The economics of nitrogen fertilizer cutbacks to reduce potential ground water contamination : a case study of selected Arizona crops

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THE ECONOMICS OF NITROGEN FERTILIZER CUTBACKS TO REDUCE POTENTIAL GROUND WATER CONTAMINATION: A CASE STUDY OF SELECTED ARIZONA CROPS

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1992

STATEMENT BY AUTHOR

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ACKNOWLEDGEMENT

I wish to thank the faculty members, staff, and friends who provided expertise, instruction, and support to help me throughout my research.

I am grateful to Dr. Harry Ayer for guiding this research and for his advice and insight regarding the economics of nitrogen fertilizer use in Arizona. Dr. Gary Thompson's experience with computer applications and knowledge of production theory were invaluable. In addition, his enthusiasm for the knowledge gained from studies such as this one continuously sparked my curiosity and motivation. I would like to thank Dr. Roger Dahlgran for his instruction in econometric theory and applications in the classroom and as a member of my thesis panel. I would also like to thank Dr. Satheesh Aradhyula for his help on the Mitscherlich-Baule estimation and Lew Daugherty for information concerning Arizona crop budgets. Finally, I would like to express my appreciation to Dr. Thomas A. Doerge of the Department of Soil and Water Science who generously provided all of the experimental data used in this study and who patiently answered my many questions about yield response research and crop management practices.

Special thanks go to Dave Harpman, a gifted teacher, for advice on Mitscherlich-Baule and von Liebig estimation, econometrics, and computer applications. Most of all, I would like to thank Dave for his friendship which inspired me to persevere. Thanks to my fellow graduate students for their companionship and good humor. The long nights in the computer lab would have been lonely without Njambi Njoroge. I also appreciate the help Gregory Gimello and Dean Fairchild gave me in the computer lab on many occasions.

I am grateful to the Department of Agricultural and Resource Economics for a research assistantship and to the U. S. Environmental Protection Agency which also provided funding for this research.

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ABSTRACT

Agricultural uses of nitrogen have contributed to the degradation of ground water quality nationwide. Although the seriousness of nitrate contamination of Arizona ground water has yet to be determined, nitrogen rates in Arizona agriculture are among the highest in the country. This study used experimental crop data for 11 Arizona crops to examine the relationships between nitrogen fertilizer use and short-run net returns and yield. The results showed that 1) farmers may apply nitrogen 20 to 30 percent above the profit maximizing level with little effect on profits; 2) a nitrogen tax will be ineffective in reducing nitrogen use; and 3) farmers could often reduce nitrogen applications 10 to 20 percent below the yield maximizing level with minor losses in net returns.

1. INTRODUCTION

Nitrogen Contamination of United States Ground Water

The use of commercially produced nitrogen fertilizer has increased sharply since World War II and is now a vital part of agricultural production in the United States. Commercial nitrogen fertilizer is relatively easy to use and can significantly affect crop growth and quality at a relatively low cost. Improved crop varieties allow higher response to higher fertilizer rates than do traditional varieties. However, high rates of commercial fertilizer have been identified as an important cause of ground water degradation nationwide (McSweeney and Shortle, 1988). Nitrates are highly soluble and mobile in the soil, making nitrate leaching inevitable under many agricultural production systems (Scherpers and Fox, 1989). The presence of elevated concentrations of nitrate in ground water used for drinking may be harmful to human health.

To determine the extent of nitrogen contamination (actually nitrate-nitrogen, NO_3-N) of ground water in the United States, Madison and Brunett (1985) conducted a study on ground water quality based on water samples collected nationwide from approximately 120,000 wells over a 25-year period. On a national basis, 20 percent of all wells sampled were found to exceed 3 mg NO_3-N/l and 6.4 percent of the wells were found to exceed 10 mg NO_3-N/l which is the drinking water standard for nitrate-nitrogen set by the United States Public Health Service. Wells and the ground water exhibiting nitrate concentrations in excess of 10 mg NO_3-N/l were found in every state. According to Madison and Brunett, concentrations of NO_3-N in water samples greater than 3 mg/l indicate contamination by human activity. Natural ecosystems such as forested areas allow only low levels of nitrate to leach below the root zone because nutrient inputs and uptake are relatively balanced.

Madison and Brunett noted that agricultural fertilizer and animal waste from feedlots and other intensive animal operations were major sources of the nitrate contamination. Areas of the United States with the highest reported ground water nitrate concentrations are the northeast where intensive livestock and poultry operations are common, the intensively farmed area of the grain-belt in the midwest, and certain areas of California and Texas where irrigated agriculture is practiced (Hallberg, 1989).

Finally, it is notable that the quality of surface water sources in the United States is partially dependent upon the extent and seriousness of nitrate contamination of ground water sources. According to the United States Geological Survey, 40 percent of average annual streamflow nationwide is from ground water (USDA, 1991). Thus, contaminated acquifers may discharge ground water into streams. In addition, agricultural runoff has caused eutrophication of major bodies of surface water in many areas of the United States, including Lake Champlain, the Great Lakes, the Chesapeake Bay, and the San Francisco Bay (USEPA, 1984). Eutrophication has caused undesirable changes in the quality of these waters such as depletion of dissolved oxygen leading to fish kills, unfavorable tastes and odors, and restricted navigation.

Nitrogen Contamination of Arizona Ground Water

In Arizona, Madison and Brunett sampled 4,161 wells and found that 13.9 percent of these wells contained more than 10 mg NO_3-N/l. Based on other results from the Madison and Brunett study, the USDA (1991) reported that in the 50 states and Puerto Rico, 4.8 percent of the wells exceeded 10 mg NO_3-N/l. Arizona was one of six states (Delaware, Kansas, New York, Oklahoma, and Rhode Island) which exceeded the 10 mg NO_3-N/l drinking water standard in 10 percent of the wells sampled (The Conservation Foundation, 1987).

Nitrate can reach Arizona ground water from a variety of sources including agricultural activities. Arizona crops (primarily cotton, wheat, melons, and vegetables) are grown in intensive, large-acreage, monoculture systems and are highly dependent upon synthetic nitrogen fertilizer and irrigation water to attain commercial quantities and quality. Nitrogen fertilizer rates in Arizona are among the highest (ibid.).

In the 1980s, the production of vegetable crops with high nitrogen requirements expanded in Arizona. A 1991 USDA study evaluating on-farm agricultural chemical use for vegetable and fruit crops in Florida, Michigan, Texas, and Arizona ranked Arizona highest for the percentage of vegetable and fruit crop acreage (98 percent statewide) treated with nitrogen. The study also reported that in 1990, lettuce (all types) was the dominant vegetable grown in Arizona accounting for 57 percent of total vegetable acreage planted (57,500 acres). Lettuce is a shallow-rooted crop which has high nitrogen requirements compared to other vegetables and fruits. For example, in 1990, the average nitrogen application rate for all types of lettuce was 292 lbs/acre. In comparison, the 1990 nitrogen application rate for other Arizona crops was: watermelon, 220 lbs/acre; cantaloup, 110 lbs/acre; upland cotton, 159 lbs/acre; and sweet corn, 123 lbs/acre (Wade et al, 1990; USDA, 1991).

Nitrogen application for another important Arizona crop, durum wheat, surpassed even the application rate for lettuce. In Maricopa county, the nitrogen application rate for durum wheat was estimated to be 358.6 lbs/acre (Wade et al., 1990). Durum wheat was planted on 45,000 acres in Arizona in 1990 (Arizona Agricultural Statistical Service, 1991).

The intensity and extent of current nitrogen use in

Arizona raises concerns about the quality of Arizona ground water in the future. Analysis of ground water samples taken from beneath citrus groves throughout California show that in some locations, nitrates required more than 50 year's travel time before ground water was penetrated (Pratt _et_ _al_., 1972). Pratt _et_ _al_. found nitrate plumes which had moved far below the root zone over a period of years but had not yet reached ground water. They concluded that the ground water underlying former citrus groves would continue to exhibit high nitrate levels for years after nitrogen fertilizer applications had ceased (Ayers and Branson, 1973).

Human Health Effects

Medical research has positively linked the ingestion of nitrate-nitrogen in drinking water to Methemoglobinemia (metHb) or Blue Baby disease. MetHb affects infants under 6 months of age for numerous physiological reasons, including the immaturity of their digestive systems. Nearly all cases of infant metHb reported in the United States have resulted from ingestion of nitrate contaminated private well water used to make infant formula. Due to increased awareness of the symptoms by the medical profession, there has only been one documented infant death of metHb in the United States since 1960 (USDA, 1991).

Nitrate poisoning in adults is rare and reports of adult metHb are unconfirmed. Poisoning of an adult from a single oral ingestion would require 1 to 2 grams of nitrate-nitrogen which is far above normal exposure episodes (Keeney, 1983). MetHb is rarely fatal, is readily diagnosed, and is reversible with clinical treatment (National Research Council, 1978).

In 1962, the United States Public Health Service established a drinking water standard for nitrate-nitrogen equal to 10 mg/l or a nitrate level of 45 mg/l to protect against infant metHb. No cases of infant metHb have been identified below these concentrations and risk increases significantly at nitrogen levels above the national standards (ibid.).

In 1990, a study conducted by a private consulting firm found that out of an estimated 219 million people using public drinking water supplies, approximately 1.7 million (less than 0.8 percent) are exposed to nitrate-nitrogen levels above 10 mg/l (USDA, 1991). The contamination found may be seasonal or "transient" rather than sustained because public water systems are subject to compliance. However, the USDA also cited a 1990 General Accounting Office report which stated that some drinking water violations were probably going undetected and that enforcement actions by States were often inadequate.

Policy Approaches

Economists and policymakers have considered four policy options to reduce nitrogen fertilizer applications for improved water quality: taxes based on nutrient losses to the environment, taxes on purchases of commercial nitrogen government-imposed restrictions on nitrogen application rates, and education about Best Management Practices (BMPs) to promote voluntary improvements in fertilization practices.

Griffin and Bromley (1982) state that a negative economic incentive policy based on nutrient losses to the environment is infeasible because of the difficulty of monitoring nonpoint flows. However, this policy has been imposed on farmers in the Netherlands (McSweeney and Shortle, 1988). Dutch farmers keep records of nutrient flows onto and off the farm by computing total nutrient load applied per hectare and comparing this application level to a standard. A tax rate is applied to all loadings above the standard. The advantage of this policy is that only farmers fertilizing in excess of crop requirements pay the tax. However, actual nutrient losses through nonpoint flows are still unknown.

Imposition of an excise tax on commercial nitrogen fertilizer imposes a penalty whether or not fertilizer is in excess of crop requirements. Taxes on nitrogen fertilizer purchases have been imposed in Iowa and Sweden. The Iowa tax is small and was designed to earn income to support research on agricultural chemicals rather than to reduce nitrogen applications. In Sweden, nitrogen fertilizer is taxed 33 percent. The tax appears to have only a marginal influence on nitrogen application rates (Swanson and Taylor, 1989).

Arizona Legislation

The Arizona Environmental Quality Act (EQA) was enacted in 1986 to prevent and reduce the discharge of pollutants from point and nonpoint sources into ground and surface water. At the heart of the Act are mandatory, enforceable BMPs for agricultural producers. BMPs are defined in Title 49-201 as ".... those methods, measures, or practices to prevent or reduce discharges and include structural and nonstructural controls and operations and maintenance procedures. BMPs may be applied before, during, and after discharges to reduce or eliminate the introduction of pollutants to receiving waters. Economic, institutional, and technical factors shall be considered in developing BMPs." The concept of BMPs as the primary means of controlling agricultural nonpoint source pollution was developed as a result of interest in more comprehensive water quality management, stimulated by amendments to the Federal Water Pollution Control Act of 1972 (Malstede and Dutweiler, 1983).

The EQA specifies that certain facilities and/or activities such as agriculture are automatically eligible to receive general permits which require compliance with BMPs to meet water quality standards. To avoid confiscation of the permit, an agricultural producer must implement BMPs. Once the general permit is lost, a producer must apply for an individual permit. The individual permit imposes additional conditions upon agricultural operations and requires payment of fines up to $10,000 before it can be obtained. Arizona’s nitrate control legislation is among the toughest (regarding enforcement) in the nation (National Governors Association, 1991).

The EQA divides regulated agricultural activities into two categories: concentrated animal feeding operations and nitrogen fertilizer application. The BMPs for nitrogen fertilizer address the application and timing of nitrogen fertilizer and irrigation water and the use of tillage practices which maximize nitrogen and water uptake by crops.

The BMPs constitute a statewide goal-oriented approach from which farmers may choose alternative technologies according to site-specific conditions and production goals. The BMPs must be the "most practical and efficient means of reducing or preventing the discharge" of nitrates into ground water by the regulated activities (Hardt, ed., 1989).

Conclusion

Ground water contamination in Arizona is a potentially serious problem because of the high intensity of nitrogen fertilizer applications in several agricultural counties. In Arizona, ground water provides a large proportion of high quality drinking water resources at a relatively low cost. Over 90 percent of rural Arizona residents rely on ground water for domestic uses (USDA, 1991). Once ground water is contaminated, it recovers very slowly if ever because, unlike surface water, it is not subject to sunlight, heating and cooling cycles, microbial transformation, and oxidation that help to chemically transform or degrade pollutants (ibid.).

Conventional drinking water treatment does not remove nitrate. Treatment methods which can remove nitrate from drinking water are highly advanced, costly, and require careful operation. Furthermore, the removal of nitrate from drinking water may result in the addition or formation of undesirable substances, (OECD, 1986).

Objectives

This study investigates the reasons why farmers may apply more fertilizer than needed to maximize profits, the impact of reduced nitrogen on farm profits, and the impact of a tax on nitrogen use. The specific objectives of this study are to:

1. Estimate crop yield response to nitrogen fertilizer

for cotton, sweet corn, leaf lettuce, romaine lettuce, collards, mustard, spinach, honeyloup, watermelon, cantaloup, and wheat grown in Arizona.

2. Estimate the effect on net returns when nitrogen applications exceed the profit maximum level.
3. Estimate the effect on net returns when nitrogen fertilizer applications are decreased by 10, 20, and 30 percent below yield maximum levels.
4. Estimate the effect of a 100 percent tax on nitrogen use.

The remainder of the study proceeds as follows. Chapter 2 reviews the relevant literature on production functions and the effect of relative prices upon optimal nitrogen applications. Chapter 3 describes the analytical techniques. Chapter 4 presents the experimental data and price data. Chapter 5 discusses the statistical results of the estimated production functions. Chapter 6 presents the economic results. Chapter 7 summarizes the study and findings and draws implications for crop management and environmental policy.

2. LITERATURE REVIEW

Traditionally, nitrogen management research focused upon increasing agronomic effectiveness and economic returns (Bock and Hergert, 1991). While these goals are still priorities, since the 1970s nitrogen management research has also aimed to reduce and prevent harmful environmental impacts from nitrates by improving nitrogen-use efficiency (ibid.).

Estimation of crop response functions to nitrogen can reveal the nature of production relationships and help guide nitrogen application decisions for both profits and lower levels of nitrogen leaching.

This chapter reviews the literature on nitrogen fertilizer management and ground water quality in Arizona, the estimation of yield response functions, and the effect of relative prices upon optimal nitrogen applications.

Nitrogen Fertilizer Management and Ground Water Quality in Arizona

Although no studies have been conducted in Arizona which conclusively show that significant amounts of nitrogen have been leached into the ground water, lawmakers have been concerned because nitrogen applications per acre in Arizona are among the highest in the nation (Ayer *et al.*, 1990). Desert soils contain relatively low levels of organic matter.

Thus, mineralization of nitrogen, which must occur before plants can use nitrogen, is insufficient to support intensive, high-input cropping systems common in Arizona agriculture (Doerge, 1991). Therefore, agricultural production in Arizona is highly dependent on off-farm sources of nitrogen generally in the form of synthetic fertilizers.

In Arizona, as in other states, nitrogen costs are low relative to other input costs. Also, the results of Ayer _et al_. show that for several commercial crops, yields do not decrease significantly when nitrogen is used in excess of the level needed to maximize yields. Thus, farmers may apply nitrogen in excess of even yield maximizing levels because it is inexpensive to do so and they can avoid the risks associated with not knowing yield response at lower nitrogen levels. Ayer _et al_., (1990) and Doerge (1991) also show that for several Arizona crops, nitrogen applications can be reduced by as much as 20 percent without significantly affecting yield or profits.

Doerge, Roth, and Gardner (1991) published a book, intended for commercial farm use, which centers on nitrogen fertilizer practices for cultivation of field and vegetable crops in Arizona. Their work addresses the environmental problems which result from excessive nitrogen fertilizer use. Doerge, Roth, and Gardner provide specific information on seven BMPs and Guidance Practices (which farmers implement to achieve the goals stated by BMPs) which can help farmers use nitrogen more efficiently and in accordance with the 1986 Arizona Environmental Quality Act (EQA). The EQA recognizes the contribution of nitrogen fertilizers to ground and surface water pollution.

Yield Response Functions

Neither agronomic theory nor empirical evidence clearly establishes a single functional form of crop response to nitrogen use (Tronstad and Taylor, 1989). Without a definitive agronomic or biological theory of crop response to inputs, researchers rely on statistical criteria, which are often inconclusive. The literature on production function estimation reflects the difficulty of selecting the "best" functional form. Testing a variety of functions is critical for examination and comparison of statistical results and predictions of agronomic relationships and optimal input levels (ibid.).

Heady and Pesek (1954); Baum, Heady, and Blackmore (1956); Heady and Dillon (1961); and Hexum and Heady (1978) conducted production function studies based on controlled experiments with one or two input variables. They wanted to learn more about the biological basis and yield response to fertilizer. Their studies were based on data from various experimental sites around the United States. Heady and his colleagues estimated and examined production functions showing crop response to fertilizer and water. Much of their work focused on the methodological problems encountered in the estimation and utilization of fertilizer response functions, selection of estimation procedures for predicting the production surface, and practical uses of production function estimates for commercial farms.

Their research mostly utilized polynomial functions because polynomials are relatively easy to estimate, allow negative marginal physical productivity and specification of input interaction, and define a unique yield maximum.

More recent studies explore the possibilities of Linear Response and Plateau (LRP) models and compare them to polynomial models. The LRP model which expresses Justus von Liebig's law of the minimum (von Liebig, 1840) is believed by many researchers to be a good representation of plant behavior. The law of the minimum states that crop yield is a proportional function of the scarcest nutrient available to the plant; increasing the availability of non-limiting nutrients does not affect crop yield (Paris and Knapp, 1989). In an LRP model a plant will respond linearly to the addition of a limiting input until a different input becomes limiting (Berck and Helfand, 1990). The von Liebig model is expressed as:

$$Y = \min\{a_i + b_i x_i,\ a_j + b_j x_j,\ m\} + u$$

where Y equals yield, x_i and x_j are two different applied nutrients, and m is a measure of the potential maximum yield imposed by the scarcity of nutrients other than x_i and x_j (Paris and Knapp, 1989). Proponents of the von Liebig model believe that inputs are perfectly complementary and no substitution occurs.

A second LRP model allows substitution of inputs within a limited range as well as a growth plateau. This model was developed by E.A. Mitscherlich with modification by Baule. This model is expressed by:

$$Y = A(1-e^{-kx})$$

where Y equals yield, A equals maximum obtainable yield, k is the constant effect factor, and x is the variable input. The Mitscherlich-Baule equation relates growth to the supply of plant nutrients based on the concept that an increase in crop yield due to the addition of a single growth factor is proportional to the amount in which the resulting yield still falls below the maximum yield.

