VALUE OF SOIL TEST INFORMATION FOR CROP PRODUCTION

SOIL pH RESPONSE TO LIME AND WHEAT YIELD RESPONSE TO SOIL pH

ECONOMIC STRATEGIES OF LOW SOIL pH MANAGEMENT IN DUAL-PURPOSE WINTER WHEAT PRODUCTION

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PREFACE

This dissertation consists of three chapters, each summarizing research problems conducted separately during my doctoral program. Each chapter is presented in a format suitable for a publication in professional journals.

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CHAPTER I

VALUE OF SOIL TEST INFORMATION FOR CROP PRODUCTION

ABSTRACT

This study was conducted to determine the value of information associated with soil testing for available nitrogen and phosphorus when choosing fertilizer application rates. Actual aggregate data of nutrient levels for winter wheat fields and average county level grain yield data were used to estimate expected yields obtained with or without soil testing. The value of soil testing information was defined as the difference between expected returns from wheat grain production based on agronomic recommendations to achieve 30 bu/ac yield goal and an application of uniform rates of nitrogen and P_2O_5. It was shown that with existing nutrient content in soil the value of soil testing information is positive.

INTRODUCTION

Farmers may use soil tests to determine the fertility level of soils. They may test for a single nutrient or they may obtain a more comprehensive analysis to determine the levels of several nutrients as well as soil pH. They may elect to obtain samples from near the surface (0 to 6 inches) or they may obtain samples form the subsoil (6 to 24 inches). If soil test results are available, applications of fertilizer may be adjusted to reflect plant needs to achieve a target yield. Alternatively, farmers may elect to not test soil and apply a level of fertilizer based upon prior experience of farming the field.

When immobile nutrients such as phosphorus are applied to the soil they are expected to either be used by the crop or remain in the tilled soil zone. However, nitrogen is mobile in the soil profile that moves throughout a soil profile with water. A test of the tilled surface layer of soil may not identify the presence of nitrogen in the subsoil that would be available for plant use.

When fertilizers are applied in excessive amounts or reduced yields due to bad weather prevent nutrient removal, nutrients may accumulate in soils to the level that "would allow application of lesser amounts of fertilizers to produce normal yields" (Zhang et al.). There are potential savings on fertilizer costs when fertilization programs are based on the principle to apply fertilizers when needed and where needed.

Objectives of the Study

The purpose of this study is to determine potential benefits of soil testing information for wheat grain producers. The study is different from previous research that actual aggregate data of nutrient levels for continuous wheat fields were used rather than site-specific data. The value of independent nitrogen and phosphorus soil test information for wheat production was estimated based on the assumption that only one nutrient was deficient. The value of joint nitrogen and phosphorus test was derived when both nutrients were assumed to be deficient.

The Value of Information

Several methods for estimating the value of information have been proposed. Bosch and Eidman used a stochastic dominance (Meyer) approach to value information.

An alternative approach to estimate the value of information is based on obtaining the posterior probability distributions to find the optimal or Bayes strategy and the expected returns associated with that strategy. Then, those returns are compared with expected returns obtained using the prior, or no-data, probabilities (Eidman, Dean and Carter; Baquet, Halter and Conklin).

Response Functions and Fertilizer Recommendations

Several assumptions were imposed to enable estimation of net return distributions for winter wheat. The first set of assumptions relates the soil nutrient status and yields in terms of Bray's mobility concept (Bray). This concept is used to make fertilizer recommendations for a target yield based upon soil tests (Johnson et al.). According to the mobility concept, nitrogen is a mobile nutrient. Nitrogen rates are estimated as the difference between the amount that is taken up by plants and the amount of the nutrient in the crop root layer. For immobile nutrients including phosphorus, sufficiency levels are used to determine fertilizer recommendations. Given the knowledge provided by soil testing, fertilizer recommendations for both nitrogen and phosphorus can be made for a specified target yield.

A second set of assumptions is made to enable estimation of conventional fertilizer strategies, based on knowledge other than soil test information. Two types of fertilizer strategies are plausible. One option is to posit a strategy based on average fertilizer application rates used by Oklahoma winter wheat producers. The second option is a "safety" rate that guarantees a sufficient (but not necessarily efficient) level of nutrients. For example, Zhang et al. report that many farmers in the region arbitrarily apply 100 pounds of nitrogen and 46 pounds of phosphorus per acre to fields seeded to winter wheat. On average, Oklahoma wheat producers used 52 pounds of nitrogen and 32 pounds of P_2O_5 per acre in 1996 (Economic Research Service, USDA).

Third, wheat response to nitrogen is assumed to be appropriately represented by a linear response plateau (LRP) model. This type of response may be expressed as:

$$y = min\ [f(X_i), y_m] + u, \tag{1}$$

where y is crop yield, $f(X_i)$ is a function that determines yield, X_i is a yield limiting nutrient, y_m is a maximum yield that can be achieved eliminating deficiency of X_i, and u is an error term. Based upon this crop response model, application of excessive amounts of fertilizers will not result in yields different from y_m.

Fourth, the response to phosphorus is expressed in terms of sufficiency levels, which represent the availability of the nutrient in the soil. Calibrated potential reduction of yields due to phosphorus deficiency is presented in Table 1.1. This effect can be expressed as

$$y(X_N, X_P) = s(X_P)y(X_N), \tag{2}$$

where s is a phosphorus sufficiency level.

MATERIALS AND METHODS

Definition of Returns

The returns to fertilization can be expressed as the difference between the revenue from an expected yield and the cost of fertilizer, similar to as described in Perrin:

$$\Pi = p_w y(X_S, X_F, \theta) - p_F X_F, \tag{3}$$

where Π is the returns above the cost of fertilizer, p_w is the price of wheat, y is yield expressed as a function of X_S nutrient content in soil, applied fertilizers X_F, and θ is a weather state. A fertilizer price is denoted as p_F. In the following discussion prices of inputs and output are assumed to be constant.

When the value of X_S is unknown (without soil testing), the variability of expected returns is determined by the variability in both X_S and θ. Soil testing (assuming that it describes perfectly the state of nutrient content in soil or sampling and analytical errors are relatively small) removes uncertainty about X_S and allows adjusting the fertilizer rate X_F, to maximize expected returns. The expected returns are maximized with respect to X_F, which may either be a fixed value under uniform (without soil test) application, or varies depending upon the results of a soil test.

The expected returns using the fertilizer scheme based on the soil test can be expressed in the following equations:

$$\Pi_v = \sum_{i=1}^{n}\left[\sum_{j=1}^{s}\{p_w y_{ij}(X_i, F_i) - p_F F_i\}P(\theta = \theta_j)\right]P(X = X_i), \tag{4}$$

where Π_v is returns obtained from the i^{th} range of soil nutrients under j^{th} state of nature, p_w and p_F are the prices for wheat and fertilizer, respectively, y_{ij} is a yield achieved given the level of nutrients in soil X_i and a weather state j, F_i is a recommended fertilizer rate given a soil test, and $P(\theta = \theta_j)$ is a probability of observing the j^{th} state of nature.

The returns with uniform fertilizer application are determined by:

$$\Pi_u = \sum_{i=1}^{n}\left[\sum_{j=1}^{s}\{p_w y_{ij}(X_i, \overline{F}) - p_F \overline{F}\}P(\theta = \theta_j)\right]P(X = X_i). \tag{5}$$

Expected returns with and without soil test information, $\Pi(y(X_S, X_F(k), \theta))$ can be compared, where $X_F(k)$ is either a fertilizer rate based upon a soil test, or a fixed rate used traditionally by farmers who do not use soil testing.

Estimation of Returns

Examples used to teach farm management often are based upon a known strictly concave twice-differentiable crop response function and a set of expected prices. A deterministic returns function may be optimized to find precise fertilization levels. In practice, agronomists provide fertilizer recommendations based upon an expected or target yield independent of expected prices. Fertilizer is recommended to supplement what is available in the soil to provide the amount of nutrients that the crop will need to achieve the target yield. For the present study, rather than optimizing the levels of nitrogen and phosphorus fertilizers, returns were calculated based on practically recommended fertilization strategy to achieve a certain targeted yields. The yield of 30 bu/ac was chosen in the estimation.

To capture yield variability due to states of nature, the θ factor, distributions for yields lower than 10, 20, 30, 40 and 50 bushels per acre were estimated using Oklahoma county level data for 1993-1997. The data are presented in Table 1.2.

To simplify calculations, it was assumed that expected yield is a random variable subject to a production function and variability due to states of nature. It was also assumed that the occurrence of yield within the yield ranges does not depend upon the level of nutrients, which implies independence between states of nature and the nutrient levels. A LPR functional form is assumed to represent wheat grain yield response to nitrogen with a 50 bushel per acre maximum yield (Westerman). It can be expressed as

$$(6) \qquad y(X_N, \overline{X}_P) = \begin{cases} 0.5X_N, & y < 50bu/ac \\ 50 & y \geq 50bu/ac \end{cases},$$

where X_N is the amount of nitrogen in lb/ac available to the crop given 100 percent sufficiency in phosphorus. When phosphorus is deficient, it becomes first limiting and expected wheat grain yield is decreased according to the equation (2).

Soil test data were obtained from an extension service sponsored soil-testing program (Zhang et al.). A total of 3,079 surface (0 to 6 inches) and 2,957 subsurface (6 to 24 inches) soil test observations from a single season for a single crop were available. These data were used to generate the distributions of nitrogen and phosphorus in soils. The joint distribution of nitrogen and phosphorus reported in Table 1.3 was obtained with an assumption that nitrogen and phosphorus are distributed independently. Both nitrogen and phosphorus distributions are clearly skewed. Fitting a continuous distribution function, for example a gamma function (Babcock, Carriquiry and Stern) would complicate calculations without assurance that it would reflect the real distribution of nutrients. Therefore, for simplicity, it was assumed that nutrients were uniformly distributed within a given range of concentrations. It was also assumed that the number of soil samples was sufficiently representative to make an inference about soil nutrient status. The range intervals correspond to those used to provide fertilizer recommendations (Johnson et al.).

RESULTS AND DISCUSSION

Expected returns with and without soil testing information were calculated based on the equations (4) and (5). The equation (4) uses fertilizer rates that would have been recommended to achieve a target yield of 30 bu/ac in the case of nitrogen fertilizers or to reach 100 % sufficiency level for phosphorus fertilizers given the i^{th} state of soil nutrient content. In equation (5), the application rates, $\overline{F}$, were used such that the expected returns from the uniform strategy were maximized. They are shown in Table 1.4 as the optimal rates. The difference between Π_v and Π_u is referred to as the gross value of soil testing information and also presented in Table 1.4. Returns were calculated for output prices of \$2.50 and \$4.00 per bushel of wheat, and fixed input prices of \$0.27 and \$0.28 per pound for nitrogen, and phosphorus, respectively.

The reported gross value of soil testing does not include the cost associated with obtaining the information such as the cost of time and labor required to obtain samples, shipping and laboratory charges. A number of soil samples required for accurate fertilizer recommendations may vary depending on field landscape or soil characteristics.

To estimate the value of separate nitrogen and phosphorus soil tests, it was assumed that the sufficient quantity of other nutrient was present in soil. To estimate the value of N (0-24 inches) test, the assumption was that all nitrogen in the subsoil could be available for crop consumption.

Phosphorus fertilizers have a strong carryover effect. Application of phosphorus fertilizers above the sufficient level will not cause a loss of fertilizers since they will still be available for the next year crop, however, the value of residual phosphorus must be discounted. When estimating the expected returns in the cases where phosphorus is a limiting factor, the discounted value of residual phosphorus was added. The carryover phosphorus was defined as the difference between applied fertilizer and the amount of removed with crop. The assumption was that every bushel of wheat grain removes phosphorus equivalent to 0.675 lb P_2O_5 of fertilizer. The value of residual phosphorus was discounted at 10%.

Table 1.2 suggests that subsoil contained a considerable amount of nitrogen. If subsoil nitrogen does not leach out of soil to groundwater, then it is likely to be available to the crop. In this case, under the assumption that phosphorus is not limiting, the gross value of soil testing was \$5.69/ac and \$7.69/ac when the price of wheat grain was \$2.50 and \$4.00 per bushel, respectively (Table 1.4).

The estimated gross value of soil P test was lower than the value of soil N test, mostly due to the fact that the cost of phosphorus fertilizers was adjusted for the carryover effect. Soil testing indicated that a significant amount of phosphorus accumulated in wheat fields. If the results of soil testing are neglected then residual phosphorus would have less and less value and the value of soil testing information would be significantly higher.

