Fertilizer Demand Functions for Specific Nutrients Applied to Three Major U.S. Crops

Roland K. Roberts and Earl O. Heady

Several past studies used time series data to estimate price elasticities of demand for fertilizer or nutrient use on all crops in the United States or by region. In this study, demand functions for nitrogen, phosphorous and potassium applied per acre of corn, wheat and soybeans in the United States were estimated, using a combination of autoregressive least squares and seemingly unrelated regression techniques. The results suggest that the demands for nitrogen, phosphorous and potassium applied to corn are price elastic, while similar responses for wheat and soybeans are price inelastic. Nitrogen and phosphorous applied per acre of corn were found to be positively related to government sponsored acreage diversion. The estimated elasticities could provide policymakers with insight for developing fertilizer and crop policies.

The demand for fertilizer as a factor of production in U.S. agriculture has been the focus of several past studies, some of which include work by Griliches [1958, 1959], Heady and Yeh, Brake, King and Riggan, Rausser and Moriak, Carman, and Gunjal, Roberts and Heady. In general, emphasis has been on national or regional demand estimates for total fertilizer or nutrient application to all crops. Little emphasis has been placed on estimating fertilizer demand functions for individual crops using time series data.

Griliches [1958] estimated aggregate demand functions for fertilizer use on all crops in the United States. He demonstrated for 1911 to 1956 that most of the increase in fertilizer use could be explained by changes in fertilizer and crop prices and by the previous period's fertilizer use. Using the same model, Griliches [1959] estimated regional demand functions for total fertilizer consumption over the 1931 to 1956 period. Again his model explained a large portion of the variation in regional fertilizer use, and he found that estimated price elasticities of demand varied across regions.

Heady and Yeh estimated fertilizer demand functions for total fertilizer and for individual nutrients used on all crops in the United States. In addition, they estimated relationships for total fertilizer use in ten different geographical regions of the United States. Their study allowed a comparison of aggregate fertilizer and individual nutrient demand elasticities, with respect to fertilizer price, average crop prices, and other relevant variables, across regions. Carman also disaggregated fertilizer use by nutrient and estimated nutrient demand functions for 11 western states.

Data are now available to not only disaggregate fertilizer use by plant nutrient, but also by major crop. Gunjal, Roberts and

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Roland K. Roberts is an assistant professor in the Department of Agricultural and Resource Economics at the University of Hawaii at Manoa. Early O. Heady is C. F. Curtis Distinguished Professor of Agriculture and Professor of Economics, Center for Agricultural and Rural Development, Iowa State University.

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Heady estimated aggregate U.S. fertilizer demand functions for five major crops (feed grains, wheat, soybeans, cotton and tobacco). Generally, their study suggested that elasticities of demand, with respect to prices and other explanatory variables, were not similar for fertilizer applied to different crops. In their study, fertilizer was not disaggregated into individual nutrients.

It would be interesting and useful for crop-specified policy purposes to estimate empirically the response of fertilizer use for individual crops to changes in economic phenomena. Also, in times of increased awareness of energy scarcity and the environmental effects of fertilization, it would be interesting to understand more fully the response of individual nutrient demand for use on specific crops to changes in economic conditions. For example, if price elasticity of demand estimates for a particular nutrient were different among crops, projections could be made of differential impacts upon crops caused by higher nutrient prices resulting from a restricted supply of the nutrient. Elasticity estimates by crop and nutrient might additionally provide policymakers with insight for developing fertilizer pricing policies designed to promote certain crops and/or ration scarce nutrients. If the effects of government policies on nutrient application rates were known for specific crops, policymakers would be more able to foresee changes in nutrients applied to different crops and anticipate production responses stemming from government action.

The purpose of this paper is to estimate three nutrient demand functions from time series data for each of three major U.S. crops and to draw policy implications from the estimated elasticities of demand. To this end, separate nutrient demand functions are estimated for nitrogen (N), phosphorous (P) and potassium (K) applied per acre of corn, wheat and soybeans grown in the United States. Discussion of derived input demand theory, data sources and statistical considerations precede the presentation of the estimated nutrient demand functions and elasticities. As the estimated demand functions are presented, policy implications are drawn by comparing elasticities of demand, with respect to relevant explanatory variables, across crops and nutrients.