The von Liebig and Mitscherlich-Baule models had been ignored in empirical work because they are difficult to estimate. The development of sophisticated econometric and statistical software packages has enabled researchers to estimate these models and subject them to rigorous statistical testing. Presently, new arguments are arising concerning continued use of polynomial models such as the quadratic, square root, and three-halves. Critics of polynomial models state that they poorly represent plant behavior (Ackello-Ogutu, Paris, and Williams, 1985; Grimm, Paris, and Williams, 1987; Paris and Knapp, 1989). Ackello-Ogutu, Paris, and Williams advise against the use of polynomial models because they force biological substitution between nutrients and overestimate the optimal quantity of fertilizer and maximum yield. Ackello-Ogutu, Paris, and Williams blame excessive fertilizer use and consequent waste of resources and environmental pollution on recommendations based on polynomial functions.

Ackello-Ogutu, Paris, and Williams' criticisms of polynomial models are based on their 1985 study which used corn yield response data to compare a generalized nutrient nonsubstitution model (von Liebig) and polynomial (quadratic and square root) models by testing the assumptions underlying these specifications using nonnested hypothesis testing. The data used in the study originate from a 30-year experiment at Purdue University although only observations from 1960 to 1966 were used. Purdue researchers rotated the corn crop with soybeans, wheat, and hay. Superphosphate (P) and potassium chloride (K) were the nutrients studied. The polynomial and von Liebig production functions include estimation of "accounted for" carryover P and K by combining geometric lags and first order autoregression forms applied to the four crop rotations. The carryover functions were used by Ackello-Ogutu, Paris, and Williams to allow for carryover effects through time.

Four nonnested hypothesis tests with the von Liebig tested against the square root and quadratic forms as the null and alternative hypotheses were conducted using the CP and C-test discussed in Cox (1961), Pesaran (1974), and Davidson and MacKinnon (1981). Results from the hypothesis test revealed that the nonsubstitution hypothesis could not be rejected and that the polynomial specifications could be rejected in five out of six cases. Since the nonsubstitution hypothesis which accounts for plateaus could not be rejected, the authors concluded that the study data show evidence of a plateau. Furthermore, the square root model which has a slightly flatter surface than the quadratic was rejected at a lower significance level than the quadratic. The authors concluded that polynomial specifications are not recommended to represent crop yield response because polynomials cannot account for plateaus or bends in the response surface. When plateaus exist, the use of polynomials may lead to costly biases if their recommendations are passed on to farmers. The authors' final remarks state that polynomials should be abandoned and nonsubstitution models should receive serious consideration.

Grimm, Paris, and Williams (1985) hypothesize that crop response to water and nitrogen follows von Liebig's principle of a linear response to a limiting nutrient with a sharp transition to a plateau maximum. To test their hypothesis, Grimm, Paris, and Williams contrast the von Liebig model for each of five independent experiments on corn, corn silage, cotton, wheat, and sugar beets respectively against the polynomial form (quadratic, square root, or three-halves forms) selected for each experiment by Hexum and Heady (1978). Nonnested hypothesis testing is used to determine which model is the correct specification of crop response to water and nitrogen.

Regression analysis reveals that the von Liebig and polynomial models differ greatly regarding the amounts of nitrogen and water necessary to maximize yields. For all crops, the polynomial models show that the yield maximizing level of nitrogen is almost twice the amount of nitrogen predicted by the von Liebig to maximize yield. The differences in the yield maximizing levels of water predicted by the polynomial models and the von Liebig are smaller but yield maximizing water levels are also higher for the polynomial models for all crops. These results are consistent with findings reported by Boyd; Anderson and Nelson; Waugh et al., Sanchez and Salinas; and Ackello-Ogutu, Paris, and Williams. Grimm, Paris, and Williams believe their results confirm the tendency of polynomial models to overestimate optimal input levels.

The W and Cox-Pesaran (CP) hypothesis tests were applied to the models. According to the W test, the von Liebig model could not be rejected for any crop. In contrast, the polynomial models were rejected for all study crops. Concerning the CP test, the von Liebig outperformed the polynomial models in three out of five cases. The authors conclude that the von Liebig model can explain crop response at least as well as, and often better than, polynomial models.

Tronstad and Taylor (1989) also determined that the quadratic, Cobb-Douglas, and constant elasticity of substitution functions do not fit their data set as well as functions that impose a yield plateau or asymptotic plateau. However, after fitting 15 functional forms to experimental data showing corn yield response to nitrogen and phosphorous, Tronstad and Taylor conclude that establishing the dominance of one functional form over the others is impossible despite the robustness of the data. Researchers must use a variety of functions to examine statistical properties and optimal input rate estimates.

Frank, Beattie, and Embleton (1990) extend the work of

Ackello-Ogutu, Paris, and Williams; and Grimm, Paris, and Williams by expanding model comparison to include the Mitscherlich-Baule model. The Mitscherlich-Baule model allows plateau growth and substitution. Frank, Beattie, and Embleton note that the earlier studies limited model comparisons to plateau growth and no factor substitution or nonplateau growth and substitution.

Frank, Beattie, and Embleton estimate the Mitscherlich-Baule, von Liebig, and quadratic forms to reflect corn yield response to nitrogen and phosphorous. The forms were compared and evaluated using nonnested pairwise hypothesis tests. The authors note that elasticity of substitution and a growth plateau are two important aspects of estimating plant response. The von Liebig and the Mitscherlich-Baule both impose a growth plateau. These functions were found to fit the data better than the quadratic because the corn response to nitrogen and phosphorous displayed a growth plateau. Pairwise testing was conducted because no true null hypothesis was postulated. Each hypothesis or model was temporarily held as null and compared in a pairwise fashion with each temporary alternative. The hypothesis tests results favor the Mitscherlich-Baule over the other two functions. These results support the law of the minimum and nonzero elasticity of factor substitution. However, the authors state that with other agronomic factors, imposition of a growth plateau may be questionable.

Tronstad and Taylor (1989) conducted an analysis to determine the sensitivity of statistical criteria, parameter estimates, and optimal fertilizer rates to functional form and estimation procedures. The functional forms were estimated by minimizing the sum of squared errors (SSE), Generalized Least Squares, and/or Minimum Absolute Deviations. Optimal levels of nitrogen and phosphorous varied more due to functional form than to estimation procedures followed. This result occurred because different sets of specific parameter values create different estimating lines and different sets of residuals (Kennedy, 1985).

Homoscedasticity and normality of the error structures were tested to check whether these assumptions for estimation were appropriate. Presence of heteroscedasticity and non-normality of the error structures are violations of the basic assumptions of the classical linear regression model concerning the manner in which observations are generated (ibid.). In the presence of heteroscedasticity, the Ordinary Least Squares (OLS) estimator becomes less efficient because it no longer has the minimum variance relative to all other linear unbiased estimators. The consequences of non-normality of the error terms are quite serious; hypothesis testing and interval estimation cannot be undertaken meaningfully. Tronstad and Taylor's examination of the error structures of the SSE estimates indicates that assumptions of homoscedasticity and normality are often unwarrented and should be tested more often.

Relative Prices and Optimal Nitrogen Applications

Swanson, Taylor, and Welch (1973) used data from eight experimental sites in Illinois from 1967 to 1971 to estimate corn yield response to nitrogen fertilizer. Four game-theoretic models: Man vs. Nature, Criterion of Simple Average, Criterion of Maximizing Minimum Return, and Criterion of Minimizing Maximum Regret were used as alternative decision models to estimate optimal nitrogen rates for each location and year. Each decision model made different assumptions about the possible response function to be experienced in future growing seasons. The results were used to determine the effect of relative prices of corn and nitrogen upon optimal nitrogen applications levels for each year and location assuming that the yield response function was known with certainty at the time of fertilizer application.

Swanson, Taylor, and Welch selected the quadratic function because the predicted yields from the quadratic equations were the most consistent with the deviation of yields at treatment means. The regression results reflected differences in soil productivity and climatic conditions and/or differences in the number of years the experiment had been conducted. The game-theoretic models estimated the optimal nitrogen rates at all locations and years to cover a range from 100 to 240 lbs/acre. The optimal nitrogen rate for most locations and years show little sensitivity to changes in the corn/nitrogen price ratio.

Similarly, in Arizona, Ayer _et al_., (1990) found that optimal nitrogen rates for barley, upland cotton, and lettuce were fairly insensitive to changes in nitrogen or crop prices. The greatest price effect occurred in barley and wheat because, in these crops, nitrogen accounts for a larger proportion of total variable costs of production than for cotton and lettuce. Additionally, Ayer _et al_. showed that yield and net returns for lettuce were more responsive to decreases in applied nitrogen than to increases in the price of nitrogen. A 30 percent reduction in nitrogen caused yield to decrease approximately 15 percent and net returns to decline more than 22 percent. A 100 percent increase in the price of nitrogen left the profit maximizing level of nitrogen unchanged. Their results were based upon polynomial crop yield response functions estimated from experimental data.

Fuez, Follett, Echols, and Skold (1988) found that optimal levels of nitrogen for Colorado winter wheat change depending upon relative prices for inputs and outputs. The authors also found that optimal nitrogen levels differed by approximately 10 lbs/acre depending on region and whether or not a farmer participated in a government wheat program. They estimated winter wheat yield response to nitrogen fertilizer. The data were from fertilizer trials conducted by Colorado State University in eastern Colorado from 1982 to 1987, excluding 1984. The trial data were divided into northeast and southeast regions of Colorado. Quadratic nitrogen-yield production functions were estimated. The purpose of their report was to illustrate that at any given location, the optimal level of nitrogen is influenced by nitrogen fertilizer prices, the price of wheat, and the yield response of wheat to fertilizer.

3. ANALYTICAL TECHNIQUES

Production Functions, Input Use, and Profits

A crop production function shows plant responses to inputs and is used with input and output prices to determine profitability.

A two-input production function can be expressed as

(3.1) $Y = f(x_1, x_2)$.

Output produced (Y) is the maximum amount attainable given the combination of inputs (x_1 and x_2) applied. In its traditional form, equation (3.1) is assumed to be continuous and twice differentiable. Profits are expressed as:

(3.2) $\pi = pf(x_1, x_2) - r_1x_1 - r_2x_2$,

where r_1 and r_2 are the prices for inputs x_1 and x_2, and p is output price. Profit maximizing input levels are identified by satisfying the first order conditions for profit maximization:

(3.3a) $\pi_1 = \partial\pi/\partial x_1 = pf_1 - r_1 = 0$ and

(3.3b) $\pi_2 = \partial\pi/\partial x_2 = pf_2 - r_2 = 0$.

Equations (3.3a) and (3.3b) state that a producer would employ resources up to the point where the marginal value product of the input (pf_i or $pMPP_i$) equals the price of the last unit of input, or r_i. An alternative statement of this concept is $MPP_i = r_i/p$ meaning the marginal physical product of input x_i equals relative input and output prices at the profit maximizing point of production. Assurance of profit maximization also requires that the second order or sufficient conditions be satisfied:

(3.4) $d^2\pi_i/dx^2_i = pf_{ii} = p(dMPP_i/dx_i)<0.$

This statement can be summarized as $f_{11}<0$ and $f_{22}<0$ for two variable factors. Equation (3.4) is a statement of the law of diminishing returns which means that the marginal physical product diminishes with added inputs. However, the sign of the cross-partial derivative, f_{ij} is also important. Therefore, the second order conditions for profit maximization require that the second partial derivatives or principal minors of the Hessian matrix alternate in sign beginning with a negative sign and that the value of the determinant of the Hessian matrix be greater than zero. With two variable factors:

(3.5) $f_{11}f_{22} - f^2_{12} > 0.$

The conditions stated in (3.5) are equivalent to requiring that the production function be strictly concave in the neighborhood of the values of x_1 and x_2 that satisfy the first order conditions (Beattie and Taylor, 1985). These conditions are satisfied if isoquants are convex to the origin signifying decreasing marginal physical productivities.

Estimates of maximum yields and profit maximizing input and output levels depend upon the mathematical form of the model used to estimate the production function. All functional forms, whether they are linear, polynomial, multiplicative, linear response and plateau (LRP), or other forms, have their limitations. Controversy concerning which form is most appropriate for a particular situation remains, as shown in the literature review, despite the sophistication of statistical and econometric techniques and availability of a broad range of selection criteria.

Mitscherlich-Baule

In 1909, E. A. Mitscherlich proposed that a crop should produce a maximum yield under ideal conditions. However, if any essential growth factor is deficient, a corresponding decrease in yield occurs. An increase in yield due to the addition of a unit of the deficient factor would be proportional to the decrement from the maximum yield (Redman and Allen, 1954). This idea was expressed by Mitscherlich as:

(3.6) $dY/dX = (A - Y)C$,

where Y equals yield, X equals the quantity of the growth factor present, A equals the maximum yield that could be produced by increasing indefinately the amount of growth factor X, and C equals a constant or proportionality factor. C is constant for each growth factor independent of other conditions such as soil or crop type.

Baule modified Mitscherlich's equation to include interaction of all yield-influencing factors. Mitscherlich's work had been criticized because researchers noted that yield response to a particular nutrient or growth factor must be affected by other yield-influencing factors. Baule believed that yield-influencing factors corresponded to Mitscherlich's ideas and that final yield is a product of all the factors combined. Furthermore, according to Baule, each limited nutrient affects yield by a percentage of the maximum affect it would exert on yield if the nutrient were available to the plant in the optimum amount.

Additions of inputs must be understood in terms of Baule units. A Baule unit is the amount of any input necessary to produce a yield that is 50 percent of the difference between the maximum possible yield and the yield before the unit was added. For example, if all inputs but one, x, were present in the amount necessary to attain the maximum yield, the addition of 1 Baule unit of x would produce a yield that was 50 percent of the maximum possible. If all but two inputs, x_1 and x_2, were present at maximum yield levels, and the simultaneous addition of 1 Baule unit of each is added, the yield obtained will not be 50 percent but 50 percent times 50 percent or 25 percent of the maximum (Tisdale, Nelson, and Beaton, 1985). Baule's yield equation is expressed as:

$$(3.7) \quad Y = A(1 - 10^{c_1 x_1})(1 - 10^{c_2 x_2}) \ldots (1 - 10^{c_n x_n}),$$

where Y equals yield, A equals maximum obtainable yield, $c_1, c_2, \ldots, c_n$ are constant effect factors, and $x_1, x_2, \ldots, x_n$ are variable inputs. Thus, the idea that growth factors simultaneously exert influence on yield response of a plant came from Baule and was adopted by Mitscherlich. Mitscherlich also stated that all yield influencing factors must exist in balanced proportions to each other in order to enhance each other. The influence of a particular factor may remain dormant in the absence of adequate support from one or another factor. This idea suggests that a high degree of complementarity is present among the factors in the production of crops.

Mitscherlich modified his equation with the assumption that the slope of the yield curve at all points is proportional to the amount of increase theoretically yet possible from the use of the nutrient in question (ibid.). Mitscherlich's modified equation is:

$$(3.8) \quad Y = A(1 - e^{-kx}),$$

where e^{-k} indicates the ratio of any two consecutive increments in yield due to consecutive unit increments in the nutrient in question (ibid.). Redman and Allen note that Mitscherlich developed this equation simultaneously with Spillman. Spillman's equation is expressed as:

$$(3.9) \quad Y = A(1 - R^{x}).$$

Spillman's R equals Mitscherlich's e^{-k}. Neither Mitscherlich nor Spillman allow for increasing marginal returns (stage I) nor negative marginal returns in their equations.

For the one-variable input model (nitrogen only), two and three parameter Mitscherlich-Baule models were specified in this study. For the two-variable input model (nitrogen and water), three-parameter and five-parameter models were specified. Due to the asymptotic properties of the maximum likelihood estimator used to estimate the equations (see pg. 44), the Mitscherlich-Baule model was only fit to data sets with $n \geq 30$. The one-variable model was specified as:

(3.10a) $Y = \beta_1[1 - e^{-\beta2(\beta3 + N)}]$ and

(3.10b) $Y = \beta_1[1 - e^{-\beta2(NRES + N)}]$

where NRES is the measured residual nitrogen level in the soil before fertilizer nitrogen was applied to the crop.

The nitrogen x water equations were specified as:

(3.11a) $Y = \beta_1[1 - e^{-\beta2(\beta3 + N)}][1 - e^{-\beta4(\beta5 + W)}]$ and

(3.11b) $Y = \beta_1[1 - e^{-\beta2(NRES + N)}][1 - e^{-\beta3(SM + W)}]$

where SM equals the measured soil moisture level before irrigation was applied. Equations (3.10a) and (3.11a) are common specifications of the Mitscherlich-Baule model used by Tronstad and Taylor (1989) and Frank, et al., (1990). Equations (3.10b) and (3.11b) were specifications suggested by Heady and Hexum (1978) when two variables such as irrigation water and fertilizer are introduced. Additionally, Tronstad and Taylor (1989) state that β_3 and β_5 in the long forms can be thought of as nutrients (in their case phosphorous and nitrogen) provided to the plant by the soil.

The equations were estimated first with all sample observations and second with the mean yields calculated from each replicated nitrogen or nitrogen x water test level.

Estimation of Parameters: Maximum Likelihood Function

Maximum likelihood estimation procedures were used to estimate the Mitscherlich-Baule model. This estimation method is based on the idea that different populations generate different samples, and that any one sample is more likely to come from some populations than from others. For example, if a random variable X has a probability distribution f(x) characterized by parameters θ_1, $\theta_2,\ldots,\theta_k$ and if we observe a sample x_1, $x_2,\ldots,x_n$, then the maximum likelihood estimators of θ_1, $\theta_2\ldots,\theta_k$ are those values for which the probability density of a given set of sample values is at a maximum. The values of $f(x_1, x_2,\ldots,x_n)$ must be maximized in order to find the maximum likelihood estimators of θ_1, $\theta_2,\ldots,\theta_k$. The maximum likelihood estimator of a vector of parameter values β is the particular vector β^{MLE} which gives the greatest probability of drawing the sample actually obtained; no other values would be preferred to this value of β (Kennedy, 1985). Therefore, the maximum likelihood estimators are found by maximizing the likelihood function (ℓ) with respect to the parameters. To find the maximum, the first order conditions must be solved by taking the partial derivative of ℓ with respect to each parameter; the resulting equation is set equal to zero.

The maximum likelihood estimator has several desirable properties:

1. The estimator is consistent so that the sampling distribution becomes concentrated on the true value of the parameter as the sample size approaches infinity.

2. The estimator is asymptotically efficient which means that as the sample size approaches infinity, the sampling distribution of the maximum likelihood estimator has the smallest variance or this estimator has the smallest dispersion about the true value of the parameter.

3. Maximum likelihood estimators are asymptotically distributed normally and the estimated asymptotic variances of the estimators can be determined in the estimation process.

Although the maximum likelihood estimator only has asymptotic properties, Goldfeld and Quandt (1972) state that maximum likelihood estimators perform well for relatively small sample sizes down to n = 30 for the estimation of coefficients. However, the estimation of estimator variances requires much larger sample sizes. A drawback to the calculation of the maximum likelihood estimator is that the distribution of the error term must be known.

Before the likelihood function (ℓ) can be formed, the nature of the error term must be specified. Assuming that ε is normally and independently distributed with a probability density function equal to $f(\varepsilon)$:

$$(3.12)\quad f(\varepsilon) = (2\pi\sigma^2)^{-1/2} \exp\{-\varepsilon^2/2\sigma^2\}.$$

According to Kennedy (1985) the relationship in (3.12) can be rewritten as:

(3.13) $\varepsilon = Y - \beta_1 - \beta_2 X - \beta_3 Z$,

so that for the i^{th} value of ε

(3.14) $f(\varepsilon_i) = (2\pi\sigma^2)^{-1/2} \exp\{-1/2\sigma^2(Y_i - \beta_1 - \beta_2 X_i - \beta_3 Z_i)^2\}$.