Finally, in the less restrictive scenario, when both nutrients were assumed to be distributed as shown in Table 1.3, the value of soil testing was \$4.59 and \$8.30 per acre for wheat prices of \$2.50 and \$4.00 per bushel, respectively.

CONCLUSIONS

The expected returns from wheat production with or without soil testing information were estimated using conditional probabilities of yields given a state of nature and the distribution of nutrients in soils. The difference between the expected returns obtained with and without soil testing was defined as the gross value of soil testing information. The obtained results could indicate the upper limit of the cost of obtaining the information on soil nutrient content.

For the purposes of this study, the value of soil testing was estimated under the assumptions that soil test sampling accurately represented the state of nutrients in the soil and that the results of the test would be used for only a single growing season. Variable rate and site-specific technologies provide farmers with the opportunity to fine-tune fertilizer application. However, the optimal grid size and frequency of soil testing remain to be determined.

The analysis used in this paper has several shortcomings. The distributions of soil nutrients were presented as discrete with the uniform distribution of nutrients within each interval. Having only slightly more information, the distributions could be easily transformed into continuous functions. Working with county average data simplifies analysis, which may result in inaccuracy of estimates. However, the fact that estimated results are close to those that observed in practice can be an argument for validity of this approach.

The response function to nitrogen fertilizer used in the analysis was based on the rule of thumb used by agronomists to compensate the nutrient removal with wheat grain harvest. Using more precise production function together with a site-specific distribution of nutrients in soil would produce more accurate estimates of the value attributed to soil testing.

It should be pointed out that the nutrient content in soils may not be completely independent from θ, the weather state parameter. Abnormally bad weather may limit nutrient removal by crops and vice versa.

The variable rate technologies (VRT) of fertilizer application have been getting more and more attention in the several years (Raun et al.). The major concern is the cost effectiveness of utilization of such technologies. The estimates of the value of soil test information obtained in this paper may help in determining the cost limits for introduction of VRT into agricultural production.

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Table 1.1. Phosphorus Sufficiency Levels and Fertilizer Requirements (P_2O_5 lb/ac) for Small Grains.

P Soil Test Index	Percent Sufficiency	Fertilizer Requirement
0	25	80
10	45	60
20	80	40
40	90	20
65	100	0

Note: Adapted from Johnson et al.

Table 1.2. Distribution of Winter Wheat Yields in Oklahoma, County Level Data, 1993-97.

Yield range bu/ac	Expected yield (bu/ac)	Frequency	Occurrence θ
Less than 15	10	21	0.055
16 –25	20	165	0.434
26 – 35	30	145	0.382
36 – 45	40	45	0.118
More than 45	50	4	0.011

Source: Oklahoma Agricultural Statistics, various issues

Table 1.3. Joint Probability Table for N-P Distribution in Soil.

		Soil Nitrogen, 0 - 24" Soil Layer (lb/ac)					
		5	15	30	50	70	90
		Probability (Soil $N = N_j$)					
Soil P Index	Probability (Soil $P = P_i$)	0.03	0.04	0.11	0.14	0.15	0.53
5	0.01	0.0003	0.0004	0.0011	0.0014	0.0015	0.0053
15	0.03	0.0009	0.0012	0.0033	0.0042	0.0045	0.0159
35	0.16	0.0048	0.0064	0.0176	0.0224	0.0240	0.0848
57.5	0.32	0.0096	0.0128	0.0352	0.0448	0.0480	0.1696
87.5	0.34	0.0102	0.0136	0.0374	0.0476	0.0510	0.1802
110	0.14	0.0042	0.0056	0.0154	0.0196	0.0210	0.0742

Note: Adapted from Zhang et al.

Table 1.4 Expected Returns with and without Soil Test Information Net of Fertilizer, Harvesting and Application Costs, and Value of Soil Testing Information.

Wheat Grain Price ($/bu)	With Soil Testing [a] Expected Returns ($/ac)	Without Soil Testing [b] Expected Returns ($/ac)	Optimal Rates N(lb/ac)	P(lb/ac)	Gross Value of Soil Testing Information ($/ac)
	N (0 – 24") (assuming that P is not limiting and subsoil N is 100% available)				
2.50	46.63	40.95	10	-	5.69
4.00	84.67	76.98	25	-	7.69
	P (0 – 6") (assuming N is not limiting)				
2.50	44.43	42.20	-	40	2.23
4.00	83.35	80.85	-	40	2.50
	Combined N – P (assuming that nutrients are distributed as shown in table 1.3)				
2.50	38.83	34.24	0	25	4.59
4.00	77.78	69.48	10	40	8.30

[a] Expected returns calculated using recommended rates based on soil testing information. Nitrogen fertilizer rates are recommended to achieve a target yield of 30 bu/ac; phosphorus fertilizer rates are recommended to reach 100% sufficiency level.

[b] Optimal rates assuming the application rates that maximize expected returns obtained without soil testing information.

CHAPTER II

SOIL pH RESPONSE TO LIME AND WHEAT YIELD RESPONSE TO SOIL pH

ABSTRACT

Crop yields can be greatly influenced by soil pH. This study was conducted to determine soil pH response to applications of agricultural lime, wheat yield response to soil pH, and the economics of lime application to soils used to produce winter wheat. Data were obtained from field trials. An original functional form was specified and used to model soil pH response over time to lime application. Quadratic, linear-response plateau, and quadratic-response plateau functional forms were used to model wheat yield response to soil pH. Single and multiple lime application models were used to obtain the optimal application strategy that maximizes net present value of returns from wheat production. The optimal strategies were found for several levels of initial soil pH.

INTRODUCTION

In a 1940 USDA bulletin, Shorey presented a “lime line” drawn near the geographical center of the continental United States. At the time, soil acidity was not a problem for most cropland soils to the west of the lime line that included most of the Great Plains. These soils were characterized by Shorey as “lime accumulating”. Hence, for many years land in the southern Great Plains was cropped continuously with little concern for soil pH.

Crop yields can be greatly influenced by soil pH. The pH of the soil plant-root zone influences the ability of plants to acquire essential nutrients from the soil. If the soil pH declines below some undefined critical level, the solubility of aluminum and manganese ions increases, resulting in toxicity and lower yields.

Historically, acidity (low pH) has not been a problem for soils of the Great Plains west of the lime line. However, a 1985 survey of Oklahoma fields cropped continuously to winter wheat found that more than 30 percent of 17,000 samples had pH less than 5.5. A similar survey in 1996 found that 39 percent of samples had a pH less than 5.5 (Zhang et al.). These soil-testing programs were not conducted for the purpose of drawing statistical inferences regarding changes in pH over time or proportion of the state's cropland with various pH levels. However, these data suggest that acidity levels in many Oklahoma fields may be sufficiently high to reduce wheat grain yield and that the number of fields for which acidity is a problem has increased over time.

Agricultural lime is a soil amendment that may be applied to increase soil pH. The term “agricultural lime” is usually applied to any form of liming materials that contain calcium or magnesium oxides, hydroxides or carbonates and can be used in neutralizing soil acidity (Shorey, p.23). Field experiments have demonstrated that lime application changes the soil pH over time and helps to remove negative effects of soil acidity (Coventry et al.; Krenzer and Westerman; Malhi et al.). Lime does not contain primary nutrients and is classified as a soil amendment rather than a fertilizer. Unlike many fertilizers, lime has a strong carryover effect. The economics of liming for cropland west of the historical lime line have not been determined. Precise specification of wheat-grain yield response to soil pH in the region has not been done.

Objectives of the Study

The objective of this study is to determine soil pH response to applications of agricultural lime, wheat yield response to soil pH, and the economics of lime application to soils used to produce winter wheat in the southern Great Plains. Since it is soil pH that affects crop production and liming is a tool to regulate soil pH, it is logical to first consider the lime effect on soil pH, second the effect of pH on yields, and finally the economics of lime application.

Soil Acidity and Liming

Soil acidity affects plant growth in several ways. Toxicity, caused by increased mobility of soil aluminum, is thought to be the most serious of these effects (Black, p. 698). Aluminum is the most abundant metal in soils and becomes readily soluble when the pH drops below 5.5. At pH 4.0, the cation exchange complex of soils is completely saturated with aluminum ions, which results in plants being deprived of essential cations (Foth and Ellis).

Acidification of soils over time is a consequence of the removal of base elements with harvested crops and the application of nitrogen fertilizers. Harvested crops contain base elements such as potassium, magnesium, and calcium. For example, a harvest of 100 bushels of wheat grain removes base elements in the amount that is equivalent to 65-85 pounds of calcium. Although this quantity would not appreciably change soil pH in one year, continuous cropping and removal of grain will over time increase soil acidity of the plant root zone.

Application of nitrogen fertilizers affects soil acidity through microbial activity of soil microorganisms. Soil microbes convert ammonia cations (base) into nitrates (acid), a process that releases hydrogen cations (acid) as byproducts. The speed of the conversion depends on soil and climatic factors (temperature and water content). It reaches the maximum when soil is moist and well aerated (not waterlogged). The process becomes significant at 40°F (5°C) and accelerates when the temperature increases to 85° F (30°C) (Paul and Clark, pp. 194-195).

Lime application may be used to increase soil pH. Studies of lime application on cropland used to produce winter wheat have produced contrary results. Some researchers reported positive effects of lime application on wheat grain yield and attributed it to pH increase and decrease in aluminum toxicity (Coventry et al.; Krenzer and Westerman; Mahler and McDole; Malhi et al.). However, in several experiments, lime application did not increase grain yield and in some cases there were significant reductions in grain yield. These reductions in grain yield were attributed to an increase in fungal diseases associated with a relatively high pH (Boman et al.; Bockus and Claassen; Williams and Boman; Westerman). These studies suggest that for cropland used to produce continuous wheat, application of lime may be used to increase soil pH, and increase grain yield. However, if too much lime is applied the pH may increase to a level that favors the growth of wheat grain yield reducing pathogens.

The Carryover Effect of Lime Application

From an economic perspective, liming is a capital investment rather than an operating input because of its long-term effect. Change in soil pH over time in response to lime application depends upon the soil type, lime rate and lime quality (Foth and Ellis). Foth and Ellis describe soil pH change over time due to liming as a rapid increase following application and gradual decrease with time. It is difficult to quantify the value of liming to increase pH because lime application has a long-term impact that may last from two to 20 years (Black; Coventry et al.; Malhi et al.) Higher lime rates may lead to substantial (2-3 pH units) changes during the first years, which is not always favorable due to the proliferation of wheat grain yield-reducing soil pathogens. Therefore, it is important to determine the dynamics of pH change over time after lime application.

Bongiovanni and Lowenberg-DeBoer tested a lime carryover formula adapted from Black to model pH change over time:

$$pH_t = B_s\left(\sqrt{LA - \sum_t LC + 1} - 1\right) + pH_0 \tag{1}$$

where soil pH at year t is a function of initial soil pH, pH_0, lime rate, LA, crop consumption of base elements, LC, and soil buffering capacity, B_s. The equation assumes an immediate increase in soil pH due to lime application and a continuous decrease over time due to removal of base elements with the harvested crop. Bongiovanni and Lowenberg-DeBoer found that this specification overestimated soil pH in the initial years after lime application.

Black (p. 550) cites a class of the half-life, or decay, models that have been extensively exploited to study residual effects of fertilizers. The half-life concept assumes that the rate of change in the level of some factor, x, is proportional to the difference between x_t and an equilibrium level, x_{eq}. This concept is described by a negative exponential function:

(2) $$x_t = x_{eq} + \left(x_{init} - x_{eq}\right)e^{-ct},$$

where x_{init} is an initial level of x and c is a loss constant (Black, p.550-551). The level of x asymptotically approaches to x_{eq} as time passes. This type of model was used by Bromfield et al. to model soil acidification over time in Australian pastures for a period of 55 years. Bromfield et al. used equation (3), which is a transformed form of (2):

(3) $$pH_t = pH_0 + k\left(1 - e^{-ct}\right),$$

where k and c are constants related to soil types (notation has been changed slightly). The model does not consider the effect of lime applications on soil acidity.

An analogous form of (2) can be borrowed from studies dealing with modeling of biological systems (Hannon and Ruth, p.28):

(4) $$x_{t+1} = x_t + kx_t\left(1 - \frac{x_t}{x_{crit}}\right)$$

Equation (4) is a discrete representation of the logistic function (Hannon and Ruth, p.28). Equation (4) approaches x_{crit} asymptotically when t approaches to infinity. The constant k reflects a rate of adjustment from the initial state to the final or critical state (x_{crit}).