Conceptual Framework

The demand for an input used in production is a derived demand hinging on the demand for the final product. The plant nutrients, N, P and K, are combined with other production inputs to produce crops in the United States. Nutrient derived demand functions can be formulated if farmers are assumed to maximize profits under competitive conditions. The profit function is expressed as revenues minus costs, where revenues are stated in terms of the product price and the underlying production function, and costs are the sum of input quantities times their respective prices. The partial derivatives of the profit function, with respect to the input quantities, are set equal to zero and solved simultaneously to obtain the derived demand functions. Formulated in this manner, the derived demand for a particular nutrient is a positive function of the product price and a negative function of its own price, while the signs of the relationships with other input prices are indeterminate.

Though prices may be important in determining nutrient application rates, they are possibly less important than other less measurable influences. The introduction of new technology such as improved crop varieties, new cultural practices, increased and more rapid acceptance of these new technologies and cultural practices by farmers, expanded irrigation, and fertilizer product diversification for the purpose of increasing product acceptability on particular crops have all caused shifts in the production function, causing the derived demand for plant nutrients to shift over time. A time trend can be used to represent the influence of shifts in the production function over time. Carman represented production function shifts by the farm productivity index (an index of output per unit of input, 1967 = 100) and in some instances by a time trend. The simple correlation coefficient between time and the U.S. farm productivity index is .98. Generally, the time trend proved to be more useful in explaining nutrient application rates in the present model because it introduced less multicollinearity as evidenced by lower coefficient standard errors, and because in addition to productivity changes it captured the influence of other relevant time-correlated variables.

The prices of substitute and complementary inputs should theoretically be included in the model. However, for practical reasons other input prices were excluded.[1] Preliminary scans of the data suggested a high degree of correlation among prices of land, labor, machinery, motor supplies, farm supplies, time, and lagged crop gross income. Simple correlation coefficients were all over .8 in absolute value and in the vast majority of cases over .9. Because of the high degree of correlation among candidates for inclusion in the model, the time trend was assumed to represent shifts in derived demand caused by a variety of influences. Other variables, such as the wage rate, were eliminated from the model to reduce multicollinearity. Had the wage rate been included in place of the time trend, it would have been incorrect to attribute changes in nutrient consumption solely to changes in the wage rate because of its high correlation with other relevant variables over time. Thus, the time trend captures in one proxy variable several correlated influences, yet it does not lead to overemphasis of any single economic variable. Additionally, because multicollinearity is reduced by replacing a number of highly time-correlated variables with a time trend, more efficient estimates of price elasticities of demand result.

Government acreage control programs are designed to control supply and support crop prices by reducing crop acreage. It seems likely that farmers would apply on their remaining acreage some of the resources they might have used on their diverted land. Also, with the program comes a greater degree of certainty about the product price. Therefore, a positive relationship is postulated between the number of acres diverted and the quantity of fertilizer applied to the remaining acreage.

Finally, since the output price is unknown when plant nutrients are required, fertilizer decisions must be based on expected price. If farmers are assumed to use crop prices of the most recent past to form their expectations, then the derived demand for the j-th nutrient applied per acre of the i-th crop as hypothesized thus far can be expressed as

$$\begin{aligned} i\text{-}j\mathrm{AC} = \mathrm{a}_0 + \mathrm{a}_1\, j\text{-PR} + \mathrm{a}_2 i\text{-PR} \\ + \mathrm{a}_3 i\text{-DIV} + \mathrm{a}_4\mathrm{T} + \mathrm{u}_{ij} \end{aligned}$$

where i-jAC is the quantity of nutrient j per harvested acre of crop i, j-PR is the price of nutrient j, i-PR is the price of crop i lagged one period, i-DIV is the number of acres diverted from production of crop i, T is a time trend, u_{ij} is the stochastic disturbance of the j-th nutrient applied to the i-th crop, and $\mathrm{a}_0 - \mathrm{a}_4$ are parameters to be estimated.