The likelihood function is a formula for the joint probability distribution of the sample. The joint probability distribution of the sample is proportional to the probability of drawing the particular error terms inherent in this sample (Kennedy, 1985). The likelihood function is given by the product of all the $f(\varepsilon)$'s (one for each sample observation) if the error terms are independent of each other. Using Kennedy's example in (3.13):

(3.15) $\ell = (2\pi\sigma^2)^{-n/2} \exp\{-1/2\sigma^2 \Sigma^n{}_{i=1}(Y_i - \beta_1 - \beta_2 x_i - \beta_3 z_i)^2\}$.

ℓ is a function of the sample data and β_1, β_2, β_3, and σ^2. In practice, the logarithm of ℓ is maximized rather than ℓ because solving the first order conditions with $\ln\ell$ is easier than with ℓ. Parameter values that maximize ℓ also maximize $\ln\ell$ because $\ln\ell$ is a monotonic transformation of ℓ. Therefore, the values of β_1, β_2, β_3, and σ^2 which maximize ℓ may be found by:

$$(3.16)\quad \ln\ell = n/2\ \ln(2\pi\sigma^2) - 1/2\sigma^2\ \Sigma^n{}_{i=1}(Y_i - \beta_1 - \beta_2X_i - \beta_3Z_i)^2.$$

To estimate nonlinear functions like the Mitscherlich-Baule by maximum likelihood estimation, the computer follows an iterative or trial and error approach to find the parameter values that maximize the likelihood function. Maximizing the ℓ is equivalent to minimizing the sum of squared errors in ordinary least squares estimation. The procedure begins with the economist providing appropriate starting values (guesses) for the parameters. The residuals and the sum of squared errors (SSE) are computed after the equation is linearized around the initial set of parameter values. The computer then generates a new set of parameter values, relinearizes around these values and recalculates the SSE. The computer checks if the SSE have increased or decreased in value. The parameter values are changed by the computer in directions that lead to smaller SSE until it finds the set of parameter values that, when changed slightly, produces an increase in the value of the SSE. These parameter values are the least square estimates in a nonlinear context (Kennedy, 1985).

All efforts failed to maximize the likelihood function of the Mitscherlich-Baule model. The Mitscherlich-Baule model was not used for the economic or statistical analyses in Chapters 5 and 6 of this thesis. Results of the Mitscherlich-Baule estimation are discussed in Appendix D.

Polynomial Models

Four polynomial models, the quadratic, square root, three-halves, and natural log forms were estimated by Ordinary Least Squares (OLS). These forms are relatively easy to estimate and have historically been used in many crop production function studies.

When nitrogen (N) was the only input variable, the polynomial forms to describe yield (Y) response, including the error term ε_i, were specified as:

(3.17) Quadratic $Y_i = \beta_1 + \beta_2 N + \beta_3 N^2 + \varepsilon_i$

(3.18) Square root $Y_i = \beta_1 + \beta_2 N + \beta_3 N^{.5} + \varepsilon_i$

(3.19) Three-halves $Y_i = \beta_1 + \beta_2 N + \beta_3 N^{1.5} + \varepsilon_i$

(3.20) Natural Log $\ln(Y) = \beta_1 + \beta_2 \ln(N) + \varepsilon_i$

Polynomial yield response models with nitrogen and irrigation water (W) inputs were specified as:

(3.21) Quadratic $Y_i = \beta_1 + \beta_2 N + \beta_3 W + \beta_4 N^2 + \beta_5 W^2 + \beta_6 NW + \varepsilon_i$

(3.22) Square root $Y_i = \beta_1 + \beta_2 N + \beta_3 W + \beta_4 N^{.5} + \beta_5 W^{.5} + \beta_6 (NW)^{.5} + \varepsilon_i$

(3.23) Three-halves $Y_i = \beta_1 + \beta_2 N + \beta_3 W + \beta_4 N^{1.5} + \beta_5 W^{1.5} + \beta_6 (NW)^{1.5} + \varepsilon_i$

(3.24) Natural Log $\ln(Y) = \beta_1 + \beta_2 \ln(N) + \beta_3 \ln(W) + \varepsilon_i$

The three-halves and the quadratic functions are similar as these functions increase to a maximum at uniform rates and allow for factor substitution in the two input (N and W) models. The slope of the square root function increases more rapidly at low application levels but then flattens out more than the three-halves or quadratic forms as nitrogen levels increase. The square root and the natural log forms also allow factor substitution. All four forms may exhibit stages II and III of the production function.

Diagnostic Tests for the Ordinary Least Squares Estimates

Each polynomial model (quadratic, square root, three-halves, and natural log) estimated by OLS was tested for homoscedasticity and non-normality. The Breusch-Pagan-Godfrey (BPG) test for homoscedasticity and the Jarque-Bera test for normality of the regression residuals were applied using Shazam software. Both tests use a Lagrangian multiplier (LM) procedure. In large samples the critical values of the LM procedure are distributed asymptotically as chi-square. The LM test is asymptotically equivalent to the likelihood ratio test and therefore has good asymptotic power but can be easily computed by least squares regression. The small sample properties of the LM statistic in both tests have been determined in Monte Carlo studies (Godfrey, 1978; Breusch and Pagan, 1979; Bera and Jarque, 1981; Bera and John, 1983).

Regarding the BPG test, Godfrey states that when heteroscedasticity is present, the power of the LM test is not good especially if the 5 percent significance level is used for sample size $n \leq 20$. The power of the LM test is good for $n = 30$. Breusch and Pagan state that for small sample sizes the LM test is no worse than other tests. In the Jarque-Bera procedure, the estimated LM statistic performs with relatively good power for $n = 20$. The power of the estimated LM statistic for both tests will be relatively low for all models fit to data sets which have as few as 12 observations.

The BPG test is easily computed because the LM statistic is defined as a regression. The null hypothesis is:

(3.25) $H_o\colon \alpha_2 = \ldots \alpha_p = 0.$

Heteroscedasticity is specified as:

(3.26) $\sigma^2{}_t = h(z_t{}'\alpha).$

The representation of heteroscedasticity in (3.26) is general and includes most of the heteroscedastic models (Breusch and Pagan, 1979). In both equations, α is a (p x 1) vector of unrestricted parameters unrelated to the β coefficients. The first element of z is unity. To begin the procedure, the least squares residuals ε_i are estimated from:

(3.27) $Y_i = A + \beta x_i + \varepsilon_i$

where Y_i equals yield and x_i represents the input. The residuals in equation (3.27) are used to estimate the residual variance:

(3.28) $\hat{\sigma}^2 = \Sigma\hat{\varepsilon}^2{}_i/n.$

The test statistic is provided from the following regression:

(3.29) $\hat{\varepsilon}^2{}_i/\hat{\sigma}^2 = \gamma + \delta z_i + v_i$

where z is a random variable. For equation (3.27) and (3.28) the LM statistic is ½RSS (the regression sum of squares from (3.29)) which follows a χ^2 distribution with (p - 1) degrees of freedom when H_o is true. The higher the value of the RSS, the more highly correlated is z with the error variance and therefore H_o is less likely to hold (Pindyck and Rubinfeld, 1991). In cases where a model is fit to a data set with 12 observations, the presence of heteroscedasticity is suspect even if the null hypothesis is not rejected because the power of the test is low.

The LM test statistic in the Jarque-Bera test is easily computed because under the null hypothesis, only the parameters of the model need to be estimated. However, this procedure uses an estimated LM statistic ($\hat{LM}$) because the true errors cannot be observed in regression analysis. $\hat{LM}$ is based on the estimated observations of the residuals. $\hat{LM}$ is obtained by replacing u_j by $\hat{u}_j$, where $E(u_j)$ may be estimated by $u_j = \Sigma u_j/n$, where $u_j = y_i - g(x_i, \beta)$ and where $\hat{\beta}$ is a consistent estimator of β. $\hat{LM}$ has the same distribution as LM equal to χ^2_2. Jarque and Bera give the $\hat{LM}$ statistic as:

$$(3.30) \quad \hat{LM} = n[\sqrt{b_1})^2/6 + (b_2 - 3)^2/24].$$

According to Geary (1947) $\sqrt{b_1}$ and b_2 have optimal properties for large samples if the departure from normality is due to either skewness or kurtosis. Tronstad and Taylor (1989) present the Jarque-Bera $\hat{LM}$ test statistic as:

$$(3.31) \quad \hat{LM} = n[(\text{Skewness})^2/6 + (\text{Kurtosis} - 3)^2/24].$$

Model Selection

The polynomial models (quadratic, square root, three-halves, and natural log) were evaluated and selected for the sensitivity analysis on the basis of the adjusted coefficient of determination ($\bar{R}^2$), the significance of the coefficients (t-test), F test, BPG test, Bera-Jarque test, and expected signs of the coefficients.

R^2 Computation

The coefficient of determination (R^2) reported in this study was derived by calculating the square of the correlation (ρ^2) between the actual yield (Y) and the predicted yield ($\hat{Y}$). The value of ρ^2 is equal to the value of R^2. In the case of the natural log model, ρ^2 was calculated between Y and the antilog of $\widehat{\ln(Y)}$.

ρ^2 is considered here rather than R^2 calculated by $1 - \Sigma(y - \hat{y})^2/\Sigma(y - \bar{y})^2$ so that the predictive power of all models estimated in this study can be compared. Comparing models using the R^2 equal to 1 minus the ratio of unexplained variation to total variation is appropriate only for linear models with an intercept term. The fits of a linear and nonlinear model cannot use the same R^2 expression because the models use different variables: y and $\hat{y}$ for the linear model and ln(y) and $\widehat{\ln(y)}$ for the nonlinear or transformed model used in this study. To make a sensible comparison between the fits of a linear and a nonlinear model to the same set of data, comparable data points (y, $\hat{y}$) and R^2 must be used; otherwise misleading results may be obtained (Kvålseth, 1985). Thus the square of the correlation between Y and $\hat{Y}$ for the quadratic, square root, and three-halves models and Y and the antilog of $\widehat{\ln(Y)}$ for the natural log model was used.

The adjusted R^2 ($\bar{R}^2$) was calculated as:

(3.32) $\bar{R}^2 = R^2 - (K - 1/n - K)\ (1 - R^2)$,

where K equals the number of parameters and n equals the sample size.

Estimation of Yield and Profit Maximizing Rates of Nitrogen

Models selected for the economic analysis were used to estimate the yield maximizing and profit maximizing levels of nitrogen. The percentage change in yield and net returns as nitrogen applications were decreased from the yield maximizing level and increased above the profit maximizing level were examined. A 100 percent tax was imposed on nitrogen under varying crop prices to observe the corresponding impact upon net returns. Net returns are defined as total revenue less the total operating costs (including the cost of nitrogen, harvest, and all other operating costs). Lastly, the price elasticities of demand for nitrogen were calculated based on the selected models using a wide range of crop and nitrogen prices.

4. DATA

Experimental Crop Data

The data analyzed in this thesis are from numerous field studies at the University of Arizona Maricopa Agricultural Center (MAC). Dr. Thomas Doerge, Department of Soil and Water Science, University of Arizona, designed and conducted the studies from 1985 to 1991, to determine yield response to nitrogen and in some cases nitrogen and water. The test plot data cover 11 crops including, leaf lettuce, romaine lettuce, collards, mustard, spinach, sweet corn, cotton, wheat, cantaloup, watermelon, and honeyloup. Soil type, experimental design, and nutrient levels differed across experiments. These characteristics and observed yields are described for each experiment. The nitrogen, water, and yield data for each experiment are given in Appendix A.

Durum Wheat

During the 1985 to 1988 crop years, five field experiments were conducted at the MAC on irrigated durum wheat (Triticum turgidum L. var.). The experiments investigated the effects of varying nitrogen rates on grain yield. NO_3 and NH_4-N levels contained in irrigated water applied in each experiment were determined. Rainfall was recorded during each crop year at automated on-site weather stations. The experimental sites were cropped with unfertilized sudangrass (Sorghum sudanenses L.) 5 months prior to planting the wheat to reduce the level of residual nitrogen in the rooting zone and to minimize variation of remaining nitrogen in the soil (Knowles et al., 1991).

Experiment 1, 1986

This experiment was conducted on a Casa Grande sandy loam soil. Soil samples taken at various depths ranging from 0 to 2.7 ft showed preplant residual NO_3-N levels to be less than 1.2 lbs/acre. The wheat received 27.6 inches of water in seven irrigations. During the growth period, 2.87 inches of rain fell. Irrigation water contained 74.8 lbs nitrogen/acre. The nitrogen contained in the irrigation water was accounted for in the cumulative nitrogen rate by the researchers when this experiment was conducted. Eight nitrogen treatments were replicated four times in a randomized complete block (RCB) design. Nitrogen rates for treatments 1 to 5 were preassigned. Treatments 6 to 8 were equivalent and were guided by soil and stem NO_3-N analysis as recommended by Pennington et al., (1983) and Knowles et al., (1991). The actual nitrogen treatments were 75, 200, 289, 324, 450, and 574 lbs/acre.

Experiment 2 1987

This experiment was conducted on a Trix clay loam soil. Five soil samples were taken for the preplant soil NO_3-N analyses at depths of 0-.9 ft, .9-1.8 ft, 1.8-2.7 ft, 2.7-3.6 ft, and 3.6-4.5 ft. NO_3-N was present in the samples at levels of 12.8, 5.2, 3.6, 3.2, and 3.2 lbs/acre respectively. The assignment of nitrogen rates and experimental design were similar to those described above for experiment 1. A total of 3.09 ft of irrigation water was applied in six irrigations. During the growth period, 2.6 inches of rain fell. The irrigation water contained 81 lbs NO_3-N/acre. The nitrogen contained in the irrigation water is reflected in the nitrogen levels reported with the data. The nitrogen levels in this experiment were 81, 207, 296, 330, 456, and 580 lbs/acre.

Experiment 3, 1988

Data from experiment 3 were not used in this study because the yield response of Aldura durum wheat to applied nitrogen was very low. High levels of organic and inorganic nitrogen (64 lbs/acre in the top foot of soil) remained in the soil because alfalfa was cropped on the experimental site just prior to planting the wheat. Thus fertilizer nitrogen did not increase grain yields at this site.

Experiment 4, 1987

This experiment was performed on a Casa Grande sandy loam soil. Preplant soil NO_3-N and NH_4-N analysis of the top foot of soil indicated 22.4 and 11.6 lbs/acre respectively. A total of 1.8 ft of irrigation water containing 36 lbs nitrogen/acre was applied in six irrigations. Rainfall totaled 2.6 inches during the growth period. Nitrogen treatments 1, 2, 3, 5, and 6 were preassigned. The nitrogen rate in treatment 4 was based on soil plus stem NO_3-N analysis as described by Pennington _et_ _al_., (1983). The nitrogen treatment rates were 39, 149, 200, 249, 298, and 349 lbs/acre. The experimental design was a split plot factorial design with variety (Aldura and Westbred-881) as main plots. Only the data on Aldura durum wheat were available. Six nitrogen rates were arranged in subplots with four blocks.

Experiment 5, 1988

This experiment was conducted on a Trix clay loam soil. The preplant soil NO_3-N level in the top foot of soil was 10.8 lbs/acre. The assignment of nitrogen rates, plot size, and experimental design were identical to those used in experiment 4. A total of 31.5 in irrigation water was applied to the wheat crop in four irrigations. The irrigation water contained 39.19 lbs NO_3-N/acre. During the growth period, 2.87 inches of rain fell.

Cotton

In 1984 and 1985, the effects of nitrogen and water on drip irrigated cotton were studied on the same plots at the MAC. Data on the 1984 cotton crop were not used in this study because yield was unresponsive to applied nitrogen due to sufficient preplant nitrogen levels in the soil for maximum yield under the existing experimental conditions. Initial soil NO_3-N levels were measured at 80 lbs/acre in the top foot of soil. Barley was planted after harvest of the 1984 cotton crop to remove as much residual nitrogen as possible and to even out remaining nitrogen levels throughout the field. The barley was mowed and removed before the field was prepared for seeding the 1985 cotton crop (Tucker, Fangmeir, Husman, Stroehlein, Doerge; 1986).

Cotton cultivar DPL-62 was planted on a Casa Grande sandy loam soil with a buried drip irrigation system in 1985. The experiment consisted of six nitrogen treatments which were randomized within each of three water treatments. Each water x nitrogen treatment combination was replicated three times. Irrigation water corresponding to the assigned treatment levels was applied on a four-day-a-week schedule. The irrigation water levels were 28.6, 40.4, and 48.9 inches. The initial nitrogen levels contained in the irrigation water were measured at 26, 37, and 45 lbs nitrogen/acre in water levels 1, 2, and 3 respectively. The nitrogen levels contained in the irrigation water were accounted for in measuring total nitrogen applied to the cotton by adding these concentrations to the nitrogen treatments. Applied nitrogen treatment rates in this experiment were 0, 50, 67, 100, 200, and 300 lbs/acre.

Leafy Vegetables 1990

During the 1990 growing season a 3-year study to determine the yield response of leaf lettuce, romaine lettuce, collards, mustard, and spinach to varying rates of nitrogen was begun. The experiments in the first year of this study were conducted for exploratory purposes to determine which nitrogen rates should be used in field tests involving these leafy vegetable crops and to establish guidelines for evaluating the crops' nitrogen requirements. Only three nitrogen levels, each repeated four times, were used in the experiments. Although the experiments for each crop were conducted separately, they were located next to each other on one field. Therefore, certain experimental conditions such as soil type and quality, irrigation system and application level, preplant soil nitrate-nitrogen (NO_3-N) levels, and statistical designs were uniform (irrigation levels and nitrogen rates differed for mustard and spinach). These conditions will be described here for the 1990 leafy vegetable crops.

The crops were planted on a Casa Grande sandy loam soil containing 4.8 lbs/acre preplant soil NO_3-N in the top foot of soil. An Arizona study examining soil NO_3-N levels from 1965 to 1984 determined that the statewide average residual NO_3-N level is 72.4 lbs/acre (Doerge, 1985). Thus, 4.8 lbs/acre NO_3-N is considered a very low level of residual nitrogen (ibid.). Irrigation water equal to 16.1 inches was applied to the crop through a buried drip system. Rainfall data were unavailable. The irrigation water contained 8.0 lbs NO_3-N/acre. In the current study, the water nitrogen level was added to the experimental nitrogen rates. Three nitrogen treatments were replicated four times in a RCB design. Specific information about the vegetable crops and data on yields and nitrogen rates are provided below.

Vates collards, Waldmann's Green Leaf lettuce, and Paris Island Cos Romaine lettuce were three crop varieties planted for this study. Trimmed weights were given for a head of romaine rather than total head weight because romaine is marketed based on its trimmed weight. Certain parts of the head must be trimmed to remove damage, discoloration, or some other undesirable characteristic before the romaine can be marketed. The nitrogen treatments in the collards experiment were 88, 173, and 257 lbs/acre. Leaf and romaine lettuce had identical nitrogen treatment levels which were 39, 115, and 191 lbs/acre.

Southern Giant mustard was cut twice during the growth season. Yields from harvests 1 and 2 were analyzed separately. Mustard received 15.3 inches of water. The nitrogen treatments applied on mustard were 39, 115, and 191 lbs/acre.