Equations (1) to (4) describe a decrease in effectiveness of the factor x with time assuming that an initial rapid equilibration of fertilizer or lime with the soil have already taken place (Black, p. 550). Data from long-term experiments with lime application suggest that the carryover effect of liming should accommodate for an initial increase followed by the gradual decrease in soil pH (for example, see fig.8-9 in Black, p. 682). In the experiment reported by Black, the soil pH continued to rise for five years after lime application, and began decreasing in the sixth year. No prior modeling efforts have accounted for that type of a dynamic process. However, after considering several functional forms, it was determined that this process can be expressed by equation (5) that combines an exponential increase with an exponential decay:

$$x_t = x_{init} + bt^{\alpha}e^{\beta t}, \tag{5}$$

where b is a parameter that defines a magnitude of an increase, and α and β are parameters related to slopes of increase and decrease. This model can be used to model the dynamics of soil pH change after lime application. The parameter b relates to lime rates and the parameters α and β relate to soils. If data are available, these parameters can be estimated using the nonlinear least-squares procedures.

Wheat Yield Response to pH

There is extensive literature on modeling crop response to various agronomic inputs (Ackello-Ogutu, Paris, and Williams; Burt; Hall; Frank et al.; Berck and Helfand; Spillman). A number of functional forms have been used to model crop response. Some functions are easier to estimate (polynomial, logarithmic). Others are posited as being more consistent with plant response (von Liebig, Mitcherlich-Baule). Frank, Beattie, and Embleton performed a series of nonnested tests to model corn yield response to two inputs and concluded that data favored growth plateau functions. Paris and Knapp provided a computational means to estimate plateau crop response functions, therefore preserving the biological relationship between nutrients and yields (Paris and Knapp).

In terms of crop physiology, crop production response to some input factor is observed when the factor is limiting. This concept is described as a plateau response function that can be summarized as follows:

(6) $$y = \min\,[f_1(X_1, u_1), f_2(X_2, u_2), \ldots, f_n(X_n, u_n)]$$

where $X_1, \ldots, X_n$ are inputs, $u_1, \ldots, u_n$ are disturbances associated with each input, and $f_1, \ldots, f_n$ are functions of responses to the certain input yields (Paris and Knapp).

For specifying the response function for a single variable input, model (6) can be written as:

(7) $$y = \min\,[f(X, u_X), M]$$

where M is a yield at the level where X is no longer a limiting factor. Here, M is a function of n-1 factors in (6) and represents a random variable related to factors that cannot be controlled in a given experiment. Relative to input X, M is a constant, and assuming the normality of disturbances around M, there should be observations above and below M.

Many experiments include treatments in which inputs under investigation are applied in excessive amounts. According to (7), yields from treatments with excess quantity of a controllable input are no longer a function of that input, because it is not limiting. Fitting a regular quadratic response function will associate the yields beyond the maximum point with X, whereas (7) suggests that after some threshold level of X, this factor is not limiting and does not affect the crop yield. Observations below M would suggest a negative effect of excess of X and observations above M would shift the maximum of a quadratic function rightward. These arguments explain the observed overestimation of optimal input levels when non-plateau functions were fitted (Frank, Beattie, and Embleton; Hall).

Hall used a simplified functional relationship between lime rates and yields of alfalfa, corn, and soybeans. Hall estimated the optimal values of lime application based on one year's data, and arbitrarily assumed the longevity of the lime effect as five years. Based on those assumptions he fitted several response functions (linear-plateau, logarithmic, power, quadratic-plateau, and square root) and concluded that plateau functions avoid extremely large optimal rates. His findings regarding specification of a functional form are consistent with those of Paris and Knapp and Frank, Beattie and Embleton.

Hall suggested that least squares estimation criteria would not prohibit large prediction errors at or near economic optimum if they would be offset by small errors elsewhere. Plateau functions disregard errors above the maximum, which results in smaller values of R^2, however, estimates of optimal rates become more reasonable and practical.

In this study, it is proposed that wheat grain yield response to soil pH is theoretically more likely to be correctly modeled as a plateau function than a non-plateau function. The hypothesis is that wheat grain response can be represented as a function of soil pH. At the same time, pH is a function of lime rate and time, which results in the specification:

$$Y_t = f(pH_0, LR, t) \tag{8}$$

where Y_t is wheat grain yield, pH_0 is initial soil pH, LR is lime rate and t is time. The dynamics of soil pH after liming is modeled by equations (4) and (5).

OPTIMAL ECONOMIC STRATEGIES OF LIMING

Single Application Model

Consider the objective function:

$$\max_{LR_1} \quad NPV = \sum_{t=1}^{T} \frac{p_G G_t - r_L LR_1 - CA_1}{(1+i)^t}, \tag{9}$$

where NPV is the present value of returns (\$/ac) net of the cost of lime application over T years, p_G is the price of wheat (\$/bu), G_t is the grain yield (bu/ac) at year t, r_L is the cost of lime (\$/ton) in terms of ECCE, and CA_1 is lime application cost in year 1. The choice variable is LR_1, lime application rates at year 1, in tons of ECCE/ac.

Define G_t as a function of soil pH at time t:

$$G_t = \min\left(a_0 + a_1 pH_t, \quad Y_{\max}\right), \tag{10}$$

where a_0 and a_1 and $Y_{\max}$ are the parameters of the linear response and plateau function.

The dynamics of soil pH after lime application include the decrease in soil pH when lime is not applied or an increase followed by a gradual decrease. The total effect will be:

$$pH_{t+1} = pH_t + \Delta pH_t + \Delta l_t, \tag{11}$$

where ΔpH_t is an annual soil pH change with no lime application and Δl_t is the change in soil pH after lime application. A modification of equations (4) and (5) results in:

$$\Delta pH_t = kpH_{t-1}\left(1 - \frac{pH_{t-1}}{pH_{crit}}\right), \tag{12}$$

and

$$\Delta l_t = bt^{\alpha} e^{\beta t}. \tag{13}$$

Multiple Application Model

In the previous section, economic optimization was modeled under the limiting assumption that only a single application of lime could be made at the beginning of a fixed time period. This single application model ignores several issues. It does not determine the optimal frequency of lime application. It also does not consider that the potential for applying additional lime in subsequent years may influence the optimal lime rate in the initial year. In this section a less restrictive model is formulated that enables simultaneous determination of the optimal application in year one and the optimal frequency and quantity of subsequent lime applications.

Now, the objective function is:

(14) $$\max_{LR_t} \quad NPV = \sum_{t=1}^{T} \frac{p_G G_t - r_L LR_t - CA_t}{(1+i)^t},$$

where the choice variables are LR_t, lime application rates at year t, in tons of ECCE/ac.

For a multiple application model the total effect of lime application accumulates effects of all previous applications. Depending on whether lime was applied in any particular year or not, Δl_t can be represented by equation:

(15) $$\Delta l_t = d_1 b\, t^\alpha e^{\beta t} + d_2 b_2 (t-1)^\alpha e^{\beta(t-1)} + \ldots + d_k b_k (t-k-1)^\alpha e^{\beta(t-k-1)} + \ldots + d_T b_T e^{\beta},$$

or,

(15a) $$\Delta l_t = \sum_{k=1}^{t} d_k b_k (t-k-1)^\alpha e^{\beta(t-k-1)},$$

$$t = 1, 2, \ldots, T,$$

$$k = 1, 2, \ldots, t.$$

The parameter d_k is a binary variable that equals one when the decision is to apply lime and zero otherwise.

MATERIALS AND METHODS

Estimation of Soil pH Change after Liming

Data from a long-term lime rate experiment were used to estimate changes in soil pH after liming and winter wheat grain yield response to soil pH[1]. Experimental plots were located in northwestern Oklahoma near Carrier. The observations of pH were taken from 1978 to 1987. The initial pH of the Pond Creek silt loam soil was 4.6. The lime rate that would increase soil pH to near neutrality (pH of 6.5 to 7.0) was estimated to be 4.8 tons of Effective Calcium Carbonate Equivalent (ECCE) lime per acre. Lime rate treatments used in the experiment were derivatives of this recommended rate and referred to as ¼X, ½X, X, and 2X, respectively. Treatments of 1.2, 2.4, 4.8, and 9.6 tons of ECCE lime per acre were replicated four times. All other nutrients, including nitrogen and phosphorus were applied at the same rates across all plots. The levels were sufficient to ensure that yield was not limited as a result of these nutrients. A total of 120 observations were used to estimate the long-term impact of a single lime application on soil pH change.

The carryover equation of liming based upon the characterization of pH change was estimated using equation (13). The parameters were estimated using the SAS NLIN procedure (SAS Version 6.12). To account for different lime rates, equation (5) was specified for parameter estimation as:

$$pH_{it} = pH_0 + \sum_{i=1}^{r} D_i b_i t^{\alpha} e^{\beta t}, \tag{16}$$

[1] Data were kindly provided by Dr. W. R. Raun, Department of Plant and Soil Sciences, Oklahoma State University.

where D_i is a dummy variable for the i^{th} lime rate (except control). Parameter estimates are reported in Table 2.1. The expected change in pH over time resulting from various levels of lime application is depicted in Figure 1. For this particular experiment, the carryover effect of the high lime rate continued throughout the ten-year study. Soil pH on the limed treatments had not declined to the initial level when the study was terminated.

Experimental data were not available to estimate parameters k and pH_{crit} for equation (12). Westerman observed a decrease in soil pH of 1.5 – 2.5 units over a period of more than 20 years. Assuming that the soil pH has changed by 2 –2.5 units within 25-30 years from an initial pH level of 6.5-7.0 and that the critical soil pH level cannot drop below pH 3.9 (the aluminum concentration reaches toxic levels at that level of soil pH), one can calibrate the parameter k as 0.03, and $pH_{crit} = 3.9$, which results in an approximate change of 1.5 pH units during the first 10 years and 0.5 units during the second 10 years.

Estimation of Grain Yield Response to Soil pH

Wheat (varieties Osage and TAM-101) grain yield data from the Carrier experiment were observed from 1979 to 1984. A total of 77 yield observations were used to estimate yield response to soil pH.

Since the lime effect on crops is spread over time, it is important to consider yield variability among years. Burt discussed the structure of the error terms for a nonlinear model specification. He pointed out the existence of large correlation among years in pooling long-term experiments. He suggested a multiplicative heteroskedasticity form of disturbances associated with year effects.

Since the lime data are repeated measures over time, a test of random factors such as time and lime rates was conducted. The hypothesis is that years may introduce additional variability into the data, which would reduce the efficiency of parameter estimates. If yield is specified as:

$$y_{it} = \mu + \lambda_i + \tau_t + \varepsilon_{it} \tag{17}$$

where y_{it} is yield from the i^{th} lime treatment in year t; λ_i is a fixed effect of the i^{th} lime rate; τ_t is a random effect of time, τ_t is distributed *iid* $N(0, \sigma_t^2)$; and ε_{it} is the error term, then y_{it} is iid $N(\mu + \lambda_i, \Sigma)$, where:

$$\Sigma = \begin{bmatrix} \sigma_{11}^2 + \sigma^2 & \cdots & \cdots & \cdots \\ \cdots & \sigma_{22}^2 + \sigma^2 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \sigma_{tt}^2 + \sigma^2 \end{bmatrix}. \tag{18}$$

Tests for the first-order autoregressive process and multiplicative and groupwise heteroskedasticity due to the time factor were conducted using the SAS 6.12 MIXED procedure.

Three different response models were estimated. A quadratic response model was estimated using the SAS 6.12 MIXED procedure using the REPEATED statement with the GROUP = REPLICATION × LIME option. Linear-plateau and quadratic-plateau models were estimated using the SAS 6.12 NLIN procedure (SAS Institute). The parameters of equation (10) were corrected for heteroskedasticity using the estimated generalized nonlinear least squares method. The following procedure was used. First, residuals from the nonlinear least squares estimation were obtained. Second, separate estimates of σ_t^2 were determined for each t. Third, the independent and dependent variables and the intercept and plateau parameters of the model were weighted by σ_t^2. These three steps were repeated until the variance of the residuals converged.

Parameter estimates for the wheat grain yield response to soil pH are reported in Table 2.2. Nonlinear estimates under the assumption of homoskedasticity of error terms, as well as maximum likelihood estimates of parameters with an assumption of groupwise heteroskedasticity are presented. The quadratic, linear-plateau and quadratic-plateau models were compared using the non-nested hypothesis *J*-test, where predicted values from one model were used as an explanatory variable in another model (Greene, p. 365). The results of the tests were inconclusive. No model was rejected in favor of an alternative based on the *J* - test.