Data Sources

Annual time series data for 1952 through 1976 were used to estimate the derived demand functions for N, P and K applied to corn, wheat and soybeans. A major difficulty in estimating these functions was the lack of appropriate time series data that could be used directly from published sources. Therefore, various assumptions were used to form the necessary time series from the available data. The task of forming the appropriate time series was greatly simplified by using Stoecker's data for 1952-69.

Stoecker obtained preliminary nutrient application rates per acre receiving fertilizer,

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[1] Attempts were made to include all three nutrient prices in each equation, but because of multicollinearity, coefficient variances were high and several coefficients had incorrect signs. The simple correlation between the prices of N and K was .98. Consequently, only one nutrient price was included in each equation.

the proportion of harvested acres receiving fertilizer, and harvested acreage for all states and crops for 1954, 1959 and 1964 from studies based on the Census of Agriculture [USDA 1957; Ibach and Adams; Ibach, Adams and Fox]. Similar data were obtained for major states producing corn, wheat, soybeans and cotton for 1965-69 from survey data on cropping practices [USDA 1971]. Preliminary application rates per acre receiving fertilizer and the proportion of harvested acreage receiving a particular nutrient for states and crops not included in the sources cited above were obtained by interpolation. Preliminary application rates were then modified to conform with published data series. The methodology for modifying the data will be discussed after presenting the methods used to extend the preliminary observations.

To be consistent with Stoecker's data, the authors used his techniques to extend the data to 1976. Preliminary data for 1970-76 were taken from Statistical Reporting Service Objective Yield Survey Data [USDA 1977b]. The 1970-76 Objective Yield Survey Data included most of the corn, wheat and soybean acreage. For example, in 1976 it covered 94, 92 and 88 percent of the harvested acreage of corn, wheat and soybeans respectively [USDA 1977a]. Preliminary application rates and proportions of acreage receiving nutrients for states and crops not included in the 1970-76 surveys (minor states and crops) were obtained by interpolation. Major states and crops (states and crops included in the surveys) were used as references in developing preliminary data for minor states and crops. Using Stoecker's 1969 data, the application rate for a particular crop in a minor state was divided by the application rate in an adjacent major state to form a ratio. A similar ratio was formed from the unpublished background data of the 1974 Costs of Production Survey [USDA 1976]. The ratio was interpolated between 1969 and 1974 and extended to 1976. The preliminary application rate for the minor state was then obtained by multiplying the interpolated ratio by the major state's application rate in each year. This procedure was used for each minor state and crop, using major crops as references for minor crops and major states as references for minor states. The same procedure was used to obtain preliminary estimates for minor states and crops of the proportion of harvested acres receiving a particular nutrient.

The final nutrient application rates per harvested acre used in this study were obtained by modifying the preliminary 1952-76 data. Preliminary national totals for each nutrient were calculated by forming the product of harvested acreage, the proportion of harvested acreage receiving fertilizer, and the preliminary application rate per acre receiving fertilizer, and summing across crops and states. Final application rates per acre receiving fertilizer were then derived by adjusting the preliminary application rates so that the national totals of each nutrient conformed with the published national totals (USDA 1978 and previous issues). 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 and K use for corn, wheat and soybeans in the United States were formed by summing nutrient use across states for each crop and nutrient. Final application rates per harvested acre were then obtained by dividing by the harvested acreage of the appropriate crop. For the interested reader, more detail concerning the derivation of these nutrient application rates can be found in Schatzer, et al.

Nutrient prices in cents per pound were formed by averaging compound prices after converting them to elemental prices [USDA 1952-59; 1961-77]. The number of acres diverted from production under the corn and wheat programs were taken directly from *Agricultural Statistics* [USDA 1975].

