FERTILIZER DEMAND FUNCTIONS FOR FIVE CROPS IN THE UNITED STATES

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Fertilizer consumption by the U.S. agricultural sector has increased dramatically for several decades. Nitrogen fertilizer use increased 632 percent between 1952 and 1976. Phosphate and potash fertilizer use increased 138 and 229 percent, respectively, in the same period (USDA 1978). However, the upward trend in fertilizer use was temporarily interrupted during the early and mid-1970s as the real fertilizer price began to increase after many years of decline.

Higher levels of aggregate fertilizer consumption over the 1952-1976 period outweighed the decline in the real price of fertilizer as real dollar expenditures for fertilizer continued to rise. Our study includes an attempt to relate fertilizer use for different crops to relevant economic variables.

STUDY FEATURES

Studies by Griliches and by Heady and Yeh during the 1950s analyzed short-run and long-run demand elasticities for total fertilizer use on a regional basis, but did not estimate fertilizer demand for each crop. Data for doing so are now available. It is interesting and useful for crop-specific policy purposes to estimate empirically the changes in fertilizer use for different crops. Accordingly, we estimate separate demand functions for fertilizer over the period 1952-1976 for five major crops.

In our study, expenditures for fertilizer and lime use are disaggregated among various crops. Fertilizer expenditures for each individual crop are obtained by summing nutrient quantities times 1967 nutrient prices. The resulting measures of fertilizer consumption for the individual crops are in terms of real-dollar expenditures. Farmers are assumed to be indifferent between various kinds of fertilizers as long as the total expenditures on them are the same. This assumption implies a perfect substitution among N, P_2O_5, and K_2O in terms of a dollar spent, as their respective costs are simply added up to get total fertilizer use in monetary units. Such a measure of total fertilizer use is certainly not the most appropriate one with respect to economic theory, but has less error in it than summing the tonnage of different nonhomogenous nutrients to get total fertilizer use as is done in the study by Griliches.

The logic of this approach of analyzing crop-wise fertilizer use is based on the fact that decisions are made to fertilize individual crops. Also, relative prices and fertilizer nutrients differ among crops. Each crop has a response function different from that of other crops. For example, the fertilizer required to produce a bushel of corn differs markedly in amount and type from that required to produce a bushel of soybeans. The profitability of different crops, and therefore the amounts of fertilizer applied to them, change over time. Hence, estimation of aggregate fertilizer demand functions for all crops has implicit errors, some of which can be avoided by estimating a separate demand function for each crop.

Accordingly, we developed regression models for five crops: feed grains (corn, grain sorghum, oats, and barley), wheat, soybeans, cotton, and tobacco. The emphasis of the study is less on technique than on fertilizer consumption for different major crops. More specifically, our objective is to estimate the separate fertilizer demands and elasticity coefficients and offer possible explanations for them.

CONCEPTUAL MODEL

In this section we summarize the theoretical basis on which the regression estimates were initially based.

The demand for a production input, such as fertilizer, is a derived demand based on the demand for the final product. Farmers are assumed to behave rationally and maximize their profits. A general profit function can be expressed as

$$\pi_y = P_y\, f(X_1, X_2, ..., X_n) - \sum_{i=1}^{n} P_i X_i$$

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where P_y and P_i are the prices of the output and the i^{th} resource and f represents a production function. The first-order profit maximization conditions state that the resource should be utilized up to the level where the marginal physical product equals the input-output price ratio as expressed by

$$\frac{df}{dX_i} = \frac{P_i}{P_y} \qquad i = 1, 2, ..., n.$$

These n first-order conditions can be solved simultaneously to obtain input demand functions, the quantity of the input demanded being a function of its own price, the prices of substitute and complementary inputs, and the output price. An increase in the fertilizer price increases the fertilizer-to-output price ratio if output price is held constant. For the farmer to maximize profits, if one assumes that marginal physical product is declining at the profit-maximizing level of input usage, the marginal physical product must be increased. This can be accomplished if the farmer reduces fertilizer application. Hence, a negative relationship between the fertilizer price and the quantity of fertilizer used is expected. The opposite relationship is expected for the output price.[1]

An individual farmer's income determines his ability to buy fertilizer and other inputs. A positive effect therefore is hypothesized between per-acre farm income and per-acre fertilizer demand. The value of stock of physical assets — viz. machinery, commodities, and land — determines the farmer's risk-bearing ability and credit availability for fertilizer and other resources. Therefore, a positive relationship is hypothesized between value of physical assets and fertilizer usage.

