An Economic analysis of nitrogen fertilization of winter wheat grown in south central Montana
by Christopher Watson Wessells

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Applied Economics
Montana State University

Abstract:
The objective of this research was to estimate profit maximizing rates of nitrogen fertilizer applied to hard red winter wheat. The relationship between protein and yield response of winter wheat to nitrogen fertilizer and various soil and climatic factors were determined by using data from 30 fertilizer experiments conducted in south central Montana during the years of 1976 through 1980. The yield and protein response functions were estimated by a generalized nonlinear least squares regression.

The variables important in explaining yield and protein response were applied nitrogen, applied phosphorus, soil phosphorus, precipitation (composed of logged summer and winter precipitation), various interaction terms, and locational and periodic binary variables.

A wheat protein-premium function was estimated with simple regression to determine the relationship of premium paid for various levels of grain protein. The function was specified with a hyperbolic tangent form.

Profit functions were formulated from the response functions and protein-premium function. Profit was specified in an unconditional context, and it was specified conditionally on given levels of winter precipitation. Analysis of profit in these two contexts facilitated a measure of the additional expected profit gained from knowledge concerning winter precipitation. Furthermore, because fertilization is a prospect involving risk, based on random events such as precipitation, profit was analyzed with a safety first risk constraint. This constraint required the farmer to forego expected profit until meeting the probability constraint that expected marginal profit is negative no more than 25 percent of the time.

Analysis determined that approximately 88 pounds per acre of applied nitrogen was optimal for unconditional profit without the risk constraint; and about 64 pounds per acre with the risk constraint. Optimal profit was also obtained for various conditional profit functions. In comparison, the expected conditional and unconditional profit suggested that only a slight additional amount of profit could be expected from gauging nitrogen fertilization according to levels of winter precipitation. Finally, it was evident from comparing constrained and unconstrained profit, that nitrogen fertilization of winter wheat is a relatively riskless prospect.

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by

Christopher Watson Wessells

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

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CHAPTER I

INTRODUCTION

Background

North America's remarkable agricultural productive capacity and export position have made substantial contributions to global economic development and to the world hunger problem. For example, American wheat is a significant food staple for many countries, and comprises the largest proportion of all agricultural commodities traded throughout the world. Within the United States, Montana farmers are among the leading producers of wheat. In fact, Montana's total annual output of winter wheat, approximately 90 million bushels per year, ranks sixth within the United States. The environment is well suited for dryland winter wheat production, which requires a cool climate at seeding, a freezing period when the wheat remains dormant, thus promoting vernalization, a moderate amount of precipitation as the wheat matures, and a warm climate at harvest [52]. These conditions, along with soil structure and management practices, result in a grain with a relatively high protein content. Growing periods in Montana typically begin with planting in late September and early October and end with harvest in August through early September. Finally, from 1960 through 1980, the area of hard red winter wheat harvested in Montana has consistently remained near 2.5 million acres. Although in 1983, Montana wheat acreage decreased considerably because of the government Payment In Kind (PIK) program. The benefits for the 1984 PIK program appear to be less lucrative for producers, and consequently, one would expect an increase in acreage harvested in hard red winter wheat over the 1983 level.

Problem Statement

Agricultural production is characterized by a decision making unit which selects combinations of scarce inputs, or factors of production, to yield some quantity and quality of product. More specifically, with intentions of increasing or at least maintaining yields, grain quality, and profit levels, virtually all agricultural producers include fertilization techniques in their farm management programs. This holds for Montana producers who have increased consumption of nitrogen, phosphorus, and potassium fertilizers approximately 60, 11, and 89 percent respectively between 1976 and 1981.[1] In spite of this trend, one should not infer that continual increases in applied fertilizers will yield optimal economic outcomes.

Frequently people presume that greater application of fertilizer is responsible for higher yields, and so, eventually, results in larger profits. This presumption is false for a number of reasons: The wheat producer must realize that exogeneous factors such as soil moisture, soil type, soil nutrients, and climate vary between farms and can greatly influence the effect of nitrogen application levels on yield. Furthermore, essentially all agricultural response functions exhibit some degree of diminishing marginal productivity. In other words, as equal and successive increments of nitrogen are applied to soil, the resulting physical product (winter wheat in this case), will increase at a decreasing rate; and, beyond some point where yield is maximized, additional applications of nitrogen will have the exasperating effect of causing a decline in the total product. Finally, in order to maximize profit, wheat producers must take into account input and output prices in conjunction with the information concerning marginal productivity and marginal factor use. Thus, economists reject the notion that augmented fertilizer applications always lead to higher yield and profits.

