The Demand for Nitrogen, Phosphorous and Potash Fertilizer Nutrients in the Western United States

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An economic model of the demand for fertilizer is specified and equations for nitrogen, phosphorous and potash are estimated for individual states in the western United States. The results are acceptable from both an economic and statistical viewpoint. The estimated price elasticity of demand demonstrates considerable variation between states and nutrients. The quantity of each nutrient sold per acre has increased with expected crop price increases and land price increases. In general, the sales response to shifts in the crop production function has been very elastic. Future shifts in fertilizer demand will be heavily dependent on changes in agricultural productivity.

Applications of commercial fertilizers in the 11 western states have increased substantially since 1955. Total 1977 fertilizer sales in these states were 2,168,500 tons, up 309 percent from the 530,000 tons sold in 1955 (Table 1). The largest increase was for nitrogen, which increased 315 percent from 340,300 to 1,413,200 tons. Nitrogen now accounts for almost two-thirds of commercial fertilizer sales in the West with phosphorous and potash accounting for 27.4 and 7.4 percent, respectively. As shown in Table 1, there is significant interstate variation in total sales of each nutrient.

Western farmers, public officials and others have expressed concern over the impact of increased energy prices and possible restrictions on energy supplies available for fertilizer production. Apparent fertilizer shortages in 1973 and 1974, accompanied by sharply increased prices, are still fresh in their memories.[1] There has been little detailed information available on which to base assessments of likely future occurrences. One would be hard-pressed, for example, to estimate the impact on individual fertilizer nutrient prices in the various states of alternative levels of supply restrictions. Likewise, the impacts on fertilizer sales of changes in various economic parameters are difficult to assess. This paper attempts to partially alleviate this situation by presenting the empirical results of a state-by-state study of the aggregate demand for nitrogen (N), phosphorous (P), and potash (K), the major plant nutrients.

The Demand for Fertilizer

The demand for production inputs is a derived demand based on the demand for the final product. Fertilizer is one of a number of inputs used in crop production. This section presents a summary of previous studies of the demand for fertilizer and outlines the model utilized for the analysis. The impacts of data availability on the model finally estimated are discussed.

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[1]Concern about fertilizer prices and future supplies resulted in a number of hearings and special reports. For examples see U.S. Senate, Bell, *et al.*, and Reidinger.

TABLE 1. Sales of Fertilizer Nutrients and Harvested Crop Acreage in the 11 Western States, 1977

State	Nutrient sales			Harvested crop acreage
	Nitrogen	Phosphorous	Potash	
	---------1,000 tons---------			---1,000 acres---
Arizona	110.0	41.5	1.2	1,182
California	596.1	213.2	69.1	6,131
Colorado	118.1	43.8	11.0	5,837
Idaho	139.0	61.1	12.8	4,235
Montana	64.0	74.3	8.6	9,111
Nevada	4.8	2.1	.2	490
New Mexico	32.3	17.6	1.6	1,313
Oregon	127.2	50.3	25.6	2,615
Utah	27.0	17.1	.8	1,009
Washington	175.1	65.3	30.2	4,657
Wyoming	19.6	6.8	1.1	1,773
Total	1,413.2	593.1	162.2	38,353

Source: U.S. Department of Agriculture, Statistical Reporting Service, *Commercial Fertilizers, Consumption for Year Ended June 30, 1977,* November 1977.

U.S. Department of Agriculture, Economics, Statistics and Cooperatives Service, *Crop, Production, 1977 Annual Summary,* January 1978, p. B-7.

Previous Work

Models of both national and regional demand for fertilizer have been estimated in a number of empirical studies. A partial list includes reports by Griliches, 1958, 1959; Heady and Yeh, Brake, King and Riggan, and Rausser and Moriak. The models specified in these studies exhibit many similarities and some differences. The dependent variable has most often been specified as total fertilizer use for a region or for the United States. Griliches, 1958, deflated total plant nutrient use by an index of cropland acreage while Rausser and Moriak employed total nutrient use per acre as their quantity variable. Only Heady and Yeh examined the demand for the individual major nutrients (N, P, K). The variables affecting quantity demanded have included fertilizer prices, crop prices, total cash receipts from crops, total crop acreage, acres of specified crops, cash rent, wage rates, wholesale price index, and time. Each of the models was estimated by single equation methods on the assumption that prices of fertilizer, other inputs, and output prices can be regarded as predetermined at the time the purchase decision is made. Each study concentrated on estimating functions specified as linear in logarithms.

