Effect of Nitrogen Fertilization and Liming on Rye-Ryegrass Yield and Soil pH Dynamics

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Abstract
Using ammonium based nitrogen fertilizers in crop production has been shown to acidify soils. Lime used to correct soil pH is an important cost to producers. Recommendations of the optimal level of nitrogen to apply typically ignore the cost of lime created by nitrogen fertilization. This study was aimed to estimate soil pH change in response to nitrogen and lime application, and determine the effect of considering the cost of lime on recommendations about the optimal level of nitrogen. Yield response and pH functions were estimated and used to determine optimal levels of inputs. The effect of the cost of lime on recommendations about the optimal level of nitrogen was found to be marginal. Nitrogen acidification was found to be more severe with nitrogen application amounts above recommended rates than does with nitrogen that is used by the crop.

Key words: *Lime, Nitrogen, pH, Rye-ryegrass*

Introduction

Using ammonium based nitrogen fertilizers in crop production has been shown to acidify soils (Mahler and Harder 1984). This is particularly true on crop lands that are under continuous cultivation and receive high rates of nitrogen fertilizer. Research shows that three major factors cause soil pH to drop. One is the removal of base cations such as calcium and Magnesium through crop harvest. The other is nitrogen (N) fertilizer application and N transformation (nitrification), a process that releases hydrogen ions (H+) into the soil (Tabitha et al 2008; Adams 1984). The third effect comes from nitrate that is not taken up by the growing crop. Nitrates are very soluble and, if not taken up by plants, leach to deeper soil layers taking with them base elements like calcium and magnesium. Their removal in this manner has the same acidifying effect on soils as removal by crop harvest (Mahler and Harder 1984).

Historically, soil acidity was not a problem for most croplands in the southern Great Plains of USA (Shorey 1940). However, in the past decades, soil pH values have declined due to continuous cropping and long-term use of large amounts of ammonium-based N fertilizers (Zhang and Raun 2006). A survey in 1985 supported by Oklahoma Cooperative Extension

Services of wheat fields cropped continuously showed more than 30% of 17000 soil samples analyzed had pH levels less than 5.5. In 1995 a similar survey of 3709 samples showed that 39% of the samples had pH levels less than 5.5 (Zhang et al. 1998). These surveys suggest that soil pH levels in fields under continuous cultivation in the region have declined to yield limiting or near yield limiting levels and that the problem has increased over time.

Associated with very acid soils are problems that limit crop and pasture growth and yield. Plant utilization of many nutrients becomes less efficient as soil acidity increases (Haynes and Ludecke 1981; Black 1993). Detrimental effects from soil acidity vary with crop, rooting depth, and crop tolerance (Black 1993). The most serious problems are due to aluminum (Al) and manganese (Mn) toxicities which increase as the soil pH drops below 5.0. Al toxicity restricts the development of crop root systems, which in turn reduces nutrient uptake and Mn toxicity results in deficiencies of essential mineral nutrients Calcium (Ca), Phosphorous (P) and Molybdenum (Mo) (Black 1993).

Acidic soils can be amended by liming. Field studies show that lime is effective for several years. Benefits of liming include improved nitrogen fixation and availability of essential nutrients (Ca, P, Mo) and decreasing the solubility of toxic elements Al and Mn (Haynes and Ludecke 1981).However, the use of lime is not without cost. The per unit cost of lime is low relative to other fertilizers, but lime application rates are significantly higher than for fertilizers such as nitrogen and phosphorous. Because large amounts of neutralizing material are often needed, benefits of liming come at a significant cost to the farmer.

Recommendations of the optimal level of nitrogen to apply based on 'yield goal' typically ignore the cost of lime. This may lead to higher nitrogen and lime rate recommendations than is needed in most years. Most studies use data from short-term (one- or three-year) experiments. In such experiments, there is inadequate variation in weather variables to find the effect on yields. Tembo *et al*. (2008) and Tumusiime *et al*. (2010) used data from long term experiments on wheat and rye-ryegrass respectively and showed that the expected profit function is relatively flat with respect to nitrogen. That is, it does not cost the producer very much to change the optimal level of nitrogen. Further, precision sensing systems to improve N use efficiency have been shown to be marginal at best in terms of economics (Daberkow and McBride 2003; Biermacher *et al.* 2006; Lambert *et al.*2006; Biermacher *et al*. 2009). If the cost of liming is large enough, it could make precision sensing systems more competitive economically.