Estimated values of the soil pH that produce maximum response of wheat grain yields are different for the models. As expected, the quadratic model resulted in the highest pH_{max}. Based upon the MLE quadratic model, a soil pH level of 6.16 would be required to obtain the maximum expected yield of 45.6 bushels per acre. The linear-plateau model estimated with weighted least squares indicates that a pH level of 5.26 is sufficient to obtain the maximum expected yield of 44 bushels per acre. Plateau functions produced estimates that were more rational from the agronomic point of view. The linear-plateau model was used for the following economic analysis.

Optimization Techniques for The Multiple Application Model

The specified model has a discontinuous, nonlinear objective function, which makes it difficult to solve using traditional optimization techniques that require twice-differentiable objective functions. Dynamic programming could be a possible approach to this specific problem; however, the curse of dimensionality due to the interaction of liming effects in different periods of time complicates the search over the domain of choice variables.

More recent optimization methods based on evolutionary algorithms have been developed for non-smooth, multi-dimensional, or discontinuous objective functions (Mayer, Belward and Burrage). Evolutionary algorithm is a term used to describe a class of computational models that attempt to mimic natural evolution to solve optimization problems. Several evolutionary methods have been proposed including genetic algorithms, evolutionary programming, and evolution strategies. Mayer, Belward and Burrage demonstrated that genetic algorithms escape local optima to find the global optimum in case of "ill-behaved" objective functions. They used various optimization methods, including quasi-Newton, direct search, genetic algorithm, and simulated annealing, to solve a problem with an objective function that consisted of the combination of 48 factors. They concluded that the last two methods performed better in search of the global optimum – 100% for simulated annealing, and 99.7% for genetic algorithm. The quasi-Newton method with randomly selected initial values converged to the optimum in only 31% of re-runs.

The genetic algorithm applies the basic concept of the theory of natural selection - survival of the fittest. The method converts independent variables in the feasible region into sets of randomly chosen starting points. The values of each set are converted into a binary string, called a "chromosome". Each "chromosome" represents a unique combination of the choice variables. A set of chromosomes forms a "parent" or initial population. The fitness of the population to the objective is estimated and those "chromosomes" are allowed to "cross-breed" based on their relative goodness of fit. The crossover, or "gene exchange," occurs randomly, and the fitness of the "children's" population is tested against the previous one. Successful combinations have more probability to "reproduce" and over time, the population converges to a single point or a number of near-optimal solutions (Mayer et al.).

The evolutionary algorithms use numerical optimization methods (Michalewicz). They use the concept of "mutation," or generating random numbers from a multivariate normal (μ, λ) where μ is a vector of initial randomly chosen independent variables, and λ represents a vector of self-adapting step sizes. The selection process replaces the least fit members from the population; the process goes on until λ converges to zero. A detailed description and comparison of algorithms can be found in Michalevicz (p. 164).

One shortcoming of the evolutionary techniques is that they do not have the concept of the optimal condition. The selection for the best solution is made only by testing against alternative solutions. These methods are more appropriate in situations when it is difficult or impossible to test the first order conditions.

Equation 13 was solved to determine optimal lime rates and optimal timing of lime applications using the standard evolutionary algorithm (Frontline Systems, Inc.) that is an add-in package to MS Excel. The spreadsheet was designed to accommodate the carryover effect from possible applications in years one to 25.

The Evolutionary Solver was run several times (4-6) to verify that the global solution was found. In some cases, after the first run, the model had chosen applications in consecutive years with a reasonable rate in year t and a small one at year $t+1$. In those cases, the binary variables were changed manually to remove consecutive applications and then the model was resolved.

Economics of Liming Based on a Single Application Model

Optimal lime rates were estimated for four levels of initial soil pH for lime application costs of $20 per ton of ECCE and a wheat price of $3 per bushel. The net present value of expected yields for a single lime application was calculated for a ten-year time horizon with a 7% discount rate. Economically optimal lime rates and the difference in the net present values of returns above the cost of liming compared with a no-lime strategy for each model are reported in Table 2.3. The difference in NPV was estimated by subtracting the NPV of yields obtained with the constant initial pH from the estimates of NPV. Results are shown for the linear-plateau model.

The benefits of lime application were positive for all models. Sensitivity tests showed that when the price of wheat is increased to $4.50 per bushel, the optimal lime rates increased no more than ten percent. For continuous wheat production in the region lime application is not economically feasible when the initial soil pH is above 5.2.

Implications of the Multiple Application Model

The Evolutionary Solver algorithm was used to estimate optimal lime rates for winter wheat grain production systems under conditions of low soil pH. When multiple applications are allowed, the number of dimensions in the dynamic model increases exponentially. When running the model, the algorithm did not always converge to a single solution. To restrict the search domain, additional constraints were added to the optimization problem. The first application rate was restricted to a range between zero and five tons per acre and consecutive applications were restricted to be equal to each other with the maximum rate of 1 ton per acre. The dynamics of the soil pH in response to multiple lime applications with the initial pH of 4.8 is presented in Figure 2.2.

The underlying result of the multiple application model is that when soil pH level is below the critical level (which is about 5.2 – 5.3 for wheat grain production), an initial application is needed to reach the critical level. The consecutive applications maintain the soil acidity near that level.

An attempt was made to design a dynamic programming (DP) model to select the optimal path of lime applications that maximizes the net present value. The DP solution could provide the global optimal solution and obtain the optimal path of lime applications. However, since the carryover effect can be traced for more than 10 years, the carryover equation became impracticably complex. Running a DP problem with just four dimensions took more than an hour of computer time, and it was very difficult to debug the program. The further implementation of the DP problem was abandoned.

Although the solutions provided by the Evolutionary Solver seem practical, they should be considered as “near-optimal solutions”. However, the solutions are expected to be more precise than machines used to apply lime.

The results show that given the initial soil pH level, the best strategy is to achieve a certain optimal soil acidity level, and maintain this level over time. The initial applications require substantial investments, especially when the initial soil acidity is very low, however, the results in Table 2.4 demonstrate that this strategy is economically optimal over time. For an initial pH of 4.8 the optimal strategy is to apply 1.3 tons per acre ECCE in year one followed by 0.6 tons ECCE per acre in years 10 and 17.

Table 2.4 shows that the maximum net present value of returns net of the cost of liming decreases with the decrease in the initial soil pH. One unit of soil acidity (from 4.1 to 5.2) was "worth" about $100 net present value per acre in terms of grain production. This suggests that land appraisers should consider the soil pH when valuing land use to produce wheat in Oklahoma.

CONCLUSIONS

It is important to account for the residual effect of liming when estimating economically optimal lime rates. In this experiment, the carryover effect of one-time lime application lasted for over ten years. The approach used in this study captures beneficial effects of liming over time for this period of time.

One caveat of this study is that conditions that determine soil pH are highly specific for different soil types. Parameters α and β in the model used to estimate soil pH change over time may be different for different soils under different climatic conditions, which is a common problem for studies of carryover effects of fertilizers.

The results showed that the optimal input rates were greatly affected by the choice of the crop response model. The difference between the optimal rates from the quadratic model and the plateau models was more than one ton of lime per acre. Critical pH levels derived from plateau models appear to be consistent with physiological requirements of wheat.

Continuous representation of the carryover effect of lime application allows seeing the pattern of lime application strategies. Depending on the initial soil acidity level, the model determined an initial optimal application level and the timing and level of follow-up applications.

Finding the optimal solution for an applied problem can be achieved either through simplifying a system to the level of well-behaved models and using conventional analytical optimization methods or attempting to find the optimal solution to the complex system through numerical optimization techniques. The optimization strategies based on genetic algorithms offer practical tools for non-smooth-discontinuous simulation problems. This approach can be an appropriate alternative to dynamic programming setting, especially when a problem suffers from the curse of dimensionality.

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Table 2.1. Parameter Estimates of Equation (16) Used to Model pH Change over Time in Response to Lime Application.

Parameters	Control	Lime Rates (X =4.8 ton ECCE /ac)			
		1/4 X	1/2 X	X	2 X
b	-	0.3456	0.5582	0.9440	1.0671
	-	(12.44)[a]	(14.16)	(16.23)	(16.70)
pH_0	4.9510				
	(49.48)[a]				
α	0.7660				
	(4.28)				
β	-0.1098				
	(-2.16)				
Predicted pH_{max}[b]	-	0.71	1.12	1.94	2.11

[a] Values in parentheses are asymptotic t-statistics.

[b] Maximum increase in pH due to liming as compared with control.

Table 2.2. Parameter Estimates of Wheat Grain Response to Soil pH.

	Quadratic		Linear - Plateau		Quadratic - Plateau	
Parameters	OLS	MLE	NLS	Weighted NLS	NLS	Weighted NLS
Intercept	-74.51	-72.56	0.80	-5.99	-149.6	-160.0
	(-1.80)	(-2.33)	(0.05)	(9.63)	(-1.08)	(1.46)
pH	39.46	38.40	8.11	9.50	69.13	73.00
	(2.69	(3.46)	(2.57)	(18.31)	(1.26)	(1.68)
pH^2	-3.26	-3.20	-	-	-6.17	-6.51
	(-2.56)	(-3.21)	-	-	(-1.15)	(-1.52)
Y^b_{max}	44.76	45.61	43.62	44.00	44.06	44.65
	-	-	(18.94)	(124.3)	-	-
Pred. PH_{max}	6.05	6.16	5.28	5.26	5.60	5.61

[a] Values in parentheses are asymptotic t-statistics.

[b] Y_{max} for the quadratic model is reported as a maximum point of a quadratic function.

Table 2.3. Economically Optimal Lime Rates and Expected Present Values of Returns Net of the Cost of Liming (Based on the Linear-Plateau Response Model and of a Ten-Year Time Horizon).

Initial Soil PH	Optimal Lime Rates (tons ECCE /ac)	Expected NPV[a] ($/ac)
4.1	2.75	154
4.4	1.82	118
4.7	1.17	81
5.0	0.54	38

[a] NPV is the returns from the increase in wheat yield attributed to lime application minus the costs of lime application with a 7% discount rate.

Table 2.4. Economically Optimal Lime Rates and Expected Present Values of Returns Net of the Cost of Liming for a Multiple Application Model (Based on the Linear-Plateau Response Model and a 25 – Year Time Horizon).

Strategy	Net present value, $ / acre Initial soil pH 4.1	4.4	4.8	5.2
No lime applied	$1,154	$1,230	$1,329	$1,424
Multiple applications	$1,429	$1,464	$1,502	$1,528
First application (t/ac)	2.85	2.25	1.30	0.59
Followed applications (t/ac)	0.30	0.48	0.60	0.45
Years applied	1,10,13,16,19, 22,25	1,11,16,21	1, 10, 17	1,8,14,20

Figure 2.1. Soil pH Response over Time in Response to Lime Application.

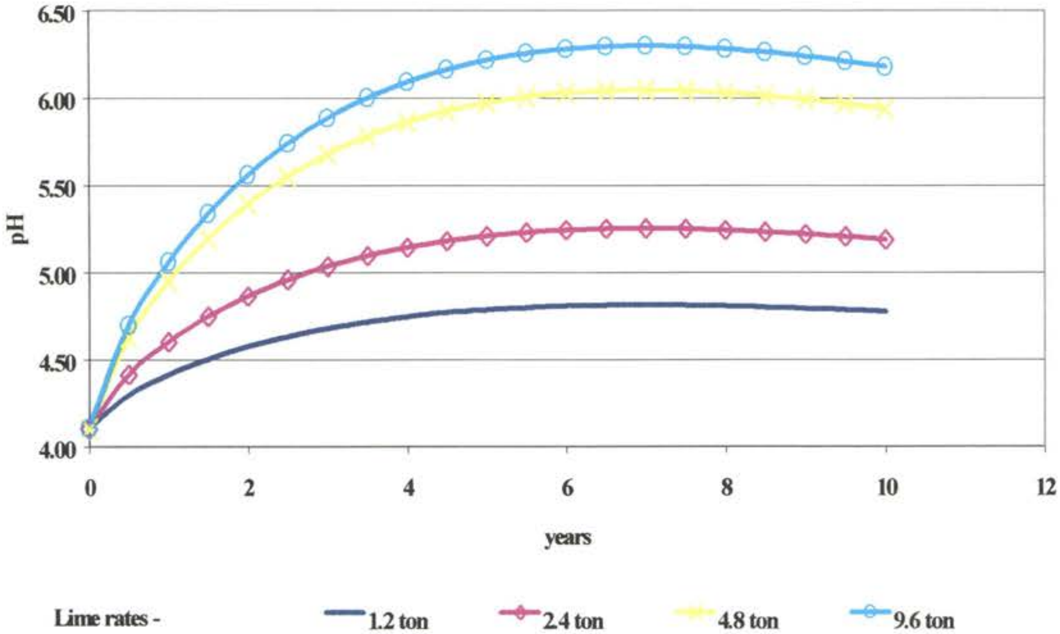
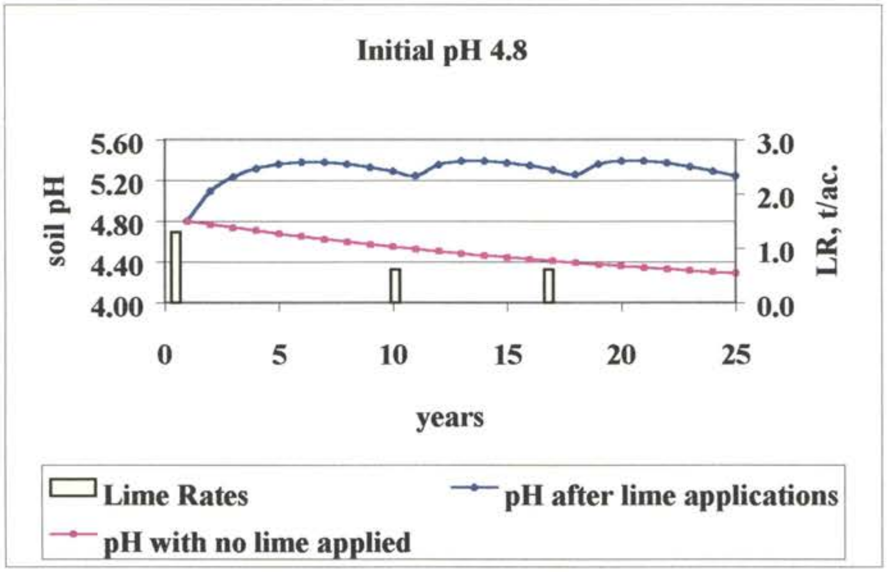