[1] See page 20 of [67].

Montana winter wheat producers employ a variety of decision criteria for determining fertilizer application levels. Not surprisingly, this is due to insufficient information regarding fertilization of winter wheat. Prior to 1960, fertilizers were practically absent from the dryland farming sector in Montana [39]. Following the introduction of commercial fertilizers, producers expanded their use rapidly and, correspondingly, generated a need for accurate information regarding application rates: first, they must know the response of winter wheat (in terms of yield and protein) with respect to different levels of nitrogen and phosphorus fertilizers, changing climatic conditions, and varying soil conditions. Second, the producer requires knowledge of marginal changes in yield and protein content of the wheat caused by incremental changes in factor inputs. Third, the farmer needs accurate estimates of fertilizer prices and winter wheat prices, the latter of which has historically displayed large fluctuations. Over the past three years, from 1981 through 1983, the price of nitrogen has remained stable between 24 and 28 cents per pound. From 1972 to 1982 the nominal cost of nitrogen, in the form of ammonium nitrate, varied between 8 and 28 cents per pound.[2] During the same period, nominal winter wheat prices fluctuated between 1.56 and 6.05 dollars per bushel.[3] To further perplex the situation, wheat prices contain a "protein premium price structure." That is, prices received for wheat are based on the percentage of protein content of the grain. Relatively high protein grain sells for a higher price, or, more formally, a premium is paid. Fourth, the producer must determine his risk preferences toward recovering input costs from expected profit. In other words, the farmer selects a frequency at which he is willing to tolerate a loss. If the above information is available, then the farmer can apply it to a more scientific criterion in order to select an economically optimal fertilizer program.

[2] These fertilizer prices are yearly averages taken from [22].

[3] These are actually prices paid for hard red winter wheat upon delivery to Portland, Oregon. Note the low price is for ordinary protein and the high price is for thirteen percent protein.

Purpose of the Study

In brief, the primary goal of this study is to design a decision criterion that will assist Montana winter wheat producers in selecting optimal levels of nitrogen fertilizer. Second, the project serves to expand upon previous agricultural economic research concerning Montana wheat production, by Garnick [31] in 1977, and by Simons [88] in 1980. More precisely, the objectives of this project are as follows:

1. To estimate the yield and protein response of winter wheat with respect to nitrogen fertilization and other significant variables such as applied phosphorus, applied potassium, soil nutrients, and precipitation.

2. To determine the optimal amount of applied nitrogen by considering the properties of the response function, input prices, the protein premium price structure of wheat, the level of winter precipitation, and a risk constraint.

3. To compile and present the information and conclusions of this study in a format that will aid farmers in determining a profit-maximizing fertilization program.

CHAPTER II

LITERATURE REVIEW

The contents of this chapter summarizes previous research related to the topic of winter wheat production. The literature is reviewed in three sections. The first section presents the founding studies in plant response research. The second section provides a general overview of qualitative and quantitative studies concerning the factors influential to crop growth and management. Finally, the third section analyzes the procedures and results of a few selected articles which include fertilizer recommendations.

Scholars have conducted extensive research concerning the relationship of yield and protein response of crops to a variety of agronomic factors. Generally, Dr. Justus Liebig is credited with the first scientific attempt to explain the relationship between plant growth and nutrient levels. His model related the factors of growth linearly to yield, and restricted plant growth by any single factor diminishing to a "minimum" state, which he referred to as the "law of the minimum" [53].

Since Liebig's pioneering studies in 1840, scientists have discovered that crop responses to nutrients are significantly more complex than initially thought. Mitscherlich [65] conducted numerous greenhouse experiments between 1911 and 1921 on corn, wheat, and other crops in order to empirically test his hypothesized yield-nutrient relationship. In 1921, Mitscherlich proposed the function: $Y = A(1 - e^{-cx})$ for the single factor case, where Y is yield, a is the approximated maximum yield, c is the coefficient associated with the single input x [66].

Briggs [15] points out the central deficiencies of the Mitscherlich function. Namely, it assumes increasing returns even at infinite applications of input x, and it implies an instantaneous and irreversible response to the input. Instead, Briggs suggests either a quadratic function, $Y = a + bx - cx^2$, or a function of the nature, $Y = a(x/x + c)$, in order to better represent a "true" plant growth function, which includes diminishing returns. Also, he postulates that some crop response functions may be cubic in form.

