inputs

Table 4.3. Report of Allen-Uzawa Partial Elasticity of Substitution (Standard deviation (S.D.) in parentheses).

	Static Mean	Dynamic (LR) Mean	Dynamic (SR) Mean	1948-1960(LR) Mean	1948-1960(SR) Mean
Allen-Uzawa					
σ_{lk}	-0.947(0.366)	-0.338(0.159)	-0.347(0.160)	-0.476(0.175)	-0.486(0.176)
σ_{ld}	-0.077(0.184)	-0.054(0.077)	-0.061(0.078)	0.185(0.060)	0.179(0.060)
σ_{le}	-0.309(0.451)	-0.891(0.467)	-0.904(0.470)	-0.729(0.426)	-0.740(0.429)
σ_{lm}	0.680(0.204)	0.762(0.093)	0.761(0.094)	0.787(0.083)	0.786(0.084)
σ_{kl}					
σ_{kd}	0.322(0.247)	-0.025(0.101)	-0.032(0.102)	-0.230(0.122)	-0.238(0.122)
σ_{ke}	0.436(0.706)	-0.424(0.556)	-0.433(0.559)	-1.020(0.788)	-1.033(0.793)
σ_{km}	0.084(0.309)	0.498(0.138)	0.495(0.139)	0.304(0.191)	0.300(0.193)
σ_{dl}					
σ_{dk}					
σ_{de}	0.109(0.288)	-0.546(0.258)	-0.556(0.260)	-0.537(0.257)	-0.547(0.258)
σ_{dm}	0.239(0.164)	0.522(0.091)	0.518(0.092)	0.535(0.089)	0.532(0.089)
σ_{el}					
σ_{ek}					
σ_{ed}					
σ_{em}	0.597(0.123)	1.292(0.278)	1.294(0.279)	1.335(0.319)	1.337(0.279)
σ_{ml}					
σ_{mk}					
σ_{md}					
σ_{me}					

Table 4.3. (continued)

	1961-1970(LR) Mean	1961-1970(SR) Mean	1971-1980(LR) Mean	1971-1980(SR) Mean
Allen-Uzawa				
σ_{lk}	-0.264(0.150)	-0.272(0.151)	0.039(0.114)	0.033(0.115)
σ_{ld}	-0.041(0.076)	-0.048(0.077)	-0.031(0.076)	-0.038(0.076)
σ_{le}	-0.779(0.439)	-0.791(0.442)	-1.189(0.540)	-1.204(0.544)
σ_{lm}	0.792(0.081)	0.791(0.082)	0.738(0.103)	0.736(0.103)
σ_{kl}				
σ_{kd}	-0.299(0.128)	-0.307(0.129)	0.444(0.055)	0.441(0.055)
σ_{ke}	-0.720(0.671)	-0.732(0.676)	0.086(0.356)	0.080(0.359)
σ_{km}	0.437(0.155)	0.433(0.156)	0.693(0.084)	0.691(0.085)
σ_{dl}				
σ_{dk}				
σ_{de}	-0.951(0.326)	-0.964(0.328)	-0.351(0.226)	-0.360(0.227)
σ_{dm}	0.439(0.107)	0.436(0.108)	0.602(0.076)	0.599(0.077)
σ_{el}				
σ_{ek}				
σ_{ed}				
σ_{em}	1.326(0.310)	1.328(0.312)	1.288(0.273)	1.289(0.275)
σ_{ml}				
σ_{mk}				
σ_{md}				
σ_{me}				

Table 4.3. (continued)