Statistical Considerations

Efficient estimates of the nutrient demand function parameters cannot be obtained from ordinary least squares (OLS) estimation for three reasons. *First,* the data contain a high degree of autocorrelation preventing efficient estimation by OLS. This problem can be solved by estimating each equation by an efficient autoregressive method. *Second,* some degree of multicollinearity exists among the explanatory variables. As mentioned earlier, attempts were made to reduce multicollinearity by using a time trend as a proxy for technological innovations and other potentially relevant variables that are correlated over time. Still, there is a certain amount of correlation among the variables remaining in the model. Correlation of nutrient prices with lagged crop prices is a possible problem. Wheat demonstrates the highest degree of correlation among prices. Simple correlation coefficients for N, P and K prices with the lagged wheat price are .904, .833 and .882 respectively. As tests of significance are performed later, it should be recognized that inefficiency caused by multicollinearity might result in high standard errors causing a failure to reject certain hypotheses that should rightly be rejected. Though multicollinearity cannot be totally eradicated from the model, it is much less serious than the other two causes of inefficiency discussed here. *Third,* if the disturbances (u_{ij}'s) are correlated across equations, then a systems approach such as seemingly unrelated regression would provide more efficient estimates of the parameters.

The disturbances are likely to be correlated across nutrient demand equation for a particular crop because of errors in farmers' expectations. Farmers often apply nutrients to crops in the form of mixed fertilizers. Consequently, if farmers apply a non-optimal quantity of P per acre, it is also likely that they will apply non-optimal quantities of N and K. Weather conditions and other factors that affect the application of fertilizer in general might also cause the disturbances to be correlated.

Disturbances across crops for the same nutrient are also possibly correlated. In some regions, all three crops are produced, and in many instances they are produced in a multiproduct firm situation. Again, weather conditions that cause non-optimal fertilization of one crop might cause non-optimal fertilization of another crop. More importantly, however, errors in output price expectations could cause disturbances across crops to be correlated. For a corn-soybean farm, a relative increase in the expected corn price might cause more fertilizer per acre to be applied to corn and less to soybeans, especially if there is a budget constraint restricting fertilizer purchases. If relative expected prices are in error, then errors for nutrients applied to corn would be correlated with errors for nutrients applied to soybeans.

Another statistical problem not easily remedied stems from the procedures used to formulate the dependent variables. Because the observations are obtained through various assumptions and interpolation, the estimated coefficients are possibly biased. However, the authors feel that the application rates derived from these procedures are acceptable. The estimated equations presented later show that nutrient application rates are responsive to changes in nutrient and crop prices. The interpolation procedures used to obtain preliminary observations allow application rates for minor states and crops to vary in relation to application rates of major states and crops. Therefore, interpolation is not linear in application rates. While the generation of data in this manner imposes certain statistical problems, it is felt that these problems are small relative to the results obtained.

Results and Implications

To obtain greater efficiency over OLS parameter estimates, each of the nine nutrient demand functions was estimated with a maximum likelihood autoregressive technique [White]. The correlation matrix of the resulting estimated residuals showed that 58 percent of the correlation coefficients were significantly different from zero at the 5 percent level, suggesting that seemingly unrelated regression would further increase the efficiency of the estimates. Equations 1 through

9, presented in Table 1, were estimated with seemingly unrelated regression [Zellner], after using the estimated first order autoregressive parameters, also presented in Table 1, to transform the original data [Kmenta]. All coefficients except two have the hypothesized signs. Though the coefficients for acreage diversion in equations 3 and 6 are negative, high standard errors suggest that they are not significantly different from zero.

Of the nutrient and lagged crop price variables, only five have coefficients that are less than twice their standard errors. Conversely, only two of the coefficients for diverted acreage have coefficients that are more than two times their standard errors. All of the trend coefficients are positive and highly significant.

Table 2 contains the estimated elasticities (at the means of the data) obtained from equations 1-9. Several pair-wise asymptotic t-tests are performed to ascertain whether elasticities of nutrient application per harvested acre, with respect to any given explanatory variable, are statistically different from one another.[2] These tests for nutrient and crop price elasticities are presented in Tables 3 and 4. Tests for other variables are mentioned in the text where appropriate as implications are drawn from the results.