Proceeding three years after Briggs' criticism of the Mitscherlich equation, in 1928 Balmurkand [6] reveals Mitscherlich's failure to statistically test the precision of the values obtained for his parameter estimates, leaving the reader only to speculate upon the accuracy of the Mitscherlich studies. Furthermore, the original Mitscherlich equation was constrained to the single factor case, thus disregarding any interaction between nutrients. Balkmurkand proposed a modest variation of Liebig's inverted yield equation, with the following resistance formula: $Y = (a_n/n + N) - (b_n/(n + N)^2) + 1/c$, where a,b, are parameters, c is the maximum yield, n is a measure of soil nitrate, and N is the amount of fertilizer. Additionally, to improve readers' confidence in the presentation of agronomic research, he further proposed that researchers conduct analysis of variance tests on their estimated coefficients. Incidentally, Balmurkand intended this suggestion to improve the statistical precision and quality of early plant and soil science research, which it undoubtedly succeeded in doing. Yet unfortunately, a majority of contemporary agronomy, soil science, and plant science research still employs analysis of variancé as a sole measure of statistical accuracy, when other known statistical tests and models exist that would serve as more precise measures, and thus give more credibility to modern agronomy research.

The founding work of Liebig and his colleagues has fostered the development of more sophisticated physiological plant growth models. In 1976, Smith presented an analytical model which simulates nitrogen, phosphorus, and potassium utilization in the plant-soil system for a variety of crops including corn, beans, oats, rutabagas, and pine trees [94]. To paraphrase Smith, the model is a measure of general physiology of many species subjected to a wide range of nutrient availability.

Along with the advancements in biological and physiological knowledge of crop growth, a general awareness of the technical relationship between inputs and products has increased. From inspection of the contemporary yield-response literature, one observes a variety of agronomic factors affecting protein and yield levels.

Many research projects have shown that both yield and protein content of winter wheat can be greatly enhanced from applications of nitrogen fertilizer [31,41,54,61,88, 90]. In 1950, agronomists found that Tennessee wheat grain yields and quality, in other words, yields and protein, are influenced by nitrogen fertilizer, with the most potent yield response occurring from November applications of nitrogen. Later fertilization resulted in a smaller response, with practically no response resulting from applications made in the late spring, after May fourth [54]. Conclusions drawn in the preceding study coincide with results from earlier projects. In particular, research regarding the response of soft winter wheat grown in Ohio revealed that applications of nitrogen made at or near seeding tended to increase yield; and, in contrast, nitrogen applied in spring tended to inhibit yields [9]. Yet on other locations, where growing conditions differ greatly from those in Ohio or Tennessee, fall application of nitrogen is frequently less effective than spring application in increasing yield. For example, in the prairie provinces of Canada, scientists report substantial losses of fall applied nitrogen fertilizers over winter [81]. Urea, KNO_3, and $(NH_4)_2SO_4$ comprise three forms of nitrogen tested in this experiment. The loss of nitrogen, occurring in early spring, was primarily due to denitrification rather than leaching. In fact, in the extreme case, denitrification accounted for 87 percent of the fall applied KNO_3 lost. Consequently, agronomists advise Canadian farmers to use a starter fertilizer, then apply larger treatments of nitrogen in the springtime. Additionally, agronomists found that late spring applications of nitrogen improved yields and grain protein for both spring and winter wheat grown in Illinois [41]. Clearly, as Williams and Smith [111] emphasize, the timing of fertilization will vary between geographic locations, depending upon soil and climatic indigeneous to a given area.

Commonly, yield studies include at least one explanatory variable that represents a soil characteristic such as soil nitrate (NO_3-N), soil phosphorus (in soil solution, organic, and inorganic forms [26]), or soil moisture, and often these studies analyze interactions between nitrogen, phosphorus, and potassium. Extensive soil potassium tests conducted in Montana from 1972 through 1974 reveal that "nearly all major agricultural soils of Montana are on the 'high' category of K (potassium)."[4] Meaning that ". . . crop responses to potassium fertilizer would occur only infrequently."[5] Nevertheless, the study further states that on potassium deficient soils, on average, winter wheat yields increase by 5 bushels per acre, provided the presence of adequate nitrogen and phosphorus. Experiments by Koch and Mengel [49] showed that potassium improves the translocation of nitrogeneous compounds in wheat, which, in turn, increases the formation of amino acids and protein during grain formation.

Similar to potassium, phosphorus is a critical component in plant and soil systems [12]. Canadian researchers observed pronounced, and frequently variable, crop response to phosphate fertilizers, to plant utilization of applied fertilizers, and to interactions between nitrogen and phosphate [42]. They conclude that plant failure to mobilize phosphorus may be due to one of the following causes [42]:

1. The absorption capacity of the roots may be damaged from moisture stress.
2. Changing physical conditions of moisture in the soil may result in decreased availability of soil phosphorus in the root zone.