	1981-1990(LR) Mean	1981-1990(SR) Mean	1991-2002(LR) Mean	1991-2002(SR) Mean
Allen-Uzawa				
σ_{lk}	-0.305(0.155)	-0.314(0.156)	0.206(0.094)	0.201(0.095)
σ_{ld}	-0.477(0.109)	-0.487(0.109)	-0.187(0.087)	-0.195(0.088)
σ_{le}	-1.091(0.516)	-1.105(0.519)	-0.947(0.480)	-0.960(0.483)
σ_{lm}	0.684(0.124)	0.682(0.124)	0.765(0.092)	0.764(0.093)
σ_{kl}				
σ_{kd}	0.204(0.079)	0.199(0.079)	0.361(0.063)	0.356(0.064)
σ_{ke}	0.127(0.340)	0.122(0.343)	0.187(0.317)	0.182(0.319)
σ_{km}	0.631(0.102)	0.628(0.102)	0.725(0.075)	0.724(0.076)
σ_{dl}				
σ_{dk}				
σ_{de}	-0.361(0.227)	-0.370(0.229)	-0.674(0.279)	-0.685(0.281)
σ_{dm}	0.495(0.097)	0.491(0.097)	0.503(0.095)	0.500(0.096)
σ_{el}				
σ_{ek}				
σ_{ed}				
σ_{em}	1.243(0.231)	1.245(0.233)	1.277(0.263)	1.279(0.265)
σ_{ml}				
σ_{mk}				
σ_{md}				
σ_{me}				

may have unintended effects upon energy use or changes in the use of non-energy inputs may moderate the effects caused by rising energy price.

The AUES between material and the other inputs are positive: 0.76 for material and labor, 0.50 for material and capital, 0.52 for material and land, and 1.29 for material and energy, indicating that materials substitute for the other inputs. The AUES between material and energy is the only one that is bigger than one, meaning the substitution relationship between them is the strongest. A 1% increase in energy prices causes a 1.29% increase in material use. This sensitivity may be because materials include agriculture chemicals, which can respond to changes in energy prices more quickly than the other inputs. Therefore, changes in the demand of materials can have expected effects upon energy prices. As a result, declining material prices can lead to reductions in energy use because of this substitution effect.

The AUES between energy and capital is -0.42, indicating that energy and capital are complements. However, the relationship between energy and capital has changed over time. In the 1950s, energy and capital were complements (AUES = -1.02) perhaps due to relatively low energy prices and falling relative prices of farm machinery. The level of complementarity declined in the 1960s, to an AUES estimate of -0.73. However, in the 1970s, energy and capital became substitutes (AUES = 0.08). Rapidly rising energy prices may have forced farmers to adapt more energy efficient on-farm practices, such as adopting reduced- or no-tillage practices, switching to diesel-powered engines, and reducing fertilizer application rates. After the 1980s, the AUES between energy and capital increased to 0.18 over the 1991-2002 period. These changes may have result from adoption of advanced technologies on farm, like increasing use of precision farming practices, planting of genetically engineered crops, and creating new methods of crop drying and irrigation, etc. This may indicate that U.S. farmers have made adjustments to mitigate the impacts of changing energy prices. The combined effects of more energy efficient equipment and practices along with changes in crops produced and increasing yields has allowed U.S. agriculture to become more energy flexible over the last 40 years.

The short-run AUES for capital and labor in the 1948-1960 period was -0.49, indicating they were complements. The complementary relationship between them changed to substitutability during the 1991-2002 period (AUES = 0.20). We hypothesized that the high level of high mechanization underlies the change in the capital and labor relationship.

The long-run AUES estimates for energy-labor and energy-land were both negative, indicating that these two inputs are complements to energy. However, their sub-period estimates of the AUES showed that the complementary relationship became more elastic over time. The AUES between energy and labor during the 1948-1960 period was -0.74, but it was -0.96 during the 1991-2002 period. The AUES between energy and land changed from -0.54 during the 1948-1960 period to -0.69 during the 1991-2002 period. These changes suggest what changes have occurred in the production technology underlying U.S. agriculture during the 1948-2002 period.

Own-Price Elasticity

The own-price elasticity of demand measures the responsiveness of demand for an input to changes in its price. Own-price elasticities are expected to be negative based on the comparative statistics associated with the cost minimization assumption. Own-price elasticity estimates are shown in Table 4.4. The Le Chatelier principle is satisfied because all the short-run, own-price elasticities are less than their long-run counterparts in absolute value.

Table 4.4. Report of Price Elasticity of Demand (Standard deviation (S.D.) in parentheses).