Nutrient Prices

The magnitudes of the coefficients presented in Table 2, in conjunction with the contents of Table 3, reveal that nutrient price elasticities of demand for nutrients applied to corn are greater than analogous elasticities for wheat and soybeans. One of Marshall's rules governing derived demand elasticities states that the elasticity of demand for a factor varies directly with the elasticity of demand for the product the factor produces [Layard and Walters]. The demand for nutrients applied to corn is derived from the demand for corn. But corn is most often fed to livestock, and therefore, its demand is derived from the final consumer demand for livestock products. On the other hand, the demands for wheat and soybean, though in part derived from the demand for livestock products, are more dependent on the demands for cereals and edible oils. Price elasticities of demand for livestock products are typically greater than demand elasticities for cereals and edible oil [Brandow]. Therefore, the finding that price elasticities of nutrient demand for corn are greater than those for wheat and soybeans is in accordance with *a priori* expectation.

The results of tests not reported in tabular form reveal that all except one of the elasticities of nutrient demand with respect to nutrient prices, are significantly different from unity. The exception is the P price elasticity of demand for P applied to wheat. Nutrient price elasticities of demand for nutrients applied to corn are all greater than unity in absolute value, implying that demand is price elastic. Conversely, nutrient demand is price inelastic for nutrients applied to wheat and soybeans. Therefore, any attempt by government to ration plant nutrients through excise taxes, or other price rationing mechanisms, would result in a greater decrease in nutrients applied per acre of corn than wheat and soybeans.

The nutrient price elasticities of demand obtained from this research can be compared with results found in other studies. Carman reported N price elasticities of demand for 11 western states ranging between −1.8 for Montana and −0.3 for Washington. He also reported both elastic and inelastic P and K

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[2] The test statistics were calculated by SHAZAM (White) and test whether a linear combination of two regression coefficients is equal to zero. The *t*-statistic takes the form

$$t_{n-k} = \frac{c_1\hat{\beta}_1 - c_2\hat{\beta}_2}{s}$$

where $n-k$ is the degrees of freedom, c_1 is the mean of explanatory variable X_1 divided by the mean of dependent variable Y_1, c_2 is the mean of explanatory variable X_2 divided by the mean of dependent variable Y_2, $\hat{\beta}_1$ and $\hat{\beta}_2$ are estimated regression coefficients and s is the standard error of $c_1\hat{\beta}_1 - c_2\hat{\beta}_2$.

TABLE 1. Estimated Seemingly Unrelated Regression Equations for N, P, and K per Harvested Acre of Corn, Wheat and Soybeans.

Equation Number	Dependent Variable	Explanatory Variables					Estimated Autoregressive Parameter ($\hat{\rho}$)
		Intercept	*j*-PR	*i*-Pr	*i*-DIV	T	
1	CR-NAC[a]	18.395	−7.501	52.250	0.293	4.062	−0.369
		(7.820)[b]	(.705)	(4.377)	(.093)	(.242)	(.190)
2	CR-PAC	11.673	−0.879	7.976	0.064	1.249	−0.495
		(.995)	(.044)	(.542)	(.015)	(.021)	(.177)
3	CR-KAC	29.528	−7.995	15.925	−0.043	2.220	−0.028
		(7.181)	(1.264)	(2.260)	(.052)	(.138)	(.204)
4	WT-NAC	−5.554	−0.403	2.882	0.002	1.668	0.446
		(2.715)	(.240)	(.919)	(.042)	(.106)	(.183)
5	WT-PAC	3.174	−0.169	1.202	0.013	0.301	0.102
		(.570)	(.041)	(.305)	(.015)	(.017)	(.203)
6	WT-KAC	1.588	−0.231	1.166	−0.012	0.228	0.442
		(1.511)	(.291)	(.298)	(.016)	(.026)	(.183)
7	SB-NAC	−3.415	−0.058	0.048		0.334	0.900
		(1.860)	(.031)	(.109)		(.079)	(.089)
8	SB-PAC	1.948	−0.135	0.699		0.242	0.717
		(.713)	(.021)	(.149)		(.036)	(.142)
9	SB-KAC	1.089	−1.606	0.052		1.046	0.864
		(4.738)	(.409)	(.327)		(.212)	(.103)