The objectives of this study are to determine cereal rye-ryegrass pasture (*Lolium multiflorum*) yield response to soil pH; determine the effect of considering the cost of lime on recommendations about the optimal level of nitrogen; determine the optimal lime rate, and liming frequency; and estimate soil pH change in response to nitrogen fertilization, and lime application. Results from this study will give much more precise estimates of optimal lime rate and liming frequencies and nitrogen fertilization strategies which may be useful in improving fertilizer use efficiency, reduce potential negative environmental impacts of over use of fertilizers, and improve farm net returns.

Materials and Methods

1. *Data*

A long term experiment was conducted at the Red River Demonstration and Research Farm near Burneyville, Oklahoma by The Samuel Roberts Noble Foundation’s Agriculture Division. The experiment started in 1979 and was aimed to establish the effect of liming, nitrogen fertilization rate and timing on rye (*Secale cereal*)-wheat (*Triticum aestivum*)-rye-ryegrass (*Lolium* *multiflorum*) yield response, and soil pH dynamics. The effect of nitrogen fertilization timing and rate on forage yield and quality has been analyzed by Altom et al. (1996) using data from 1979 to 1992. Our data set is for rye-ryegrass pasture for the period from fall 1993 to spring 2007.

Since 1993, rye-ryegrass has been planted in early fall at a seeding rate of 20lbs/acre. A split-plot randomized complete block design with three replications was employed. Six treatment levels of nitrogen were administered: 0, 100, 150, 200, 300, and 400 pounds per acre per year. Nitrogen applied as ammonium nitrate (34-0-0) was broadcast and incorporated prior to planting in the fall. Ammonium nitrate applied in the spring was broadcast. Phosphorous applied as diammonium phosphate (18-46-0) was banded with the seed at a rate of 50lbs P_2O_5/acre every year. Potassium as potassium chloride KCl, (0-0-60) was broadcast and incorporated prior to planting at an average rate of 100lbs K_2O/acre.

Lime was applied in 1979, 1996, 1998, and 2004. In 1979, lime was applied at a rate of 2 tons per acre. Over time, the soil acidified**.** In 1993, the pH of the sub surface soil (0-6 inch) ranged from 4.3 to 5.2. Experimental plots were limed to raise the soil pH to 6.0-6.5. Lime rates were applied in small quantities periodically to assess the impact of frequent small lime applications on yield and soil pH. In 1996, 2.5 tons per acre of effective calcium carbonate equivalent (ECCE) was added to all plots on the east half (split plot). In 1998, lime was applied again to the east half of the split plots, but was varied with N rates as follows: to plots that had not been fertilized with N, no extra lime was added; to plots that had received 100 lbs and 150lbs of N, 1 ton of ECCE was added; while plots that had been fertilized at a rate of 200lbs, 300lbs, and 400lbs of N, 1.5 tons, 2 tons and 2.5 tons per acre respectively of ECCE was added. In 2004, lime was applied at a rate of 1 ton per acre to all the east side plots.

Top soil pH was measured twice every season: at the start of the season and at the end. We used the average. Soil pH was determined in a 1:2 soil/water suspension. The pH reading was then taken using a glass electrode on a pH meter. Average annual soil pH variation for limed and unlimed plots is shown in figure 1, and the relationship between soil pH and nitrogen rate is shown in figure 2. Forage yields were determined by clipping from individual plots that were 12 by 13 ft. Plots were clipped multiple times to simulate grazing. Additional information regarding the experiment can be found in Altom et al (1996). Yearly dry matter forage yields were the sum of all clippings for that year. Average rye-ryegrass yield response to nitrogen fertilization is shown in figure 3, and the relationship between soil pH and rye-ryegrass forage yield is shown in figure 4.