	Static Mean	Dynamic (LR) Mean	Dynamic (SR) Mean	1948-1960(LR) Mean	1948-1960(SR) Mean
Price					
η_{ll}	-0.129(0.076)	-0.230(0.041)	-0.227(0.042)	-0.263(0.035)	-0.260(0.036)
η_{lk}	-0.134(0.052)	-0.048(0.023)	-0.049(0.025)	-0.052(0.019)	-0.053(0.020)
η_{ld}	-0.011(0.026)	-0.008(0.011)	-0.009(0.013)	0.028(0.009)	0.027(0.010)
η_{le}	-0.013(0.018)	-0.036(0.019)	-0.037(0.021)	-0.027(0.016)	-0.028(0.017)
η_{lm}	0.287(0.086)	0.322(0.039)	0.321(0.040)	0.314(0.033)	0.313(0.034)
η_{kl}	-0.242(0.094)	-0.086(0.041)	-0.089(0.041)	-0.144(0.053)	-0.147(0.054)
η_{kk}	0.144(0.078)	-0.103(0.036)	-0.098(0.037)	0.096(0.047)	0.103(0.047)
η_{kd}	0.045(0.034)	-0.003(0.014)	-0.004(0.016)	-0.035(0.018)	-0.036(0.019)
η_{ke}	0.018(0.029)	-0.017(0.023)	-0.018(0.023)	-0.038(0.030)	-0.039(0.030)
η_{km}	0.035(0.131)	0.210(0.058)	0.209(0.061)	0.121(0.076)	0.119(0.077)
η_{dl}	-0.020(0.047)	-0.014(0.020)	-0.016(0.022)	0.056(0.018)	0.054(0.019)
η_{dk}	0.046(0.035)	-0.004(0.014)	-0.004(0.015)	-0.025(0.013)	-0.026(0.014)
η_{dd}	-0.131(0.034)	-0.181(0.030)	-0.176(0.032)	-0.224(0.027)	-0.220(0.028)
η_{de}	0.004(0.012)	-0.022(0.010)	-0.023(0.011)	-0.020(0.010)	-0.020(0.011)
η_{dm}	0.101(0.069)	0.220(0.039)	0.219(0.042)	0.213(0.035)	0.212(0.036)
η_{el}	-0.079(0.115)	-0.228(0.119)	-0.231(0.121)	-0.221(0.129)	-0.225(0.130)
η_{ek}	0.062(0.100)	-0.060(0.079)	-0.061(0.080)	-0.111(0.085)	-0.112(0.086)
η_{ed}	0.015(0.040)	-0.076(0.036)	-0.078(0.037)	-0.082(0.039)	-0.083(0.040)
η_{ee}	-0.250(0.123)	-0.181(0.107)	-0.176(0.108)	-0.119(0.116)	-0.113(0.117)
η_{em}	0.252(0.052)	0.546(0.117)	0.546(0.118)	0.532(0.127)	0.533(0.128)
η_{ml}	0.174(0.052)	0.195(0.024)	0.195(0.025)	0.239(0.025)	0.239(0.025)
η_{mk}	0.012(0.044)	0.071(0.020)	0.070(0.022)	0.033(0.021)	0.032(0.022)
η_{md}	0.033(0.023)	0.073(0.013)	0.072(0.014)	0.081(0.014)	0.081(0.015)
η_{me}	0.024(0.005)	0.052(0.011)	0.053(0.013)	0.050(0.012)	0.050(0.013)
η_{mm}	-0.243(0.098)	-0.391(0.038)	-0.390(0.038)	-0.403(0.040)	-0.402(0.041)

Table 4.4. (continued)

