Economic Analysis of Optimal Nitrogen Application in Corn Production

Prashant Amatya
Mark Yu
Frank Ewell
Department of Agribusiness, Agronomy, Horticulture, and Range Management
Tarleton State University, Stephenville, TX 76402

ABSTRACT

Identifying the fertilizer-output relationship for a crop would be an important tool for determining optimal rate of fertilization and hence maximum profit. Proper nutrient management also minimizes environmental degradation. The model described in this paper is useful to forecast the production and productivity for corn based on optimal nitrogen application. An empirical production function was estimated using SAS GLM model that best describes the data. The economically optimal level of nitrogen fertilization was obtained by maximizing the profit function. It was observed that the current level of corn production in U.S. Corn Belt is slightly below the optimal. It is suggested to increase the present level of nitrogen use from 143.22 lb to 153.35 lb per acre to obtain maximum possible profit. The net revenue is estimated to be $316.47 from each acre of corn with the optimal rate of nitrogen fertilization at the current price structure. Both the net revenue and the incremental profit are expected to be much larger if the price structure remains as in earlier years.

KEYWORDS: Production Function, Crop Forecasting, Production Modeling, Corn Production, Modeling

INTRODUCTION

One of the most important cereal crops produced in the United States is corn, in terms of both acreage and production. The United States grows around 78 to 80 million acres and produces around 9 to 11 billion bushels of corn annually (National Agricultural Statistics Service (USDA-NASS, 2006). In 2005, total corn production stood at 81.76 million acres and production reached 11.11 billion bushels. The trend for the last five year indicates that both the acreage and yield are constantly increasing (USDA-NASS, 2006). The U.S. Corn Belt is located in the north central plains, and includes Iowa, Illinois, southern Minnesota, southeast South Dakota, eastern Nebraska, northeast Kansas, northern Missouri, Indiana, and western Ohio (Forcella et al., 1992). Most of the U.S. corn is produced in this area. Corn has been one of the most important crops for in

U.S. agriculture. It is a major constituent of animal feed. Furthermore, the importance and hence the demand of corn is estimated to escalate due to its increasing use for producing ethanol (Pimentel and Patzek, 2005; Dailyfutures.com, 2006).

Corn is a voracious nutrient-requiring crop and must have adequate amount of nitrogen and phosphorus for profitable production (Alley et al., 1997; Heckman et al., 1996; Morris et al., 1993; and Yu et al., 2000). Determining the fertilizer-output relationship can provide a means to proper fertilizer management by selecting economically optimal rates of fertilization that have direct implications on crop profitability. Fertilization beyond optimal results in inefficient use of the resources, while fertilization below optimal would be a compromise in total production potential. Nitrogen and phosphorus are also the nutrients that result in eutrophication in surface water when concentration increases beyond certain critical levels (Alley et al., 1997). Thus, proper nutrient management reduces the impact on environmental degradation and also minimizes the energy use in manufacturing these nutrients. Further, the relationship can be used as a tool to forecast the production and productivity of a crop in a given scenario. This would be an important tool for planners.

The objectives of this study are: (1) to estimate the maximum potential corn yield in the U.S. Corn Belt, (2) to find the economically optimal rate of nitrogen fertilization for corn production in the U.S. Corn Belt that maximizes profit, and (3) to evaluate the sensitivity of the variation of prices of corn and nitrogen to the rate of nitrogen fertilization. The nitrogen fertilizer optimization is chosen because of the facts that it the most important plant nutrient and highly volatile in the soil and thus needs constant replenishments (Alley et al., 1997).

An agricultural production function is generally defined as a bio-physical relationship between inputs and an output where a physical quantity of crop production can be attained for a given sets of inputs used at given treatments (Griliches, 1964). In other words,

$$Y = f(X_1, X_2, \ldots\ldots\ldots\ldots\ldots\ldots X_K \mid X_L \ldots\ldots\ldots X_N) \qquad (1)$$

where, Y represents the crop yield. $X_1 \ldots X_N$ are the quantities of the inputs used in the production in which $X_1, X_2, \ldots\ldots X_K$ represent the variable factors, while $X_L \ldots\ldots X_N$ represent the fixed factors.