Farmers' decisions also are affected by government agricultural policies. In the mid-1970s, changing world circumstances and adjustments in the U.S. government's agricultural policies returned U.S. agriculture to a free market situation with little government intervention. During periods of higher agricultural prices and less emphasis on supply-control programs, planted acreage might increase. Fertilizer application rates are expected to decline as more land is brought into production. Therefore, a negative relationship between a free market situation and fertilizer application rate is hypothesized.

Farmers are expected to make adjustments to changes in economic phenomena. However, because of imperfect information and habit persistence, farmers might not make the full adjustment to long-run equilibrium within one year. To capture this possibility, we include lagged fertilizer use as suggested by Nerlove. Finally, a time variable is included to account for the effects of many influences that are not quantifiable in the model. Technological advances are an example of these influences. As crop varieties more responsive to fertilizer are developed, more fertilizer is used. Positive regression coefficients are expected under these conditions. Also, positive coefficients are expected when farmers are still in the process of adoption as many were for corn, wheat, and cotton during the sample period.

On the basis of the conceptual model, fertilizer demand functions are developed for five individual crops.

THE DATA

Annual time series data for 1952 through 1976 were used to estimate the five crop-specific fertilizer demand functions. Time series for nitrogen (N), phosphoric acid (P_2O_5), and potash (K_2O) consumption by crop are not published. Therefore, we used and extended data for 1952 through 1969 developed at the Center for Agricultural and Rural Development (CARD) by Stoecker. Nutrient application rates by state for corn, cotton, wheat, and soybeans were obtained from survey data on cropping practices (USDA 1971) for 1965-69. Estimates of consumption rates for all crops were available for 1954, 1959, and 1964 from studies based on the Census of Agriculture (USDA 1957; Ibach and Adams; Ibach, Adams, and Box). Observations on nutrient application rates other than those published in the sources cited were obtained by interpolation or by projections of past rates. Stoecker's data were extended for 1970-76 by similar techniques.

Preliminary national totals for each nutrient were then calculated by forming the product of harvested acreage, the proportion of harvested acreage receiving fertilizer, and the application rate per acre receiving fertilizer and summing across crops and states. Final application rates were derived by adjusting the preliminary application rates so that preliminary national totals of each nutrient were in conformity with the published national totals (USDA 1978). This was done by multiplying each of the preliminary application rates by the ratio of the published national total to the preliminary national total. Estimates of N, P_2O_5, and K_2O used for each crop in the United States were formed by summing across states for each crop and nutrient.

Estimates of tobacco fertilizer expenditures were developed and updated from data used by Ray. Fertilizer application rates per harvested acre for 1930-67 were used to estimate per-acre

[1] As hypothesized, the quantity demanded of an input in physical units is a function of input price and output price. Therefore, the quantity demanded in monetary units (real dollars) is also a function of the same set of prices.

application rates for 1968-76. These per-acre application rates were then multiplied by tobacco harvested acreage to compute estimates of N, P_2O_5, and K_2O used on tobacco.

Estimates of fertilizer expenditures in constant 1967 dollars (the sum of expenditures on N, P_2O_5, and K_2O) for feed grains, wheat, soybeans, cotton, and tobacco were obtained by multiplying the quantities of N, P_2O_5, and K_2O by their respective 1967 prices for all years (USDA 1952-59; 1961-77) and then summing for each crop. Nutrient prices were obtained by averaging compound prices and converting them to elemental prices.

The distribution of phosphate fertilizer in tons applied to crops for each year was used to distribute total lime expense (USDA 1977c) among the model crops. Lime expenditures for each crop in constant 1967 dollars were computed by deflating current lime expenditures by a 1967-based index of the price of liming materials. The implicit price of liming materials was formed by dividing aggregate lime expenditures (USDA 1977c) by the aggregate quantity of liming materials in tons (USDA 1977b). Fertilizer and lime series were formed by summing expenditures in constant dollars on N, P_2O_5, K_2O, and lime for each crop.