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[4] See page 1 of [92].
[5] Ibid.

Experiments involving spring wheat and barley production, grown on four different soils in North Dakota, suggest that phosphorus alone has no influence on yield, but its interaction with nitrogen and water significantly affects yield. A study completed in Nebraska [70], using wheat and oats, indicates that combined nitrogen and phosphorus functions synergistically as compared to the effect of the same elements individually.

Field experiments on a diversity of crops show that efficient combinations of the three paramount fertilizers, render increased yields [26,56,57]. In particular, this is true for soils which contain relatively low levels of nutrients. For example, Michaelson et al. [64] estimated multiple regression equations to predict barley grain yields on nutrient deficient subarctic soils. They found significant parameters for nitrogen and phosphorus, in addition to significant interactions between nitrogen and phosphorus, nitrogen and potassium.

Numerous investigations show that soil chemicals and nutrients essential to plant growth can limit crop yields. In many areas, the most limiting soil component is soil nitrate [78,101,107]. This is especially true in countries where relative prices of nitrogen fertilizers are extremely high or where availability of applied nitrogen is scarce or nonexistent [19]. In Nebraskan corn and winter wheat experiments [71] soil nitrate significantly influenced yields and grain protein percentages. Young et al. used multiple regression techniques to determine explanatory yield factors. They found that at seeding, soil nitrate to a depth of 61 centimeters has a significant relationship with yield response of spring cereal grains to applied nitrogen [115]. Other research, particularly relevant to winter wheat crops grown in Montana [51,89], concludes that frozen soil profiles impair the translocation of soil nutrients to plant roots. In wheat and rye experiments, Gashaw and Mugwira [32] discovered that applied ammonium (NH_4-N) increases the uptake of nitrogen, phosphorus, and iron, while soil nitrate increases the uptake of magnesium, calcium, and manganese. Traditionally, soil scientists have maintained that soil nitrate substitutes perfectly for applied nitrogen [35,50]. Although, in contrast to that idea, recent research indicates that nitrogen fertilizer is approximately three times more efficient that soil nitrate in producing winter wheat [19,36].

At this point, concerning soil nutrients, it is worthwhile to note that considerable controversy exists between soil scientists as to the accuracy of soil testing. Most soil scientists profess that procedures for measuring soil nutrients are accurate [35]. However, others believe that no precise tests exist for certain chemicals and micronutrients [43]. Thus one must maintain discretion when one undertakes research involving soil nutrients.

In addition to edaphatic influences on crop yields and grain protein, other factors such as soil moisture, precipitation, and temperature usually exhibit significant relationships to successful crop production [5,13,91]. Canadian greenhouse experiments demonstrate that increased wheat yields may be obtained from larger quantities of soil moisture (up to three-quarters of field capacity) in loam but not in loamy sand [21]. Wheat and barley field experiments show that yield responses to nitrogen fertilizer on nonfallowed soils are significantly affected by growing season precipitation and available stored soil moisture at seeding. In fact, the sum of growing season precipitation and soil moisture comprised 40.3 percent of the yield response to nitrogen [8]. In 1924, Fisher used linear regression techniques to predict wheat yields from rainfall distribution at Rothamsted, England [25]. Since then, many researchers have utilized Fisher's methods on different crops in dissimilar environments. One such study, completed in India [30], concluded that 75 percent of the yield variation was due to rainfall distribution. Furthermore, the study presents response curves depicting expected changes in yield caused by marginal increases in precipitation at any point in time. These response curves show that precipitation exceeding the average during the period of a month prior to seeding and during the period of germination is generally beneficial to the crop, while precipitation at tillage is damaging [30].

A Montana study [14] examining the long term fertilizer and climatic influences on morphology and yield of spring wheat shows that water use efficiency increases with increasing rates of applied nitrogen and phosphorus. The most efficient combination of nitrogen (45 kg/ha) and phosphorus (180 kg/ha) resulted in water utilization of 91 kg/ha/cm by the plant.

Variation in management practices, such as tillage [7,104,110]; timing and rates of seeding [74]; types and application methods of fertilizers [37,111], insecticides, and herbicides; all influence crop yields. Pendleton and Dungan [74] present evidence that yield response to the seeding rates and dates of applied nitrogen differs between four varieties of winter wheat. The Knox variety showed the strongest response to nitrogen, and maintained the highest yields as seeding was increased from three to eighteen pecks per acre. Moreover, they explain that,

> Variety selection showed the greatest effect on grain yield, heading date, test weight, plant height, straw yield, ratio of straw to grain yield, and kernel weight. Application of nitrogen exhibited the greatest effect on plant erectness, clover stands, and protein content of the grain. Seeding rate . . . (influenced) . . . the number of grain-bearing heads per plant [74]. page 312.