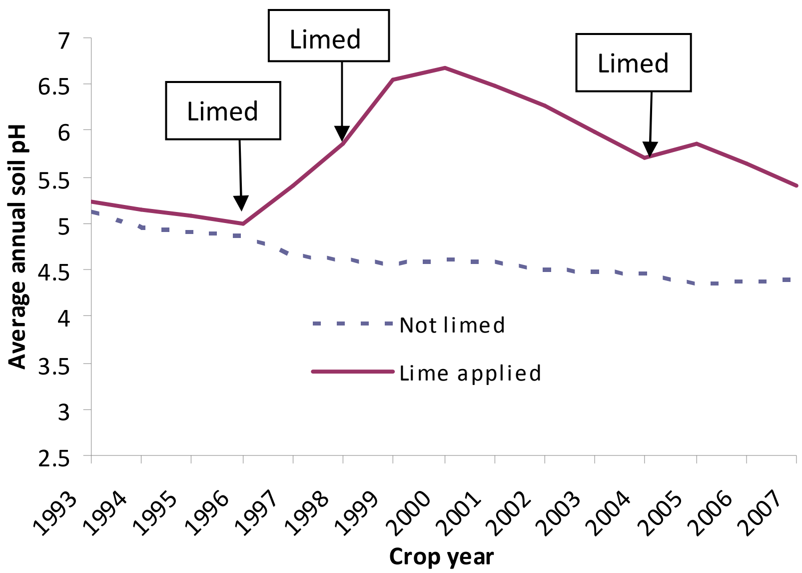

Figure 1. Annual soil pH change over time in limed plots and unlimed plots. Soil pH is the mean of spring and fall measurements averaged over nitrogen rate.

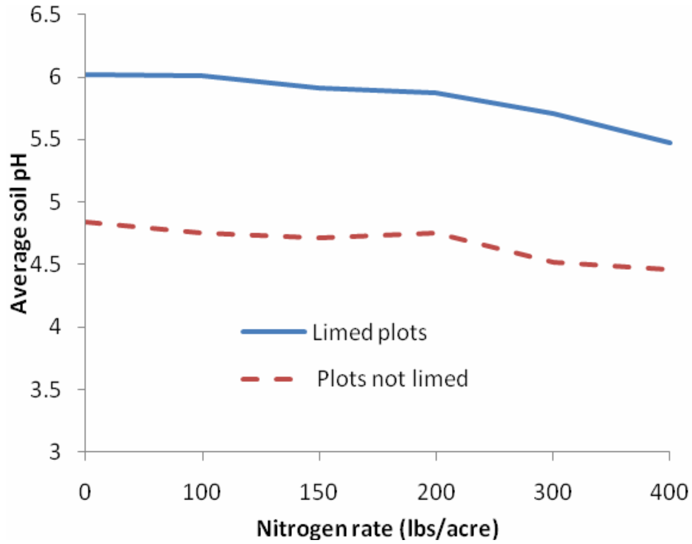

Figure 2. Average soil pH change with varying levels of applied nitrogen fertilizer.

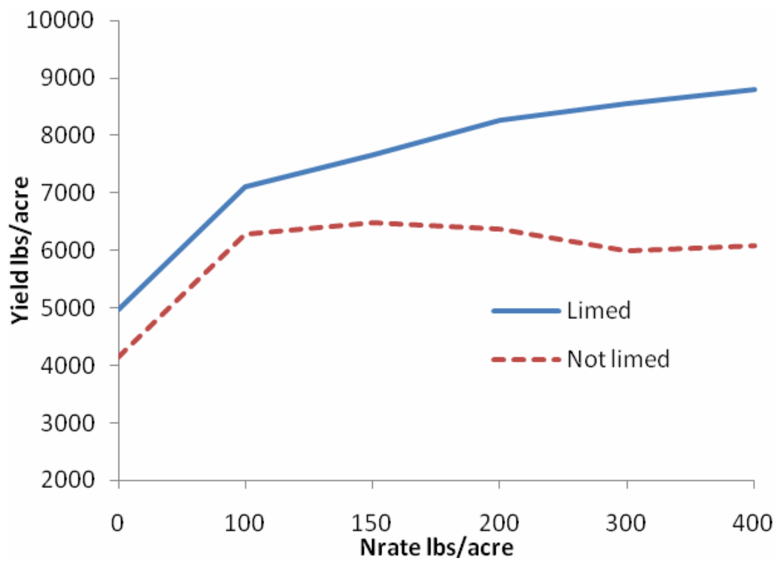

Figure 3. Effect of liming and nitrogen fertilization on rye-ryegrass forage yield. Yield is the annual total average over three replications.