Figure 2.2. Soil pH Response over Time in Response to Multiple Lime Applications.



CHAPTER III

ECONOMIC STRATEGIES OF SOIL pH MANAGEMENT IN DUAL - PURPOSE WINTER WHEAT PRODUCTION

ABSTRACT

This study compares several strategies of soil acidity management in winter wheat production including application of agricultural lime, phosphate banding in the seed furrow and the use of cultivars with higher tolerance to soil acidity. The economics of the strategies were compared for tolerant and susceptible wheat varieties. Lime application is the preferable choice when the cost of liming is discounted over a period of five years. Tolerant varieties are more profitable than susceptible varieties if no lime is applied. The conditions of crop sharing contracts are considered: when a variable input has a multiyear effect, the optimal structure of revenue and cost shares changes.

INTRODUCTION

On average, 6.8 million acres have been planted annually to winter wheat in Oklahoma, and 5.1 million acres were harvested for grain production, which is about 50 percent of the total Oklahoma cropland acres (Oklahoma Agricultural Statistics, 1998). The area of intensive wheat production includes a belt from north to south through the west central part of Oklahoma. More than three-fourths of the total wheat acreage is concentrated in 20 counties in the North Central, Central, West Central, Southwest, and the Panhandle crop reporting districts.

The area of intensive monocropped wheat production is subject to the process of soil acidification. Soils of the wheat producing regions were formed under prairie grasses and were not acidic. Long-term changes in soil quality, and particularly in soil pH, can be illustrated with data from the US Soil Survey for selected counties of the Oklahoma wheat belt. Among other soil characteristics, soil surveys report the range of pH reaction for each soil map unit. The area of the soils where the lower limit of the pH range belonged to the moderately acid category expressed as a percent to the total area is presented in Table 3.1. The survey data show that soil acidity was not a problem in Oklahoma in the 1960s. However, surveys conducted in the 1970s and 80s found more occurrences of acidic soils. Spatially, the north-central and central regions were affected more than the southern and Panhandle regions (Figure 1).

There are several reasons why cropped soils become acidic over time. One of them is the removal of certain nutrients from fields with harvested crops. On average, a wheat grain harvest of 45 bushels removes about 63 lb of potassium, 15 lb of calcium and 27 lb of magnesium, which are the base soil composites (Wolf). Unnoticed in one or two years, the effect of nutrient removal with harvest accumulates with time. Application of acid-forming fertilizers, such as anhydrous ammonia, aqueous ammonia, ammonium nitrate, diammonium phosphate or urea, intensifies the reduction in soil pH (Wolf, p.173). Westerman reported an increase in the soil acidity levels in Oklahoma as 1.5-2.5 pH units during the period of more than 30 years. Westerman considered the ratio of base removal to nitrogen as the tool to estimate the contribution of a crop to soil acidification. It has been estimated that 100 lb of diammonium phosphate would require 70 lb of pure calcium carbonate to neutralize its acidity (Westerman; Wolf).

STRATEGIES TO CONTROL SOIL ACIDITY PROBLEMS

Lime application is a common method to control soil acidity. Lime materials contain calcium and magnesium cations that neutralize soil acidity. The neutralizing value of liming materials depends on the concentration of calcium and magnesium and the size of lime particles. The finer the lime materials are, the shorter the period of pH adjustment. The relative efficiency of lime materials is expressed in terms of the effective calcium carbonate equivalent (ECCE). ECCE is a measure of the ability of various lime composites to change soil pH relative to that of pure calcium carbonate adjusted for the particle size. In 1998, Oklahoma farmers spent an estimated \$9.5 million on lime materials. They applied approximately 400,000 tons of lime (Table 3.2).

Wheat cultivars vary in the degree of their tolerance to acid soils. Replacement of less tolerant cultivars by varieties with high tolerance to soil acidity can be an alternative to lime application, especially, when the expected yield of the tolerant cultivar exceeds that of the susceptible cultivar on acid soils and when the cost of liming exceeds the expected benefits (Heylar). In Oklahoma, acid-tolerant cultivars, such as Jagger (29 % of seeded acres in 1998) and 2137 (9.2%), became popular varieties (Oklahoma Agricultural Statistics). However, there have been no studies to compare the economics of using tolerant varieties rather than lime application.

Yet another practice to alleviate negative impact of soil acidity on wheat growth is to remove aluminum toxicity by applying phosphate fertilizers. Experimental data from dual-purpose wheat production trials demonstrated that phosphate banding in the seed furrow increased forage production (Boman et al.). Grain response to phosphorus banding application was observed only up to 30 lb P_2O_5 per acre. Boman et al. concluded that the yield response to lime was more likely if the soil did not have an adequate supply of phosphorus.

The research question for this study is whether the choice of wheat variety or application of phosphorus fertilizers can be an economical alternative to lime application in low pH soils continuously cropped to wheat. These alternatives do not remove the acidity problem, however, they may be preferable when a producer rents land on a short-term lease contract. On the other hand, a landowner may wish to consider the long-term impact of each strategy.

Objectives of the study

The objectives of this study are to determine the economically optimal winter wheat production strategy under conditions of low soil pH. First, it is necessary to characterize wheat forage and grain yield response to alternative production practices, including liming, phosphate banding and choice of varieties tolerant to low soil pH. Second, expected net returns must be determined and compared to identify the optimal strategy depending upon land-tenure conditions.

PHYSICAL RELATIONSHIPS BETWEEN SOIL ACIDITY MANAGEMENT STRATEGIES AND WHEAT FORAGE AND GRAIN YIELDS

Lime Rate Trial

An experiment with various lime rates was conducted on a wheat-producing farm near Garber, Oklahoma. The initially acidic soil (Tabler silt loam, fine, smectitic, thermic Udertic Agriustoll, initial pH of 4.5) was limed in July of 1997. Initial soil chemical characteristics are reported in Table 3.3. Lime rates were proportional to the rate deemed necessary to neutralize soil acidity up to pH 6.5. This was equivalent to 2.5 tons of ECCE per acre for the site. Lime treatment rates were $^1/_{16}$, $^1/_8$, $^1/_4$, $^1/_2$, 1, and 1 $^1/_2$ of the recommended rate applied in July 1997. Lime rates were randomly assigned to plots of 18 by 10 feet (6 by3 m) size. The plots were seeded with the variety Tonkawa, which is considered sensitive to low soil pH (Krenzer). The seeding rate was 120 lb per acre. Forage yields were collected by hand clipping once in the fall and once in late winter prior to first hollow stem. Grain yield data were collected at harvest in June. Each treatment was replicated four times in 1997 and 1998. The lime trial experiment near Garber was designed to establish production relationships between lime application and wheat forage and grain yields.

The analysis of variance and the treatment means for forage and grain yields are presented in Tables 3.4 and 3.5. Significant year by lime rate interaction for grain yields prevents considering two-year averages of grain yields in interpretation of the lime effect. Rather, annual average grain yield for each lime treatment is reported. Two-year averages were reported for forage data, since there was no significant interaction between lime rate and year effects.

In the first year after lime application, a significant increase in grain yield was observed only at the lime rate of 2.5 tons per acre. During the second year, control grain yields were lower than lime treatments, excluding the highest lime rates. Grain yields were significantly different from control at lime rates of 0.156 ($^1/_{32}$ X) tons and 0.625 ($^1/_8$ X) tons of ECCE per acre.

Forage yields averaged over two years showed positive response to liming. It is unclear whether the response curve reached its maximum at a rate equal to 2.5 tons per acre. Quadratic, linear – plateau, and quadratic – plateau models were fitted to forage and grain yield data. Model parameters for forage response to lime rates are presented in Table 3.6. For all models, slope parameters are significant at the 0.01 level of significance. The linear – plateau model indicates that the forage yield plateau is achieved with application of 1.38 tons per acre (0.55 X). There were no significant parameters for grain yield response to lime rate in any of three models.

Winter Wheat Variety Trials

Variety Trial

Winter wheat variety trials were designed to determine how cultivars with various degrees of tolerance to low soil pH respond to lime and phosphate applications. The experiment was conducted on a farm located near Eakly, Oklahoma. The initial soil acidity level was 4.5 pH units (Table 3.7).

Commercial wheat varieties with different degrees of tolerance to soil acidity (Table 3.8) were evaluated in terms of their response to the application of lime and phosphorus. A complete factorial arrangement of lime (0 and 1.25 tons of ECCE per acre) and phosphorus (0 and 130 lb of diammonium phosphate (DAP), 18-46-0, applied in the seed furrow) treatments were distributed in a split-block design. In this experiment, DAP rather than triple superphosphate (0-46-0) was used as a phosphorus source for several reasons. First it is the most common source used by Oklahoma wheat producers. Second, the average price per ton of DAP \$264/ton is comparable with \$255/ton for triple superphosphate. Lime was applied in July 1997 and DAP was applied in the seed furrow. Nitrogen fertilizer (46-0-0) was applied at the rate of 120 lb per acre. The wheat varieties were randomly assigned to each treatment combination in three replications. Due to the fact that several varieties were not seeded in both years, only data for 13 varieties were used in the analysis.

The question of interest was to estimate the differences in variety response to lime and DAP treatments. Due to the large number of varieties relative to the degrees of freedom it was decided to group varieties into two categories based on their index of tolerance to low pH. Cultivars with index 1 and 2 were placed into the tolerant group and varieties with index 3 and 4 were categorized as susceptible.

The experimental data were analyzed using the PROC MIXED of SAS 8.0. The model has lime and DAP treatments as fixed effects with replication×category×year as a random component. Grouping the data into two variety categories allowed for detection of effects of experimental treatments.

Treatment means for forage and grain data grouped by tolerance index are shown in Table 3.9. Simple effects of lime and DAP applications are shown in Table 3.10. The susceptible category showed increase in forage and grain yields when either lime or DAP was applied, or when both treatments were used. For the tolerant category, forage yields had similar response, however grain yields did not respond to lime application on either DAP rate. Treatments with 130 lb DAP applied were significantly different from control.

From a physical production point of view, susceptible varieties did show a slight grain yield response to lime and did not show the response to DAP. Varieties in the tolerant category responded to DAP application on the unlimed plots. Forage yield increased with either each treatment separately, or with their combinations. The effect of DAP was greater than that of lime application for both categories. However, this result may be explained by additional nitrogen applied (23 lb/ac) with the high DAP rate.

<u>Lime – DAP Application Trial</u>

At the same location, the similar experimental design included additional DAP treatments to determine whether the application method affects wheat yield response to DAP. The DAP treatments were as follows: control, 65 lb DAP applied in the seed furrow, 130 lb DAP applied in the seed furrow, and 130 lb applied broadcast. Two winter wheat varieties - Tonkawa (susceptible) and 2137 (tolerant), were seeded in three replications on each lime by DAP combination. Two years of forage and grain yield data were generated.