Two spinach varieties, Indian Summer (smooth leaf) and Crystal Savoy (crinkly leaf), were planted for the 1990 nitrogen trials. During the growth season, 12.1 inches of water were applied to the spinach crops. The irrigation water contained 5.8 lbs/acre of nitrogen. Both spinach varieties received nitrogen treatments equal to 77, 162, and 255 lbs/acre.

Sweet Corn

During the 1987 through 1990 crop years, field experiments were conducted at the MAC on two varieties of sweet corn. In the 1987 to 1989 experiments, water and nitrogen levels were varied to examine the effect of these factors on yield and to observe the efficiency of nitrogen uptake by the crop at different water levels. In the 1990 trial the water was fixed leaving the nitrogen rate as the only variable. All the sweet corn experiments were planted on Casa Grande sandy loam soil and were irrigated by a subsurface drip system. Nitrogen concentrations contained in the irrigation water were accounted for by adding the levels of the nitrogen concentrations to the nitrogen treatment levels.

Jubilee Sweet Corn 1987

This experiment was designed as a split plot factorial with phosphorous treatments as the main plot. There was no significant main effect due to phosphorous since the phosphorous had no effect on the yield or on the absorption of nitrogen by the crop. Therefore, only the nitrogen and water treatments were used for this study. Nitrogen and water treatments were in a RCB factorial design. Application of three nitrogen rates were arranged in nine subplots in each main plot. The water and nitrogen rates were replicated eight times. The water applications were 16, 24, and 29 inches. The nitrogen treatments were 25, 29, 31, 141, 145, 147, 274, 278, and 280 lbs/acre. Soil analysis for residual nitrogen levels measured 7.2 lbs/acre in the top foot of soil. Irrigation water was found to contain 7.1 lbs nitrogen/acre.

Jubilee Sweet Corn 1988

The statistical design of this experiment was similar to that used in 1987 except that phosphorous treatments were not included. Residual soil nitrogen levels were measured to be 14 lbs/acre in the top foot. There were three water and three nitrogen treatments. The water treatments were 15, 22, and 28 inches. The nitrogen treatments were 51, 116, and 172 lbs/acre. Water and nitrogen rates were replicated four times. The irrigation water was found to contain 10.6 lbs nitrogen/acre.

Sweetie 82 Sweet Corn 1989

Three water and three nitrogen rates were arranged in a RCB factorial design as in 1988. Analysis of the top foot of soil showed 4.8 lbs/acre of nitrogen to be present. Irrigation water treatments were 14, 21, and 25 inches. Nitrogen treatments were 75, 76, 78, 164, 165, 168, 253, 254, 257 lbs/acre. The nitrogen and water rates were replicated four times. The irrigation water was found to contain 13.4 lbs nitrogen/acre.

Sweetie 82 Sweet Corn 1990

Six nitrogen treatments were replicated four times in a RCB design. Applied nitrogen was 54, 143, 187, 232, 276, and 454 lbs/acre. Residual soil nitrogen was 6.8 lbs/acre in the top foot of soil.

Melons 1990

In 1990, a field experiment to examine the fertilizer and water response of Mirage Watermelon, Laguna Cantaloup, and Gallicum Honeyloup was conducted at the MAC. This field experiment was the first of several nitrogen x water studies to be conducted over the following 3-years on melons. Like the field experiments with leafy vegetables, the melon experiments were conducted for exploratory purposes to determine which nitrogen rates should be used in field tests involving melons and to establish guidelines for the melons' nitrogen requirements. All three experiments were conducted on Casa Grande sandy loam soil with a buried drip irrigation system. Residual soil nitrogen was 27.2 lbs/acre in the top foot of soil. The statistical design was a split plot factorial with nine water x nitrogen treatments in the main plot and variety on the subplots. One row of watermelon, cantaloup, and honeyloup were planted in each mainplot. Water treatments were replicated four times within each nitrogen treatment. The water and nitrogen treatments respectively were 8, 16, and 25 inches; and 36, 116, and 240 lbs/acre for all melons.

Nitrogen Fertilizer and Crop Price Data

Nitrogen and crop prices from 1985 to 1990 were obtained from Arizona Agricultural Statistics (Bloyd, 1991) and Arizona Field Crop Budgets (Wade et al., 1990). The prices were standardized to 1990 price levels using the GDP price deflator (1990 base). For each crop and for nitrogen, six standardized prices (one for each year from 1985 to 1990) were averaged to obtain one price for each crop and nitrogen in 1990 terms.

The nitrogen price represents the price of actual nitrogen material. The price of nitrogen was derived from the price of anhydrous ammonia 82-0-0 after it was standardized to 1990 prices and averaged as described above. The price of anhydrous ammonia in 1990 terms was \$.15/lb (\$293.33/ton). To derive the price of actual nitrogen, \$.15 (\$293.33/ton) was divided by .82 because 82 pecent of anhydrous ammonia is nitrogen. The price of nitrogen was determined to equal \$.18/lb (\$357.72/ton). The price of nitrogen is for nitrogen material only and excludes nitrogen application costs. These costs were considered in farm budgets. However, the application costs were minimal especially when applied through the irrigation system with water applications and, therefore, were not factored into the nitrogen price used for the study. Nitrogen and crop prices (for crops which showed a statistically significant yield response to nitrogen) are listed below:

Nitrogen	\$.18/lb
Sweet Corn	\$.17/lb
Spinach	\$.27/lb
Romaine Lettuce	\$.20/lb
Leaf Lettuce	\$.18/lb
Durum Wheat	\$.07/lb
Watermelon	\$.07/lb
Collards	\$.19/lb
Mustard	\$.19/lb.

5. STATISTICAL ANALYSIS

One objective of this study was to estimate crop response to applied nitrogen fertilizer. Four fertilizer response functions, quadratic, square root, three-halves, and natural log were specified and estimated by OLS for 11 Arizona crops. The estimated models were evaluated on the basis of the adjusted coefficient of determination ($\bar{R}^2$), the expected signs of the coefficients, and significance of the F and t statistics. Two diagnostic tests, the Jarque-Bera test for normality of the error structure and the Breusch, Pagan, Godfrey test for homoscedasticity of the errors were conducted. The power for both of these tests is low with sample sizes less than 20. The results of these tests are presented only in cases where the sample size is adequate. The Mitscherlich-Baule function will not be analyzed here or in Chapter 6 because of failure to find the parameter values that maximize the likelihood function. Further discussion of the procedures and results of Mitscherlich-Baule estimation may be found in Appendix D.

Estimation Problems

Although crop yield response to nitrogen was investigated for 11 crops, only seven crops will be analyzed further. The estimated equations from data for cantaloup, honeyloup, cotton, Indian Summer spinach, wheat 1, and mustard 2 were eliminated because the estimated equations failed to satisfy statistical criteria. The reasons for the elimination of these crops are discussed below. Estimated equations eliminated from further analysis are listed in Appendix B.

Further estimation problems were encountered with crops that were retained for analysis. These problems are multicollinearity and the absence of observations about the yield maximum. This section summarizes the reasons for elimination of certain crops from further analysis and the effect of multicollinearity and narrow treatment ranges upon the parameter estimates.

Cantaloup, honeyloup, and wheat 1 were eliminated from further analysis because the Jarque-Bera statistic for these crops suggests that the error terms were not normally distributed. The Jarque-Bera statistic, which is distributed χ^2 with 2 degrees of freedom for these crops, equals 22.927 for cantaloup, 10.277 for honeyloup, and 12.407 for wheat 1. These Jarque-Bera statistics are significant at the 1 percent level for cantaloup and honeyloup, and at the 5 percent level for wheat 1. Although the OLS estimator is still b.l.u.e. when the assumption of normality is dropped, tests of significance of the parameters may be biased. Thus cantaloup, honeyloup, and wheat 1 will be excluded from further analysis.

The upland cotton experiment was eliminated because the parameter values showed no statistical response to applied nitrogen. Only one coefficient with nitrogen, the NW interaction term in the quadratic model, is significant at the 10 percent level. The lack of yield response to applied nitrogen reflects high soil nitrogen levels prior to planting. In 1984, residual soil nitrogen was measured to be 80 lbs/acre. Before the 1985 growing season, barley was planted on the experimental plot to reduce and even out the amount of residual nitrogen. However, soil analysis taken before the 1985 cotton crop was planted showed that residual nitrogen was sufficient to produce 2.5 bales/acre of cotton. Gardner and Tucker (1967) estimate that 52 lbs/acre of nitrate-nitrogen in the surface soil following pre-irrigation is sufficient nitrogen to produce 3 bales of cotton per acre. This yield is considered at or near maximum yield in many areas of Arizona.

For Indian Summer spinach, the yield maximum level of nitrogen, calculated by solving for nitrogen when the first derivative of the quadratic model was set equal to zero, was 754 lbs/acre. The nitrogen treatment levels did not surpass 255 lbs/acre. The yield maximum level of nitrogen equal to 754 lbs/acre was far beyond the bounds of the experimental observations and, therefore, its accuracy is questionable. The yield maximizing level of nitrogen was also solved using the logarithmic model but the result far exceeded the nitrogen treatment range. Neither the square root nor the three-halves models for Indian Summer spinach had significant t-statistics. The estimated models for Indian summer spinach were excluded from further analysis.

For mustard 2, the $\overline{R}^2$ for the logarithmic model equals .627 and was the highest of the models estimated. However, the predicted nitrogen rate for yield maximization greatly exceeded the nitrogen treatment range. Since none of the other models reflected a statistically significant response to nitrogen, mustard 2 was excluded from further analysis.

Multicollinearity existed in the crop response models retained for analysis (wheat 2, wheat 4, wheat 5, sweet corn 1987, sweet corn 1988, sweet corn 1989, sweet corn 1990, watermelon, Crystal Savoy spinach, romaine lettuce, leaf lettuce, collards, and mustard 1) because the correlation coefficients between pairs of the independent variables in each of the models were high. In the two-input models (nitrogen and water) analyzed in this chapter and Chapter 6 (sweet corn 1987 to 1990 and watermelon 1990) only three values of ρ were below .9. None of the ρ values was below .98228 for the one-variable (nitrogen) models (wheat, romaine and leaf lettuce, Crystal Savoy spinach, collards, and mustard 1). Multicollinearity occurs because two or more of the independent variables have an approximate linear relationship, for example between N and one of the following variables, N^2,

$N^{.5}$, and $N^{1.5}$. Multicollinearity may reduce the reliance that can be placed on the coefficients. However, the OLS estimates will remain b.l.u.e. and the R^2 is still valid.

Except for the logarithmic models, the t-statistics of the parameter estimates for the quadratic, square root, and three-halves models for mustard 2 and Indian Summer spinach; and the square root and three-halves for collards are not statistically significant. The low values of the t-statistics could be a result of multicollinearity which typically causes high standard errors of the parameter estimates or they may signify a lack of response by the crop to applied nitrogen.

The nitrogen test levels were too narrow to include observation of the yield maximum levels for sweet corn 1987 to 1989, watermelon, Crystal Savoy spinach, collards, romaine lettuce, leaf lettuce, and mustard 1. The function or functions selected for each crop were used to predict their behavior around the maximum yield and beyond.

Uncertainty concerning the accuracy of the forecasted yield maximums is exacerbated in the case of the leafy vegetable and melon experiments because they were conducted for exploratory purposes - the researchers did not have prior experience or knowledge concerning the pattern of crop response to nitrogen given the nitrogen application rates utilized (Doerge, 1992). These experiments were first-time trials to provide observations of response that could be used to guide the design of future experiments. Therefore, evaluation of these estimated crop response functions and their behavior based on statistical properties is uncertain. However, they were retained for analysis.

Analysis

The functions considered the best statistically and used later in economic analysis, are shown in Table 1. Graphs of the selected functions are found in Figures 1 - 19 in Appendix C. The graphs relate nitrogen application levels to yield in lbs/acre.

All variables in the selected models are statistically significant to the 10 percent level or better. The statistical results for each crop will be discussed in the following order: wheat, leafy vegetables, sweet corn, and watermelon.

Durum Wheat

The $\bar{R}^2$ for the selected production functions for the three wheat experiments ranged from .521 to .970 (Table 1). The t-statistics for all nitrogen variables were significant at the 1 percent level. The error terms in the selected models were normally distributed and homoscedastic because the Jarque-Bera (JB) and Breusch, Pagan, Godfrey (BPG) statistics for these models were not significant as shown in Table 1.

Table 1. Production Function Estimates

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F	JB(df) BPG (df)
Watermelon 1990					
Square Root					
a_0	-139520.0	-2.123**	.849	40.283	1.951(2)
N	-707.20	-3.528***	30		2.052(5)
W	-9275.4	-2.404**			
$N^{.5}$	8447.8	1.696			
$W^{.5}$	62385.0	2.018*			
$(NW)^{.5}$	2945.7	4.760***			
Sweet Corn 1987					
Square Root					
a_0	-11653.0	-0.639	.910	143.978	.942(2)
N	-58.720	-5.032***	66		6.434(5)
W	-458.06	-0.547			
$N^{.5}$	1631.2	4.352***			
$W^{.5}$	3424.7	0.437			
$(NW)^{.5}$	125.35	1.968*			
Sweet Corn 1988					
Square Root					
a_0	-26702.0	-1.238	.926	89.002	1.480(2)
N	-149.37	-2.707**	30		4.756(5)
W	-634.54	-0.667			
$N^{.5}$	3366.8	2.555**			
$W^{.5}$	3633.0	0.411			
$(NW)^{.5}$	318.09	2.069**			
Sweet Corn 1989					
Quadratic					
a_0	-5641.3	-0.670	.855	42.110	1.121(2)
N	110.53	3.810***	30		2.754(5)
W	24.669	0.030			
N^2	-0.205	-2.835***			
W^2	3.249	0.156			
NW	0.433	0.525			
Sweet Corn 1990					
Square Root					
a_0	-10274.0	-2.140**	.635	21.040	0.382(2)
N	-91.017	-3.817***	21		1.382(2)
$N^{.5}$	3238.2	4.672***			

Table 1, continued.

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F	JB(df) BPG(df)
Wheat 2 1987					
Quadratic					
a_0	1301.3	2.458**	.970	40.159	0.660(2)
N	29.493	8.962***	29		0.859(2)
N^2	-0.041	-8.664***			
Wheat 4 1987					
Square Root					
a_0	-2906.2	-1.998*	.521	13.229	.503(2)
N	-42.059	-3.972***	21		.960(2)
$N^{.5}$	1145.1	4.437***			
Wheat 5 1988					
Quadratic					
a_0	3145.7	10.509***	.774	40.345	2.957(2)
N	21.328	6.341***	21		0.015(2)
N^2	-0.038	-4.566***			
Mustard 1 1990					
Quadratic					
a_0	4636.3	2.844**	.964	148.310	
N	171.99	4.951***	9		
N^2	-0.263	-1.772			
Three-Halves					
a_0	3889.5	1.943*	.964	148.310	
N	226.39	3.474***	9		
$N^{1.5}$	-7.286	-1.772			
Crystal Savoy Spinach 1990					
Quadratic					
a_0	1208.3	0.307	.811	24.578	
N	144.43	2.647**	9		
N^2	-0.264	-1.630			
Square Root					
a_0	-16414.0	-1.130	.811	24.578	
N	-105.82	-1.059	9		
$N^{.5}$	4026.0	1.630			
Three-Halves					
a_0	-634.81	-0.127	.811	24.578	
N	225.69	2.168*	9		
$N^{1.5}$	-8.847	-1.630			

Table 1, continued.

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F
Romaine Lettuce 1990				
Quadratic				
a_0	-367.49	0.093	.955	118.21
N	590.58	7.009***	9	
N^2	-1.555	-4.321***		
Square Root				
a_0	-44672.0	-3.241**	.955	118.21
N	-414.53	-2.751**	9	
$N^{.5}$	12993.0	4.321***		
Three-Halves				
a_0	-4785.1	-0.985	.955	118.21
N	912.35	5.773***	9	
$N^{1.5}$	-43.096	-4.321***		
Leaf Lettuce 1990				
Quadratic				
a_0	3698.2	0.693	.724	15.403
N	317.96	2.797**	9	
N^2	-0.898	-1.849*		
Square Root				
a_0	-21883.0	-1.177	.724	15.403
N	-262.38	-1.291	9	
$N^{.5}$	7501.8	1.849*		
Three-Halves				
a_0	1147.5	0.175	.724	15.403
N	503.74	2.363**	9	
$N^{1.5}$	-24.883	-1.849*		
Collards 1990				
Quadratic				
a_0	1858.6	0.282	.914	48.076
N	183.91	2.126*	9	
N^2	-0.190	-0.764		

Table 1

*** Signifies statistical significance at the 1 percent level.

** Signifies statistical significance at the 5 percent level.

* Signifies statistical significance at the 10 percent level.

- JB and BPG are not listed for crops with less than 20 observations.

Leafy Vegetables

Crystal Savoy Spinach

The quadratic and three-halves functions for crystal savoy spinach had an identical $\bar{R}^2$ equal to .811 and an F statistic equal to 24.578. The coefficients on nitrogen in the quadratic and three-halves functions were significant at the 5 percent and 10 percent levels respectively (Table 1).

Romaine Lettuce

The quadratic, square root, three-halves models had identical $\bar{R}^2$ and F statistics equal to .955 and 118.21 respectively. The t-values in each of the models were highly significant (Table 1).

Leaf Lettuce

The $\bar{R}^2$ and F values were identical and equal to .724 and 15.403 respectively for the quadratic, square root, and three-halves models (Table 1). These models have t-values on the nitrogen coefficients that are significant at the 5 percent level; the N^2 and $N^{1.5}$ coefficients are statistically significant to the 10 percent level.

Collards

The quadratic model had the highest $\bar{R}^2$ (.914) compared to the other models fit to collards data. The coefficient on nitrogen was statistically significant at the 10 percent level, but the coefficient for N^2 was not statistically significant (Table 1).

Mustard I

The quadratic and three-halves models had $\bar{R}^2$ values of .964. In both models the coefficient on nitrogen was significant at the 1 percent level.

The natural log model had the highest $\bar{R}^2$ equal to .968 and significant t-values. However, the estimate of the yield maximizing nitrogen rate was impractical. The quadratic and three-halves models were analyzed instead (Table 1).

Sweet Corn

In Table 1, the variation in yield is well explained for crop years 1987, 1988, and 1989. The $\bar{R}^2$ for these experiments ranged from .855 to .926. Except for the t-statistic on the interaction term in the 1987 square root model which was significant at the 10 percent level, the t-statistics on the nitrogen variable for the 1988, 1989, and 1990 corn experiments were significant at the 5 percent level or better. The basic assumptions corresponding to the error terms held for the selected models.

Watermelon

The square root model was chosen for its high $\bar{R}^2$ (.849) and satisfactory statistical results for the F, Jarque-Bera, and Breusch, Pagan, Godfrey statistics (Table 1). The coefficients on the nitrogen and the interaction terms were significant at the 1 percent level.

Conclusion

Statistical analysis suggests that the models listed in Table 1 are the best specifications of the crop response relationships under investigation. These models are used in Chapter 6 to further describe crop response to inputs and to estimate profit maximizing nitrogen levels.