A Montana study [76] concludes that rates at which winter wheat is seeded possess little influence on yields. However, in a general sense, the study recommends seeding dates from September tenth through the twenty-fifth for western and central sections of the state, and from September first through the tenth for eastern Montana.

Typically, dry fertilizers are either side-dressed or broadcast, and liquid fertilizers are either injected into the soil or sprayed on the surface. Soil scientists have also observed successful results from other techniques of application. For instance, Altman et al. [1] experimented with foliar sprayed urea, applied to immature spikes of hard red winter wheat. They discovered increases in average grain protein percentage and in average yield by thirteen and six percent respectively, over a control plot which received no urea. Other studies [93] have similarly found foliar sprayed fertilizer quite effective in increasing protein and yield of wheat grain.

Research also shows that efficient use and absorption of nitrogen by plants depends highly on the amount and type of nitrogen available [32]. Peterson et al. [75] concluded that, in general, the broadcasting method of fertilization is frequently less effective than row applications. However, the effectiveness ratio of broadcast to row applications of phosphorus appears to depend solely upon the level and availability of soil phosphorus present in the plant root zone. Often for cereal crops, agronomists recommend split applications of fertilizers, with treatments in the fall and spring, in order to enhance production of grain and protein. Winter wheat experiments [41] involving a series of three spring nitrogen applications (April 2, 23, and May 9) displayed markedly greater yields and higher percent protein over plots which received a single dose of fertilizer (on April 2) equivalent to the sum of the split nitrogen treatments.

In addition to a fertilizer plan, the manager must also select a crop rotation scheme. Research concerning dryland wheat production in the southern Great Plains [4] suggests that the optimal cropping pattern, based on long term precipitation records, is an alternating wheat-fallow, and wheat-sorghum-fallow rotation. An innovative farm management study [16] demonstrates how stochastic dynamic programming can be used to select an optimal policy, either crop or fallow, for any given state (soil moisture at seeding) at each stage (a year within the farmer's planning horizon). The resulting long-run expected return per year under the optimal policy, the continuous wheat policy, and the alternating fallow and wheat policy are, respectively, $25.60, $22.56, and $20.60 per acre.

Cochran et al. [18] found that direct drilling of winter wheat into soil covered with crop residue promotes more efficient water use, and decreased soil erosion, but tends to result in stunted plants and lower grain yields. Ecofallow [110], which minimizes tillage within a crop rotation, and chemical fallow [79], which employs herbicides and insecticides, have both shown fruitful results in regard to crop water management and soil conservation. Yet the central drawback of those methods is lower mean yields compared with yields obtained after traditional fallow practices. Note that chemical fallow, nontillage, and limited tillage practices considerably reduce the farmers' diesel fuel costs. Studies have been undertaken to explore the profitability of various fallow techniques in cereal grain production [7,79].

The crop response literature contains extensive analysis of protein yields for grain crops. Most experiments [42,60,90] show that an inverse relationship exists between grain yield and protein content of grain. This relationship is intuitively appealing because, in general, one would expect that as yield or grain mass increases, protein becomes diluted in a sizably larger kernel.

In order to clarify conflicting observations on the nature of the relationship between yield and protein, McNeal et al. [62] engaged in meticulous experimentation with eight wheat varieties, grown under many conditions, in locations near Kalispell, Bozeman, and Huntley, Montana. They confirmed an inverse relationship between yield and protein for wheat grown in Montana. Furthermore they suggest that grain protein formation depends on a combination of genetic and environmental variables.

> (Specifically) . . . it appears that grain protein percentages were entirely dependent upon the amount of carbohydrate (amino acids) translocated into grain. This may have been influenced by the number of kernels present to act as carbohydrate sinks, and by the ability of plants to translocate carbohydrates into kernels. Both kernel number and kernel weight are affected by environment, but are also under genetic control [62]. page 601.

Moreover, the two paramount ingredients for protein formation in wheat grain are nitrogen and potassium [40]. In short, within the plant, nitrogen is restructured into amino acids, primarily lysine and methionine. Then elemental potassium and water carry the free amino acids to the kernels, where conversion of the amino acids builds the four types of grain protein: Albumin, globulin, prolamin, and glutelin [63].