Treatment means for forage and grain yields are shown in Table 3.11. Tests of simple effects of lime and DAP treatments are shown in Table 3.12. From Table 3.12, it is evident that lime has a significant effect on forage production of the susceptible variety Tonkawa when DAP is not applied, or when DAP is broadcast. Application of DAP in the seed furrow at 65 or 130 lb/ac rate masked the lime effect. The DAP effect was significant with or without lime application. On the other hand, grain yield of the Tonkawa variety was affected by lime at the rate of 65 lb DAP/ac applied in the seed furrow or 130 lb/ac applied broadcast.

Variety 2137 was not affected by liming in terms of forage production when DAP was not applied, applied at the rate of 130 lb DAP/ac, or 130 lb/ac broadcast. Lime application in combination with DAP application improved grain yields for this variety.

ECONOMIC ANALYSIS OF SOIL ACIDITY MANAGEMENT STRATEGIES

Estimation of Expected Returns

In production economics, the general idea to find an optimal level of input factors is to maximize profits, defined as the difference between output revenues and the total factor costs, using levels of variable factors as choice variables. Since the total factor costs, at least in theory, are easily separated into fixed and variable costs, and since the fixed costs are often assumed to be constant, only variable costs are relevant for the analysis. However, in interpretation of results obtained at the point where conditions of optimality hold, it is not technically correct to use the term "profits" if the fixed costs have not been included into the analysis. Rather, the results would be better described by the term "returns" to specified fixed factors, or "returns" net of specified variable costs. In the following sections the term "returns" will be used to specify the difference between output revenues and variable costs of production. Applied to the experiments described in previous sections, it will mean, revenue from wheat grain and wheat forage minus the cost of lime, DAP, DAP application, and harvesting. It is assumed that the seed cost of tolerant and susceptible varieties is the same. It is also assumed that no additional costs are incurred when DAP is applied with a grain drill.

The expected returns from a multi-product production, π, may be specified as in equation (1):

$$(1) \qquad E[\pi] = \sum_{i}^{n} p_i E[Y_i(X_1,...,X_m] - \sum_{j}^{m} r_j X_j - E[C(X_1,...,X_m;Y_1,...,Y_n)],$$

where Y_i is the level of the i^{th} output, with its corresponding price per unit, p_i, X_j is the level of the j^{th} input with per unit cost, r_j, and C is a cost function that reflects cost/price differences in various levels of input and/or output. The necessity to separate C from the usual specification of variable factor costs is due to the fact that assumptions of smoothness and continuity of production functions are not always plausible. For example, an extra charge for each bushel of wheat harvested above a specific base level, or addition of application costs to the cost of fertilizer, would bring discontinuity into the structure of the cost function.

When relationships between outputs and production factors are not well established as, for example, in the case of nitrogen and phosphorus fertilizers, the expectations are taken around the output functions. To simplify the analysis, product prices and factor costs are assumed to be constant. To conduct the economic analysis of the experiments described in the previous section, the expected returns were estimated as defined in equation (1).

Lime Rate Trial at Garber

In dual-purpose wheat production in acid soils, the problem of determining an optimal lime rate represents maximization of net returns with two outputs (fall – winter forage and grain) and one nonallocable factor (lime). For a nonallocable factor to be at the economically optimal level, the sum of the values of marginal physical productivity of the factor used to produce both forage and grain must be equal to the price of the factor (Beattie and Taylor, p. 219). The problem of determining optimal lime rates is complicated due to strong carryover effect of lime application.

The expected net returns from the treatment plots of the Garber experiment can be expressed as:

$$E[\pi_l] = p_G E[G_l] + p_F E[F_l] - r_l LIME_l - E[C(G_l, F_l)], \tag{2}$$

where π_l, G_l and F_l are net returns, grain and forage yields from plots with lth level of lime. Output prices, p_G and p_F were assumed to be constant ($3.00 per bushel of wheat, and $0.02 per lb of forage, respectively). Price of lime, r_l, was taken as $20 per ton of ECCE. Other costs, C, associated with production were specified as a function of outputs due to the differences in harvesting costs, application costs, and compensation for nitrogen removal with forage and grain. The extra charge for each bushel harvested above 20 bu/ac was equal to $ 0.13. Each 1,000 lb of wheat forage removes 30 lb of nitrogen. Similarly, each bushel of wheat removes 2 lb of nitrogen. The differences in nitrogen removal across treatments were compensated by including the shadow costs of nitrogen fertilizers.

Since a grain yield response function could not be established from the given data set, the expected net returns for each experimental plot were estimated using a Monte

Carlo integration technique. The distribution of yields was assumed to follow a normal distribution. Normality was not rejected at the 5 % confidence level using the Kolmogorov's goodness of fit test. The correlation between forage and grain yields was found to be insignificant. Therefore, it was assumed that distributions of forage and grain yields were independent.

For estimation purposes, the expected profits can be expressed as:

$$(3) \qquad E[\pi_{lv}] = \iint p_F f(F_{lv}) + p_G g(G_{lv}) - C(F_{lv}, G_{lv}) dF_{lv} dG_{lv} ,$$

where $f(\cdot)$ and $g(\cdot)$ are normal distributions of forage and grain yields, respectively, and $C(\cdot)$ represents the cost function. To simplify the analysis, expected net returns, rather expected utilities were estimated with the underlying assumption of risk neutrality.

The values of the integral in equation (3) were estimated by generating 1000 observations of grain and forage yields for each combination of treatment plots. The simulation was performed using a Visual Basic for Applications (VBA) macro in MS Excel 97.

Winter Wheat Variety Trials at Eakly

The variety and lime – DAP application trial at Eakly included two nonallocable factors in the variable factor cost function. Equation (2) is modified by including a DAP treatment:

$$(4) \qquad E[\pi_{flv}] = p_G E[G_{flv}] + p_F E[F_{flv}] - r_f DAP_f - r_l LIME_l - E[C(G_{flv}, F_{flv})],$$

where π_{flv} is net returns from a plot with fth level of DAP, lth level of lime and vth variety planted (either tolerant or susceptible). Price of DAP, r_f, and lime, was \$0.13 per lb of

DAP. In the lime – DAP trial, an additional charge for broadcast application of DAP, \$2.50/ac was included in the cost function.

Expected net returns for each treatment combination were estimated using the same technique as in the previous section.

RESULTS AND DISCUSSION

Lime Rate Trial at Garber

Since the grain yields did not show a pronounced response to lime rates, the economic analysis was performed on a treatment level rather than finding the optimal solution based on established response functions. Expected net returns for each lime treatment are presented in Table 3.13.

Since the optimal level of factor use occurs at the level where the marginal value of product is equal to the marginal factor cost, the optimal level of lime rates will depend on whether the cost of lime is discounted. When the cost of lime must be recovered in the first year of production, the optimal rates fall between 0.16 and 0.32 tons per acre, with the highest returns of \$130/ac and deviations of 13 and 20, respectively. Discounting lime expenses for two years did not change the optimal lime rate. If discounted for five years, the highest net returns (\$137/ac) were obtained by applying 2.5 tons per acre. However, this is only \$1 per acre more than the expected returns of \$136 from application of 0.32 tons per acre. The 0.32 tons per acre rate shows less variability than 2.5 tons per acre. Applying lime at the rate 3.75 tons per acre led to substantial decrease in net returns.

Optimal lime rates reported here are consistent with the results presented in chapter II. There, optimal lime rates for soils with initial pH 4.4 were 2.25 tons ECCE/ac, considering that lime costs can be discounted over five years.

Lime – DAP Trial

The agronomic objective of this experiment was to determine forage and grain yield responses to combinations of lime and DAP applications for both acid tolerant and susceptible varieties. Also, the effect of an application method was considered by comparing seed furrow versus broadcast application of DAP fertilizer. The purpose of the economic analysis is to determine the economic consequences of each treatment for two categories of wheat varieties.

Having only few reference points to build a surface response model of lime and DAP inputs, expected net returns from each combination of treatments were compared using their means and standard deviations (Table 3.14). Expected net returns for plots with variety 2137 were higher than expected returns for the susceptible cultivar, Tonkawa, for all lime by DAP treatments. The differences in returns between the two varieties from similar DAP treatments with no lime applied ranged from \$8 to \$30 per acre. At the same time, the variability of expected returns for unlimed treatments was lower for the Tonkawa cultivar.

When lime was not applied, the susceptible cultivar required more DAP application than the tolerant one. The highest expected returns (\$120/ac) for Tonkawa was obtained at the rate of 130 lb DAP per acre applied in the seed furrow. Variety 2137 required only half of that rate to produce \$133/ac.

Usage of high rates of phosphate fertilizers or varieties that can withstand elevated levels of aluminum in soil does not eliminate the soil acidity. In contrast, lime applied in adequate quantities alleviates the problem of aluminum toxicity for several years. It is more appropriate to estimate economic benefits of lime application by spreading the costs of liming over the period when it is still effective. Hall and Bongiovani and Lowenberg-DeBoer used the period of five years to estimate the net present value of lime application. Here, instead of calculating the net present value, the cost of lime application ($25/ac) was discounted for the period of two and five years. Expected revenues and costs other than the cost of lime were not discounted, so the expenses on lime represent amortized loan payments over two and five years.

Lime is a costly input, however its effect lasts for several years. When the discounted for five years cost of lime application was included into the cost function, the difference in returns between unlimed and limed treatments was as high as $22/ac for Tonkawa and $13/ac for 2137.

Table 3.14 shows that lime application can be paid off within two years in combination with 65 lb DAP/ac. It appears that the choice of tolerant cultivar along with phosphate banded in seed furrow is a good alternative to liming. However, if the cost of liming can be spread over more than two years, the combination of 1.25 ton of ECCE per acre and 65 lb DAP in the seed furrow or 130 lb DAP broadcast becomes preferable. The combination of 130 lb DAP/ac (furrow and broadcast) with lime application decreased net returns for both varieties.

Winter Wheat Variety Trial

The effect of a combination of lime and DAP treatments on winter wheat forage and grain yields for various wheat cultivars was studied in this experiment conducted at Eakly. The cultivars were grouped based on their index of tolerance to soil acidity into tolerant, index 1 and 2, and susceptible, index 3 and 4, categories (see Table 3.8). The expected net returns and standard deviations of returns estimated using the same method as in the previous sections are reported in Table 3.15.

When lime was not applied, there was a positive marginal effect of DAP application for the susceptible group. Although the lime application improved forage production and increase grain yields, the marginal effect of liming was negative, because forage yield marginal value was less than lime cost.

Discounting the cost of lime application over five years makes lime application a more attractive method to manage soil acidity for both groups. When lime cost was discounted over five years, the limed treatments without DAP application had the highest expected returns ($125 and $124 for susceptible and tolerant categories, respectively). The combination of both treatments, liming and DAP decreased expected returns in all scenarios.

CROP SHARE LEASING MODEL

Farms are operated under various land ownership and tenure conditions. Land tenure can be in a form of cash renting or crop share renting. Crop share tenure can be also subdivided into two categories depending upon whether a landowner shares input costs with a tenant.

Conditions for optimal fertilizer levels in crop production from a position of an owner-operator are well defined (Heady; Kennedy). Under the assumption of the existence of a twice-differentiable production function, which represents the diminishing marginal productivity of inputs, the profit maximizing condition occurs at the level of input, X, where the marginal product of fertilizer equals the ratio of the cost of fertilizer, r, and the crop price, p:

$$\frac{\partial Y(X)}{\partial X} = \frac{r}{p}. \tag{5}$$

Solving (5) for X, one can obtain the efficient level of input use, X^*, given a production function $Y(X)$. This is the case where the producer is the landowner.

The crop share leasing agreement implies that the landowner receives a certain percent of farm revenues produced by a tenant. At the same time, the landowner may share input costs such as cost of fertilizers, pesticides, or long-term investments in soil amelioration or irrigation. One difference between cash rent and crop share leasing contracts is that with the latter landowners are subject to crop price and yield risk.

Following the analysis described by Heady, consider the case where the producer is a tenant who shares the revenues from the crop sale with the landowner. Define α ($0 \leq \alpha \leq 1$) as a percent of revenues, which the tenant must pay to the owner as a rent. The tenant's profit function given α and prices, p and r, is:

$$\pi_T(X \mid \alpha, p, r) = (1-\alpha)pY(X) - rX. \tag{6}$$

The choice variable is the amount of variable inputs, X, such as fertilizers. Differentiating (6) with respect to X, the first order condition is:

$$\frac{\partial \pi_T}{\partial X} = (1-\alpha)p\frac{\partial Y(X)}{\partial X} - r = 0. \tag{7}$$

The tenant chooses a level of X_1 that maximizes the profit, π_T:

(8) $$\frac{\partial Y(X)}{\partial X} = \frac{r}{(1-\alpha)p}.$$

In this case the cost-to-price ratio is greater than r/p, which is the result of profit maximization for the owner-operator. The optimal level of X_1 is lower than X^* obtained in (5).