[a] Variable definitions: NAC, PAC, and KAC are pounds of nitrogen (N), phosphorous (P), and potassium (K) per harvested acre; prescripts CR, WT, and SB refer to corn, wheat, and soybeans; prescript *i* equals CR in equations 1, 2, and 3, WT in equations 4, 5, and 6, and SB in equations 7, 8, and 9; prescript *j* equals N in equations 1, 4, and 6, P in equations 2, 5, and 8, and K in equations 3, 6, and 9; N-PR, P-PR, and K-PR are cents per pound of N, P, and K deflated by the implicit GNP price deflator with 1967 = 100; CR-PR, WT-PR, and SB-PR are prices in dollars per bushel of corn, wheat, and soybeans deflated by the implicit GNP price deflator with 1967 = 100, lagged one period; DIV is millions of acres diverted from production under the respective crop program; and T is a time trend with 1952 = 1, 1953 = 2, ..., 1976 = 25.

[b] Numbers in parentheses are asymptotic standard errors.

TABLE 2. Estimated Elasticities at the Variable Means for N, P, and K per Harvested Acre of Corn, Wheat, and Soybeans.[a]

Equation Number	Dependent Variable	Explanatory Variables			
		j-PR	*i*-PR	*i*-DIV	T
1	CR-NAC	−1.148	1.053	0.046	0.784
2	CR-PAC	−1.131	0.592	0.037	0.887
3	CR-KAC	−1.298	0.633	−0.013	0.845
4	WT-NAC	−0.232	0.312	0.001	1.213
5	WT-PAC	−0.737	0.432	0.010	0.726
6	WT-KAC	−0.236	0.417	−0.009	0.549
7	SB-NAC	−0.293	0.065		2.113
8	SB-PAC	−0.824	0.504		0.815
9	SB-KAC	−0.956	0.015		1.461

[a] Variables are defined in Table 1.

TABLE 3. Comparisons Between Elasticities of Nutrient Demand with Respect to Nutrient Prices at the Means.

Nutrient Prices by Crop	Corn			Wheat			Soybeans		
	N-PR(1)[a]	P-PR(2)	K-PR(3)	N-PR(4)	P-PR(5)	K-PR(6)	N-PR(7)	P-PR(8)	K-PR(9)
Corn:									
N-PR(1)	--								
P-PR(2)	5.478[b,c]	--							
K-PR(3)	5.818[c]	5.893[c]	--						
Wheat:									
N-PR(4)	2.202[c]	--	--	--					
P-PR(5)	--	1.298	--	0.735	--				
K-PR(6)	--	--	3.358[c]	0.468	0.317	--			
Soybeans:									
N-PR(7)	10.216[c]	--	--	1.629	--	--	--		
P-PR(8)	--	11.715[c]	--	--	4.855[c]	--	5.952[c]	--	
K-PR(9)	--	--	5.977[c]	--	--	0.190	4.034[c]	3.558[c]	--

[a] j-PR(n) represents the j-th nutrient elasticity of demand, with respect to the j-th nutrient price, calculated from the n-th equation. Where j = N, P, and K and $n = 1 - 9$.

[b] This number is a t-statistic with 174 degrees of freedom testing the null hypothesis that the mean elasticity of N applied to corn with respect to the N price is equal to the mean elasticity of P applied to corn with respect to the price of P. Other numbers have analogous interpretations for other nutrients and crops.

[c] Significantly different at the 5 percent level.

TABLE 4. Comparison Between Elasticities of Nutrient Demand with Respect to Crop Prices at the Means.

Crop Price by Nutrient	N			P			K		
	CR-PR(1)[a]	WT-PR(4)	SB-PR(7)	CR-PR(2)	WT-PR(5)	SB-PR(8)	CR-PR(3)	WT-PR(6)	SB-PR(9)
N:									
CR-PR(1)	--								
WT-PR(4)	5.844[bc]	--							
SB-PR(7)	5.610[c]	1.341	--						
P:									
CR-PR(2)	4.326[c]	--	--	--					
WT-PR(5)	--	1.046	--	1.426	--				
SB-PR(8)	--	--	2.542[c]	0.825	0.437	--			
K:									
CR-PR(3)	3.842[c]	--	--	0.147	--	--	--		
WT-PR(6)	--	0.878	--	--	0.230	--	1.597	--	
SB-PR(9)	--	--	0.502	--	--	4.455[c]	4.816[c]	2.782[c]	

[a] i-PR(n) represents the nutrient elasticity of demand, with respect to the i-th crop price, calculated from the n-th equation. Where i=CR, WT, and SB and $n=1-9$.