In a study concerning irrigation experiments, Terman et al. [101] explain that the primary effect of applied nitrogen in the presence of adequate water was to increase yields, while in a situation with low water levels, nitrogen mainly increased grain protein. From the same article, when dryland wheat experiments displayed significant grain yield response to nitrogen, simultaneously, scientists observed the unusual result of increasing percent grain protein. Although, when yield response to nitrogen was negligible, an extremely potent protein response resulted from applied nitrogen. Furthermore, in a third experiment, Terman and his colleagues stated that,

> Average protein contents of about 20 hard red winter wheat varieties at different locations in Nebraska in 1966 and 1967 were . . . negatively related to grain yields. Protein contents varied more widely among locations than among varieties at each location [101]. page 755.

A project conducted in Belgrade, Montana [61] tested the protein contents of five spring wheat varieties, including short, medium, and tall genotypes. Grain yields were similar for all varieties, but grain protein percentages decreased as the grain to straw ratio increased. This implies that the quantity of top growth serves an important role in extracting soil nutrients. Also, water use by all five varieties increased with increasing rates of applied nitrogen. Oswalt and Schlehuber [72] point out three fundamental factors responsible for protein development in grain. Specifically they mention the environment or climate, composition of the soil, and wheat variety. Environmental elements are especially important because the availability of sufficient precipitation or soil moisture dictates the amount of nitrogen and other essential nutrients transferred in the soil and within the plant, then engendering protein formation in the kernels. As early as 1942 researchers [73] employed a "regressional integral" technique to show the importance of rainfall to protein content in wheat. Oswalt and Schlehuber conclude that nitrogen has greater influence on protein content than on grain yield.

A majority of yield and protein response studies lead to a fertilizer recommendation for a crop grown under specific geographic conditions. These recommendations are often based on experiments with fertilizer applied at, for example, rates of 0, 30, 60, and 90 pounds per acre; then researchers [41,64,70,75,77] mistakenly report one of the four levels of fertilization as "optimal," using highest average yield as a criterion. Furthermore, the most glaring error in the plant science, soil science, and agronomy literature is the total disregard for input and output prices [44,85]. For many years economists have known that prices are among the essential components for making appropriate profit maximizing production decisions [2,19,38]. Thus, failure to include prices in analyses leads to suboptimal recommendations. In sophisticated studies [71,74], atypical to the majority of current literature, researchers properly apply statistics and calculus to their data in order to maximize profit surfaces. Fertilizer recommenations based on this type of logic are much more accurate than those founded on maximum yield or protein, on fertilizer budget models [85], or on personal opinions.

De Janvry's [19] effort to estimate production of Argentine wheat and corn under risk exemplifies one reasonable process which leads to economic fertilizer recommendations. Five environmentally different sites, representative of growing conditions in Argentina, served as data sources for observations on wheat response to nitrogen and phosphorus fertilization. Grain yields were estimated for each location with Cobb-Douglas functional specifications. The independent variables included in the regressions were: nitrogen, phosphorus, organic matter in the soil, rainfall at seeding, rainfall at plant emergence, rainfall at tasseling, and dummy variables representing location and wheat variety. Nitrogen recommendations were formulated from a "fertilization possibilities frontier,"[6] depending on

[6] See De Janvry [19], page 4, for the mathematical derivation of the "fertilization possibilities frontier."

various price ratios, organic matter, probabilities of incurring revenue less than the cost of fertilization, and other variables fixed at their means.

Figure 1, copied from De Janvry's article, displays two "fertilization possibility frontiers" as a function of soil organic matter for southern Argentina farms.