The landowner's profit function is equal to the revenue share and does not affect the production level:

(9) $$\pi_L = \alpha p Y(X).$$

Since X_1 is less than X^*, the sum of π_T and π_L is less than π for the owner operator.

Now, consider the situation in which the land owner covers a part of the tenant's variable costs. Define γ ($0 \leq \gamma \leq 1$) as a proportion of the variable cost paid by the owner. Then, the net profit, π_T, of a tenant can be expressed by the equation:

(10) $$\pi_T(X \mid \alpha, \gamma, p, r) = (1-\alpha)pY(X) - (1-\gamma)rX.$$

The landowner's profit in this case is:

(11) $$\pi_L = \alpha p Y(X) - \gamma r X.$$

The optimal level of X that maximizes the tenant's profit can be found from:

(12) $$\frac{\partial Y(X)}{\partial X} = \frac{(1-\gamma)}{(1-\alpha)}\frac{r}{p}.$$

The cost sharing increases the optimal level of the input use. When the landowner and the tenant share revenues in the same proportion as they share variable input costs (α equals γ), the condition of (12) is equal to the cost-to-price ratio, r/p, which is the optimal solution for the producer who also owns the land.

When inputs have a long-term impact on production, the input costs can be amortized over a period more than one year. In the case of lime application, the residual effect of applying lime lasts for several years depending on soil type, lime characteristics and the application rate. This does not affect the cost structure of tenants on the short-term contract. In contrast, the landowner's investment in the input will result in improved yields during following years. Therefore, for the landowner, the cost of lime application can be discounted over the time of the residual effect.

Define d as the discounting factor for the input costs given the interest rate, i, and the time, t, of the residual effect of the input factor. It can be represented as the ratio of the payment on an amortized loan over time t to the cost of the lime input. Then, the landowner's profit function in (11) will change to:

(13) $$\pi_L = \alpha p Y(X) - \gamma d r X .$$

For the landowner, the profit maximizing level of X is:

(14) $$\frac{\partial \pi_L}{\partial X} = \alpha p \frac{\partial Y(X)}{\partial X} - \gamma d r = 0 .$$

(15) $$\frac{\partial Y(X)}{\partial X} = \frac{\gamma d}{\alpha} \frac{r}{p} .$$

Combining (12) and (15), the optimal share of lime input costs, γ^* is:

(16) $$\gamma^* = \frac{\alpha}{\alpha + d - \alpha d} .$$

When input costs can be distributed over several years ($0 < d < 1$) then γ^* will be greater than α. The optimal share, γ^* is equal to α when the discounting factor is 1, in the case of no carryover. When d is zero, the variable input is virtually free for a landowner and his share is equal to 100 percent.

The cash lease agreements can be considered as a particular case similar to that of an owner operator. The rent payment is a part of tenant's fixed costs and should not affect the choice of optimal levels of variable inputs. The landowner is indifferent to the tenant's choice of the input levels, since the rent is fixed. However, a landowner may charge a higher cash rent if land is more productive as the result of a higher soil pH.

Implications of Land Tenure Conditions on Liming Strategy

The type of tenure affects the choice of a profit maximizing level of factor use. Profit maximizing conditions reflected in equation (1) are valid for the case of an owner operator. Now consider how the various conditions of land tenure affect the strategy of soil acidity management for tenants and landowners.

Consider a tenant who rents land with soil pH 5.0. What strategy could we recommend to that tenant under different types of land tenure?

A simplified presentation of the preferred economic strategies based on the data of the lime – DAP trial is displayed in Table 3.16. The strategies were selected as the highest value of net returns for the tenant under various conditions of land tenure.

Cash Lease Agreement

Suppose that a typical tenure agreement is a cash lease where tenant supplies all variable inputs. It is not in the landowner's interest to interfere in production, unless the land productivity is reflected in the rent. In this case, a tenant on a single year cash lease contract would prefer to plant the tolerant wheat cultivar (2137) and apply 65 lb DAP/ac in the seed furrow to reduce the negative impact of pH (Table 3.16).

Crop Share Lease Agreement

Now, consider the same situation that was described above with crop share lease agreement. Assume that the landowner's share is one-third of crop revenues. If the landowner does not share the input costs, the tenant's strategy would be to apply less inputs and the preferred choice would be 65 lb DAP in the seed furrow in combination with a tolerant variety (Table 3.16).

When the landowner shares input costs, then the optimal input cost share will be γ^* from equation (16). The discounting coefficient d would be equal to 6.10/(1.25*20) = 0.24. Then, the optimal landowner's share of the input cost that have a carryover effect according to equation (16) is 0.33/(0.33 + 0.24 – 0.33*0.24) = 0.67, or two-thirds of the cost of lime must be covered by a landowner. In this case, lime application becomes an attractive option to the tenant. The tenant chooses 1.25 tons ECCE/ac and 65 lb DAP/ac in the seed furrow. The tenant's returns are $78/ac and landowner's, $61/ac, and the sum of the net returns is $139/ac. When a landowner chooses to cover cost of lime application (δ =1 in Table 3.16) the tenant is better off by $8/ac, but the landowner's net returns are lower by $2/ac. Evidently the landowner may increase the land rent to compensate for the lime cost.

CONCLUSIONS

Three strategies of managing low soil pH, including lime application, DAP banding and variety choice, have been studied in combination. Winter wheat forage yields positively responded to lime applications up to the rate of 2.5 tons ECCE/ac on the soil with initial soil pH of 4.5. High year-to-year variability in grain yields did not allow detecting any significant grain yield response to liming in these short-term experiments.

On soils with low pH (4.5), high yields at the lime rate of 2.5 tons ECCE/ac were not economically reasonable when the cost of lime had to be recovered during the year of application. Discounting lime costs over five years makes application of 2.5 tons ECCE/ac a preferable choice.

In the experiments with susceptible and tolerant varieties planted on plots treated with either lime, DAP or the combination of both, grain yield of susceptible varieties responded to lime, whereas for tolerant varieties, it did not. Grain and forage yields responded better to 130 lb DAP/ac than to 1.25 tons of ECCE/ac on the soil with initial pH of 5.0.

Tolerant varieties produced higher returns than susceptible cultivars on unlimed treatments. When lime was applied, there was little difference between the two categories.

Optimal factor use depends upon land ownership conditions. Short-term cash lease agreements and crop sharing with no cost sharing inhibits the use of lime. In crop sharing lease agreement, when there is a carryover effect of input factors, the optimal factor share is not equal to the revenue share but has to account for the longevity of the carryover (in the case of lime application, up to 5 - 10 years).

Applying 1.25 tons ECCE/ac of lime in combination with 65 lb DAP/ac in the seed furrow under winter wheat variety 2137 was a preferred strategy for an owner operator in the conditions of the Eakly experiment (pH = 5.0). This strategy was also preferable for a tenant, when landowner covered either two-thirds or total lime cost. For a landowner, sharing one-third cost of DAP and two-thirds cost of lime was the best choice.

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TABLE 3.1. Percent Area of Soils with the Lower Limit of pH Range below 6. US Soil Survey Data.

County	Previous Observations [a]		Most Recent Observations [b]	
	Percent Area [c]	Year	Percent Area	Year
Alfalfa	22	1975	48	1997
Caddo	38	1973	71	1997
Garfield	6	1967	58	1996
Grant	59	1985	68	1996
Kingsfisher	4	1962	55	1996
Kiowa	2	1979	5	1996
Texas	0	1958	0	1996
Tillman	0	1974	7	1996
Woods	0	1950	27	1996

[a] Source: US Soil Surveys, various years.

[b] Source: Soil Survey data, National Soil Survey Center, NRCS-USDA.

[c] pH data were reported as the range for each soil map unit. The area was estimated for soil map units with the moderately acidic (pH below 6) lower limit and expressed as a percent of the total area.

TABLE 3.2. Quantity and Cost of Commercial Fertilizers and Lime Applied in Oklahoma in 1998.

	Quantity [a] tons	Cost [b] $/ton	Value mln $
Nitrogen	668,236	155	103.8
Phosphate	2,109	236	0.5
Potash	52,220	180	9.4
Multiple nutrient fertilizers	232,233	219	50.2
Micro nutrients	4,744	1,800 [c]	8.5
Total spent on fertilizers	959,543	-	173.0
Total spent on fertilizers and lime	-	-	182.5
Lime materials	422,222	22.5	9.5 [d]

[a] Source: Oklahoma Agricultural statistics.
[b] Source: NASS, USDA.
[c] Estimated numbers.
[d] Expenditures on lime materials were obtained by subtracting the total amount spent on fertilizers and lime and total spent on fertilizers.

TABLE 3.3. Initial Chemical Characteristics and Classification of the Experimental Site near Garber, Oklahoma, 1997.

Location	pH	NO_3-N surface	NO_3-N subsurface	P	K
		lb acre^{-1}			
Garber	4.5	14	46	107	591

Classification: Tabler silt loam (fine, smectitic, thermic Udertic Agriustoll)

pH was measured in $CaCl_2$ solution, available potassium (K) and phosphorus (P) in Mehlich III extractant.

TABLE 3.4. Analysis of Variance for Forage and Grain Yields at Garber, OK, 1997-98 and 1998-99 Crop Years.

Source of Variation	df	Forage Yield	Grain Yield
Year	1	NS	*
Lime	6	*	NS
Year × Lime	6	NS	*
Residual	42	--	--

*, NS - significant at 0.05 probability level, or insignificant, respectively.

TABLE 3.5. Treatment Means for Forage and Grain Yields at Garber, OK, 1997-98 and 1998-99 Crop Years.

Lime Rate	Year				Two-year average
	1997-98		1998-99		
	Forage	Grain	Forage	Grain	Forage
ton ECCE / ac	lb/ac	bu/ac	lb/ac	bu/ac	lb/ac
0	1,112	54.9	1,168	30.5	1,140
0.16	1,334*	50.1	1,499	41.1**	1,416*
0.31	1,535*	52.5	1,626*	39.4	1,580*
0.62	1,585*	51.1	1,714*	40.9**	1,649*
1.25	2,032*	55.2	2,065*	32.2	2,048*
2.50	2,219*	61.1*	2,159*	35.4	2,189*
3.75	2,076*	51.7	2,186*	29.8	2,131*

*, **, - significantly different from control at 0.05, and 0.1 probability level, respectively.

TABLE 3.6. Parameter Estimates for Wheat Forage Yield Response to Lime Application. [a]

Model	Equation	F	Pr >F
Quadratic	$y = 1256.8 + 765.6\,x - 144.0\,x^2$	90.84	<0.001
	(17.1) [b] (8.7) (-6.2)		
$x_{max} = 2.66$ [c]			
Linear Plateau	$y = \min\,[1261.8 + 649.1\,x;\ 2160.4]$	49.31	<0.001
	(20.1) (6.6) (76.8)		
$x_{max} = 1.38$			
Quadratic - Plateau	$y = \min\,[1212.1 + 981.4\,x - 254.3\,x^2;\ 2159.0]$	50.87	<0.001
	(16.8) (4.5) (-2.4)		
$x_{max} = 1.93$			

[a] The dependent variable, y, is fall-winter wheat forage yield prior to first hollow stem in dry matter lb/ac. The independent variable, x, is tons of ECCE applied per acre.

[b] Numbers in parentheses are asymptotic t values.

[c] x_{max} is the level of lime rate at which the response function reaches the maximum.

TABLE 3.7. Initial Chemical Characteristics and Classification of the Experimental Site near Eakly, Oklahoma, 1997.

Location	pH	NO_3-N	P	K
		---------- lb acre^{-1} ----------		
Eakly	4.5	72	102	453

Classification: Carey silt loam (fine-silty, mixed, superactive, thermic Typic Agriustolls)

pH was measured in $CaCl_2$ solution, available potassium (K) and phosphorus (P) in Mehlich III extractant.

TABLE 3.8. Degree of Tolerance to Soil Acidity for Selected Winter Wheat Varieties.