Time series for the stock of physical assets by crop are also unpublished. The stock of physical assets for a particular crop in a given year was obtained by summing the constant 1967 dollar average value of commodity stocks of that crop on farms, the average constant dollar value of machinery stocks used for the production of the particular crop, and the constant dollar value of land and buildings attributed to the crop. The complexity of the formulation of these time series precludes a description of their derivation in this article. A detailed description of the derivation techniques and data sources is given by Ray and by Schatzer et al. All other data used in this article are taken from published sources.

ESTIMATED EQUATIONS

The fertilizer demand functions are estimated for the five crops with constant 1967 dollar fertilizer expenditures per harvested acre as dependent variables. Regression equations retained for analysis are only those in which the estimated coefficients, having signs consistent with the theory, are statistically significant at a level of 10 percent or less. The demand functions obtained are listed in Table 1. The functions are interesting in the sense that the coefficients of determination (R^2) ranges from .94 to .99, with most of the variables being significant at less than the 5 percent level. The five columns of Table 1 represent dependent variables for five crops and the 11

TABLE 1. ESTIMATED FERTILIZER DEMAND FUNCTIONS FOR FIVE CROPS IN THE UNITED STATES (1952-76)[a]

$i\text{-}FERT_t / i\text{-}HAC_t$ Regressor	Feed Grains Est. Coef.	Wheat Est. Coef.	Soybeans Est. Coef.	Cotton Est. Coef.	Tobacco Est. Coef.
Intercept	-2.7437	1.7383	2.8278	5.5524	56.2722
$(i\text{-}GINC/i\text{-}HAC)_{t-1}$	0.658 (2.49)[b]			.0089 (1.95)	.0365 (7.33)
$i\text{-}STKPA_t$	.0003 (4.02)	.00008 (2.27)	.0001 (3.37)		
$FERTPI_t$		-3.0591 (3.70)	-1.0116 (4.30)	-2.4784 (2.84)	-32.4237 (7.76)
$(FERTPI/i\text{-}PR)_t$	-363.3933 (6.86)				
$i\text{-}PR_{t-1}$		.6915 (3.32)			
FMDUM 73-76=1	-4.3927 (4.68)				
FMDUM 74-76=1					20.2848 (9.65)
TIME	.3737 (4.08)	.1560 (6.82)		.2634 (10.98)	
LOGTIME			- .7455 (2.87)		
$(i\text{-}FERT/i\text{-}HAC)_{t-1}$			.4793 (3.27)		
R^2 [c]	.985	.980	.978	.938	.968
DW[d]	2.16	1.65	2.02	1.41	1.72

[a]Variable Definitions: FERT = fertilizer expenditures in 1967 real dollars; HAC = harvested acres; GINC = gross income (cash receipts plus government payments), deflated by the GNP index 1967 = 100; STKPA = stock of physical assets in 1967 real dollars; FERTPI = fertilizer price index, deflated by the GNP index 1967 = 100; PR = price of crop, deflated by the GNP index 1967 = 100; FMDUM = free market dummy variable; TIME = time trend with 1952=4, ..., 1976=28; LOGTIME = log of time; t E current year; and i = feed grains, wheat, soybeans, cotton, and tobacco.

[b]Figures in the parentheses are t-statistics.

[c]R^2 is the coefficient of determination.

[d]DW is the Durbin-Watson statistic.

rows represent explanatory variables included in the regressions.

All the equations were estimated by ordinary least squares. In addition each equation was estimated by an autoregressive least squares technique. However, the autoregressive coefficient was found to be nonsignificant in all cases.

RESULTS

The most obvious feature observed in Table 1 is that the same variables are not significant in all the functions. This finding clearly implies that all types of farmers, producing different crops, may not respond to the same variables or may not consider the same type of economic variables while making their fertilizer-purchasing decisions. For example, the estimated equations suggest that wheat and soybean farmers do not consider gross income so intensely as an important factor in deciding their fertilizer purchases. We try to explain these behavioral patterns.