The construction of an agricultural production function is considered to be complex because of the existence of the interaction effect among the various inputs and uncontrollable natural exogenous factors. Despite these phenomena, attempts have been made to develop crop production models that can provide a means to forecast the production and productivity of a crop at a given bio-physical relationship (Challinor et al., 2003; Ozsabuncuoglu, 1998; Baier, 1977, and Barreto and Westerman, 1987). There has been a continuous attempt to improve forecasting of models by incorporating factors like weather, irrigation, fertilization, soil fertility, and use of techniques like remote sensing etc. Development of such models is also important for forecasting crop production which then serve as instruments for agriculture planners to respond in a timely manner to impending shortages (Chopak, 2000; and FAO, 2002). Such planning permits (or enables) preparation for harsh consequences and/or to develop early warning systems.

Crop models can be characterized by two different approaches: (1) process based models, which seek to represent many processes of crop growth and development, and (2) empirical or mathematical models, which use observed relationships to predict the variable of interest, usually crop yield (Challinor et al., 2003). Each approach has its advantages and disadvantages. Thus, a compromise must be sought between the volume of data (inputs) required and the precision of the forecast generated.

Since there is no fundamental theoretical model to represent the effect of inputs on crop yield, the selection of a particular mathematical model is generally made on the basis of observation, experience, and ease of calculation (Barreto and Westerman, 1987). General theoretical knowledge about production functions is readily available in many text books (e.g., Heady and Dillion, 1961). Literature shows that empirical models like linear, multi-linear and polynomial functions (including quadratic, square root, linear von Liebig, Mitscherlich-Baule, nonlinear von Liebig, Cob-Douglas, and transcendental) are commonly used to construct input-output relationships in agriculture. Further, the studies conducted by Colwell (1978) and Melsted and Peck (1997) stated that fertilization-yield relationship varied with crop, fertilizer, soil, management practices, and the growing season variables. Thus, a model should be simple and use minimum, readily available information that has a potential to predict with a certain given precision. Some factors are more important for yield than others (Baier, 1977). Attempts have been made to identify and incorporate factors into the model that are likely to have statistical significance in corn production.

METHODS AND PROCEDURES

In this study, a corn production function was derived based on the corn production data from the U.S. Corn Belt. Then, the optimal amount of input needed to achieve crop profit maximization was calculated. The goal of any commercial producer would be maximizing the profit rather than maximizing the production. Thus, economical optimal level of nitrogen can be obtained by maximizing the profit function. Assuming perfectly competitive markets and a crop production function with only one variable input, Y = *f*(N), the profit function can be postulated as:

$$\pi = P_c\, Y - P_N\, N \tag{2}$$

where, π represents profit. P_c is the output price. P_N is the input price. And N is the amount of input used in the production process.

In order to maximize profit, the first order derivative of equation (2) was taken with respect to variable N (nitrogen),

$$\frac{\partial \pi}{\partial N} = P_c * \frac{\partial Y}{\partial N} - P_N = 0 \tag{3}$$

$$\frac{\partial \pi}{\partial N} = P_c * MPP - P_N = 0 \tag{4}$$

or $$\text{VMP} = \text{MIC} \tag{5}$$

where, MPP = $\frac{\partial Y}{\partial N}$, represent the marginal physical productivity of the factor and VMP represent value of the marginal physical product for a given price (i.e. VMP = Pc * MPP). The marginal input cost (MIC) is the additional cost incurred due to addition of one more unit of the input. Thus, for a perfect market situation, it's a price of the input. Solving equation (5) for single variable factor N would give the optimal rate of input use that would maximize the profit (Beattie and Taylor, 1993).

Data for this research were collected from NASS and Economic Research Service (ERS) at USDA websites. The data include corn yield, average corn price, nitrogen, phosphorus and potash application rates, and their annual retail prices. The data were collected for all nine U.S. Corn Belt states for 37 years (i.e. from 1967 to 2003). To generate lag value for the corn price, the previous year's price was taken. Similarly, to estimate average annual nitrogen price, the price of 30% nitrogen solution was considered in the study. Table 1 gives a short summary about the variables that used in this study.

Table 1: Summary of the Corn Yield, Fertilizer Application and Average Corn and Nitrogen Price in U.S. Corn Belt (1967-2003).

Parameters	Average	Minimum	Maximum	Standard Deviation
Yield (bushel/acre)	103.98	59.50	139.33	23.40
Applied Nitrogen (lb./acre)	121.69	57.00	143.22	19.36
Applied Phosphorus (lb/acre)	56.97	38.44	64.11	4.63
Applied Potash (lb./acre)	64.12	30.33	84.50	11.14
Corn Price ($/bushel)	2.09	1.03	3.28	0.62
Nitrogen Price[1] ($/lb)	0.18	0.08	0.28	0.05

[1.] The price of nitrogen was calculated from price of 30% Nitrogen solution.