The Model

Economic theory suggests that the quantity of fertilizer used will be a function of expected output prices, the price of fertilizer, prices of related inputs, and the productivity of fertilizer and related inputs. A producer's demand for fertilizer is derived from the underlying production function and demand for the commodities produced with the fertilizer.[2] To derive the input demand function, one forms the profit function in terms of output price, the production function, and costs associated with the inputs. Maximization of profits with respect to the quantity of inputs by taking the partial derivatives of the profit function with respect to the inputs, setting the partial derivatives equal to zero and solving these equations for the quantity of inputs, yields the input demand functions. If one assumes a Cobb-Douglas production function, the demand function for the inputs will be linear in the logarithms. This functional form was selected as appropriate for the analysis of fertilizer demand.

[2]The theory of input demand is presented in a number of sources. For one presentation see Henderson and Quandt [pp. 69-70].

Estimation of the model requires selection of the appropriate inputs and definition of the relevant variables. Previous research results and data considerations dictated the choice here. The major inputs for crop production include land, labor, machinery, seed, water and fertilizer. Only land and labor, however, have been shown to have a major impact on fertilizer demand and their impact has been declining over time [Rausser and Moriak]. Labor was dropped from consideration in the early stages of this study when it was found to add little or nothing to the explanatory power of the estimated equations.

Since time series data are utilized here, the impact of shifts in the production function on fertilizer demand must be considered. Introduction of new crop varieties, cultural practices, other new technology, expanded irrigation, and adoption of new fertilization practices have shifted the production function through time. These shifts can be measured by the farm productivity index (an index of output per unit of input) or by a trend variable if the shifts have occurred uniformly through time.

The demand equation estimated for each state for each nutrient is specified as:

$$\ln Q_i = a_0 + a_1 \ln P_i + a_2 \ln Y_{T-1} + a_3 \ln LP + a_4 \ln FPI + u$$

where Q_i is pounds of plant nutrient sold per acre of harvested cropland in each state (i=N is nitrogen, P is phosphorous and K is potash), P_i is an index of nutrient price divided by the wholesale price index (1967=100), Y_{T-1} is average gross crop income per acre divided by the wholesale price index lagged one year, LP is an index of land prices deflated by the wholesale price index (1967=100), FPI is the farm productivity index (1967=100), and u is the error term. In a very limited number of cases, a time trend variable T (1955=1, . . ., 1976=22) substituted for the farm productivity index improved the explanatory power of the estimated equation.

The quantity of each nutrient (N, P, K) sold per acre is expected to vary inversely with the price of the nutrient and to vary directly with expected crop prices. Since expectations cannot be observed, but are based on recent experience, gross crop income per acre lagged one year is used as a proxy variable for expected crop price.[3] The coefficient on the land price index should be positive, indicating that fertilizer is used more intensively when real land prices increase. The coefficient for the farm productivity index (and T) should also be positive. Total sales of each nutrient for a state are the product of per acre sales and total harvested crop acreage.

Data

Fertilizer sales data by state are from annual issues of *Agricultural Statistics* with recent data coming from annual issues of *Commercial Fertilizers, Consumption in the United States.* Fertilizer price data are for April 15 of each year and are taken from *Agricultural Prices, Annual Summary.* The nitrogen price index is based on the price of ammonia sulphate. The prices of nitrogen containing fertilizer products move together and the price of ammonia sulphate was the only price series available for all 11 states for the sample period. The phosphorous price index is based on the price of super phosphate (20 percent P_2O_5) and the potash price index is based on the price of muriate of potash. These are representative price series for the two nutrients. Crop acreage and total cash receipts from crops are from annual issues of *Agricultural Statistics.* The crop acreage data utilized do not include acreage of

[3]A state-by-state index of crop prices is not available but gross crop income is reported for each state. If aggregate yields are relatively constant from year-to-year, then gross crop income per acre will be a good proxy for crop prices. Heady and Yeh [p. 334] utilized variables for both crop prices and cash receipts and found that the two variables were highly correlated. Lagged crop income may also capture the effect of capital availability and income tax provisions on farmer input purchasing behavior.