	1961-1970(LR) Mean	1961-1970(SR) Mean	1971-1980(LR) Mean	1971-1980(SR) Mean
Price				
η_{ll}	-0.261(0.036)	-0.258(0.037)	-0.190(0.047)	-0.186(0.048)
η_{lk}	-0.034(0.019)	-0.035(0.021)	0.009(0.026)	0.007(0.027)
η_{ld}	-0.005(0.009)	-0.006(0.009)	-0.005(0.012)	-0.006(0.013)
η_{le}	-0.0290.016)	-0.029(0.017)	-0.047(0.022)	-0.048(0.024)
η_{lm}	0.329(0.035)	0.328(0.036)	0.322(0.045)	0.321(0.046)
η_{kl}	-0.079(0.045)	-0.081(0.047)	0.009(0.026)	0.007(0.027)
η_{kk}	-0.040(0.038)	-0.034(0.040)	-0.299(0.023)	-0.296(0.023)
η_{kd}	-0.036(0.016)	-0.037(0.016)	0.072(0.009)	0.072(0.011)
η_{ke}	-0.027(0.025)	-0.027(0.027)	0.003(0.014)	0.003(0.014)
η_{km}	0.181(0.064)	0.180(0.065)	0.302(0.037)	0.301(0.038)
η_{dl}	-0.012(0.023)	-0.014(0.023)	-0.007(0.017)	-0.009(0.018)
η_{dk}	-0.038(0.017)	-0.040(0.018)	0.100(0.012)	0.099(0.013)
η_{dd}	-0.096(0.034)	-0.091(0.035)	-0.253(0.026)	-0.250(0.027)
η_{de}	-0.035(0.012)	-0.036(0.013)	-0.014(0.009)	-0.014(0.010)
η_{dm}	0.182(0.042)	0.181(0.043)	0.262(0.033)	0.261(0.033)
η_{el}	-0.232(0.131)	-0.236(0.132)	-0.267(0.121)	-0.271(0.122)
η_{ek}	-0.093(0.086)	-0.094(0.087)	0.019(0.080)	0.018(0.081)
η_{ed}	-0.115(0.039)	-0.117(0.040)	-0.057(0.037)	-0.058(0.037)
η_{ee}	-0.109(0.118)	-0.104(0.119)	-0.169(0.109)	-0.163(0.110)
η_{em}	0.550(0.129)	0.551(0.130)	0.561(0.119)	0.562(0.120)
η_{ml}	0.236(0.024)	0.236(0.025)	0.166(0.023)	0.165(0.023)
η_{mk}	0.056(0.020)	0.056(0.021)	0.156(0.019)	0.155(0.020)
η_{md}	0.053(0.013)	0.053(0.014)	0.098(0.012)	0.097(0.013)
η_{me}	0.049(0.011)	0.049(0.012)	0.051(0.011)	0.051(0.012)
η_{mm}	-0.395(0.039)	-0.394(0.040)	-0.383(0.037)	-0.382(0.038)

Table 4.4. (continued)

	1981-1990(LR)	1981-1990(SR)	1991-2002(LR)	1991-2002(SR)
	Mean	Mean	Mean	Mean
Price				
η_{ll}	-0.125(0.054)	-0.121(0.055)	-0.221(0.042)	-0.217(0.043)
η_{lk}	-0.059(0.030)	-0.060(0.031)	0.051(0.023)	0.050(0.023)
η_{ld}	-0.063(0.014)	-0.064(0.016)	-0.024(0.011)	-0.025(0.013)
η_{le}	-0.053(0.025)	-0.054(0.026)	-0.039(0.020)	-0.039(0.022)
η_{lm}	0.289(0.053)	0.288(0.055)	0.339(0.041)	0.338(0.042)
η_{kl}	-0.059(0.030)	-0.060(0.032)	0.051(0.023)	0.050(0.024)
η_{kk}	-0.252(0.026)	-0.248(0.029)	-0.320(0.021)	-0.317(0.022)
η_{kd}	0.027(0.010)	0.026(0.012)	0.046(0.048)	0.046(0.049)
η_{ke}	0.006(0.017)	0.006(0.017)	0.008(0.013)	0.007(0.015)
η_{km}	0.266(0.043)	0.265(0.045)	0.321(0.033)	0.320(0.035)
η_{dl}	-0.092(0.021)	-0.094(0.022)	-0.046(0.022)	-0.048(0.024)
η_{dk}	0.039(0.015)	0.038(0.016)	0.089(0.016)	0.088(0.017)
η_{dd}	-0.150(0.032)	-0.145(0.033)	-0.132(0.032)	-0.127(0.034)
η_{de}	-0.018(0.011)	-0.018(0.013)	-0.028(0.011)	-0.028(0.013)
η_{dm}	0.209(0.041)	0.207(0.043)	0.223(0.042)	0.221(0.043)
η_{el}	-0.210(0.100)	-0.213(0.102)	-0.234(0.119)	-0.237(0.120)
η_{ek}	0.025(0.066)	0.023(0.068)	0.046(0.078)	0.045(0.079)
η_{ed}	-0.048(0.030)	-0.049(0.031)	-0.086(0.036)	-0.088(0.037)
η_{ee}	-0.303(0.090)	-0.298(0.091)	-0.185(0.107)	-0.180(0.108)
η_{em}	0.525(0.098)	0.525(0.098)	0.565(0.117)	0.566(0.118)
η_{ml}	0.132(0.024)	0.132(0.026)	0.189(0.023)	0.189(0.025)
η_{mk}	0.122(0.020)	0.121(0.022)	0.179(0.019)	0.179(0.020)
η_{md}	0.065(0.113)	0.065(0.113)	0.065(0.012)	0.064(0.014)
η_{me}	0.061(0.011)	0.061(0.012)	0.052(0.011)	0.052(0.013)
η_{mm}	-0.391(0.038)	-0.390(0.040)	-0.379(0.036)	-0.378(0.038)