6. ECONOMIC ANALYSIS

This chapter reports the economic effects of two nitrogen management strategies and a public tax policy. The yield response functions listed in Table 1 in Chapter 5 were used in this analysis. First, incentives for "overfertilizing" were considered by examining the effects on net revenues and yield when nitrogen was increased 10, 20, and 30 percent above the profit maximizing level. Next, a 100 percent sales tax on nitrogen was imposed on the analysis to understand the implications of a tax policy on nitrogen use on Arizona crops. Two crop prices, the 1990 crop prices listed in Chapter 4, and a 20 percent reduction of these prices were used with the tax to test the sensitivity of nitrogen use to a tax under different product prices. Price elasticity of demand for nitrogen was also estimated under two nitrogen and three crop prices to show the sensitivity of nitrogen use to a nitrogen tax. Third, the effects on net revenues and yield, when nitrogen was decreased 10, 20, and 30 percent below yield maximum levels, were studied to see if farmers might profitably produce crops at lower nitrogen levels. As in Chapter 5, the analysis begins with wheat, followed by leafy vegetables, sweet corn, and watermelon.

Nitrogen Additions and Net Returns

Overfertilization is defined here as the amount of fertilizer applied in excess of the rate which would maximize farm profits under normal weather and field conditions (Edelman and Duffy, 1987). In economic analyses individuals or firms are usually assumed to be profit maximizers. However, farmers may use excess nitrogen to reduce the risk of low yields. If the cost of overfertilization is low, farmers are presumably more likely to overfertilize than if the cost is high. This section estimates the cost of overfertilization by showing how much profits decrease with fertilizer applications 10, 20, and 30 percent above the profit maximizing level (Table 2).

Durum Wheat

Analysis of the three wheat experiments showed that net returns declined only slightly, between 0.69 and 1.40 percent, with nitrogen applications 10 percent above the profit maximizing level. Net returns also decreased slightly with nitrogen applications 20 percent above the profit maximizing level. The fall in net returns varied between 2.69 and 5.16 percent. When nitrogen applications were increased 30 percent above the profit maximizing level, wheat 4 and wheat 5 still showed relatively small losses in net returns of 5.87 and 6.00

TABLE 2. EFFECT ON YIELD AND NET RETURNS OF NITROGEN ADDITIONS BEYOND THE PROFIT MAXIMIZING LEVEL

Crop	Nitrogen Addition	Yield Change	Change in Net Returns
		-----------------%-----------------	
Wheat 2			
Quadratic	+10	0.51	-1.40
	+20	-0.34	-5.16
	+30	-2.55	-11.27
Wheat 4			
Square Root	+10	0.50	-0.75
	+20	0.35	-2.76
	+30	-0.39	-5.87
Wheat 5			
Quadratic	+10	0.66	-0.69
	+20	0.56	-2.69
	+30	-0.30	-6.00
Crystal Savoy Spinach			
Quadratic	+10	-0.84	-1.15
	+20	-3.55	-4.51
	+30	-8.12	-10.08
Three-Halves	+10	-0.66	-0.95
	+20	-2.79	-3.62
	+30	-6.31	-7.95
Romaine Lettuce			
Quadratic	+10	-0.97	-1.07
	+20	-3.99	-4.26
	+30	-8.94	-9.26
Square Root	+10	-0.40	-0.47
	+20	-1.57	-1.76
	+30	-3.42	-3.77
Three-Halves	+10	-0.77	-0.85
	+20	-3.08	-3.34
	+30	-6.88	-7.40

TABLE 2., continued.

Crop	Nitrogen Addition	Yield Change	Change in Net Returns
		------------------%	------------------
Leaf Lettuce			
Quadratic	+10	-0.84	-1.02
	+20	-3.44	-4.02
	+30	-7.80	-8.97
Square Root	+10	-0.34	-0.48
	+20	-1.41	-1.78
	+30	-3.13	-3.80
Three-Halves	+10	-0.65	-0.81
	+20	-2.67	-3.16
	+30	-6.00	-6.88
Collards			
Quadratic	+10	-0.86	-1.08
	+20	-3.62	-4.22
	+30	-8.27	-9.46
Mustard 1			
Quadratic	+10	-0.75	-0.98
	+20	-3.21	-3.90
	+30	-7.36	-8.74
Three-Halves	+10	-0.54	-0.76
	+20	-2.34	-2.93
	+30	-5.35	-6.47
Sweet Corn 1987			
Square Root	+10	-0.09	-0.39
	+20	-0.78	-1.46
	+30	-1.46	-3.13
Sweet Corn 1988			
Square Root	+10	-0.42	-0.69
	+20	-1.92	-2.60
	+30	-4.36	-5.60
Sweet Corn 1989			
Quadratic	+10	-1.02	-1.47
	+20	-4.54	-5.86
	+30	-10.55	-13.19

TABLE 2., continued.

Crop	Nitrogen Addition	Yield Change	Change in Net Returns
		%	
Sweet Corn 1990			
Square Root	+10	-0.15	-0.37
	+20	-0.97	-1.50
	+30	-2.38	-3.28
Watermelon			
Square Root	+10	-0.29	-0.41
	+20	-1.22	-1.53
	+30	-2.69	-3.26

percent respectively. Net returns for wheat 2 fell 11.27 percent. Wheat 2 profits decreased more than profits earned by other crops because the profit maximizing level of nitrogen for wheat 2 was 50 percent higher than the profit maximizing level in wheat 4 and 25 percent higher than the profit maximizing level for wheat 5. Higher nitrogen costs combined with a loss in yield (2.55 percent) contributed to the relatively large decline in net returns for wheat 2. At nitrogen levels 20 percent above the profit maximum, the impact upon net returns for all three crop trials was less than 6 percent.

Leafy Vegetables

Nitrogen rates 10 percent above the profit maximizing level had only a slight effect upon net returns for leafy vegetables. The range of negative net return responses was between 0.47 and 1.15 percent. Yield showed similar responses at this nitrogen level. Net returns and yields were only slightly more responsive to nitrogen applications 20 percent above the profit maximizing level. At this rate, losses in net returns varied between 1.76 and 4.51 percent. Yield response was again similar to the change in net returns. Net returns and yields became more sensitive to nitrogen levels 30 percent above the profit maximizing level. The greatest decrease in net returns was 10.08 percent. Most crops showed negative changes in net returns between 7 and 9 percent. Yields likewise became more sensitive to nitrogen additions 30 percent above the profit maximum level and simulated the percentage changes in net returns. Overall the response of net returns and yield to nitrogen additions above the profit maximizing level may be characterized as low to moderate at the 30 percent level regardless of the model used. For leafy vegetable crops, nitrogen accounts for less than 1 percent to 4 percent of total variable production costs depending on the crop.

Sweet Corn

Losses in net returns were minimal ranging from 0.37 to 1.47 percent when nitrogen applications were 10 percent above the profit maximum level. Negative responses in net returns were low at nitrogen applications 20 percent above the profit maximum level for sweet corn 1987, 1988, and 1990. For these crops, losses in net returns were 1.46, 2.60, and 1.50 percent respectively. Net returns declined 5.86 percent for sweet corn 1989. Sweet corn 1989 again shows the highest loss in net returns (13.19 percent) when the nitrogen rate increased 30 percent above the profit maximizing level. The loss in sweet corn 1989 yield equal to 10.55 percent contributed to its loss of net returns. Nitrogen additions 20 percent above the profit maximizing level caused less than a 6 percent loss in net returns for all four sweet corn crops.

Watermelon

Net returns and yields show little negative response to nitrogen applications 10, 20, and 30 percent above the profit maximum level. At 10 and 20 percent above the profit maximum level, net returns fell 0.41 and 1.53 percent respectively. Even at nitrogen rates 30 percent above the yield maximum level net returns declined only 3.26 percent and yield fell 2.69 percent. The small response in net returns is due to a limited yield response and the small percentage of total variable costs of production (4.46 percent) attributed to nitrogen.

A Tax on Nitrogen and its Effect on Profit Maximizing Nitrogen Use and Net Returns

A tax on nitrogen sales has been suggested to discourage excess nitrogen use in some areas of the United States. Success of the tax requires demand for nitrogen to be sensitive to increases in its own price. The purpose of this analysis was to see how a 100 percent tax on nitrogen (increasing the price from $.18/lb to $.36/lb) effects profit maximizing nitrogen use and net returns on crops grown in Arizona (Table 3).

Durum Wheat

Profit maximizing nitrogen rates and net returns were not highly sensitive to a 100 percent tax on nitrogen. Net revenue fell between 16.10 and 21.55 percent when the 100 percent tax was imposed and the crop price remained at $.07/lb ($140/ton). Profit maximizing nitrogen use only decreased between 6.09 to 10.63 percent. Clearly, even a large tax has relatively little impact on the level of nitrogen which profit maximizers would apply.

Nitrogen use and net returns were more sensitive to the tax when the wheat price was $.06/lb ($120/ton). Net returns fell between 17.04 percent and 36.54 percent. The profit maximizing level of nitrogen fell between 11.17 and 16.37

TABLE 3. EFFECT OF A 100 PERCENT NITROGEN TAX ON NITROGEN USE AND NET RETURNS*

Crop Price	Change in Nitrogen Use	Change in Net Returns
	-------------%	-------------
Wheat 2		
Quadratic		
$.06/lb ($120/t)	-12.85	-28.05
$.07/lb ($140/t)	-9.55	-21.55
Wheat 4		
Square Root		
$.06/lb ($120/t)	-11.17	-36.54
$.07/lb ($140/t)	-10.63	-16.10
Wheat 5		
Quadratic		
$.06/lb ($120/t)	-16.37	-17.04
$.07/lb ($140/t)	-6.09	-17.40
Crystal Savoy Spinach		
Quadratic		
$.22/lb	-0.57	-2.34
$.27/lb	-0.46	-1.53
Three-Halves		
$.22/lb	-0.73	-2.38
$.27/lb	-0.59	-1.60
Romaine Lettuce		
Quadratic		
$.16/lb	-0.19	-0.60
$.20/lb	-0.32	-0.43
Square Root		
$.16/lb	-0.53	-0.75
$.20/lb	-0.63	-0.54
Three-Halves		
$.16/lb	-0.25	-0.01
$.20/lb	-0.20	-0.45

TABLE 3., continued.

Crop Price	Change in Nitrogen Use	Change in Net Returns
	-------------%	-------------
Leaf Lettuce		
Quadratic		
$.14/lb	-0.41	-1.30
$.18/lb	-0.41	-0.85
Square Root		
$.14/lb	-0.99	-1.49
$.18/lb	-0.79	-0.98
Three-Halves		
$.14/lb	-0.51	-0.30
$.18/lb	-0.44	-0.88
Collards		
Quadratic		
$.15/lb	-0.66	-1.75
$.19/lb	-0.52	-1.29
Mustard 1		
Quadratic		
$.15/lb	-0.71	-1.76
$.19/lb	-0.55	-1.27
Three-Halves		
$.15/lb	-1.23	-2.04
$.19/lb	-0.84	-1.48
Sweet Corn 1987		
Square Root		
$.14/lb	-4.15	-4.21
$.17/lb	-3.62	-2.74
Sweet Corn 1988		
Square Root		
$.14/lb	-1.75	-6.60
$.17/lb	-1.99	-1.46
Sweet Corn 1989		
Quadratic		
$.14/lb	-1.08	-3.19
$.17/lb	-0.89	-2.62

TABLE 3., continued.

Crop Price	Change in Nitrogen Use	Change in Net Returns
	------------%	------------
Sweet Corn 1990		
Square Root		
$.14/lb	-2.76	-2.46
$.17/lb	-1.73	-1.97
Watermelon		
Square Root		
$.06/lb	-0.69	-1.05
$.07/lb	-0.72	-0.82

* The tax increases the price of nitrogen from $.18/lb to $.36/lb.

percent.

Leafy Vegetables

For all leafy vegetables in this study, regardless of the type of model (quadratic, square root, or three-halves) nitrogen use and net returns were only slightly responsive to a 100 percent tax on nitrogen when crop prices were held constant. The greatest percentage change in nitrogen use due to the tax was -0.84 percent estimated by the three-halves model for mustard 1. The largest decrease in net revenues was 1.60 percent estimated by the three-halves model for Crystal Savoy spinach.

Net returns and nitrogen use also showed minimal response to a tax on nitrogen when crop prices were reduced 20 percent.

Net returns declined between 0.01 and 2.38 percent. Nitrogen use fell between 0.19 and 1.23 percent. Overall response to the tax is minimal because nitrogen costs make up approximately 1 percent of the total variable cost of producing leafy vegetable crops.

Sweet Corn

The profit maximizing level of nitrogen for sweet corn showed little response to a 100 percent tax on nitrogen when the sweet corn price remained at $.17/lb. Nitrogen use declined by only 0.89 to 3.62 percent depending on the crop year. The change in net revenue was small and varied between 1.97 and 2.74 percent. When the price of sweet corn was $.14/lb and the tax was imposed, nitrogen use declined between 1.08 and 4.15 percent. The loss in net returns varied between 2.46 and 6.60 percent depending upon the crop year.

Watermelon

Nitrogen use and net returns show minimal change to a tax on nitrogen when the price of watermelon was $.07/lb. The change in nitrogen use and net returns was -0.72 and -0.82 percent respectively. Reduction of the watermelon price to $.06/lb and imposition of the nitrogen tax caused net returns to fall 1.05 percent. Nitrogen use decreased only 0.69 percent.

Price Elasticity of Demand for Nitrogen

Price elasticity of demand for nitrogen (Table 4) was estimated using the production functions. Crop prices 20 percent above and below the 1990 crop prices and nitrogen prices of \$.18/lb and \$.36/lb were used for this analysis. The results showed that nitrogen fertilizer demands were highly inelastic within the range of product and nitrogen prices. Wheat was the most price elastic. Still, even under the most extreme price conditions investigated, the greatest price elasticity of demand was -.39.

TABLE 4. POINT ELASTICITIES OF DEMAND

Crop Price	Price of Nitrogen \$.18/lb	 \$.36/lb
Wheat 2		
Quadratic		
\$.06/lb (\$120/t)	-.113	-.255
\$.07/lb (\$140/t)	-.096	-.211
\$.08/lb (\$160/t)	-.083	-.180
Wheat 4		
Square Root		
\$.06/lb (\$120/t)	-.133	-.250
\$.07/lb (\$140/t)	-.115	-.218
\$.08/lb (\$160/t)	-.102	-.193
Wheat 5		
Quadratic		
\$.06/lb (\$120/t)	-.164	-.391
\$.07/lb (\$140/t)	-.137	-.318
\$.08/lb (\$160/t)	-.118	-.267

TABLE 4., continued.

Crop Price	Price of Nitrogen $.18/lb	Price of Nitrogen $.36/lb
Crystal Savoy Spinach		
Quadratic		
$.22/lb	-.006	-.011
$.27/lb	-.005	-.009
$.32/lb	-.004	-.008
Three-Halves		
$.22/lb	-.007	-.015
$.27/lb	-.006	-.012
$.32/lb	-.005	-.010
Romaine Lettuce		
Quadratic		
$.16/lb	-.002	-.004
$.20/lb	-.002	-.003
$.32/lb	-.001	-.003
Square Root		
$.16/lb	-.005	-.011
$.20/lb	-.004	-.009
$.24/lb	-.004	-.007
Three-Halves		
$.16/lb	-.002	-.005
$.20/lb	-.002	-.004
$.24/lb	-.002	-.003
Leaf Lettuce		
Quadratic		
$.14/lb	-.004	-.008
$.18/lb	-.003	-.006
$.24/lb	-.002	-.005
Square Root		
$.14/lb	-.010	-.019
$.18/lb	-.008	-.015
$.22/lb	-.006	-.012
Three-Halves		
$.14/lb	-.005	-.010
$.18/lb	-.004	-.005
$.22/lb	-.003	-.006

TABLE 4., continued.

Crop Price	Price of Nitrogen $.18/lb	Price of Nitrogen $.36/lb
Collards		
Quadratic		
$.15/lb	-.007	-.013
$.19/lb	-.005	-.010
$.23/lb	-.004	-.009
Mustard 1		
Quadratic		
$.15/lb	-.007	-.014
$.19/lb	-.006	-.011
$.23/lb	-.005	-.009
Three-Halves		
$.15/lb	-.012	-.023
$.19/lb	-.008	-.017
$.23/lb	-.007	-.014
Sweet Corn 1987		
Quadratic		
$.14/lb	-.091	-.135
$.17/lb	-.073	-.113
$.20/lb	-.070	-.096
Sweet Corn 1988		
Square Root		
$.14/lb	-.029	-.057
$.17/lb	-.024	-.047
$.20/lb	-.020	-.040
Sweet Corn 1989		
Quadratic		
$.14/lb	-.012	-.023
$.17/lb	-.009	-.019
$.20/lb	-.008	-.016
Sweet Corn 1990		
Square Root		
$.14/lb	-.028	-.055
$.17/lb	-.023	-.045
$.20/lb	-.020	-.039

TABLE 4., continued.

Crop Price	Price of Nitrogen $.18/lb	 $.36/lb
Watermelon		
Square Root		
$.06/lb	-.020	-.039
$.07/lb	-.007	-.034
$.08/lb	-.015	-.030

Nitrogen Reductions and Net Returns

Nitrogen applications were reduced 10, 20, and 30 percent below the yield maximizing level to see the effect of the reductions on net returns (Table 5). Nitrogen reductions were examined from the yield maximizing level because many agronomic recommendations are made on this basis and farmers commonly fertilize at or near this level (Pennington, Gardner, and Tucker, 1983; Doerge, Farr, and Watson, 1986).

Durum Wheat

Net returns and yield were fairly unresponsive to nitrogen reductions 10 and 20 percent below the yield maximizing level. At reductions of 10 percent, net returns increased roughly 1 percent. Reductions of 20 percent caused net returns to fall less than 1 percent from the yield maximizing level. Nitrogen applications 30 percent below the yield maximum level caused net returns to fall between 1.36 and 5.14 percent only, depending on the crop year. Thus, nitrogen applications on durum wheat could be reduced 30 percent with only a minor loss in profits.

Leafy Vegetables

Crystal Savoy

Two models, the quadratic and the three-halves models, were used in the Crystal Savoy analysis. With a 10 percent cut in nitrogen from the yield maximizing level, profits were reduced by 0.74 to 7.96 percent, depending on the model. A 20 percent cut in nitrogen caused net returns to fall by 3.85 to 10.93 percent depending upon the model. Net returns fell by 9.45 and 15.97 percent with 30 percent reductions, again depending upon the model. These results showed that the percentage change in net returns varied greatly due to differences among the functional forms.

TABLE 5. EFFECT OF NITROGEN REDUCTIONS ON YIELD AND NET RETURNS

Crop	Nitrogen Reduction	Yield Change	Change in Net Returns
	%	%	%
Wheat 2			
Quadratic	-10	-0.80	1.11
	-20	-3.21	-0.61
	-30	-7.23	-5.14
Wheat 4			
Square Root	-10	-0.42	1.13
	-20	-1.36	0.43
	-30	-2.52	-2.46

TABLE 5., continued.

Crop	Nitrogen Reduction	Yield Change	Change in Net Returns
		%	
Wheat 5			
Quadratic	-10	-0.49	1.25
	-20	-1.95	0.80
	-30	-4.39	-1.36
Crystal Savoy Spinach			
Quadratic	-10	-6.92	-7.96
	-20	-9.58	-10.93
	-30	-14.01	-15.97
Three-Halves	-10	-0.79	-0.74
	-20	-3.20	-3.85
	-30	-7.35	-9.45
Romaine Lettuce			
Quadratic	-10	-1.01	-1.02
	-20	-4.03	-4.26
	-30	-9.06	-9.43
Square Root	-10	-0.47	-0.44
	-20	-1.98	-1.98
	-30	-4.75	-4.85
Three-Halves	-10	-0.83	-0.83
	-20	-3.37	-3.47
	-30	-7.74	-8.04
Leaf Lettuce			
Quadratic	-10	-0.88	-0.90
	-20	-3.54	-3.78
	-30	-7.95	-8.63
Square Root	-10	-0.44	-0.40
	-20	-1.88	-1.91
	-30	-4.51	-4.75
Three-Halves	-10	-0.74	-0.73
	-20	-3.00	-3.17
	-30	-6.88	-7.42

TABLE 5., continued.