Fertilizer and Crop Price Variables

The current fertilizer price index or current "real" price of fertilizer is significant at the 1

TABLE 2. FERTILIZER DEMAND ELASTICITIES WITH RESPECT TO IMPORTANT ECONOMIC VARIABLES, AT MEAN LEVELS

Crop / Variable	Feed Grains[a]	Wheat	Soybean	Cotton	Tobacco
$FERTPI_t$	-.90	-.99	-.62	-.31	-.53
$i\text{-}PR_t$	.90				
$i\text{-}PR_{t-1}$		.42			
$(i\text{-}GINC/i\text{-}HAC)_{t-1}$	.29			.19	.65
$STKPA_t$	1.33	.31	.70		

[a]Price elasticities for $FERTPI_t$ and $i\text{-}PR_t$ for feed grains were derived from the coefficient of the ratio of the two prices using the following relationship. Demand elasticity with respect to a price ratio (F/P) is equal to the elasticity with respect to F holding P constant and also equal to the negative of elasticity with respect to P holding F constant. For a demand function $Q^d = f(F/P)$

$$\frac{dQ}{d(F/P)} \cdot \frac{(F/P)}{Q} = \frac{\partial Q}{\partial F} \cdot \frac{F}{Q}\Big|_{\bar{P}} = -\frac{\partial Q}{\partial P} \cdot \frac{P}{Q}\Big|_{\bar{F}}$$

percent level in the fertilizer demand functions for all crops except feed grains. The demand elasticities for fertilizers with respect to fertilizer price, at mean levels, are −.99, −.62, −.31, and −.53 for wheat, soybean, cotton, and tobacco, respectively, as shown in Table 2. However, the current ratio of fertilizer price to crop price is significant only in the feed grain equation. The elasticity, in the case of feed grains, with respect to fertilizer price is −.90. This elasticity is derived from the coefficient of the ratio of the two prices (see footnote in Table 2).

The estimated elasticities suggest that the farmers producing cereal crops (wheat and feed grains) have more elastic fertilizer demand than do those who produce soybeans (a leguminous crop requiring little nitrogen), tobacco, and cotton. These differences are possibly due to the nature of the crops and their response to fertilizer application. Cotton and tobacco are cash crops and farmers have tended to apply high levels of fertilizer to them regardless of the price of fertilizer. Cotton and tobacco are produced mainly in areas which have historically high fertilizer application per acre and where fertilization rates have increased at lower rates between 1952 and 1976 (USDA 1977b). The elasticities are greater for wheat and feed grains, which are mainly cultivated in the Northern Plains, Corn Belt, and Lake States — the areas where fertilizer use has increased mostly in recent decades (USDA 1977b). The mean fertilizer demand elasticities are highest for wheat and feed grains and lowest for cotton and tobacco.

Product prices traditionally have been economic variables explaining the derived demand for fertilizer or other inputs. Our hypothesis was that farmers tend to increase their per-acre fertilizer expenditures if they expect higher product prices. We used lagged product prices to serve as proxies for expected prices for all of the fertilizer demand functions. The lagged price variable is significant at the 1 percent level only in the case of wheat. The mean elasticity coefficient of fertilizer demand with respect to expected wheat price is .42.

Farm Income and Asset Variables

Per-acre gross income (crop price times yield) from last year's farming is a significant factor in the feed grain, cotton, and tobacco equations.[2] It may be especially important for cotton and tobacco, which have significant variations in yield, as crop prices are not significant in those two equations. The fertilizer expenditure elasticity with respect to lagged farm income in the case of feed grains is .29. The highest mean income elasticity of fertilizer use is .65 for tobacco, a cash crop grown on small farms; the lowest is .19 for cotton, a cash crop in recent times grown on large farms.

The stock of physical assets is significant at levels less than 5 percent in the feed grain, wheat, and soybean equations. The stock of physical assets includes the value of land and buildings and the annual average values of machinery and commodity stocks owned by farmers, disaggregated by crop. The mean elasticity of fertilizer with respect to the stock of physical assets ranges from 1.33 for feed grains to .31 for wheat.