tree and vine crops, but the impact of this omission is minor since tree and vine crop acreage varies slowly through time. The land price index is the index of average value of irrigated land for each state taken from *Farm Real Estate Market Developments*. The farm productivity index is reported by region but not by state in the publication *Changes in Farm Production and Efficiency, 1977*. Data for the Pacific region are used for Washington, Oregon and California and the index for the Mountain region is utilized for the other eight states. The wholesale price index for all items is from *Agricultural Prices*. All of the cited publications are published by the U.S. Department of Agriculture.

Results

The general fertilizer demand equation, as specified, was estimated for each nutrient using ordinary least squares methods and time series data for the period 1955-1976. Equations for nitrogen and phosphorous were estimated for all 11 western states but demand equations for potash were estimated for only seven states. Sales of potash in the other four states (Arizona, Nevada, Utah and Wyoming) were very small both in total tons and pounds per acre (Table 1). Any results in terms of pounds per acre would have questionable validity and limited usefulness.

The estimated coefficients for the land price variable (LP) were examined, those which were statistically insignificant were deleted, and the equations were re-estimated. The demand equation which had the highest multiple correlation coefficient adjusted for degrees of freedom $(\overline{R}^2)$ was then chosen for presentation.

Simple sales forecasting equations for fertilizer nutrients which utilized a time trend variable were estimated during the early stages of the analysis. Comparison of the sales forecasting and demand equations led to substitution of a time trend variable (T) for the farm productivity variable (FPI) in four equations. This substitution substantially improved the estimated results as shown by the test statistics. Results of estimating the demand model are presented in tabular form in Tables 2, 3 and 4.

Nitrogen

The estimated coefficients for the nitrogen demand equations are shown in Table 2. The results are quite acceptable from both an economic and statistical viewpoint. The signs on all of the coefficients are as hypothesized and most of the coefficients are significantly different than zero.[4] With the exception of the equation for Nevada, the multiple correlation coefficients (R^2) indicate that the variables included explain over 91 percent of the variation in per acre sales of nitrogen. The Durbin-Watson statistics indicate that autocorrelation in the error terms is not a serious problem. Several of the "d" values are in the inconclusive range but none would lead to acceptance of the hypothesis of positive (or negative) autocorrelation.

The coefficients for the real price index of nitrogen are relatively large in relation to their standard errors as shown by the t-statistics and most are statistically significant. Since the equations were estimated as linear in logarithms, the coefficients can be interpreted as elasticities. The results indicate that the demand for nitrogen is price elastic in Idaho, Montana, Nevada and Wyoming and price inelastic in the other western states. Thus, if nitrogen were to be rationed by increasing real prices, the largest percentage adjustments would occur in states with the highest calculated elasticities. Note that the two states with the most inelastic demand, California and Washington, accounted for almost 55 percent of total nitrogen sales in 1977.

The variable for lagged real crop income per acre has the hypothesized positive impact on nitrogen sales in each of the equations and approximately half of the coefficients are significant. Note that the sales response to changes in crop income generally is quite in-

[4]All statements concerning statistical significance are based on a 95 percent confidence interval.

TABLE 2. Regression Coefficients and Related Statistics for Nitrogen Fertilizer Demand, 11 Western States, 1955-1976[a]