Crop	Nitrogen Reduction	Yield Change	Change in Net Returns
		%	
Collards			
Quadratic	-10	-0.97	-0.94
	-20	-3.85	-4.01
	-30	-8.65	-9.22
Mustard 1			
Quadratic	-10	-0.86	-0.85
	-20	-3.43	-3.65
	-30	-7.73	-8.40
Three-Halves	-10	-0.68	-0.62
	-20	-2.78	-2.83
	-30	-6.37	-6.73
Sweet Corn 1987			
Square Root	-10	-0.28	-0.04
	-20	-1.38	-1.02
	-30	-3.45	-3.12
Sweet Corn 1988			
Square Root	-10	-0.74	-0.64
	-20	-2.85	-2.86
	-30	-6.71	-7.08
Sweet Corn 1989			
Quadratic	-10	-1.27	-1.23
	-20	-5.07	-5.44
	-30	-11.41	-12.63
Sweet Corn 1990			
Square Root	-10	-0.41	-0.26
	-20	-1.73	-1.54
	-30	-4.15	-4.06
Watermelon			
Square Root	-10	-0.38	-0.34
	-20	-1.61	-1.64
	-30	-3.87	-4.09

Romaine Lettuce

The quadratic, square root, and three-halves models provided similar estimates of changes in net returns with 10 and 20 percent reductions in nitrogen. The loss in net returns for all models was no more than 1 percent when nitrogen was reduced 10 percent. Given a 20 percent nitrogen reduction, declines in net returns ranged from 1.98 to 4.26 percent. Thirty percent reductions caused net returns to fall 4.85 to 9.43 percent depending on the model.

Leaf Lettuce

The quadratic, square root, and three-halves models displayed virtually no net return or yield response to 10 percent nitrogen reductions. Reductions of 20 percent caused declines in net returns from 1.91 to 3.78 percent. Net returns declined from 4.75 to 8.63 percent with nitrogen reductions 30 percent. Fertilization at 20 to 30 percent below the yield maximum level did not substantially hurt profits because nitrogen costs decreased and yield showed only small to moderate losses.

Collards

Nitrogen reductions of 10 percent had almost no effect (less than 1 percent) upon net returns. Reductions of 20 percent caused net returns to drop 4.01 percent. Net returns were more sensitive to 30 percent reductions in nitrogen. At this level, net returns fell by 9.22 percent.

Mustard I

The quadratic and three-halves models estimated minimal responses in net returns and yield with 10 percent reductions. Reductions up to 20 pecent caused losses in net returns of between 2.83 and 3.65 percent. Losses in net returns were estimated between 6.73 and 8.40 percent with cuts in nitrogen equal to 30 percent. Fertilization rates 20 percent below the yield maximizing level had little impact on profits because yields were fairly insensitive to nitrogen reductions and nitrogen costs decreased.

Sweet Corn

Net returns fell approximately 1 percent when nitrogen was reduced 10 percent from the yield maximizing level. At 20 percent reductions, the greatest loss was 5.44 percent, with most of the net returns falling 1 to 3 percent. Net returns for sweet corn 1989 decreased 12.63 percent with a 30 percent reduction in nitrogen. Net returns for sweet corn 1987, 1988, and 1990 showed losses between 3.12 and 7.8 percent with a 30 percent cut in applied nitrogen.

Watermelon

Nitrogen reductions of 10 and 20 percent caused minimal losses in net returns. For example, a 20 percent reduction in nitrogen showed a loss in net returns equal to 1.64 percent. Watermelon net returns were relatively insensitive to nitrogen reductions 30 percent below the yield maximum level since net returns fell only 4.09 percent. Nitrogen reductions did not have a serious impact on net revenues because the cut in nitrogen costs offset the relatively small loss in yield.

7. SUMMARY AND IMPLICATIONS

Public anxiety about the impact of agrichemicals on ground water quality has triggered state and federal legislation to restrict chemicals including nitrogen fertilizer. Although the seriousness of ground water contamination from agricultural applications of nitrogen is still largely unknown in Arizona, passage of the 1986 Environmental Quality Act shows that reduction and prevention of potential nitrate contamination is an environmental goal among state lawmakers.

This study was conducted to show why farmers may apply more fertilizer than necessary to maximize profits, the impact of a tax on nitrogen fertilizer use, and the effects upon farm profits if nitrogen applications are voluntarily reduced.

This study, which continued the earlier work of Ayer, *et al.*, was based on experimental nitrogen yield response data for 11 Arizona commercial crops including durum wheat, upland cotton, spinach, romaine and leaf lettuce, collards, mustard, sweet corn, watermelon, cantaloup, and honeyloup. New experimental data on more crops, particularly vegetables, were analyzed to show the economics of reduced nitrogen use. The crop experiments were conducted at the Maricopa Agricultural Center from 1985 to 1990 by University of Arizona agronomists. Yield response functions were estimated from the experimental data. The 1990 crop and nitrogen prices and variable production costs were used with the yield response functions to examine relationships between nitrogen fertilizer use and short-run net returns and yield.

Findings

The analysis showed that farmers may overfertilize by even 20 to 30 percent above the profit maximizing level without much loss in profits. Profits were reduced by only 1.46 to 5.86 percent with excess applications of 20 percent (beyond the profit maximizing level). The cost of the added nitrogen is low because yields are usually not significantly reduced by this much extra nitrogen and nitrogen fertilizer is inexpensive. Thus, overfertilization may be regarded as an inexpensive insurance against the risks associated with not knowing how much yields would be cut at lower nitrogen levels. One of the key purposes of this study was to reduce this risk by using experiment station data to show how much profits are lowered as nitrogen is reduced.

A 100 percent tax on nitrogen purchases showed little impact on nitrogen use and net returns. The estimated demand for nitrogen fertilizer was very inelastic.

Analysis showed that farmers could reduce nitrogen applications 10 to 20 percent below the yield maximizing level with minor losses in short-term profits. In most cases, nitrogen reductions of 20 percent reduced profits by 0.43 to 5.44 percent (Crystal Savoy spinach was the only exception with a 10.93 percent loss in net returns). Net returns were not greatly affected because yield losses were small.

Farm Level Implications

These findings suggest that farmers may wish to experiment with reduction in nitrogen applications 10 to 20 percent below what they estimate the yield maximizing level of nitrogen to be. Based on the experimental results, profits would be reduced only marginally. The fact that experimental data were used in the analyses actually strengthens this conclusion. On-farm conditions likely have higher residual soil nitrogen and poorer application efficiency than at the experimental sites. As Ayer, *et al*. have shown, these circumstances imply that nitrogen could be reduced even further than implied by the experimental results with little or no impact on profits.

Policy Implications

Taxes would have little impact on nitrogen use for most Arizona crops. Even a 100 percent tax on nitrogen reduced nitrogen use by less than 4 percent under most circumstances. This conclusion is also shown by the highly inelastic demand for nitrogen. Elasticities of demand were less than -0.40.

Accordingly, tax policy is unlikely to be an effective means to reduce nitrogen use.

Extension education based on research could have significant impact on fertilization practices. Educational programs, based on research results like those reported here, could reduce the risks associated with not knowing what happens to profits as nitrogen is reduced. As shown for most of the crops under a wide range of price circumstances, nitrogen reductions of up to 20 percent of yield maximum levels have very little effect on profits. If farmers, voluntarily and successfully reduce nitrogen applications, they reduce the threat of nitrogen contaminated water supplies and the possibility of increased regulation.

APPENDIX A: EXPERIMENTAL CROP DATA

Waldmann's Green Leaf Lettuce

Fresh Weight Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
lbs/acre				
39	16693	11382	18211	12646
115	34651	33387	23269	22258
191	27569	31869	32122	35157

Paris Island Cos Romaine Lettuce

Trimmed Head Fresh Weight Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
lbs/acre				
39	18719	19225	22514	20743
115	50845	50086	42498	44521
191	56410	50339	56663	59446

Vates Collards

Fresh Weight Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
lbs/acre				
88	18299	18136	13968	15890
173	28216	32483	23462	27820
257	40493	32487	36122	35452

Southern Giant Mustard

Fresh Weight Yield Harvest 1

N	Rep 1	Rep 2	Rep 3	Rep 4
--------------------------lbs/acre------------------				
39	12526	10122	10375	10754
115	23027	18472	22015	20243
191	27708	26822	28467	28594

Southern Giant Mustard

Fresh Weight Yield Harvest 2

N	Rep 1	Rep 2	Rep 3	Rep 4
--------------------------lbs/acre------------------				
39	17201	13913	6830	11130
115	22008	25296	12142	16443
191	26308	30102	32632	22008

Crystal Savoy Spinach

Fresh Weight Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
--------------------------lbs/acre------------------				
77	7998	9864	11822	13379
162	17998	15228	20552	16963
255	21187	19602	23074	19701

Indian Summer Spinach

Fresh Weight Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
	lbs/acre			
77	7630	8496	8136	6938
162	16356	13761	12911	15411
255	22222	18806	20950	22125

Durum Wheat

Experiment 1 1986

Grain Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
	lbs/acre			
75	4392	3629	3362	3159
200	6259	5097	3585	6337
324	5652	6944	7267	6393
450	5620	6915	4203	6196
574	5547	4657	5623	5503
289	6322	6319	6116	6723
289	5226	5997	6665	6279
289	6544	6745	6249	6659

Experiment 2 1987

Grain Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
		lbs/acre		
81	2899	3469	3155	2796
207	6659	6345	5358	6636
330	6507	7083	5371	6253
456	5582	6098	5538	4820
580	4563	5637	5026	4857
296	7466	6726	5919	5425
296	6748	7152	6591	7107

Experiment 4 1987

Grain Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
		lbs/acre		
36	2505	3123	2608	1579
136	5354	4461	3535	5388
185	4976	5560	4324	4976
235	3273	6275	4301	5159
285	2986	5560	4702	4358
335	3878	4461	4290	3295

Experiment 5 1988

Grain Yield

N	Rep 1	Rep 2	Rep 3	Rep 4
	lbs/acre			
39	4290	3733	4179	3510
149	5962	5516	4513	5739
200	6185	5683	5796	5628
249	6241	6519	5962	6464
298	6018	5851	6296	5349
349	6241	6185	5238	6185

Upland Cotton 1985

Cotton Lint

Water	N (lbs/acre)					
(in.)	0	50	67	100	200	300
28.6	805	945	686	945	826	826
28.6	1032	794	896	920	791	907
28.6	952	892	1088	948	931	882
40.4	1221	1470	1340	1515	1151	1456
40.4	1253	1466	1512	1470	1310	1529
40.4	1277	1186	1396	1288	1400	1470
48.9	1319	1529	1610	1540	1470	1718
48.9	1522	1564	1617	1568	1645	1673
48.9	1221	1823	1648	1519	1414	1515

Jubilee Sweet Corn Yield, 1987

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
16	25	5456
16	25	4278
16	141	13509
16	141	12841
16	274	12989
16	274	12767
24	29	5678
24	29	3489
24	145	12158
24	145	11171
24	278	17369
24	278	16329
29	31	7163
29	31	4268
29	147	13064
29	147	13287
29	280	15736
29	280	15536
16	25	3329
16	25	7345
16	141	12952
16	141	12433
16	274	15276

Jubilee Sweet Corn Yield 1987, continued.

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
16	274	14734
24	29	2857
24	29	6160
24	145	11252
24	145	12381
24	278	14957
24	278	14548
29	31	3044
29	31	7014
29	147	14659
29	147	13390
29	280	13078
29	280	15661
16	25	2857
16	25	3044
16	141	10615
16	141	9130
16	274	15365
16	274	13435
24	29	4046
24	29	5196
24	145	10985
24	145	12915

Jubilee Sweet Corn Yield 1987, continued.

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
24	278	16255
24	278	15105
29	31	1410
29	31	3117
29	147	13932
29	147	12619
29	280	16960
29	280	16293
16	25	2412
16	25	1819
16	141	13806
16	141	12173
16	274	11839
16	274	12396
24	29	3712
24	29	6124
24	145	12359
24	145	10949
24	278	16478
24	278	16850
29	31	3859
29	31	6012
29	147	12767

Jubilee Sweet Corn Yield, 1988

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
29	147	12581
29	280	15090
29	280	13583
15	51	2024
15	51	2488
15	51	4386
15	51	4343
15	116	11429
15	116	10881
15	116	8477
15	116	10374
15	172	11682
15	172	11682
15	172	10585
15	172	14044
22	51	2867
22	51	4778
22	51	2150
22	51	2150
22	116	9742
22	116	9911
22	116	11598
22	116	11176

Jubilee Sweet Corn Yield 1988, continued.

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
22	172	15815
22	172	15857
22	172	16616
22	172	14339
28	51	2741
28	51	2699
28	51	3458
28	51	4850
28	116	12483
28	116	12188
28	116	11555
28	116	13200
28	172	15942
28	172	15646
28	172	13833
28	172	12652

Sweetie 82 Sweet Corn Yield, 1989

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
14	75	3535
14	75	2573
14	75	4766
14	75	1939

Sweetie 82 Sweet Corn Yield, 1989 continued.

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
14	164	8477
14	164	10333
14	164	8561
14	164	8519
14	253	13411
14	253	12357
14	253	9363
14	253	10375
21	78	4007
21	78	4133
21	78	4639
21	78	1771
21	168	9067
21	168	8899
21	168	10543
21	168	13538
21	257	13158
21	257	14887
21	257	12905
21	257	16363
25	76	7507
25	76	4977
25	76	5904

Sweetie 82 Sweet Corn Yield 1989, continued.

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
25	76	3500
25	165	10080
25	165	13833
25	165	9405
25	165	13074
25	254	15225
25	254	14592
25	254	13960
25	254	12146

Sweetie 82 Sweet Corn Yield, 1990

N (lbs/acre)	Yield (lbs/acre)
54	3859
54	10881
54	10122
54	7718
143	14487
143	16321
143	14803
143	16954
187	23090
187	15815
187	19358

Sweetie 82 Sweet Corn Yield 1990, continued.

N (lbs/acre)	Yield (lbs/acre)
187	19990
232	15878
232	16954
232	15183
232	20370
276	17397
276	16258
276	16954
276	14423
454	17333
454	18978
454	17586
454	18346

1990 Melon Water X Nitrogen Study

Cantaloup Market Yield 1990

Water (in.)	N (lbs/acre)	Market Yield (lbs/acre)
8	36	34046
8	36	16714
8	36	27236
8	36	28354
16	36	30397
16	36	18642

Cantaloup Market Yield 1990, continued.

Water (in.)	N (lbs/acre)	Market Yield (lbs/acre)
16	36	35909
16	36	32119
25	36	37668
25	36	10419
25	36	35549
25	36	23781
8	116	34560
8	116	35202
8	116	39994
8	116	51274
16	116	50503
16	116	54229
16	116	64790
16	116	56490
25	116	46791
25	116	62785
25	116	55077
25	116	23986
8	240	30718
8	240	37181
8	240	45018
8	240	36756
16	240	61771

Cantaloup Market Yield 1990, continued.

16	240	114034
16	240	72232
16	240	60023
25	240	66357
25	240	52521
25	240	84574
25	240	79423

Honeyloup Market Yield 1990

Water (in.)	N (lbs/acre)	Yield (lbs/acre)
8	36	22791
8	26	6539
8	36	17216
8	36	20672
16	36	24834
16	36	9558
16	36	27018
16	36	13747
25	36	29279
25	36	25798
25	36	23948
25	36	6668
8	116	32286
8	116	20941

Honeyloup Market Yield 1990, continued.

Water (in.)	N (lbs/acre)	Market Yield (lbs/acre)
8	116	20697
8	116	20950
16	116	38452
16	116	13721
16	116	55809
16	116	46392
25	116	65599
25	116	42486
25	116	33647
25	116	37772
8	240	9854
8	240	18282
8	240	41536
8	240	20055
16	240	46495
16	240	19168
16	240	30294
16	240	39287
25	240	71522
25	240	4548
25	240	63120
25	240	56940

Watermelon Market Yield, 1990

Water (in.)	N (lbs/acre)	Market Yield (lbs/acre)
8	36	42435
8	36	35253
8	36	44593
8	36	36320
16	36	65291
16	36	37514
16	36	69852
16	36	65702
25	36	55090
25	36	60306
25	36	42461
25	36	43565
8	116	77855
8	116	33056
8	116	58006
8	116	59882
16	116	88943
16	116	88878
16	116	100313
16	116	101983
25	116	125635
25	116	116089
25	116	122025

Watermelon Market Yield 1990, continued.

Water (in.)	N (lbs/acre)	Market Yield (lbs/acre)
25	116	95239
8	116	49566
8	240	55296
8	240	62747
8	240	54184
16	240	107495
16	240	124517
16	240	113225
16	240	77470
25	240	125326
25	240	14566
25	240	118967
25	240	117837

APPENDIX B

Production Function Estimates Excluded from Statistical and Economic Analyses

Crop	Coefficient	t-Ratio	$\bar{R}^2$	F	JB(df)
Variable			df		BPG(df)
Cotton 1985					
Quadratic					
a_o	-1290.2	-2.590**	.849	60.503	.418(2)
N	-0.678	-0.701	48		3.251(5)
W	104.86	3.96***			
N^2	-0.001	-0.561			
W^2	-1.004	-2.929***			
NW	0.033	1.694*			
Square Root					
a_o	-5261.2	2.653**	.856	63.754	.499(2)
N	-1.116	-1.109	48		2.013(5)
W	126.45	-2.404**			
$N^{.5}$	-43.594	-1.112			
$W^{.5}$	1809.2	2.801***			
$(NW)^{.5}$	12.411	2.126**			
Three-Halves					
a_o	-1892.5	-2.873***	.848	60.108	.421(2)
N	1.189	0.905	48		3.003(5)
W	186.70	3.516***			
$N^{1.5}$	-0.089	-1.207			
$W^{1.5}$	-16.961	-2.958***			
$(NW)^{1.5}$	0.0002	1.552			
Natural Log					
a_o	3.183	13.295**	.829	141.699	1.429(2)
ln(N)	0.021	1.110	51		1.966(2)
ln(W)	1.051	16.558***			
Watermelon 1990					
Quadratic					
a_o	-29793.0	-1.566	.838	37.282	1.758(2)
N	540.69	3.605***	30		1.872(5)
W	7027.8	3.151***			
N^2	-2.120	-4.468***			
W^2	-195.52	-3.013***			
NW	16.565	4.386***			

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F	JB(df) BPG(df)
<u>Watermelon 1990, continued.</u>					
Three-Halves					
a_o	-67607.0	-2.939***	.826	34.149	1.295(2)
N	1287.9	5.120***	30		1.584(5)
W	15202.0	3.521***			
$N^{1.5}$	-72.170	-4.942***			
$W^{1.5}$	-2322.4	-3.244***			
$(NW)^{1.5}$	0.14645	3.959***			
Natural Log					
a_o	8.1466	24.833***	.752	43.320	2.823(2)
ln(N)	.33959	6.704***	33		2.111(2)
ln(W)	.54531	6.458***			
<u>Honeyloup 1990</u>					
Quadratic					
a_o	-523.43	-0.025	.320	4.287	10.277(2)***
N	270.07	1.653	30		8.741(5)
W	787.09	0.324			
N^2	-1.0499	-2.033*			
W^2	-16.625	-0.235			
NW	6.0347	1.4672			
Square Root					
a_o	-13446.0	-0.182	.323	4.343	9.609(2)**
N	-383.57	-1.704	30		8.632(5)
W	5.2966	0.001			
$N^{.5}$	5754.6	1.029			
$W^{.5}$	-3413.0	0.098			
$(NW)^{.5}$	1061.1	1.527			
Three-Halves					
a_o	-11183.0	-0.462	.288	4.223	10.413(2)***
N	604.74	2.285*	30		8.960(5)
W	2086.6	0.459			
$N^{1.5}$	-34.473	-2.244**			
$W^{1.5}$	-270.0	-0.358			
$(NW)^{1.5}$	0.054	1.399			
Natural Log					
a_o	7.7355	9.018***	.314	3.929	28.0926(2)***
ln(N)	0.28329	2.138**	33		22.229(2)***
ln(W)	0.40014	1.812*			

Appendix B, continued.