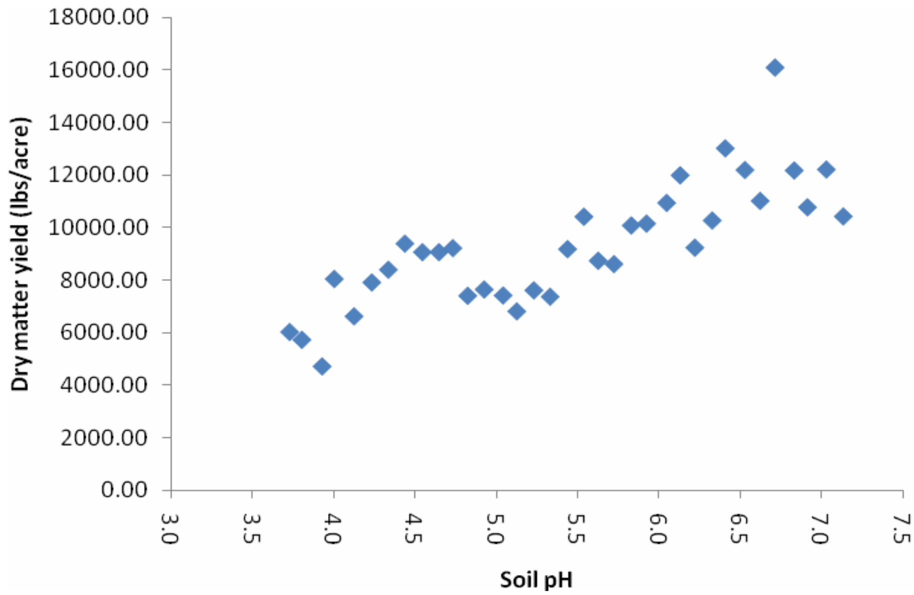

Figure 4. Relationship between annual mean rye-ryegrass forage yield and soil pH. Soil pH is the mean of spring and fall measurements. Dry matter yield is the annual total average over three replications

2. *Theoretical Models*

a) Rye-ryegrass response lime and nitrogen

Crop response to lime is principally a response to pH and the related secondary benefits (Haynes and Ludecke 1981). In this study, it is assumed that rye-ryegrass yield response can be represented as a function of soil pH and applied nitrogen. Many mathematical model specifications for yield response to fertilizer have been proposed. Agronomic studies suggest that crop response to some factor is observed when the input is limiting. This physiological concept is described by the limiting linear response plateau (LRP) model (Paris 1992). Crops vary in their response to soil pH, responding to lime applications only if pH levels are limiting crop performance. For yield response to soil pH, Adam (1984) observed that the function should exhibit decreasing marginal return to lime and/or that the plateau yield should begin somewhere below pH 7. These characteristics are exhibited by the quadratic and linear response plateau functions.

Mahler and McDole (1987) used 5 years of data and fit quadratic and linear plateau models consisting of intersecting straight lines for (wheat, barley, pea and lentil) yield response to artificially acidified soils in northern Idaho. They described the knot point of the linear response and plateau model as the minimum soil pH required to reach the plateau yield. Their findings showed that the LRP model provided a better representation of data than the quadratic model. Lukin and Epplin (2003) used 4 years of wheat yield data obtained from a lime rate experiment in Oklahoma. They fit linear response plateau, quadratic and quadratic plateau models and found that plateau functions produced soil pH estimates that were more rational from the agronomic point of view. Lukin and Epplin (2003) found that with the LRP, the minimum pH level for plateau wheat yield is 5.26; and for the quadratic, a pH level of 6.16 would be required to obtain maximum wheat yield.

The findings by Mahler and McDole (1987), and Lukin and Epplin (2003) regarding specification of the yield response function are consistent with those of Hall (1983). Hall (1983) used data of corn, alfalfa, and soybeans yield response to lime. He fit several response functions (linear plateau, quadratic-plateau, square root, logarithmic and power) to corn yield data as a function of lime rate, and concluded that linear plateau functions provided the best fit of the data. We consider the linear response plateau (LRP) function and compare it with the quadratic function. Following Tembo *et al* (2008) and Tumusiime *et al* (2010), we test hypotheses on whether the plateau of the LRP is stochastic or deterministic.