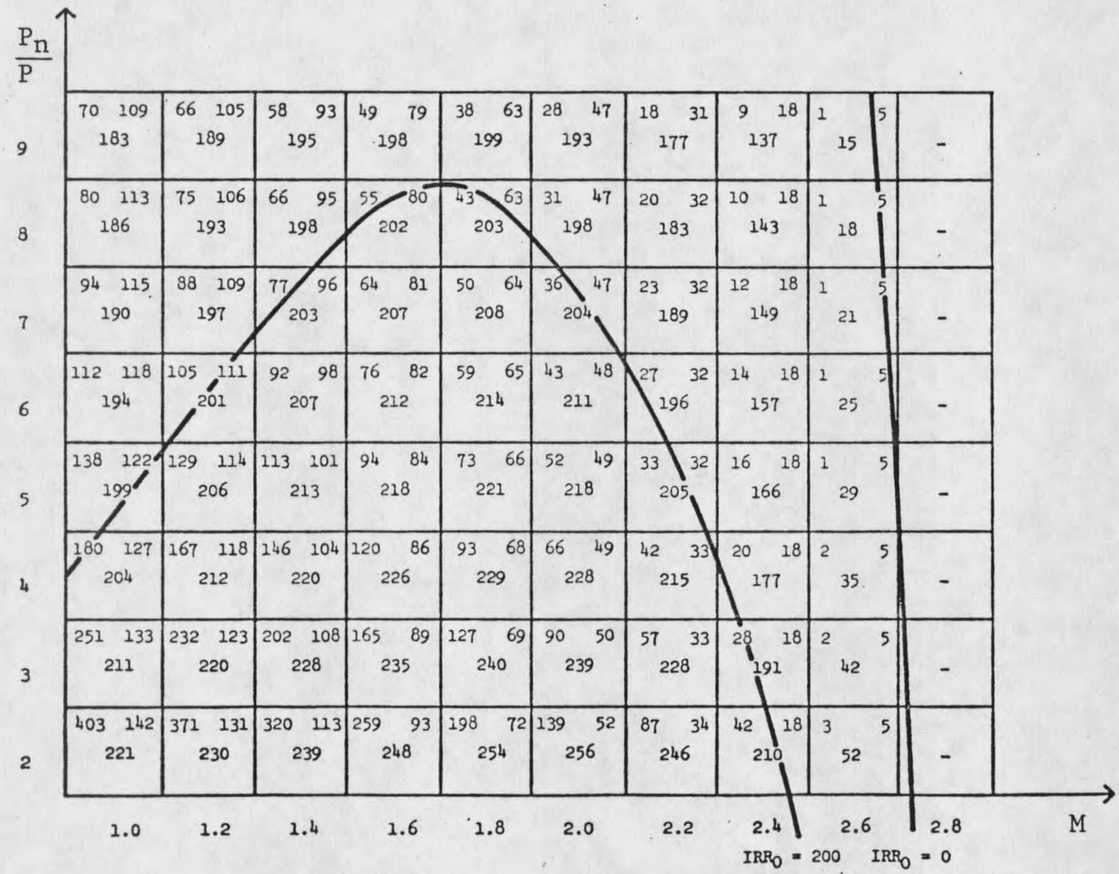

Figure 1. Optimum level of wheat fertilization in southern Argentina. (Reproduced from De Janvry, Table 4 [19]).[7]

If the producer could obtain accurate estimates of organic matter, precipitation, and prices, in conjunction with risk preferences, then they could apply their information to a table similar to the one listed, and determine optimal levels of nitrogen and phosphorus to maximize profit.

[7] The data that appear in each cell are the optimum nitrogen (N_O) and phosphorus (F_O) in kg/ha; the corresponding internal rate of return (IRR_O) in percent.

Recent efforts to quantify winter wheat yield and protein response under Montana conditions were made by Garnick [31] in 1977. His data set included observations on yield; percent protein; applied nitrogen, phosphorus, and potassium; soil nitrate; soil water; and summer precipitation from 43 experiments on 38 locations in Montana. Final yield and protein response functions were specified as third degree polynomials with interaction variables and multiplicative disturbance terms. Incidentally, with a multiplicative error contained in the model, the standard deviation of the disturbance is proportional to the mean of the dependent variable. Parameter estimates were generated by method of GNLR, a nonlinear regression computer program written by Dr. Oscar Burt (Montana State University). Garnick found that "only applied nitrogen, precipitation, and soil nitrate were significant in explaining yield response."[8] His final estimate exhibited appropriate theoretical behavior. That is, for each variable, the response function had a maximum and exhibited diminishing marginal returns. As with yield, protein showed significant reponse from nitrogen, precipitation, and soil nitrate. However, accompanying these variables, protein was also affected by applied phosphorus.

Eventually, Garnick combines the response functions with a crude estimate of protein premium to form a profit function. Optimal rates of nitrogen are displayed in two-way tables with varied rates of precipitation and price ratios on the two axes. His results show that accounting for the protein premium structure of wheat prices boosts optimal rates of nitrogen by approximately 15 pounds per acre, as compared to recommendations without a premium. Finally, a 25 percent marginal rate of return was specified as a constraint, which resulted in a slight reduction in the optimal levels of nitrogen.

Similar wheat response research was done by Simons [88] in 1980. His estimates of polynomial yield and protein functions revealed applied nitrogen, phosphorus, potassium,

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[8] See page 72 of [31].

soil nitrate, soil phosphorus, a water variable, and interactions among the factors as significant explanatory elements. Protein premium was not included in the optimization. Simons made recommendations for phosphorus and nitrogen based on three different price levels for wheat with various capital constraints. Depending on different price and constraint scenarios, optimal nitrogen varied from 45 to 85 lbs/ac, and optimal phosphorus rates were between 0 and 19 lbs/ac.