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F	JB(df) BPG(df)
Cantaloup 1990					
Quadratic					
a_o	-18093.0	-0.952	.669	12.163	22.927(2)***
N	206.60	1.378	30		3.321(5)
W	5577.5	2.502**			
N^2	-0.70692	-1.491			
W^2	-182.76	-2.818***			
NW	9.545	2.529**			
Square Root					
a_o	-114000.0	-0.698	.618	12.319	19.550(2)***
N	-143.95	-0.720	30		3.283(5)
W	-10438.0	-2.629**			
$N^{.5}$	187.12	0.037			
$W^{.5}$	70188.0	2.206**			
$(NW)^{.5}$	1649.7	2.590**			
Three-Halves					
a_o	-42978.0	-1.925*	.608	11.864	23.567(2)***
N	521.47	2.136**	30		3.312(5)
W	12442.0	2.969***			
$N^{1.5}$	-26.723	-1.885*			
$W^{1.5}$	-2083.7	-3.000***			
$(NW)^{1.5}$	0.086	2.408**			
Natural Log					
a_o	8.049	16.997***	.531	18.762	10.575(2)**
ln(N)	0.42683	5.837***	33		1.576(2)
ln(W)	0.22642	1.858*			
Sweet Corn 1987					
Quadratic					
a_o	-964.30	-0.217	.909	143.399	.996(2)
N	92.535	9.261***	66		6.341(5)
W	248.32	0.609			
N^2	-0.204	-8.691***			
W^2	-5.813	-0.638			
NW	0.539	1.719*			
Three-Halves					
a_o	-3317.1	-0.568	.909	143.206	.786(2)
N	155.73	11.800***	66		5.285(5)
W	583.96	0.713			
$N^{1.5}$	-6.774	-8.527***			
$W^{1.5}$	-82.204	-0.707			
$(NW)^{1.5}$	0.00417	1.704*			

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F	JB(df) BPG(df)
Sweet Corn 1987, continued.					
Natural Log					
a_o	5.943	13.869***	.868	161.062	59.87(2)***
ln(N)	0.599	17.871***			11.75(2)***
ln(W)	0.121	0.933			
Sweet Corn 1988					
Quadratic					
a_o	-8678.2	-1.579	.925	87.458	1.469(2)
N	178.55	5.215***	30		4.933(5)
W	317.01	0.646			
N^2	-0.558	-4.320***			
W^2	-8.837	-0.789			
NW	1.627	1.930*			
Three-Halves					
a_o	-13925.0	-2.021*	.924	85.740	1.488(2)
N	331.80	5.860***	30		5.050(5)
W	876.41	0.908			
$N^{1.5}$	-16.938	-4.562***			
$W^{1.5}$	-126.93	-0.908			
$(NW)^{1.5}$	0.014	1.762			
Natural Log					
a_o	2.330	3.848***	.866	130.545	1.548(2)
ln(N)	1.285	16.091***	33		14.810(2)***
ln(W)	0.231	1.470			
Sweet Corn 1989					
Square Root					
a_o	10505.0	0.317	.855	42.213	1.123(2)
N	-76.828	-1.698*	30		2.580(5)
W	526.48	0.315			
$N^{.5}$	2693.4	2.010			
$W^{.5}$	-3976.2	-0.270			
$(NW)^{.5}$	105.32	0.601			
Three-Halves					
a_o	-7403.4	-0.717	.854	41.999	1.109(2)
N	182.75	3.918***	30		2.868(5)
W	-44.685	-0.027			
$N^{1.5}$	-7.178	-2.841***			
$W^{1.5}$	33.706	0.136			
$(NW)^{1.5}$	0.003	0.452			

Appendix B, continued.

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F	JB(df) BPG(df)
Sweet Corn 1989, continued.					
Natural Log					
a_o	2.142	3.053***	.823	74.290	12.054(2)***
ln(N)	1.055	11.811***	33		5.019(2)
ln(W)	0.529	2.885***			
Sweet Corn 1990					
Square Root					
a_o	-10274.0	-2.140**	.635	21.040	0.382(2)
N	-91.017	-3.817***	21		1.382(2)
$N^{.5}$	3238.2	4.672***			
Three-Halves					
a_o	3488.2	1.531	.587	17.358	0.232(2)
N	142.0	4.674***	21		1.514(2)
$N^{1.5}$	-5.225	-4.102***			
Natural Log					
a_o	7.483	17.708***	.434	25.877	19.853(2)***
ln(N)	0.408	5.087***	22		3.493(1)
Wheat 1 1986					
Quadratic					
a_o	2077.4	3.728***	.582	22.609	12.407(2)**
N	23.417	6.631***	29		0.152(2)
N^2	-0.032	-6.112***			
Square Root					
a_o	-3608.3	-2.529**	.582	22.570	15.204(2)**
N	-29.723	-5.535***	29		0.255(2)
$N^{.5}$	1083.6	6.106***			
Three-Halves					
a_o	1480.8	2.338**	.588	23.115	13.114(2)**
N	40.771	6.532***	29		0.143(2)
$N^{1.5}$	-1.432	-6.185***			
Natural Log					
a_o	7.326	22.567***	.226	16.167	3.468(2)
ln(N)	0.232	4.021***	30		0.103(1)

Appendix B, continued.

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F	JB(df) BPG(df)
<u>Wheat 2 1987</u>					
Square Root					
a_o	-7205.7	-6.120***	.795	61.009	0.912(2)
N	-43.568	-10.113***	29		1.824(2)
$N^{.5}$	1546.0	10.713***			
Three-halves					
a_o	396.67	0.690	.748	46.934	0.689(2)
N	53.436	9.631***	29		1.211(2)
$N^{1.5}$	-1.913	-9.379***			
Natural Log					
a_o	7.080	18.089***	.155	15.735	4.977(2)
ln(n)	0.274	3.967***	30		0.097(1)
<u>Wheat 4 1987</u>					
Quadratic					
a_o	1454.5	2.506**	.498	12.426	1.003(2)
N	32.730	4.778***	21		1.423(2)
N^2	-0.077	-4.279***			
Three-Halves					
a_o	1013.4	1.558	.508	12.882	0.856(2)
N	57.157	4.683***	21		1.274(2)
$N^{1.5}$	-2.6571	-4.369***			
Natural Log					
a_o	6.957	19.257***	.234	14.140	1.195(2)
ln(N)	0.263	3.760***	22		0.311(1)
<u>Wheat 5 1988</u>					
Square Root					
a_o	825.56	1.041	.764	38.166	4.257(2)
N	-17.376	-3.146***	21		0.208(2)
$N^{.5}$	601.05	4.365***			
Three-Halves					
a_o	2916.2	8.562***	.772	40.010	3.409(2)
N	33.889	5.549***	21		0.047(2)
$N^{1.5}$	-1.352	-4.536***			
Natural Log					
a_o	7.541	59.251***	.712	71.817	2.150(2)
ln(N)	0.206	8.475***	22		0.064(1)

Appendix B, continued.

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F
Mustard 1 1990				
Square Root				
a_o	-2854.2	-0.502	.964	148.310
N	2.061	0.033	9	
$N^{.5}$	2196.6	1.772		
Natural Log				
a_o	7.129	46.433**	.968	315.267
ln(N)	0.592	17.756***	10	
Mustard 2 1990				
Quadratic				
a_o	9638.5	1.656	.612	9.679
N	60.392	0.487	9	
N^2	0.181	0.341		
Square Root				
a_o	14786.0	0.729	.612	9.679
N	177.16	0.799	9	
$N^{.5}$	-1509.4	-0.341		
Three-Halves				
a_o	10152.0	1.421	.612	9.679
N	23.011	0.099	9	
$N^{1.5}$	5.001	0.341		
Natural Log				
a_o	7.419	12.177***	.627	15.561
ln(N)	0.522	3.945***	10	
Indian Summer Spinach 1990				
Quadratic				
a_o	851.51	0.337	.946	96.972
N	95.053	2.708*	9	
N^2	-0.063	-0.600		
Square Root				
a_o	-3325.6	-0.356	.946	96.972
N	35.734	0.556	9	
$N^{.5}$	954.31	0.600		

Crop Variable	Coefficient	t-Ratio	$\overline{R}^2$ df	F
<u>Indian Summer Spinach, continued.</u>				
Three-Halves				
a_o	414.62	0.129	.946	96.972
N	114.32	1.706	9	
$N^{1.5}$	-2.097	-0.600		
Natural Log				
a_o	5.356	20.950***	.860	265.04
ln(N)	0.830	16.280***	10	
<u>Crystal Savoy Spinach 1990</u>				
Natural Log				
a_o	6.774	15.071***	.805	41.698
ln(N)	0.579	6.457***	10	
<u>Romaine Lettuce 1990</u>				
Natural Log				
a_o	7.536	34.703***	.912	194.36
ln(N)	0.658	13.941***	10	
<u>Leaf Lettuce 1990</u>				
Natural Log				
a_o	7.740	19.770**	.704	35.802
ln(N)	0.509	5.984**	10	
<u>Collards 1990</u>				
Square Root				
a_o	-12620.0	-0.500	.895	48.076
N	-6.383	-0.039	9	
$N^{.5}$	3171.9	0.764		
Three-Halves				
a_o	326.33	0.038	.895	48.076
N	246.02	1.470	9	
$N^{1.5}$	-6.545	-0.764		

Crop Variable	Coefficient	t-Ratio	$\bar{R}^2$ df	F
<u>Collards, continued.</u>				
Natural Log				
a_o	6.374	17.640***	.904	109.99
ln(N)	0.746	10.488***	10	

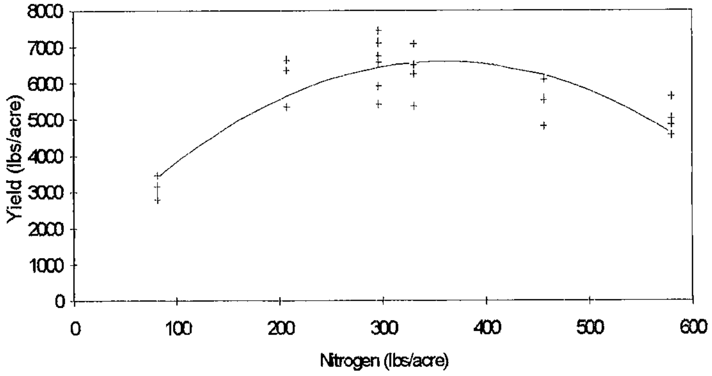
APPENDIX B
*** Signifies statistical significance at the 1 percent level.
** Signifies statistical significance at the 5 percent level.
* Signifies statistical significance at the 10 percent level.

APPENDIX C

FIGURES 1 - 19

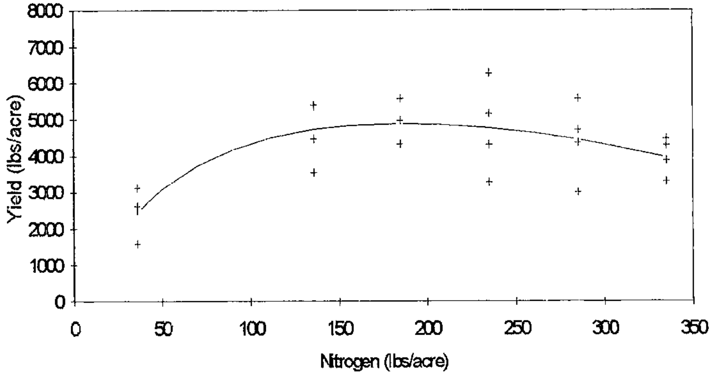
Observations and Estimated Quadratic
Production Function: Wheat 2

Fig. 1



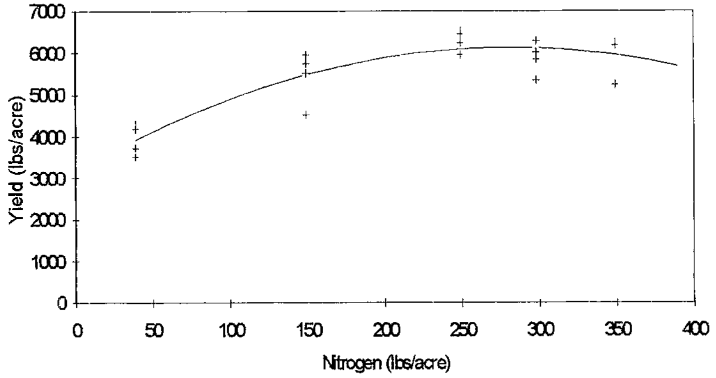
Observations and Estimated Square Root
Production Function: Wheat 4

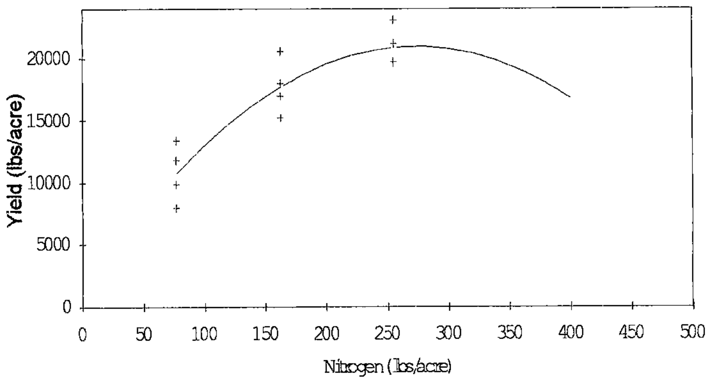
Fig. 2



Observations and Estimated Quadratic
Production Function: Wheat 5

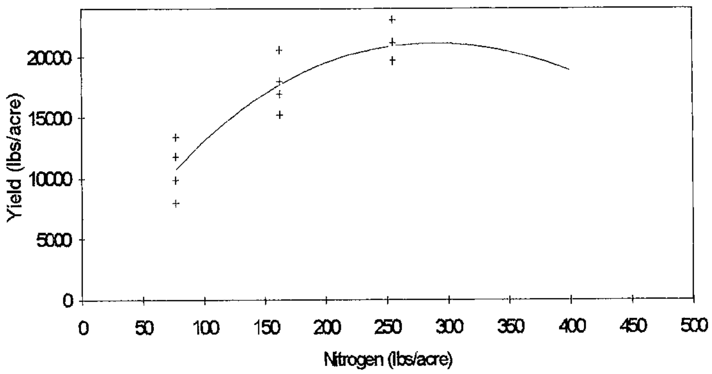
Fig. 3





Observations and Estimated Quadratic Production Function: Crys. Sav. Spinach

Fig. 4

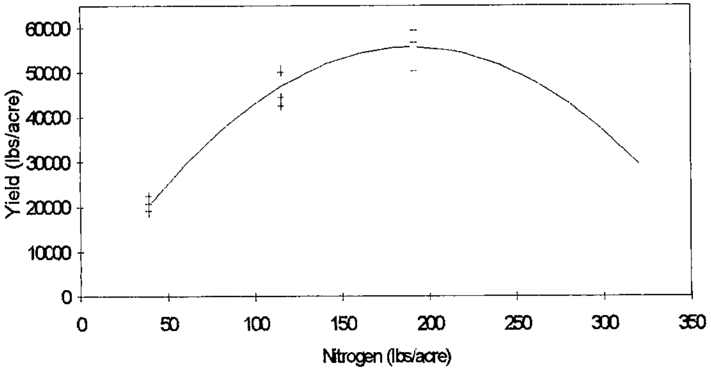


Observations and Estimated Three-Halves Production Function: Crys. Sav. Spinach

Fig. 5

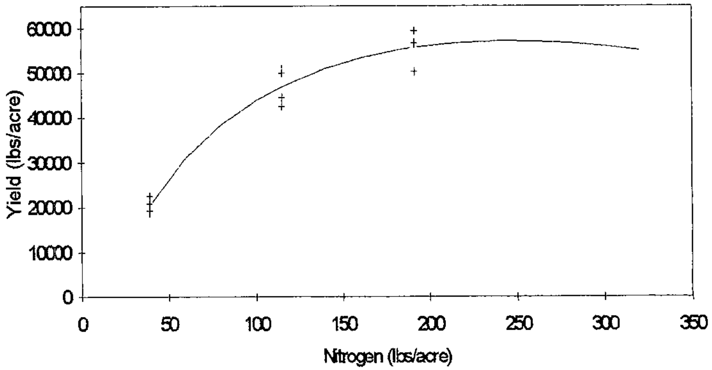
Observations and Estimated Quadratic
Production Function: Romaine Lettuce

Fig. 6



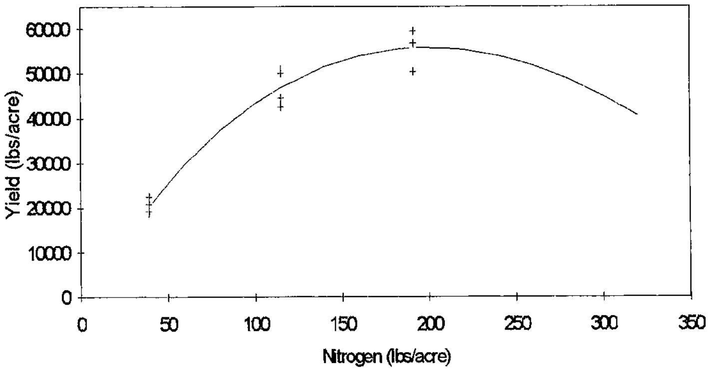
Observations and Estimated Square Root
Production Function: Romaine Lettuce

Fig. 7



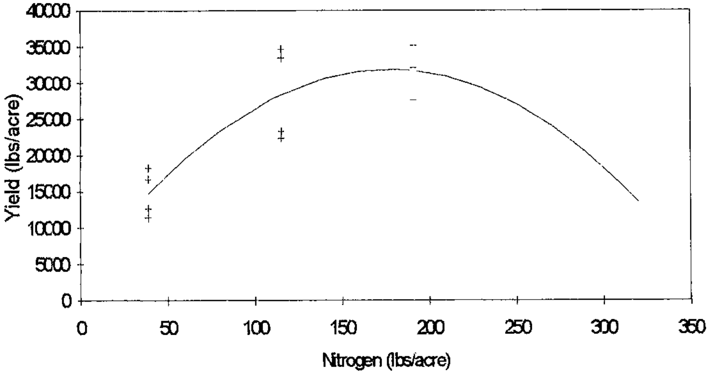
Observations and Estimated Three-Halves
Production Function: Romaine Lettuce