During the 1948-2002 period, the long-run mean own-price elasticities were -0.23 for labor, -0.10 for capital, -0.18 for land, -0.18 for energy, and –0.39 for material. All factor demands were downward sloping and inelastic. These results were similar to earlier findings. Lambert and Shonkwiler (1995) reported own-price elasticities of -0.41 for labor, -0.04 for capital, and -0.22 for material (including energy) using aggregate output and input data for the U.S agricultural sector during the 1947-1994 period. Ray (1982) reported inelastic demands for labor, capital, fertilizer, feed, seed, and livestock, and miscellaneous inputs using 1939-1977 U.S. agriculture data. Huffman and Warjiyo (1995) also found inelastic demands for labor, capital, land and intermediate inputs (including energy) using U.S. agricultural data between 1950 and 1982. Shumway, Saez, and Gottret (1988) found inelastic factor demands in their analysis of U.S. agriculture data from 1951 to 1982. The own-price elaticities reported by them ranged from -0.08 to -0.40. The estimated own-price elasticity for energy was between -0.26 and -0.28 in 1982.

The inelastic demand for energy means that an increase in energy price still can bring about an increase in energy expenditures, with possibly negative effects on net farm income. Producers have limited options to adjust to rising energy prices in the short run. Although still inelastic, the sub-period own-price elasticity for energy has increased over time. The own-price elasticity of demand for energy changed from -0.11 over the 1948-1960 period to -0.30 over the 1981-1990 period. The increase in the elasticity of demand for energy means that greater opportunities to reduce energy use may have occurred (Lambert, 2005). In contrast, own-price elasticities for labor, capital, land and material remained relatively constant between 1948 and 2002.

Cross-Price Elasticity

The cross-price elasticity of demand measures the rate of response of quantity demanded of one good due to the price change of another good, or $\frac{d\ln X_j}{d\ln P_i}$. If two goods are substitutes, we should expect to see farmers purchase more of one good when the price of its substitute increases. Conversely, if two goods are complements, we should see a price rise in one good to cause the demand for the other good to fall.

The elasticity estimates are shown in Table 4.4. Cross-price elasticities indicate limited complementarity among inputs except for material when input prices change. All cross-price elasticities are inelastic. Consistent with the Allen-Uzawa elasticity of substitution, the cross-price elasticities for material and the other four inputs are all positive, indicating substitution may occur when material prices change.