[b] This number is a t-statistic with 174 degrees of freedom testing the null hypothesis that the mean elasticity of N applied to corn with respect to the lagged price of corn is equal to the mean elasticity of N applied to wheat with respect to the lagged price of wheat. Other numbers have similar interpretations for other nutrients and crops.

[c] Significantly different at the 5 percent level.

demands among the western states. Heady and Yeh found aggregate fertilizer elasticities of demand between −3.8 for the Northern Plains and −0.4 for the Northeast. They found the elasticity of demand for the Corn Belt to be −1.392. Since most U.S. corn is produced in the Corn Belt, this finding adds credence to the price elasticities for corn presented here. In the same study, Heady and Yeh found U.S. demand for individual nutrients to be less than unity. Griliches [1958 and 1959] reported inelastic demand in the short run but elasticities greater than unity in the long run.

The nutrient price elasticities for corn are quite similar in magnitude, yet they are significantly different from one another. Even though statistical differences do exist, these elasticities are so similar that it would be difficult to distinguish one from the others for policy purposes. The same conclusion may be drawn for nutrient price elasticities for wheat, but for a different reason. In the case of wheat, the variation in elasticity estimates is larger, ranging between −0.232 for K and −0.737 for P, yet statistically it cannot be concluded that they are different. However, this conclusion must be viewed with caution because standard errors are high possibly due to multicollinearity between nutrient and lagged wheat prices.

For nutrients applied to soybeans, price elasticities vary significantly. Elasticities for P and K are fairly close to unity at −0.824 and −0.956, while the price elasticity for N is only −0.293. That the N price elasticity of demand is lower than price elasticities for P and K is not surprising, given that soybeans are legumes and need little additional nitrogen. From the results presented in Tables 2 and 3, it can be concluded that price rationing of P and K would be 2.8 and 3.3 times more effective in reducing nutrient use per acre than price rationing for N applied to soybeans.

Crop Prices

The corn price elasticity of N applied to corn is close to unity[3] and almost twice as large as the next highest crop price elasticity. An implication is that government programs, such as higher loan rates or export promotion campaigns, aimed at supporting the corn price by, say, 10 percent would encourage the increase of N applied per acre of corn by 10.53 percent, while P and K would increase by about 6 percent. Other crop price elasticities of nutrient demand are about 0.5 except for N and K applied to soybeans which are derived from insignificant coefficients in Equations 7 and 9.

Diverted Acreage

Generally, the coefficients reported in Table 2 for acreage diverted from production under government acreage control programs conform with the conventional wisdom that farmers partially offset land retirement supply control programs by using more fertilizer on the land remaining in production. The negative coefficients for K applied to corn and wheat seem contrary to expectation, but they are also insignificant.

The coefficients for diverted acreage in equations 1 and 2 are highly significant, while similar coefficients in equations 3-6 are not. Equation 1 suggests that an increase in diverted corn acreage by one million acres encouraged corn farmers to apply .29 of a pound more N per acre of corn remaining in production. In 1969, when acreage diverted from corn production was 27.2 million acres [USDA 1975], this diversion accounted for about eight pounds of additional N applied per acre on the remaining land, or about 7 percent of the N applied per acre of corn. The coefficient for P represents about 6 percent of the P applied per acre of corn in 1969.

When acreage control programs are used in attempting to meet a production target, the shift of resources from use on diverted

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[3] Hypothesis testing revealed that the crop price elasticity of N applied to corn was not significantly different from unity. All other crop price elasticities were found to be significantly less than unity.

land to the land remaining in production needs to be considered. The regression results suggest that corn land remaining in production was farmed more intensively by applying more N and P per acre, and therefore, yields per acre probably increased. To achieve a given production target, government would have to combine acreage diversion with fertilizer rationing or increase the number of diverted acres to offset higher yields caused by increased fertilizer application.