A stochastic linear response plateau function of rye-ryegrass yield as a function of applied nitrogen and soil pH is specified as

(1) $$y_{it} = \min(\beta_0 + \beta_1 N_{it}, \gamma_0 + \gamma_1 pH, P_{it} + v_t) + u_t + \varepsilon_{it}$$

where y_{it} is the forage yield of cereal rye-ryegrass from the i^{th} plot in year t, N_{it} is the level of nitrogen fertilizer, pH_{it} is the pH level, P_{it} is expected plateau yield, v_t is the plateau year random effect, u_t is the (intercept) year random effect, and ε_{it} is a random error term that is normally distributed and independent. The parameters β_0 and γ_0, are responses at the origin, β_1 and γ_1 are linear slope parameters for applied nitrogen and pH respectively. If function (1) is a non-stochastic LRP, the random parameter v_t will be zero. The random parameters v_t, u_t and ε_{it} are normally distributed and uncorrelated. Equation (1) suggests that at the plateau yield P_{it}, the factors N and pH are no longer limiting and do not affect crop yield.

A quadratic response model is specified as

$$(2) \qquad y_{it} = \alpha_0 + \alpha_1 pH_{it} + \alpha_2 pH_{it}^2 + \alpha_3 N_{it} + \alpha_4 N_{it}^2 + u_t + \varepsilon_{it}$$

where α_0 is the response parameter at the origin, α_1 and α_3 are slope parameters, α_2 and α_4 are quadratic parameters, u_t is year random effect, and ε_{it} the random error term. Soil pH level (pH^*) for which maximum yield can be obtained is determined by taking expectation of the yield function (1 and 2) and solving the first order condition for pH^*. Determination of the optimal level of nitrogen and lime rate is described in the section on economic optimization.

b) ***Soil pH change model***

Soil pH change is a complex phenomenon dependent on both site and management factors. According to Black (1993), and Mahler and Harder (1984), decrease in soil pH over time is a function of crop uptake, nitrogen acidification, leaching, and of the soil's buffering capacity. Gasser (1973) showed that the rate of pH change varies with the initial soil pH, and suggested including the initial soil pH in the regression as an independent variable. The empirical models estimated by Goulding (1989) also showed that the magnitude and duration of the effect of lime varies by initial soil pH, fertilizer additions and crop grown.

In this study we considered soil pH change to be a function of nitrogen fertilizer inputs, lime, initial soil pH, yield, and time trend. The variable yield was found not a significant predictor of soil pH change, and was not included in the empirical model. For a multiple application model, the total effect of lime and nitrogen applications accumulates effects of all previous applications. We represent annual soil pH change as:

$$pH_{it+1} = \beta_0 + \beta_1 \sum_{t=1}^{T} LR_t + \sum_{k=j}^{T} \beta_2 N_{ik} + \sum_{k=j}^{T} \beta_3 N_{ik}^2 + \beta_4 pH_{it} + \beta_5 T + u_t + \varepsilon_{it} \qquad (3)$$

where LR_t is the lime rate in year T, u_t is crop year random effect, and ε_{it} the random error term. Equation (3) is dynamic, with initial soil pH (pH_{it}) included on the right hand side. The long run effect of lime on soil pH change is determined by dividing the coefficient β_1 by the long run parameter $\alpha = (1 - \beta_4)$, and the long run effect of nitrogen on soil pH change is β_2 / α. The sum of the square of nitrogen is included as an independent variable to capture the effect of excess nitrogen fertilization on soil pH, while T is the time trend variable.

Estimation of the models

Richter and Kroschewski (2006), point to the problem of unequal variance and the existence of correlations among years in pooling long term experimental data. Since the effect of lime on soil pH is spread over time, it is important to consider yield variability among years. Diagnostic graphs indicated that the yield model should allow for heterogeneity across years in the error variance. Parameters of the linear response plateau model (equation 1) were estimated using the SAS NLMIXED procedure with the error variance an exponential function of cropyear* lime rate. Parameters of the quadratic model (equation 2) were estimated using SAS PROC MIXED with the statement repeated/local =exp(cropyear*lime rate) (SAS Institute Inc. 2003). Parameters of the regression model of soil pH change (equation 3) were estimated using SAS PROC MIXED. Estimates obtained from equation (3) will be used in equations (1) and (2) to construct the economic model determining the optimal nitrogen level, lime rate, and liming frequency.