State	Constant	ln P_N	ln Y_{T-1}	ln LP	ln FPI	ln T	R^2	d[b]
	coefficients							
Arizona	−6.998	−.705	.671		2.482		.952	1.977
	(−5.68)[c]	(−5.19)	(3.84)		(12.94)			
California	−6.009	−.204	.791	.231	1.298		.968	1.821
	(−4.42)	(−1.89)	(5.55)	(1.84)	(3.95)			
Colorado	−15.544	−.802	.510	1.824	2.626		.975	1.488
	(−6.10)	(−3.31)	(2.14)	(3.45)	(3.25)			
Idaho	−11.790	−1.477	.174	2.628	2.002		.948	1.468
	(−3.17)	(−4.13)	(.52)	(3.14)	(1.89)			
Montana	−17.137	−1.837	.029		5.893		.949	1.732
	(−3.47)	(−3.90)	(.12)		(7.90)			
Nevada	−3.675	−1.314	.809		2.061		.836	1.171
	(−.66)	(−2.80)	(2.26)		(1.87)			
New Mexico	−14.689	−.735	.243		4.480		.917	1.893
	(−6.16)	(−2.64)	(.92)		(11.74)			
Oregon	−5.857	−.551	.423	.657	1.620		.968	2.508
	(−3.39)	(−3.17)	(2.46)	(2.50)	(2.88)			
Utah	−13.933	−.454	.836	1.204	2.303		.918	1.363
	(−3.63)	(−1.54)	(1.66)	(1.07)	(2.11)			
Washington	3.682	−.302	.045			.621	.969	2.606
	(4.76)	(−1.84)	(.35)			(11.71)		
Wyoming	−19.376	−1.031	.394	1.364	4.185		.965	2.415
	(−5.75)	(−2.54)	(1.52)	(1.84)	(3.46)			

[a]The dependent variable is ln Q_N where Q_N is total nitrogen sales divided by total crop acreage.
[b]"d" is the Durbin-Watson statistic. The critical values at the five percent level of significance are: $d_L = 1.05$, $d_u = 1.66$.
[c]Figures in parentheses are t-statistics.

elastic with seven of the coefficients equal to or less than 0.51 and the remaining four less than 0.84.

The index of real land prices was positively related to nitrogen sales, as expected, but not always significant. Using the procedure outlined earlier, the land price variable was deleted from five equations because it added nothing to explanatory power. In two of the five equations, the real land price index was highly correlated with the farm productivity index.[5] Thus, if changing land prices have an impact, it likely is captured by the remaining variables.

The per acre nitrogen sales response to increasing agricultural productivity has been very elastic. As shown by the estimated coefficients, a one percent increase in productivity has been associated with per acre nitrogen sales increases in the range of 1.3 to 5.9 percent. This strong positive response is con-

[5]While multicollinearity was not a serious problem in the estimated equations, some was present. As noted, the two variables which exhibited the highest correlation were the land price index and the farm productivity index. The simple correlation between these two variables was in excess of .80 for Colorado, Idaho, Montana, Oregon, Utah and Wyoming.

sistent with increases in the marginal product (and marginal value product) of nitrogen fertilizer as a result of outward shifts in the production function. The changes in technology underlying these shifts include new crop varieties, increased irrigation, and land development.

The estimated nitrogen demand equation for Washington, as originally specified, yielded disappointing results. The equation had a relatively low R^2 and there was evidence of autocorrelation. Substitution of a trend variable (T) for the farm productivity index remedied these problems. The trend variable is undoubtedly accounting for the impact of shifts in the production function as well as other factors. Perhaps the regional farm productivity index utilized is not a valid measure of changing farm productivity in Washington.

Phosphorous

Estimated coefficients for the phosphorous demand equations are shown in Table 3. Again, the estimates are in line with expectations. One coefficient has a different sign than hypothesized, but it is not statistically significant. Eight of the 11 equations have R^2 values in excess of .90 and autocorrelation is not a problem as indicated by the Durbin-Watson statistics.

TABLE 3. Regression Coefficients and Related Statistics for Phosphorous Fertilizer Demand, 11 Western States, 1955-1976[a]