Free Market Variables

In addition to the "traditional" economic variables, some variables reflecting periods of government policies are included in the analysis. Variations in fertilizer application rates caused by U.S. government policies which returned the agricultural sector to a free market situation are explained by a dummy variable with 1973-76 equal to one and zero otherwise. This variable, with a regression coefficient of −4.4, was highly significant in the feed grain equation. The negative sign for this coefficient might be explained as follows. During this period, higher product prices and reduced government intervention encouraged farmers to bring more land into production. In 1973, the harvested acreage of feed grains increased

[2]A more appropriate measure of farm income would be net farm income. However, because of the mammoth computation of costs of production of each crop for each year, per-acre gross farm income is used as a measure of per-acre farm income.

from 94 million acres (in 1972) to 102.4 million acres or by 9 percent (USDA 1977a). At the same time, total estimated feed grain fertilizer expenditures increased only 3 percent. The increase in land planted to feed grains was more than proportional to the increase in fertilizer used for feed grains. Accordingly, expenditures on fertilizer per acre decreased during the free market period.

This variable was not significant for the other crops because of the counteracting income effect during the specified period. Incomes were high for wheat because of the large-scale Russian purchases. Also, Great Plains wheat production does not depend as heavily on fertilizer as does corn production in the Corn Belt or in irrigated areas. To reflect the effects of the free market period on tobacco fertilizer use, we used a dummy variable with 1974-76 equal to one and zero otherwise. During this period, tobacco support prices and acreage allotments were raised, but acreage, which was still under strict government control, increased only 8 percent from 1973 to 1974. At the same time, being encouraged by higher prices (USDA 1977a), farmers increased total fertilizer expenditures (in 1967 constant dollars) on tobacco by 17 percent. The positive estimated coefficient of the free market dummy variable is significant at the 1 percent level and is in conformity with the foregoing reasoning.

The time variable shows the trend in fertilizer application rates over the period of analysis. It is significant in explaining the trend in fertilizer expenditures per acre for feed grains, wheat, and cotton. The increase in fertilizer expenditure is 37.4¢, 15.6¢, and 26.3¢ per acre every year during the period of analysis for feed grains, wheat, and cotton, respectively. The magnitude indicates that during the analysis period per-acre fertilizer expenditures responded most rapidly for feed grains and least rapidly for wheat. In the latter part of the period especially, fertilization of wheat increased faster as wheat became a more commonly fertilized crop. Fertilization of cotton increased less with time because cotton already was a highly fertilized crop.

The negative coefficient for soybeans suggests a decline in per-acre fertilizer expenditures over time. However, the decline in recent years is very small because the variable used is logarithm of time. Unless it is a function of the estimation procedure, this trend is possible in the sense that soybeans are a relatively new crop and farmers are better informed over time about their leguminous nature and small nitrogen requirements.

SUMMARY

Separate fertilizer demand functions are developed for five major crops grown in the United States. Per-acre expenditures on various fertilizer nutrients (N,P,K) and lime are aggregated in terms of real dollars for each crop. A hypothesis that fertilization rates depend on the type of crop leads to the formulation of a separate model for each crop. The results indicate that different crop sectors respond in varying degrees to the same economic factor. More specifically, fertilizer demand is more elastic with respect to fertilizer price for grain (wheat and feed grains) farmers than for oil and cash crop (soybeans, tobacco, and cotton) farmers. The differences in these elasticities stem from the nature of the crop as well as its response to fertilizer application. Our findings suggest that changes in fertilizer prices and government policies will produce effects in varying degrees on different crop sectors.

The income variable is significant in the cotton, tobacco, and feed grain models, tobacco having the largest and cotton having the smallest income elasticity. Feed grains are an intermediate input used in livestock production. Tobacco and cotton are cash crops. Therefore, income generated is a significant factor in deciding fertilizer application. This variable is not significant in wheat and soybean equations as most of the variation is explained by the stock of physical assets variable. Stocks of physical assets and inventories of commodities such as wheat, soybeans, and feed grains can be used to obtain loans for purchases of fertilizer and other inputs. Consequently, the stock of physical assets variable is significant in these three fertilizer demand equations. This variable is not significant in cotton and tobacco demand functions as income is the dominating variable in explaining the variability of fertilizer expenditures.

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