Quantity of lime required to neutralize the acidifying effect of nitrogen

The acidity potential of N fertilizer additions is characterized by equation (3). The quantities of lime required to neutralize this acidity can be calculated. Most soil testing laboratories use a special buffered solution to measure exchangeable acidity. By calibrating pH changes in the buffered solution with known amounts of acid, the amount of lime required to bring the soil to a particular pH can be determined. Gasser (1973), Adams (1984), and Boswell *et al*. (1985) showed that the theoretical requirement of lime required to neutralize the acidity produced from fertilizer N inputs is 3.6 kg Calcium carbonate for 1 kg N applied as ammonium nitrate, and 7. 2 kg Calcium carbonate for 1 kg N applied as ammonium sulphate. In the study by Archer (1985) on forage grasses, he found that 200-300kg of calcium carbonate are required to neutralize the acidifying effect of 100 kg N applied as ammonium nitrate or urea, and 500- 700 kg of calcium carbonate if nitrogen fertilizer is applied as ammonium sulphate.

The practical need to neutralize acidity from nitrogen fertilizer inputs is likely to be less than the theoretical requirement because some of the ammonium and nitrate are lost by other process such as volatilization, denitrification, and microbial fixation (Chambers and Garwood 1998). The method used in this study is the acid-base accounting. This method measures empirically the acid producing potential of nitrogen fertilizers in the soil and acid neutralizing potential of lime. From (3), it follows that:

$$(4) \qquad \frac{\beta_1}{\alpha} LRate + \frac{\beta_2}{\alpha} Nrate = 0$$

Equivalent acidity is usually expressed in terms of 1 kilogram of calcium carbonate per 100kg of nitrogen (Archer 1985; Adams 1984). The quantity of lime (Q_L) required to neutralize acidity from 100kg of nitrogen fertilizer is then calculated as:

$$Q_L(kg) = \left[\frac{\beta_2 \times 100}{\beta_1}\right]. \tag{5}$$

The cost of lime (including transport and application costs) due to nitrogen fertilizer is calculated by multiplying (5) by the price of liming.

Economic optimization

Consider a risk neutral forage producer whose objective is to maximize expected net returns from winter cereal rye-ryegrass forage. Because a single application of lime affects soil pH for more than one year, it is useful to cast the economic problem in terms of maximizing discounted net returns in successive years. The objective is to maximize the expected net present value (NPV):

$$\max_{N, LR \ldots, LR_T} NPV = \sum_{t=1}^{T} \frac{P_y E[Y(N, pH_t)] - cLR_t - CA_t}{(1+r)^t} - wN \tag{6}$$

subject to

$$pH_t = pH_{t-1}(LR_t, N) \quad LR_t \geq 0, \;\; N \geq 0$$

where P_y is the price of forage, c is the per unit cost of lime, CA is the application cost of lime and w is unit cost of nitrogen N. The choice variables are N, the optimal nitrogen level and LR_t, the lime rate at year t. Equation (6) suggests that maximum net returns are obtained when lime is applied in the quantity at which the expected present value of the current forage crop and of the savings in future input applications equals the current price of lime and nitrogen. Lime is applied at time 0, but pH changes every year with cropping and fertilizer application. In order to calculate yields, the production function requires a pH value for each year. The problem of finding the optimal level of nitrogen, lime rate and liming frequency is one of optimal control, requiring dynamic analysis. To construct equation (6), the pH function (equation 3) is substituted in the yield function for pH_t.

The expected yield in (6) is obtained by taking the expectation through the production function $Y(N, pH)$. For the non-stochastic LRP and quadratic models, the random variable u_t drops out after taking expectation of the yield function since u_t is linear in the yield functions. After taking the expectation of $Y(N, pH)$, equation (6) is then maximized directly using nonlinear programming. For the stochastic LRP, the random variable v_t is nonlinear in the yield function (1), and therefore does not drop out after taking expectation as does the variable u_t. The expectation of $Y(N, pH)$ in equation (6) becomes

$$(7) \qquad E[y_t \mid N, pH] = E[\min(\beta_0 + \beta_1 N_{it}, \gamma_0 + \gamma_1 pH, P_{it} + v_t)].$$

This defines an integral with respect to v_t that must be solved numerically. We used the approach developed by Tembo et al. (2008) to solve the integral in (7) by evaluating a univariate normal probability density. The problem was set up in Microsoft Excel Software, and maximized using the standard solver. Following Lukin and Epplin (2003), a 10% discount rate was assumed.