Thus keeping aforementioned factors in mind, the study attempts to design a simple mathematical model to predict the corn yield which can be postulated as

$$Y_c = f\,(N, P, K, T) \tag{6}$$

where, Y_c represents corn yield. T is the time, N is the rate of nitrogen application. P is the phosphorus application rate. K is the rate of potassium application. The time T is inserted in the model to capture the trend. Trend in increasing yield over time exist due to factors, such as crop variety improvement, increased and more efficient irrigation and fertilizer use, and improved pest and disease control management (Challinor et al., 2003) or any stochastic climatic conditions.

Highly calibrated, comprehensive models are currently used for research, teaching, and studying crop management and prediction. Frequently these models need large amount of input data, but such data may have inherent uncertainties or not be available if spatial in nature (Challinor et al, 2003). Thus the estimated model has to be as simple as possible while taking account of the most important factors first and then gradually incorporating the other factors.

SAS generalized linear model (GLM) procedure was used in different function formats to determine the best fit, beginning with simple linear regression. Each time the fit of the model was evaluated on the basis of coefficient of multiple determination (R^2) and significance of the t statistics for the regression coefficients of each variable. The same procedure was repeated for the multiple regression model and then non-linear regression models by inserting contradictory, interactive, and finally, cubical terms into the model. This was done attempting several combinations separately and sequentially.

Running linear and non-linear models for various combinations of factors resulted in estimation of parameters as well as for goodness of fit for each model. The goodness of fit of the model was evaluated from the R^2 values. It was observed that the R^2 tended to increase as more variables were added. However, some of them were not included in the model because they were statistically insignificant.

RESULTS AND DISCUSSION

Several predefined functional forms including linear, multi-linear, quadratic, cubical, Cobb-Douglas, and other polynomial forms were tried by introducing contradict and interaction terms in the model. The following polynomial form was found to best fit the statistical observed data:

$$\underset{(0.34)}{Y_c = 114.26} \; \underset{(0.28)}{-2.60*10^{-2}N^2} \; \underset{(0.22)}{-8.43K} \; \underset{(0.23)}{+5.73*10^{-2}N*P} \; \underset{(0.20)}{+1.2*10^{-2}N*K} \; \underset{(0.18)}{-1.00*10^{-2}N*P*K} \; \underset{(0.02)}{+1.20T} \quad (7)$$

$R^2 = 0.7722$

where, Y_c represents corn yield in bushels/ acre; N is amount of nitrogen application in lb/acre; P is the phosphorus application rate in lb/acre; K is the rate of potassium application in lb/acre; and T represents the time ranged from 1 to 37. The model explains 77.22% (R^2 value) of variation in corn yield in terms independent variables included in the model. The values in the parenthesis below the coefficients are the *p*-values and reflect the level of significance of the estimated coefficients.

The estimated production function suggests that there are significant interaction effects among nitrogen, potassium, and phosphorus fertilizers in explaining corn yield variation. It was observed that the average nitrogen application was 143.22 lb/acre, which produced 143.21 bushels of corn in 2003. These were below both potential and optimal levels. The model indicated that maximum potential yield can be obtained by increasing nitrogen use to 153.35 lb/acre resulting in a yield of 145.89 bushels/acre.

Assuming a corn price of $2.42 per bushel and a nitrogen price of $0.24 per pound (price of 2003; USDA-ERS, 2006), the optimum level of corn production was estimated to be 145.79 bushels/acre resulting in a profit of $316.47 per acre. The current level of nitrogen use (i.e., 143.22 lb/acre in 2003) is estimated to yield 143.21 bushels of corn per acre and hence the profit of $312.22 per acre. It is eminent that current level of operation is below the optimum level and thus operating at optimum level can bring an incremental profit of $4.25 per each acre.

The sensitivity analysis for optimal nitrogen fertilization on corn and the net revenue for different levels of corn and nitrogen prices are presented in the Table 2. The top portion of table depicts the optimal levels of nitrogen applications for the alternative nitrogen-corn price combinations. And the bottom portion of the tables depicts the associated net per-acre present value of returns. It can be seen that the optimal fertilization rate decreases to 143.74 lb/acre if the price of nitrogen rises to $0.50 per lb and price of corn falls to $1.00 per bushel, which generates $71.62 per acre of net return. Similarly, the optimal nitrogen fertilization rate is as high as 152.97 lb/acre if the nitrogen price falls to $0.10 per lb and corn price rises to $5.00 per bushel, which increases the net returns to $714.12 per acre. The fertilizer-corn price ratio is highest on the upper left corner, which gradually decreases along the diagonal to reach its minimal on the bottom right corner. It is eminent from the table that the lower fertilizer-corn price ratio, higher optimal fertilization rate. The higher the fertilizer-corn price ratio the lower the optimal fertilization rate is.