The preceding discussion of wheat production is by no means exhaustive. In fact, the list of works which explore factors contributing to optimal wheat production could conceivably fill volumes of texts. Nevertheless, this literature review should sufficiently point out that a number of variables and interactions influence grain response. To reiterate the literature, applied nitrogen, phosphorus, and potassium fertilizers have been found to be positively correlated with grain yield and protein response. Studies also demonstrate that soil nitrate substitutes imperfectly for nitrogen. The interactions of nitrogen and potassium, and also, nitrogen and phosphorus are essential for proper grain protein formation. The presence of micronutrients in the soil, along with soil nitrate contribute positively to yields and protein, but the evidence of exactly how these nutrients interact to promote plant growth is at best vague. This problem is primarily due to our dependence on imprecise tests for measuring soil nutrients. In general, increasing water availability, in either the form of precipitation or soil water, is postively correlated with yield and has a negative relationship to protein. Management practices, such as crop rotation, varietal selection, methods of fertilizer application, and timing of planting and fertilization, exemplify a few more important factors in determining crop response. This project is intended to carefully analyze Montana winter wheat production and improve upon the existing knowledge in the field of agricultural production economics.

CHAPTER III

DEVELOPMENT AND ESTIMATION OF YIELD AND PROTEIN RESPONSE FUNCTIONS

Methodology

The data used to fit the yield and protein response functions were generated by personnel of the Southern Agricultural Research Center, Huntley, Montana, on experimental plots located on 18 farms in south central Montana. Dr. Vincent A. Haby[9] directed a series of fertilizer experiments which provided the data set. A total of 30 treatments of various combinations of nitrogen, phosphorus, and potassium were applied to each of 30 total sites over five years (1976-1980). Note that periodically the experiment was replicated some years on 18 farms, hence accounting for 30 total experiments. Furthermore, among the 30 fertilizer treatments per site, there were seven replications. The product of 30 treatments and 30 site-years result in 900 observations. Appendix A summarizes information on experimental location and year.

Selection of experimental sites was based on a specific set of characteristics. Namely, the locations chosen were adjacent sites in a crop-fallow rotation sharing uniform soil conditions, unhindered by insects, weeds, and other detrimental factors. In further efforts to achieve consistent soil types scientists examined surface color and texture, and strata concentrations of soil nitrate, elemental phosphorus, and potassium. After scientists deemed an experimental site acceptable, then individual plots (2.44 X 6.1 m) containing

[9] Currently Dr. Haby is an associate professor at the Agricultural Research and Extension Center of Texas A&M University.

eight rows of wheat were delineated. Sites which either incurred hail damage to crops or suffered from unusually high saline content were excluded from this analysis.

In the fall, prior to seeding, soil samples were analyzed for each plot. Soil nitrate was measured by depth of 0 through 15, 15 through 30, 30 through 60, 60 through 90, and 90 through 120 cm using the "CTA" method of Haby and Larson [35]. Tests were run to determine quantities of soil organic matter and the minerals potassium, calcium, and magnesium. Scientists also calculated the levels of elemental soil phosphorus by depths of 0 through 15, 15 through 30, and 30 through 60 cm. In the spring, before applications of nitrogen, soil nutrients were measured again to check for any appreciable change over winter.

Measurements of weather conditions were made for each site. Summer precipitation (April through July), temperature, and estimates of evapotranspiration were the primary factors subject to observation. Any errors in measurement were substituted with similar data from the nearest weather station. Researchers did not compile observations regarding winter precipitation (September through March). Consequently, that data was taken from records of the nearest weather station that was within the same average precipitation gradient of the site in question.[10]

Applications of nitrogen, phosphorus, and potassium were each calibrated precisely at five rates and followed a nested-cube statistical design developed by Lund and Linell [55]. The nitrogen fertilizer, ammonium nitrate, was top dressed in spring at rates varying from 0 to 89 kg/ha in increments of 22.25 kg. Phosphorus, in the form of triple superphosphate, was banded with seed at rates ranging from 0 to 35.7 kg/ha in increments of 8.925 kg. Potassium, as muriate of potash, was rototilled to a depth of 10 cm at rates of 0 to 96 kg/ha in increments of 24 kg.

[10] This precipitation gradient map designates areas of equivalent average annual precipitation within the State of Montana. It was prepared by the U.S. Soil Conservation Service, Box 970, Bozeman, MT 59715.