State	Variables						R^2	d^b
	Constant	ln P_p	ln Y_{T-1}	ln LP	ln FPI	ln T		
	coefficients							
Arizona	−10.325	−1.368	.456	.326	3.572		.941	2.197
	(−7.06)[c]	(−6.04)	(2.51)	(1.59)	(13.770)			
California	−4.833	−.975	.725	.512	1.398		.940	1.594
	(−2.77)	(−3.11)	(3.80)	(3.15)	(3.370)			
Colorado	−12.023	−.480	−.066	1.630	2.077		.914	1.141
	(−5.30)	(−1.53)	(−.27)	(2.61)	(2.070)			
Idaho	3.236	−.568	.080			.841	.950	1.170
	(1.37)	(−1.07)	(.38)			(10.83)		
Montana	−10.202	−2.384	.218	1.800	3.090		.956	2.194
	(−3.06)	(−4.65)	(1.04)	(3.17)	(2.820)			
Nevada	−9.563	−1.219	.565		3.328		.826	1.448
	(−2.45)	(−1.83)	(1.72)		(4.170)			
New Mexico	−8.997	−.732	.031	.569	2.796		.791	2.005
	(−5.02)	(−2.60)	(.11)	(1.14)	(4.620)			
Oregon	−3.215	−.892	.155	2.013	.147		.952	2.267
	(−1.21)	(−2.56)	(.69)	(6.07)	(.187)			
Utah	−18.581	−2.038	.093		6.722		.881	1.910
	(−7.27)	(−3.19)	(.13)		(9.000)			
Washington	1.228	−.291	.290			.652	.955	2.557
	(.47)	(−.48)	(1.72)			(11.50)		
Wyoming	−7.716	−1.366	.250	2.045	1.348		.904	2.554
	(−2.51)	(−2.04)	(.87)	(2.99)	(1.020)			

[a]The dependent variable is ln Q_p where Q_p is total phosphorous sales divided by total crop acreage.
[b]"d" is the Durbin-Watson statistic.
[c]Figures in parentheses are t-statistics.

Each of the phosphorous price index coefficients has a negative sign and most are statistically significant. The demand for phosphorous is price elastic in Arizona, Montana, Nevada, Utah and Wyoming and inelastic in the other six western states. Note, however, that the states with price elastic demand accounted for only 24 percent of total western phosphorous sales in 1977 (Table 1).

One equation, for Colorado, has an unexpected negative coefficient on the lagged crop income variable, but it is not significant. The other ten coefficients on the lagged crop income variable are positive, as expected, but the majority are not statistically significant. The lagged phosphorous sales response to a change in per acre real crop income is quite inelastic with the largest coefficient being .725 and seven of the 11 states having coefficients less than .250.

The coefficients for the real land price variable have the expected sign; however, the variable was dropped from four equations because it added nothing to explanatory power. Coefficients for the farm productivity index have the expected positive relationship to phosphorous sales. For eight of the nine equations which include the variable, the sales response to changes in productivity is quite elastic. The one state with an inelastic coefficient (Oregon) has a high degree of multicollinearity between the land price and farm productivity indexes making separate interpretations of the magnitude of the two coefficients difficult. A trend variable (T) was substituted for the farm productivity index for Idaho and Washington to yield improved explanatory power.

Potash

Results of estimating the potash demand equations for seven of the 11 western states are shown in Table 4. Again, the results are generally in line with expectations. There is one incorrect sign on the lagged crop income

TABLE 4. Regression Coefficients and Related Statistics for Potash Fertilizer Demand, Seven of the 11 Western States, 1955-1976[a]

State	Variables						R^2	d[b]
	Constant	ln P_K	ln Y_{T-1}	ln LP	ln FPI	ln T		
	coefficients							
California	−2.486	−1.494	−.231		2.900		.935	1.838
	(−.79)[c]	(−3.50)	(−.93)		(6.03)			
Colorado	−15.293	−1.147	.027	2.374	2.225		.958	1.980
	(−3.46)	(−2.25)	(.10)	(3.58)	(2.05)			
Idaho	−40.556	−.207	.746		8.350		.911	2.423
	(−4.54)	(−.19)	(1.16)		(5.90)			
Montana	−34.592	−2.333	.263		9.248		.912	2.462
	(−2.59)	(−1.71)	(.51)		(5.56)			
New Mexico	−20.329	−3.269	1.062	2.377	4.391		.890	1.850
	(−1.94)	(−2.22)	(1.82)	(2.26)	(3.10)			
Oregon	−4.157	−.529	.576	1.163		.259	.919	1.535
	(−1.09)	(−.97)	(1.93)	(2.10)		(1.31)		
Washington	−18.070	−.422	.498	1.695	2.584		.887	2.413
	(−2.90)	(−.59)	(1.38)	(2.01)	(2.73)			

[a]The dependent variable ln Q_K where Q_K is total potash sales divided by total crop acreage.
[b]"d" is the Durbin-Watson statistic.
[c]Figures in parentheses are t-statistics.

variable in California but it is insignificant. All other coefficients have the hypothesized signs. The R^2 values are all greater than .88 and the Durbin-Watson statistics are satisfactory.