Variety	Degree of Tolerance [a]	Patent Protected [b]	Percent Acreage [c]
Jagger	1	Yes	29.5
Custer	4	No	10.7
2137	1	Yes	9.2
Tomahawk	4	Yes	3.8
Agseco 7853	2	No	3.5
Ogallala	3	Yes	2.7
2163	1	Yes	2.7
Karl 92	4	Yes	2.5
Chisholm	3	No	1.2
Tonkawa	4	No	1.2
Coronado	2	Yes	0.8
Dominator	3	No	< 0.2
Star Champ	3	Yes	< 0.2

[a] 1 – tolerant, 4 – susceptible.
Source: Krenzer, Wheat Variety Comparison Chart 2000.
[b] Source: Krenzer, Wheat Variety Comparison Chart 2000.
[c] Percent acreage seeded in Oklahoma in 1998. Source: Oklahoma Agricultural Statistics 1999.

TABLE 3.9. Treatment Means for Forage and Grain Yields, Variety Trial, Eakly, OK, 1997-98 and 1998-99.

Treatments		Susceptible [1]		Tolerant [2]	
Lime	DAP	Forage lb/ac	Grain bu/ac	Forage lb/ac	Grain bu/ac
0	0	1,337[a]	34.6[a]	1,612[a]	34.9[a]
0	130	2,536[c]	36.3[b]	2,286[c]	38.6[b]
1.25	0	1,848[b]	36.4[b]	1,972[b]	36.2[a]
1.25	130	2,590[c]	37.0[b]	2,465[c]	36.6[ab]

Same letters indicate no significant difference at 0.05 probability level.

[1] Susceptible varieties – 2174, Chisholm, Custer, Dominator, Karl 92, Ogallala, Oro Blanco, Star Champ and Tomahawk.

[2] Tolerant varieties – 2163, 7853, Coronado, and Jagger.

TABLE 3.10. Simple Effects of Lime and DAP Treatment Combinations for Forage and Grain Yields, Variety Trial, Eakly, OK, 1997-98 and 1998-99.

			Susceptible [b]		Tolerant [c]	
Effect [a]	Lime	DAP	Forage	Grain	Forage	Grain
DAP	0		*	*	*	*
DAP	1.25		*	NS	*	NS
Lime		0	*	*	*	NS
Lime		130	NS	NS	NS	NS

*, NS – significant at 0.05 probability level, or insignificant, respectively.

[a] Simple effects were analyzed using SAS MIXED procedure with random effect×rep×variety×year, and SLICE (lime DAP) option.

[b] Susceptible varieties – 2174, Chisholm, Custer, Dominator, Karl 92, Ogallala, Oro Blanco, Star Champ and Tomahawk.

[c] Tolerant varieties – 2163, 7853, Coronado, and Jagger.

TABLE 3.11. Treatment Means for Forage and Grain Yields, Lime – DAP Trial, Eakly, OK, 1997-98 and 1998-99.

Lime	DAP[1]	Tonkawa		2137	
ton/ac	lb/ac	Forage (lb/ac)	Grain (bu/ac)	Forage (lb/ac)	Grain (bu/ac)
0	0	1,287[a]	37.5[ab]	1,484[a]	42.8[a]
0	65 SF	1,795[b]	36.2[a]	1,693[ab]	48.2[ab]
0	130 SF	2,738[cd]	40.5[abc]	2,289[c]	45.6[a]
0	130 B	1,759[ab]	37.6[ab]	1,911[b]	50.0[abc]
1.25	0	1,836[b]	39.8[abc]	1,732[ab]	49.8[abc]
1.25	65 SF	2,260[bc]	44.0[c]	2,084[bc]	54.9[bc]
1.25	130 SF	2,758[d]	43.0[bc]	2,199[bc]	53.7[bc]
1.25	130 B	2,499[cd]	46.0[c]	1,931[b]	57.2[c]

Same letters indicate no significant difference at 0.05 probability level.

[1] SF, B, - DAP applied in the seed furrow or broadcast, respectively.

TABLE 3.12. Simple Effects of Lime and DAP Treatment Combinations for Forage and Grain Yields, Lime – DAP Trial, Eakly, OK, 1997-98 and 1998-99.

			Tonkawa		2137	
Effect	Lime	DAP[1]	Forage	Grain	Forage	Grain
DAP	0		*	NS	*	NS
DAP	1.25		*	NS	*	NS
Lime		0	*	NS	NS	NS
Lime		65 SF	NS	*	*	NS
Lime		130 SF	NS	NS	NS	*
Lime		130 B	*	*	NS	NS

*, NS – significant at 0.05 probability level, or insignificant, respectively.

Simple effects were analyzed using SAS MIXED procedure with random effect×rep×variety×year, and SLICE (lime DAP) option.

[1] SF, B, - DAP applied in the seed furrow or broadcast, respectively.

TABLE 3.13. Lime Rate Trial, Garber, OK. Expected Returns and Standard Deviations of Returns in Winter Wheat for Dual-Purpose Production, $/ac.

Lime Rates	Undiscounted		Disc.[a] 2 years		Disc.[a] 5 years	
Ton/acre	Mean[b]	STD	Mean	STD	Mean	STD
0	125 [c]	35	-	-	-	-
0.16	130	13	131	13	133	13
0.32	130	20	132	20	136	21
0.64	125	23	129	22	134	23
1.25	111	36	123	35	129	36
2.5	97	36	122	35	137	36
3.75	57	31	89	30	113	31

[a] Discount rate of the cost of lime is 7 %.

[b] Means and standard deviations are results of a Monte Carlo integration (1000 runs). Price of wheat - $3.00/bu, price of forage - $0.02/lb.

[c] Expected wheat grain and wheat forage revenues minus cost of lime application, harvesting and nitrogen fertilizer.

TABLE 3.14. Lime and DAP Trial. Expected Returns and Standard Deviations of Returns in Winter Wheat for Dual-Purpose Production, $/ac.

DAP	No Lime		Lime, 1.25 t/ac					
			Undiscounted		Disc.[a] 2 years		Disc.[a] 5 years	
lb/ac	Mean[b]	STD	Mean	STD	Mean	STD	Mean	STD
				Tonkawa (susceptible)				
0	108 [c]	12	94	18	107	17	114	17
65 furrow	106	17	103	16	115	17	123	16
130 furrow	120	18	101	14	112	14	120	13
130 broadcast	102	18	105	11	116	11	124	11
				2137 (tolerant)				
0	124	20	117	19	128	19	136	18
65 furrow	133	29	126	17	138	17	146	15
130 furrow	128	27	118	17	130	18	138	17
130 broadcast	132	30	124	8	135	9	143	8

[a] Discount rate of the cost of lime is 7 %.

[b] Means and standard deviations are results of the Monte Carlo integration (1000 runs).

[c] Expected wheat grain and wheat forage revenues minus cost of lime application, harvesting and nitrogen fertilizer.

TABLE 3.15. Winter Wheat Variety Trial, 1997-99. Expected Returns and Standard Deviations of Returns in Winter Wheat for Dual-Purpose Production, $/ac.

DAP	No Lime		Lime, 1.25 t/ac					
			Undiscounted		Disc.[a] 2 years		Disc.[a] 5 years	
lb/ac	Mean[b]	STD	Mean	STD	Mean	STD	Mean	STD
				Susceptible varieties[c]				
0	116[e]	31	105	32	116	34	125	34
130	122	35	98	38	110	38	116	38
				Tolerant varieties[d]				
0	123	31	106	33	118	32	124	32
130	124	42	96	37	105	38	115	38

[a] Discount rate of the cost of lime is 7 %.

[b] Means and standard deviations are results of the Monte Carlo integration (1000 runs).

[c] Susceptible varieties – 2174, Chisholm, Custer, Dominator, Karl 92, Ogallala, Oro Blanco, Star Champ and Tomahawk.

[d] Tolerant varieties – 2163, 7853, Coronado, and Jagger.

[e] Expected wheat grain and wheat forage revenues minus cost of lime application, harvesting and nitrogen fertilizer.

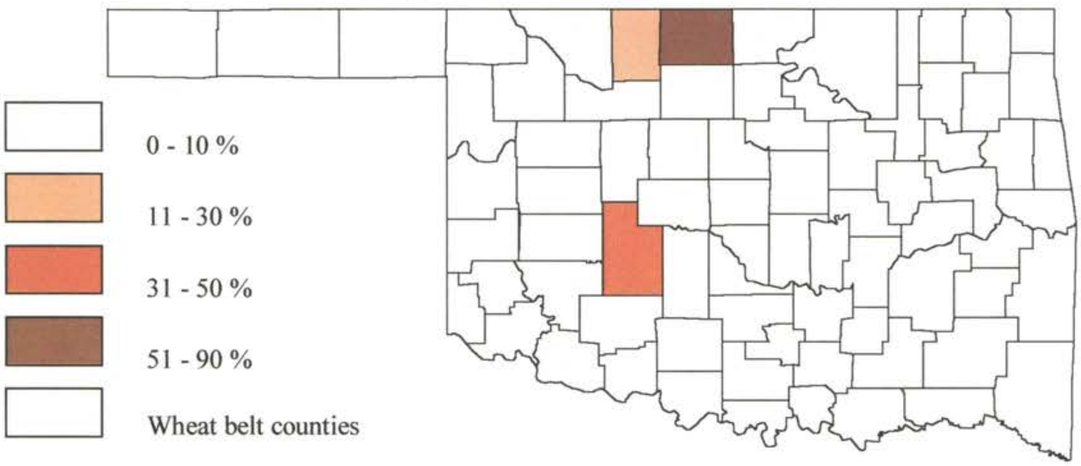
TABLE 3.16. Economically Preferred Strategies for Dual-Purpose Wheat Production under Various Land-Tenure Conditions.

Type of Tenure	Crop Share	Cost Share		Strategy [a]	Net Returns [b]		
		DAP	Lime		Tenant	Landowner	
	α	γ	δ			Undisc.	Disc.
Owner-operator	-	-	-	Lime 1.25, 65 DAP SF	-	133	146
Cash lease	-	-	-	No lime, 65 DAP SF	73	rent	rent
Crop sharing	0.33	0	0	No lime, 65 DAP SF	73	-	59
Crop sharing	0.33	0.33	0.33	No lime, 130 DAP B	76	-	57
Crop sharing	0.33	0.33	0.67	Lime 1.25, 65 DAP SF	78	-	61
Crop sharing	0.33	0.33	1	Lime 1.25, 65 DAP SF	86	-	59

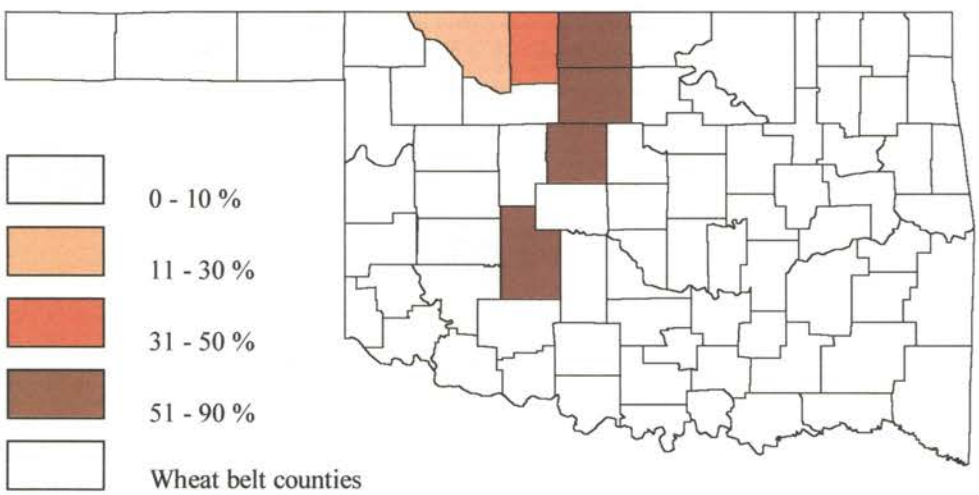
[a] Strategy is a combination of treatments from the lime – DAP experiment at Eakly, OK (lime – tons ECCE/ac; DAP – lb/ac; SF – application in the seed furrow; B – broadcast application).

[b] Net returns for a tenant are the revenues from forage and grain yields times $(1 - \alpha)$, minus the cost of DAP times $(1 - \gamma)$ minus the cost of lime times $(1 - \delta)$ minus the cost of harvesting and nitrogen removal. For a landowner, they are the revenues times α, minus the cost of DAP times γ minus the cost of lime times δ. The cost of lime for a landowner is calculated in both, undiscounted and discounted (7% for five years) cases.

FIGURE 1. Changes in the area of acidic soils (lower pH range below 6.0) in Oklahoma during the 60-80s and 90s.



Area of soils with lower pH range below 6.0, the 1960s - 80s



Area of soils with lower pH range below 6.0, 1996-97

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