The cross-price elasticity of energy and capital is -0.06 in the long run, meaning that these two inputs are weak complements. A 1% increase in energy price will lead to 0.06% drop of capital use. The capital variable in the dataset is primarily composed of farm machineries and equipment. Thus, rising energy prices will discourage energy demand, and then cut the utilization of machineries and equipment on farm practices. However, this impact of energy prices on farm equipment is quite small. Further the relationship between energy and capital has changed from complements to be substitutes since the 1970s.

The cross-price elasticity of energy and material is 0.55 in the long run, indicating that these two inputs are substitutes. The material input in our dataset includes fertilizer and pesticide. Intuitively, it seems likely that farmers will reduce fertilizer and pesticide application due to the adoption of reduced- and no-tillage practices. However, the fertilizer and pesticide are very important for farmers to achieve maximum yield.

Farmers may apply more fertilizers and pesticides while reducing direct energy use. The substitution relationship between energy and materials implies that energy prices may increase encourage material use.

The cross-price elasticity between energy and land is -0.08, indicating that energy and land are weak complements. Land use in U.S. agriculture has experienced a declining trend since the 1940s. Especially after the 1973-1974 crude oil price shock, farmers have adopted reduced- and no-tillage practices instead of conventional tillage practices to save energy consumption. Therefore, the rising energy prices and declining quantity demand for land indicate the complementary relationship between energy and land over the 1949-2002 period.

The cross-price elasticity between energy and labor is -0.23, meaning that energy and labor are complements. A 1% increase in energy price will lead to a 0.23% drop of the use of labor. Labor input in U.S. agriculture decreased at an average rate of 2.73% per year over the postwar period (Ball, 1997). There are two reasons for the decline of the labor use in U.S. agriculture. One is the mechanization of U.S. agriculture over this period, especially between 1947 and 1970 due to the relative low energy prices and stable energy supply. The massive use of farm machineries and equipment reduces the labor use in agriculture. The other is that increasing energy prices may force farmers to reduce the usage of farm machineries and equipment, especially during the four oil price shocks. Consequently, it will cause the labor use to decrease.

The relationships among inputs were not constant over time. Substitutability between capital and material increased slightly, from 0.12 over the 1948-1960 period to 0.32 over the 1991-2002 period. The sub-period cross-price elasticities of labor and capital and energy and capital changed from complements over the 1948-1960 period to substitutes over the 1991-2002 period. Consistent with the AUES, the short-run cross-price elasticties also indicate that U.S. agriculture's ability to substitute among production factors in response to energy price changes increased between the early years of the sample and the more recent time period.

Morishima Elasticity of Substitution (MES)

As defined by Chambers (1988), the Morishima elasticity of substitution is a two-factor-one-price elasticity. It measures the change of input ratio x_i / x_j in response to a change in the price of p_j. $\text{MES}_{\text{ij}} = \frac{\partial \ln x_j}{\partial \ln p_i} - \frac{\partial \ln x_i}{\partial \ln p_i}$. Inputs are Morishima substitutes if and only if an increase in p_j causes the input ratio x_i / x_j to rise ($\text{MES}_{\text{ij}} > 0$). The MES is not symmetric because MES between i and j is different from the MES between j and i. The MES depends on which input price changes.

The MES estimates are shown in Table 4.5. For all inputs, differences in MES between the short run and the long run are small. All the short-run MES are less in absolute value than their long-run counterparts, which satisfies the Le Chatelier principle. The estimates also show that all of the input pairs exhibit long-run or short-run Morishima substitutability, while only 40% of the input pairs behave as Allen substitutes.

The strongest Morishima substitutability is found for the pair energy and material (MES = 0.94), consistent with the finding of AUES and cross-price elasticity. The large degree of asymmetry for energy and material suggests that any policy that causes similar percent increase in the price of material or energy will induce very different increases in the energy/material and energy/material ratio. For example, an increase of 1% in the price of material will increase energy use relative to material by 0.94%. However, a 1% increase in the price of material will lead to only a 0.23% increase in

Table 4.5. Report of Morishima Elasticity of Substitution.