Fig. 8



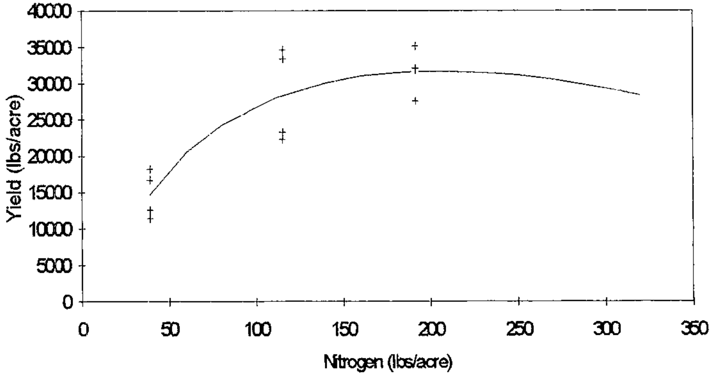
Observations and Estimated Quadratic
Production Function: Leaf Lettuce

Fig. 9



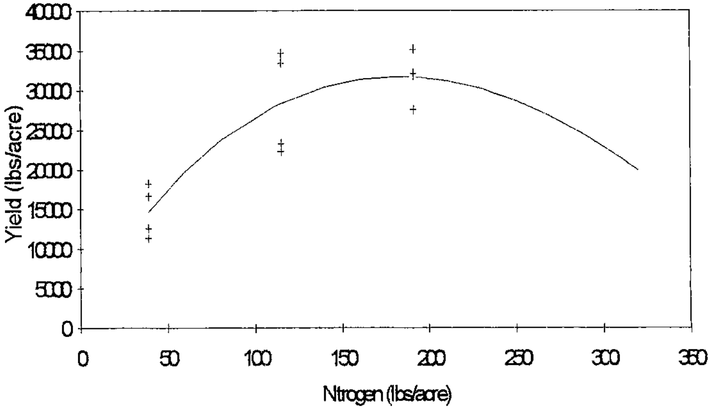
Observations and Estimated Square Root
Production Function: Leaf Lettuce

Fig. 10



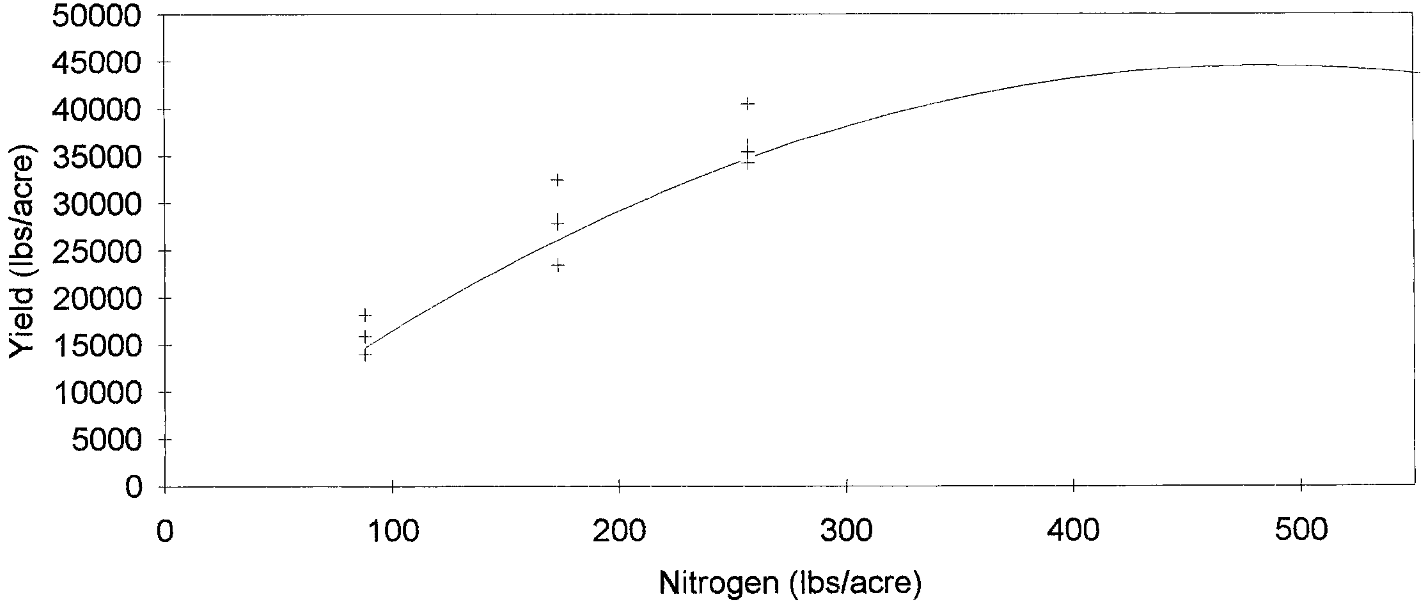
Observations and Estimated Three-Halves
Production Function: Leaf Lettuce

Fig. 11



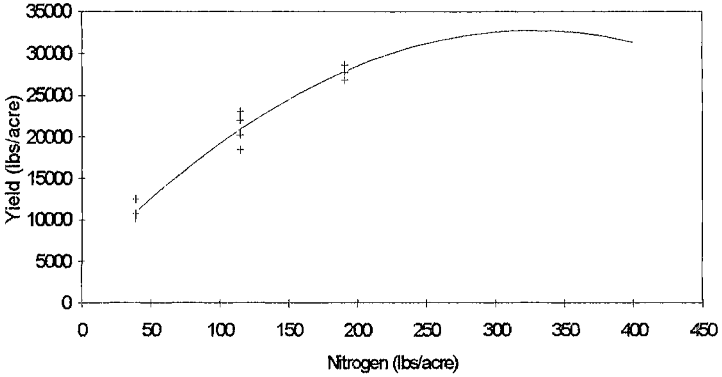
Observations and Estimated Quadratic
Production Function: Collards

Fig. 12



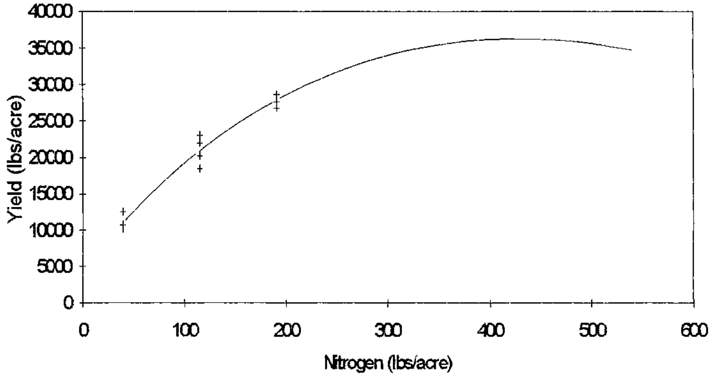
Observations and Estimated Quadratic
Production Function: Mustard 1

Fig. 13



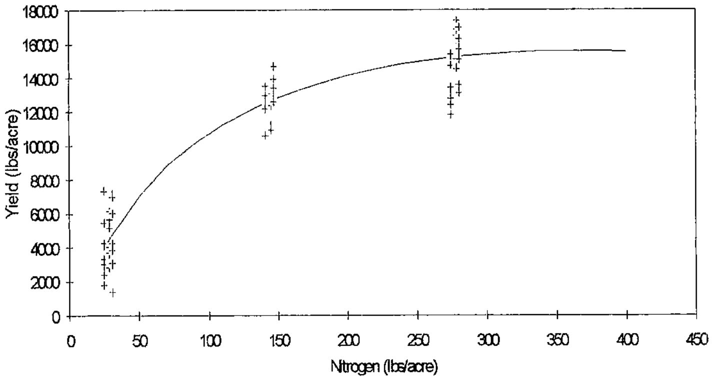
Observations and Estimated Three-Halves
Production Function: Mustard 1

Fig. 14



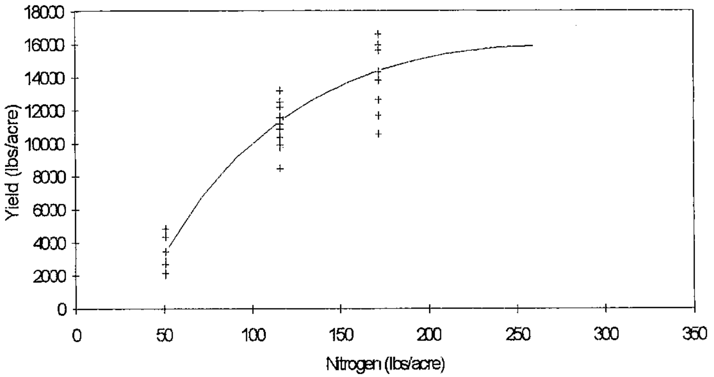
Observations and Estimated Square Root
Production Function: Sweet Corn 1987

Fig. 15



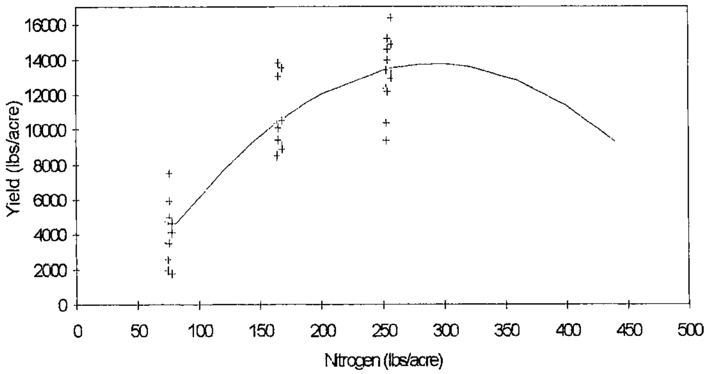
Observations and Estimated Square Root
Production Function: Sweet Corn 1988

Fig. 16



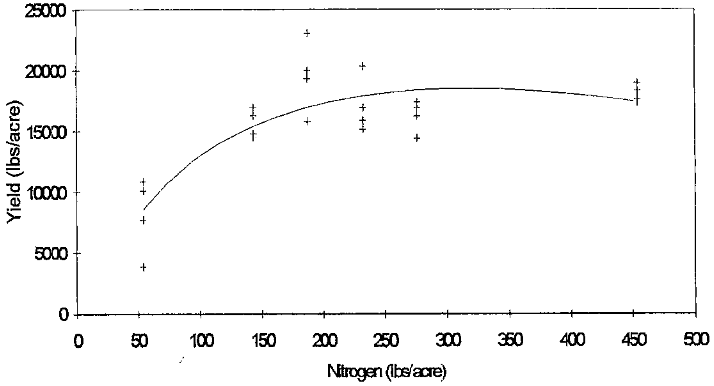
Observations and Estimated Quadratic
Production Function: Sweet Corn 1989

Fig. 17



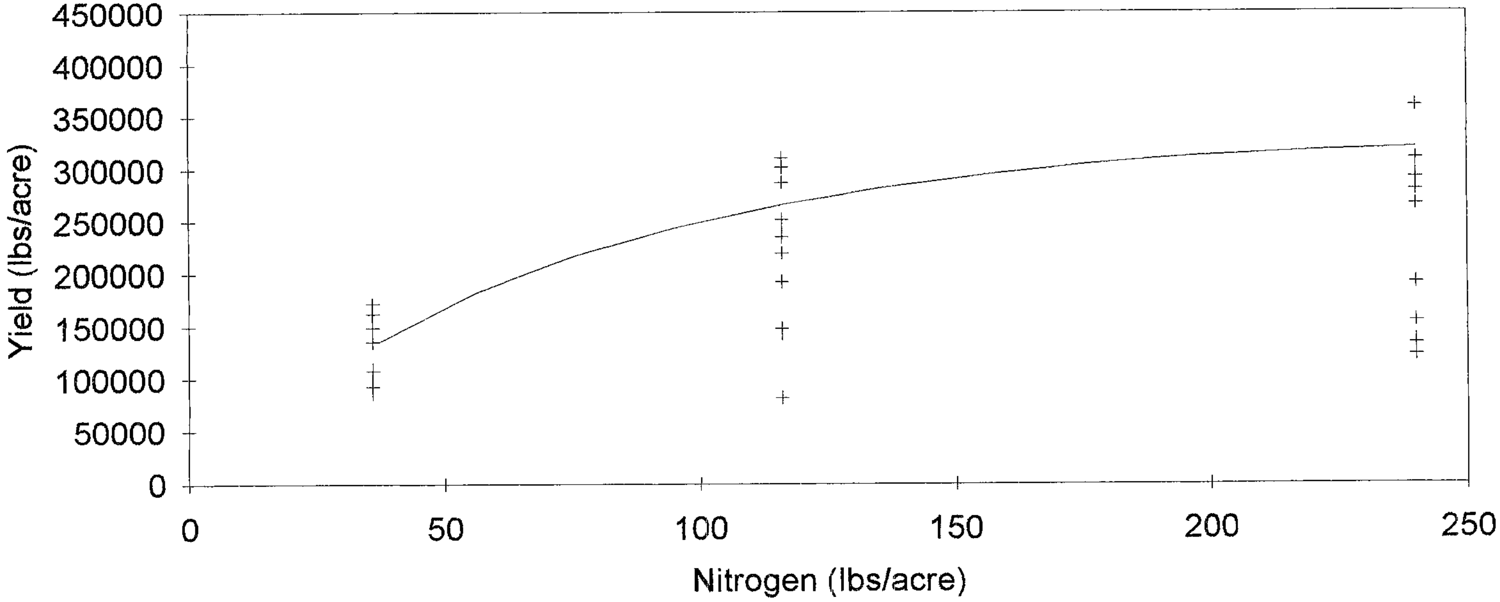
Observations and Estimated Square Root
Production Function: Sweet Corn 1990

Fig. 18



Observations and Estimated Square Root Production Function: Watermelon

Fig. 19



APPENDIX D

Mitscherlich-Baule Estimation

Estimation of the Mitscherlich-Baule model was undertaken to observe its performance as a representation of yield response for Arizona crops and to compare the model to the traditional polynomial models. As discussed in Chapter 3, two equations were specified for the one-variable and two variable models. The one-variable model was specified as:

(1a) $Y = \beta_1[1 - e^{-\beta 2(\beta 3 + N)}]$ and

(1b) $Y = \beta_1[1 - e^{-\beta 2(NRES + N)}]$.

Again, NRES is the measured soil nitrogen level before fertilizer nitrogen was applied to the crop. The two-variable model was specified as:

(2a) $Y = \beta_1[1 - e^{-\beta 2(\beta 3 + N)}][1 - e^{-\beta 4(\beta 5 + W)}]$ and

(2b) $Y = \beta_1[1 - e^{-\beta(NRES + N)}][1 - e^{-\beta 3(SM + W)}]$

where SM represents the measured soil moisture level before irrigation was applied. Equations (1a) and (2a) are common specifications of the Mitscherlich-Baule model. Equations (1b) and (2b), were estimated too because they allow the use of actual values (NRES and SM) in place of estimated values.

Procedures

Both specifications were estimated using Maximum Likelihood Estimation procedures for nonlinear regresson on Shazam software. As recommended by Goldfeld and Quandt (1972) the models were fit to data sets with 30 or more observations due to the asymptotic properties of the maximum likelihood estimator. The Mitscherlich-Baule model was fit to the following data sets: watermelon, honeyloup, cantaloup, sweet corn 1987, sweet corn 1988, sweet corn 1989, wheat 1, and wheat 2.

Each model was run 10 times for each crop as appropriate according to the number of experimental variables. At the start of each run, initial parameter values were specified according to the data and theoretical properties. For example, in the one and two-variable models, β_1 represented the maximum yield of a particular data set. Therefore, the actual maximum yield value of an individual data set and nine other maximum yield values above and below the actual value within a "reasonable" range were specified for each run. In the two-variable, five parameter model, β_3 and β_5 represented residual nitrogen and soil moisture levels. The actual residual nitrogen or soil moisture values and nine other reasonable values greater than and less than the actual values were provided as starting parameter values. β_2 and β_4 in the two-variable model and β_2 and β_3 in the one-variable model represent theoretical "efficiency values" which were postulated by Mitscherlich to be a measure of the efficiency with which a plant uses a nutrient (Tisdale, Nelson, and Beaton, 1985). Efficiency values are small; initial values specified for these parameters were between zero and one.

The convergence criterion equaled .00001 which is the default condition in Shazam. The number of iterations were first set at 100 and later opened to 300. All efforts, however, failed to maximize the likelihood function of the Mitscherlich-Baule model. When the likelihood function is maximized, the computational process converges on the same point (the same set of final parameter values are obtained) regardless of the initial parameter values specified at the beginning of the run. In this study though, the final parameter values were different each time new initial parameters were specified. Therefore, the computational process converged on local maximums of the likelihood function rather than the global maximum of the function. Maximizing the likelihood function is equivalent to minimizing the sum of squared residuals in a nonlinear context. Thus, if the function converges on a local maximum rather than the global maximum, the resulting parameter values do not minimize the sum of squared residuals.

Identifying the Problem

To determine if the failure to maximize the likelihood function was due to incorrect procedures or methods, data for published Mitscherlich-Baule parameter estimation were obtained to determine if the results could be replicated. The data were from an experiment conducted by Heady, Pesek, and Brown (1955) on corn yield response to nitrogen and phosphorus. The parameter estimation was published by Frank, Beattie, and Embleton (1990). The authors reported their parameter values as:

$$(3)\quad Y = 127.631[1 - \exp(-.0191(N_i + 13.361))][(1 - \exp(-.0275(P_i + 5.603))].$$

In an effort to replicate the above results, the Mitscherlich-Baule function was estimated on TSP (Shazam was unavailable). The results which were obtained are similar to those in (3). The final parameter values obtained were $\beta_1 = 126.907$, $\beta_2 = 0.0206$, $\beta_3 = 13.726$, $\beta_4 = .0249$, and $\beta_5 = 7.200$. The differences between these values and the values obtained by Frank, Beattie, and Embleton are probably attributed to the software and the algorithm. These results were obtained with each of 10 runs even though the starting parameter values were changed with each run. Thus, the estimation method used to fit the Mitscherlich-Baule model to the Arizona crop data appeared to be correct.

Next, the problem was postulated to originate with the statistical design of the data. The Heady, Pesek, and Brown data had 81 observations each representing a unique combination of nitrogen and phosphorous inputs (there were no replications). The treatment levels for both inputs were added uniformly in 40 lbs/acre increments beginning with 0 lbs/acre and ending with 320 lbs/acre. Most of the experiments in the current study used three or four replicated treatment levels with gaps of often more than 100 lbs/acre between treatment levels. One theory regarding the estimation problem was that the data used in this study lacked enough unique independent observations due to the replications and the relatively few treatment levels and observations. Perhaps the replications caused multicollinearity to occur. To test for this problem, the Mitscherlich-Baule model was estimated using the means within each treatment level rather than all of the data. However, results similar to those discussed above were obtained. In addition, Grimm, Paris, and Williams (1987) estimated a von Liebig function with a data set containing only 26 observations of cotton yield response with replicated treatments. The reported R^2 for this estimation is .934. Furthermore, Grimm, Paris, and Williams note that the statisitical design of the experimental data followed an incomplete factorial specification which is suitable for estimating polynomial responses. Since the statistical design and sample size is similar to the experiments used in this study, other factors may be responsible for the failure to successfully estimate the Mitscherlich-Baule model.

Conclusion

At the time of this writing, the reasons for the problems encountered in estimating the Mitscherlich-Baule model are unknown.

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