Time

The time trend coefficients (Table 1), though they contain little definitive economic information, can provide useful information to policymakers. Holding prices and acreage control programs constant, nutrient application rates would probably continue to increase as production functions shift and as other variables for which time is a proxy continue their trends. In all but a few cases, the elasticities for the time trends in Table 3 are statistically different from one another. Therefore, the estimated demand functions could be used to predict nutrient application rates over time, giving policymakers insight into the relative importance of these nutrients in the future. Even if the other variables for which time is a proxy were not expected to follow their historical trends, the time trend would be useful if modified to provide several scenarios of future nutrient application rate time paths.

Summary and Conclusion

In this study, demand functions were estimated for three plant nutrients, N, P and K, applied per harvested acre of three individual crops, corn, wheat and soybeans, grown in the United States. Time series data for 1952-76 were used to estimate the system of nine equations by seemingly unrelated regression after first obtaining maximum likelihood estimates of the first order autoregressive parameter ($\hat{\rho}$'s) and with them transforming the original data. This procedure provided relatively more efficient estimates of the model parameters than OLS estimation.

Application of the above procedure did not totally remove inefficiency problems. Multicollinearity, another source of inefficiency, was also a problem. It was found that many plausible explanatory variables were highly correlated over time, with simple correlation coefficients over .9. To reduce multicollinearity and to avoid overemphasizing any particular time-correlated economic variable, a time trend was used as a proxy for shifting production functions and variations in other input prices that were highly correlated with time. Other variables included in the model were deflated nutrient and lagged crop prices and the number of acres diverted from crop production. Correlation coefficients for the variables remaining in the model were all below .8 except for the lagged wheat price and nutrient prices.

The estimated results provide several interesting implications. The demands for N, P and K applied per acre of corn are price elastic, while similar responses for wheat and soybeans are price inelastic. Price rationing of scarce nutrients would cause a greater percentage reduction in nutrient application rates per acre for corn than for wheat and soybeans. Also, escalations in energy prices, that cause nutrient prices to increase as they did between 1972-75 and 1978-80, would cause per acre application rates to decrease for corn relative to wheat. The elasticity of demand for N applied per acre of corn, with respect to the lagged corn price, is close to unity and about twice as large as other crop price elasticities. This information would be useful to policymakers as they contemplate responses in nutrient use and crop production to price support programs or foreign market expansion. The results further suggest that acreage control programs to reduce corn production were partially offset by higher rates of N and P application per acre of corn. For every million acres diverted from production, .29 of a pound more N and .06 of a pound more P were applied per acre on the remaining land. To insure a desired reduction in corn production, policymakers would either have to combine acreage diversion with a fertilizer rationing scheme or increase the number of diverted acres to offset higher yields caused by increased fertilizer application.

Research dealing with nutrient response to changing economic conditions has hardly been exhausted by this and previous studies. This study brings up some interesting points that might be examined further. Acreage and yield response functions, combined with the nutrient demand functions estimated here, would be of interest to policymakers as they attempt to anticipate production responses to various government policy scenarios. Also, regional differences in cultural practices, climate, soil type, and the like might cause nutrient response to vary substantially for a given crop. Additionally, differences in nutrient application rate response to changes in economic variables might result because of differing nutrient characteristics. P is highly fixed in the soil, with little being leached in any given year. The depletion of P is caused mostly by plant use. On the other hand, N is highly leachable. It has to be replaced every year, either by summer fallow or by artificial application. K is also fixed in the soil, but loosely, and small amounts are lost to leaching. P and K are usually applied to maintain soil fertility, but application might also be considered an investment in the future productivity of the soil if more is applied than is needed for the current crop. These differences in nutrient characteristics, when combined with regional variations in climate, cultural practices and soil types, might cause a wide divergence in regional nutrient application rate elasticities of demand. Indeed, nutrient price elasticities of demand estimated by Carman varied greatly from state-to-state (western states) and regional price elasticities for fertilizer estimated by Heady and Yeh also varied markedly.

From the results presented here, it is difficult to say whether differences in price elasticities of demand across crops and across nutrients are caused by regional differences or by differences in crop and nutrient characteristics. It would be interesting and useful to further explore the extent to which regional, nutrient and crop differences each affect nutrient application rates.

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