	Dynamic (LR)	Dynamic (SR)	1948-1960(LR)	1948-1960(SR)
Morishima				
σ^M_{lk}	0.055	0.049	-0.148	-0.156
σ^M_{ld}	0.173	0.167	0.252	0.247
σ^M_{le}	0.145	0.139	0.092	0.085
σ^M_{lm}	0.713	0.711	0.717	0.715
σ^M_{kl}	0.144	0.138	0.119	0.113
σ^M_{kd}	0.178	0.172	0.189	0.184
σ^M_{ke}	0.164	0.158	0.081	0.074
σ^M_{km}	0.601	0.599	0.524	0.521
σ^M_{dl}	0.216	0.211	0.319	0.314
σ^M_{dk}	0.099	0.094	-0.121	-0.129
σ^M_{de}	0.159	0.153	0.099	0.093
σ^M_{dm}	0.611	0.609	0.616	0.614
σ^M_{el}	0.002	-0.004	0.042	0.035
σ^M_{ek}	0.043	0.037	-0.207	-0.215
σ^M_{ed}	0.105	0.098	0.142	0.137
σ^M_{em}	0.937	0.936	0.935	0.935
σ^M_{ml}	0.425	0.422	0.502	0.499
σ^M_{mk}	0.174	0.168	-0.063	-0.071
σ^M_{md}	0.254	0.248	0.305	0.301
σ^M_{me}	0.233	0.229	0.169	0.163

Table 4.5. (continued)

	1961-1970(LR)	1961-1970(SR)	1971-1980(LR)	1971-1980(SR)
Morishima				
σ^M_{lk}	0.006	-0.001	0.308	0.303
σ^M_{ld}	0.091	0.085	0.248	0.244
σ^M_{le}	0.080	0.075	0.122	0.115
σ^M_{lm}	0.724	0.722	0.705	0.703
σ^M_{kl}	0.182	0.177	0.199	0.193
σ^M_{kd}	0.060	0.054	0.325	0.322
σ^M_{ke}	0.082	0.077	0.172	0.166
σ^M_{km}	0.576	0.574	0.685	0.683
σ^M_{dl}	0.249	0.244	0.183	0.177
σ^M_{dk}	0.002	-0.006	0.399	0.395
σ^M_{de}	0.074	0.068	0.155	0.149
σ^M_{dm}	0.577	0.575	0.645	0.643
σ^M_{el}	0.029	0.022	-0.077	-0.085
σ^M_{ek}	-0.053	-0.060	0.318	0.314
σ^M_{ed}	-0.019	-0.026	0.196	0.192
σ^M_{em}	0.945	0.945	0.944	0.944
σ^M_{ml}	0.497	0.494	0.356	0.351
σ^M_{mk}	0.096	0.090	0.455	0.451
σ^M_{md}	0.149	0.144	0.351	0.347
σ^M_{me}	0.158	0.153	0.220	0.214

Table 4.5. (continued)

	1981-1990(LR)	1981-1990(SR)	1991-2002(LR)	1991-2002(SR)
Morishima				
σ^{M}_{lk}	0.193	0.188	0.371	0.367
σ^{M}_{ld}	0.087	0.081	0.108	0.102
σ^{M}_{le}	0.250	0.244	0.146	0.141
σ^{M}_{lm}	0.680	0.678	0.718	0.716
σ^{M}_{kl}	0.066	0.061	0.272	0.267
σ^{M}_{kd}	0.177	0.171	0.178	0.173
σ^{M}_{ke}	0.309	0.304	0.193	0.187
σ^{M}_{km}	0.657	0.655	0.070	0.698
σ^{M}_{dl}	0.033	0.027	0.175	0.169
σ^{M}_{dk}	0.291	0.286	0.409	0.405
σ^{M}_{de}	0.285	0.280	0.157	0.152
σ^{M}_{dm}	0.600	0.597	0.602	0.599
σ^{M}_{el}	-0.085	-0.092	-0.013	-0.020
σ^{M}_{ek}	0.277	0.271	0.366	0.362
σ^{M}_{ed}	0.102	0.096	0.046	0.039
σ^{M}_{em}	0.916	0.915	0.944	0.944
σ^{M}_{ml}	0.257	0.253	0.410	0.406
σ^{M}_{mk}	0.374	0.369	0.499	0.496
σ^{M}_{md}	0.215	0.210	0.197	0.191
σ^{M}_{me}	0.364	0.359	0.237	0.232

the material/energy ratio. The reason for this result is that materials account for 40% - 50% of annual U.S. agriculture production expenses, whereas energy only constitutes 11% - 16%. Hence, one percent increase in material price indicates a larger potential impact on costs than a change in energy prices, thus encouraging farmers to shift a greater share of cost onto other factors, such as energy (Lambert, 2006).