Table 2. Optimal Nitrogen Fertilization Rate and Profit Levels for Different Nitrogen-Corn Price Combinations.

a. Optimal Rate of Nitrogen Fertilization (unit: lb/acre)

		Price of Corn ($ per bu)			
		1.00	2.00	3.00	4.00
Price of Nitrogen ($ per lb)	0.50	143.74	148.54	150.15	150.14
	0.40	145.66	149.51	150.79	151.43
	0.30	147.58	150.47	151.43	151.91
	0.20	149.51	151.43	152.07	152.39
	0.10	151.43	152.40	152.71	152.87

b. Net Returns from Corn Production (unit: $ per acre)

		Price of Corn ($ per bu)			
		1.00	2.00	3.00	4.00
Price of Nitrogen ($ per lb)	0.50	71.62	216.30	361.79	507.41
	0.40	86.09	231.20	376.83	522.59
	0.30	100.75	246.20	391.94	537.76
	0.20	115.60	261.30	407.12	552.97
	0.10	130.65	276.49	422.36	568.24

However, Table 2 gives a discrete picture and may not always suit the real-life situation (Yu et al., 1999). Thus, estimation of the relationship, i.e. the optimal fertilization rate based on continuous relative prices of nitrogen and corn as defined in Equation (8) would be more useful.

$$e^N = \alpha * P_r^{\ \beta} * \varepsilon \qquad (8)$$

where, e is the exponential, P_r is the nitrogen-corn price ratio; N represents the optimal nitrogen fertilization rate for given price ratio; α and β are the parameters to be estimated; and ε is the error term. Regressing, the 19 optimal fertilization rates with respect to the nitrogen-corn price ratios (after excluding the six repeated price ratios), the following equation was estimated:

$$\underset{(209.25)}{N = 144.723} - \underset{(-9.03)}{2.5274} \ln(P_r) \qquad (9)$$

$$R^2 = 0.8273$$

where, the variables are defined as above. The values on the parenthesis below represent their associated *t*-value. All the parameters were found to be significant at 0.0001 levels. The graphical presentation of the Equation (9) is given in Figure 1. The optimal amount of nitrogen ranges from 146 to 155 lb/acre for price ratio ranging from 0.5 to 0.02.

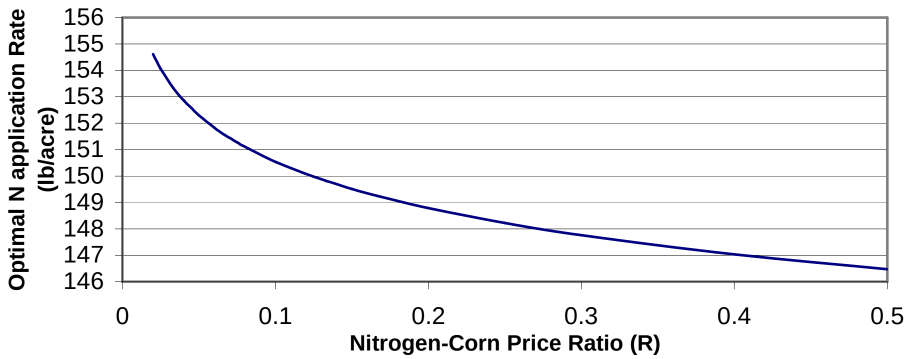

Figure 1: Continuous Form of Optimal Nitrogen Application Rate for Different Nitrogen-Corn Price Ratios.

CONCLUSIONS

The current level of corn production in U.S. Corn Belt is slightly below the optimal. Thus, operating at the maximum profitable level of corn production was estimated to bring an increment of $ 4.03 profit from each acre of corn field at the 2003 price structure. It was suggested that increasing level of nitrogen use from 143.22 lb to 153.35 lb per acre would increases net revenue from $312.22 to $316.47 per acre. Both the net revenue and the incremental profit are expected to be much larger if the price of nitrogen falls or alternatively the price of corn rises. Although, these results are more useful to policy maker (or the development planner); it could prove valuable to a producer to check if he/she is producing at optimal level.

The change in input-output price ratios alters marginal revenue and hence optimal fertilization rate. It was estimated that for nitrogen-crop price ratios ranging from 0.02 to 0.5, the optimal nitrogen application rates would range from 143.74 to 152.97 lb/acre.

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