Each real potash price variable has the expected negative relationship to potash sales. The estimated demand for potash is elastic in California, Colorado, Montana and New Mexico and inelastic in the other three states. Note that the coefficients tend to be statistically significant for states with elastic demand and insignificant for states with inelastic demand. No explanation of this relationship is offered.

The coefficients for the lagged crop income variable have the expected positive signs except for California. The response of sales to changes in crop income is inelastic for all states except New Mexico. The coefficients for the land price variable are each positive and statistically significant. The land price variable was dropped from three equations when it failed to add any explanatory power.

The coefficients for the farm productivity index are positive and significant. The responses of potash sales to changes in farm productivity are very elastic with all of the coefficients in the range of 2.2 to 9.2. A trend variable was substituted for the farm productivity index in the demand equation for Oregon.

Concluding Comments

The estimated demand equations for the three basic fertilizer nutrients in the western U.S. yield results that are in general agreement with the hypothesized relationships expressed in the economic model. Much of the variation in per acre sales of each nutrient, as measured by R^2, is explained by the variables included in the equations. All price coefficients have the expected negative sign and the majority are significant. The lagged crop income variable appears to be a reasonable proxy for expected crop prices, particularly for nitrogen fertilizer. Two coefficients for lagged crop income had unexpected negative signs, but neither was significant. Land prices had the expected positive relationship to nutrient sales, but the variable was deleted from several equations when it added nothing to explanatory power. The farm productivity index, used to measure shifts in the production function, had a strong positive impact on sales and most of its coefficients were significant.

Direct comparison of the results of this study with others is difficult even though there are many similarities in the economic and statistical specifications. Published elasticities demonstrate considerable variation based on time period considered, nutrients, and geographical region. This is illustrated by estimates of direct price elasticities for fertilizer. Rausser and Moriak, in their study of the demand for all fertilizer in the United States (U.S.), found that the estimated price elasticity had changed from −.50 in 1949 to −.70 in 1964. Griliches [1959] estimated short- and long-run price elasticities for all fertilizer for the period 1931-1956. His estimates were: Mountain region, short-run −.45, long-run −3.21; Pacific region, short-run −.408, long-run −2.57; U.S., short-run −.393, long-run −2.14. Heady and Yeh estimated separate elasticities for nitrogen, phosphorous and potash, but did not present regional results for each nutrient. Their estimated price elasticities for the U.S. were N = −.449, P = −.448 and K = −.403. Their estimated regional price elasticities for all fertilizer were Mountain, −1.266 and Pacific, −1.057. Given the results of these studies, the variation in calculated elasticities for the western states and individual nutrients is not surprising. Individual state estimates of direct price elasticities range from −.20 to −1.84 for nitrogen, from −.29 to −2.38 for phosphorous and from −.21 to −3.26 for potash. In general terms the simple average western price elasticity is inelastic for nitrogen and elastic for phosphorous and potash.

The variability in estimated elasticities for fertilizer in the western states is an important consideration when examining the possible impact of increased fertilizer prices, restricted supplies, and future demands. The impact of rationing fertilizer supplies through price increases, for example, would vary significantly from state-to-state. Likewise, supply allocations would result in quite different price impacts from state-to-state. The possible differential impacts on manufacturers, dealers and farmers as a result of differing responses are important in the formulation of future public policies.

Much of the growth in fertilizer demand in the West can be associated with significant shifts (increases) in agricultural production functions. For most states and nutrients, a one percent increase in the index of agricultural productivity has been associated with a two-to-three percent increase in per acre sales of the nutrient. Thus, future increases in the demand for fertilizer nutrients will be strongly dependent on continued increases in agricultural productivity.

This article provides some insights into the nature of demand for the basic fertilizer nutrients in the western United States. Substantial variations between states and nutrients is an interesting and important finding. More work is necessary, however, to improve estimates of the separate effects of the various demand factors. The probable nature of future innovations affecting fertilizer use is an important topic. Improved data, such as individual state estimates of changes in agricultural productivity and state crop price indexes could help to improve future analyses.

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