The MES for labor, capital, and land to energy are: 0.002, 0.04 and 0.11, indicating that these three inputs and energy are MES substitutes. However, the AUES shows that these three inputs and energy are AUES complements. To find out the connection behind them, we consider the AUES and MES for capital and energy. The AUES for capital and energy is -0.42, indicating that an increase in the energy price results in a decline in capital use. Since energy and capital are AUES complements, an increase in the energy price leads to a drop in quantity demand for energy and it also causes capital use to decrease. Therefore, both the numerator and the denominator in the capital/energy ratio are declining. In this case, the own-price effect is bigger than the cross-price effect ($\left|\frac{\partial \ln x_j}{\partial \ln p_i}\right| < \left|\frac{\partial \ln x_i}{\partial \ln p_i}\right|$), resulting in the capital/energy ratio increasing.

The MES for capital and energy in response to an energy price change (MES = 0.16) is larger than the MES for energy and capital in response to a capital price change (MES = 0.002). It implies that rising energy price would better achieve the goal of reducing energy consumption and promoting investment in energy-saving machinery than would capital subsidy approach.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Energy is a very important input in agricultural production. Energy prices can affect agricultural production costs directly through fuel and energy purchases and indirectly through fertilizer and pesticide use.

Over the past four decades, four energy prices shocks have occurred. Because demand for energy is inelastic, total U.S. agriculture energy expenditures closely followed energy prices. Due to the structure of the production sector, increases in oil and natural gas prices cannot be passed on to agricultural product markets through marketing costs. Energy price changes may thus directly affect the sector's net returns.

Comparing Miranowski (2005) and Dvoskin and Heady's (1984) results indicate that greater factor substitution may exist now than following the first energy price shock in the 1970s.

Our results provide support to these unrelated studies' findings of decreasing sensitivity to energy price changes. The own-price elasticities derived from the fully dynamic model for all five production inputs in U.S. agriculture are negative, which means that the demands for these factors are downward sloping. All five factors are also characterized by inelastic responses to own-price changes. The inelastic demand for energy indicates that rising energy prices are accompanied by increases in expenditures on energy.

The primary focus of this study is estimation of the elasticites of substitution between inputs and price elasticities of factor demands. The Allen-Uzawa elasticities of substitution and the cross-price elasticities of demand indicate that material and the other four inputs are substitutes and the other four inputs are complements to each other. Based on the AUES estimates over the sub-period of the entire sample, we find that the relationship between energy and capital changed from complementary to substitution and further the substitution elasticity is increasing. The same changes happened to labor and capital, and capital and both energy and land. Apparently the U.S. agricultural sector's flexibility to energy price changes has increased over time.

The increasing substitution elasticity of energy may be attributed to changes in production practices. The oil price shocks of the 1970s and 1980s forced the U.S. agricultural sector to develop less intensive energy using practices. Since the first oil price shock, energy use in U.S. agriculture has declined. The less intensive energy using practices arose in response to energy price increases, leading to reductions in energy use.

Energy prices increased 110% between 2001 and 2005 because of uncertainties of energy supplies and increasing demand for energy from the developing countries, such as China and India (Ishida, 2007). It is likely that energy prices will continue to rise in the near future. Our results indicate that U.S. farmers may continue to adopt more efficient production practices and adjust cropping and livestock production levels to mitigate the effects of changing energy prices. However, the demand for energy is still inelastic, and substitutability between energy and the other inputs is limited. Further initiatives are still needed to improve the energy flexibility of U.S. on-farm production practices.

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