Net present value maximizing level of nitrogen and lime are evaluated at 2010 input and output prices (The Samuel Roberts Noble Foundation, Inc. 2010). The price of nitrogen is \$0.45/lbs, and the cost of liming-including application is approximately \$32/ton 100% ECCE. The price of forage is determined as the cost of beef gain per pound divided by the pounds of forage required by a stocker animal to produce a one-pound gain. Based on the National Research Council (1984) net energy equations used to estimate livestock requirements, Ishrat , Epplin, and Krenzer (2003) and Krenzer et al (1996), show that one pound of beef gain requires

10 lbs (dry matter) of standing forage. In the Great Plains, the cost per pound of gain has ranged from \$0.32/lb since 2005 to \$0.55/lb in 2010, which is approximately \$0.45/lb gain on average. At the cost of beef gain per pound of \$0.45, the price per pound of forage is \$0.45/10=\$0.045.

Results and discussion

Results from the regression of rye-ryegrass yield models

The estimated parameters for the yield functions (equations 1 and 2) are reported in Tables 1 and 2. All parameter estimates are statistically significant at the 95% significance level based on the Wald *t* test except the pH intercept of the non-stochastic linear response plateau function. The stochastic and non-stochastic LRP models were compared using the nested likelihood ratio (LR) test. The calculated LR test statistic is 17.6 and the critical chi-square value $(X^2_{(1),.01})$ is 6.6. The null hypothesis that the plateau year random effect is equal to zero is rejected.

The estimated soil pH levels (pH*) for which maximum yield can be obtained are different for the models, but within the range of agronomic recommendations for forage grasses (Banes *et al.* 2003). The estimated pH level necessary to reach maximum yield was highest for the nonstochastic (deterministic) LRP model. With the nonstochastic LRP model, a pH level of 6.2 would be required to obtain plateau yield of 8220.9lbs/acre (3728.5kg/acre). With the stochastic LRP, a pH level of 5.10 is sufficient to obtain plateau yield of 8210.3 lbs/acre (3724kg/acre). From estimates of the quadratic model, soil pH level of 5.73 would be required to obtain maximum yield.

Estimates of pH reported above are critical levels for which maximum yield can be obtained according to the specific model. A pH estimate from the stochastic LRP is consistent with findings from previous studies that rye-ryegrass is tolerant to low soil pH (Barnes *et al.* 2003). The result suggests a soil pH of 5.10 is the critical level for which expected plateau yield can be obtained. The Oklahoma Cooperative Extension Service currently recommends lime for forage production when soil pH is below 5.5 (Zhang and Raun 2006). Based on estimates from the stochastic LRP model, liming for rye-ryegrass pasture would be necessary below a pH of 5.10.

Results from the regression of soil pH change model

Parameter estimates from the regression of soil pH change model (equation 3) are reported in table 3. All parameter estimates are statistically significant at the 99% significance level except the time trend parameter. All estimates have the expected signs. Estimates from (3) show that 100kg/acre of nitrogen applied as ammonium nitrate (34-0-0) will lower the soil pH by 0.06 units in the long run, while 1kg/acre of 100% ECCE will raise the soil pH by 0.0003 units in the long run. From equation (5), 174.3kg/acre of 100% ECCE is required to neutralize the acidifying effect from 100kg/acre of nitrogen fertilizer applied as ammonium nitrate (34-0-0). These estimates are less than theoretical estimates found in laboratory studies (Archer 1985; Gasser 1973; and Adams 1984). The result is expected since some of the nitrogen fertilizer added to soil is lost to other biological process other than acidification process (nitrification and leaching).

According to Adams (1984) and Gasser (1973), theoretical acidification potential is equivalent to 360 kg of 100% ECCE per 100kg of nitrogen fertilizer applied as ammonium nitrate (34-0-0). In practical terms, however, Adams (1984) showed that soil acidification due to nitrogen fertilization is about one half of the theoretical estimate. Model predictions found in this study compare well with findings by Adams (1984) and Boswell *et al.*(1985). From (5), we estimated the cost of lime due to nitrogen acidification. Results showed 100kg N applied as ammonium (34-0-0) costs the producer $6.15 in lime cost. Ideally, the producer recovers this cost from the yield increase due to nitrogen fertilization.

However, if excessive rates of N are applied; more acidity is produced than what is actually necessary. To determine the effect of excess nitrogen fertilization on lime requirements, equation (5) was modified to include the parameter $\beta_3 Nrate * Nrate$ (from equation 3). We found that 376.2kg of ECCE would be required to neutralize the acidifying effect from 100 kg ammonium nitrate applied in excess. This shows nitrogen acidification may be more severe with nitrogen application amounts above recommended rates. The cost of lime due to excess nitrogen fertilization was estimated at $7.12 per 100kg N. In terms of precision agriculture, this cost would be the benefit to precision sensing systems.

Optimal nitrogen rate, lime rate and liming frequency

Estimates from (3) were used in the economic model (6), and the model solved using the standard solver in Microsoft Excel Software to determine the optimal nitrogen level, lime rate, and liming frequency. Optimal levels of nitrogen with the yield models are reported in the respective tables of results. With the quadratic model, the optimal level of nitrogen is 211.7 lbs (96 kg) per acre. With the non-stochastic LRP, 123.5lbs (56 kg) per acre of N are required to obtain plateau yield, and with the stochastic LRP, 157.6lbs (71.5 kg) per acre of N are optimal for economic production.

To determine the effect of the cost of liming about recommendations of optimal level of nitrogen, the objective function (equation 7) was solved with and without the cost of liming. The latter case sets the cost of liming equal to zero. Optimal levels of N were noted in both cases, and the effect of the cost of liming about recommendations of optimal level of nitrogen was determined as the difference between the two nitrogen levels. Results from the economic model showed that, regardless of the initial pH, the effect of the cost of ECCE (lime) on recommendations about the optimal level of nitrogen is not much. When the cost of liming was

$32/ton ($0.016 /lb), the optimal level of nitrogen calculated for the yield models above was less than or equal to 3 lbs (1.34 kg), but estimates of lime rate changed much.

The optimal lime rate changed with initial soil pH. With an initial pH of 4.8, the stochastic LRP predicted 1.45 tons/acre of lime would be sufficient to restore rye-ryegrass yield to the plateau level. For an initial soil pH of 4.8, the pH function (3) determined 1.45 tons would raise the pH to 6.2 by the fourth year. It would take 21 years for the pH to drop below 5.0 (Figure 5). When the model was solved with an initial soil pH of 4.6, a stochastic LRP estimated 1.61tons/acre would be required to raise the pH to 6.2.

According to the quadratic model, the optimum pH is 5.73. When equation (7) was solved with an initial pH of 4.8, the model determined a lime rate of 1.75 tons/per acre would raise the soil pH to 6.2 after 4 years, and reached a pH level of 5.73 after 12 years. The underlying result of the economic model is that when the soil pH level is below the expected maximum yield level, an initial application of lime is necessary to increase the pH to reach the maximum yield level. Subsequent lime applications are made to maintain the pH near that level depending on the cost of lime application.

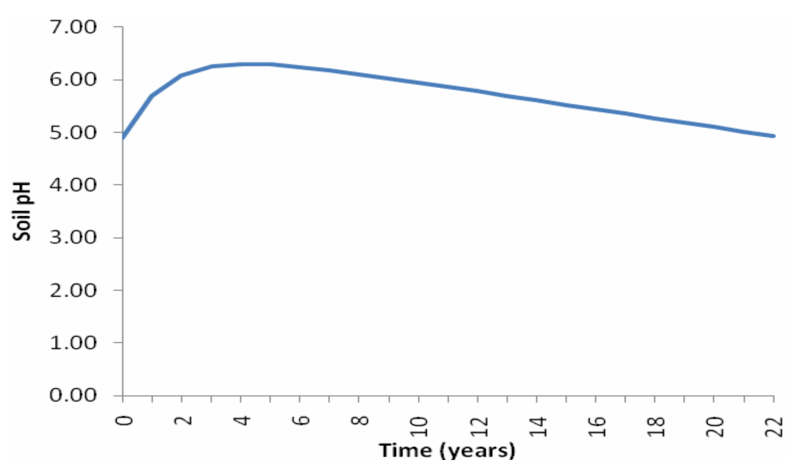

Figure 5. Change in time of mean soil pH: Initial pH 4.8, Lime rate 1.45 tons/acre, Nitrogen rate 157 lbs/acre.

Conclusion

This study was aimed to determine rye-ryegrass yield response to soil pH and nitrogen fertilizer; estimate soil pH change in response to nitrogen fertilization and liming; and determine the effect of considering the cost of lime on recommendations about the optimal level of nitrogen fertilizer.

Optimal levels of nitrogen fertilizer, soil pH and lime rate were greatly affected by the choice of the yield function. Estimates of optimal nitrogen and pH from the stochastic LRP were more rational from the agronomic point of view for rye-ryegrass pasture production. At current input and output prices, the effect of the cost of liming about recommendations of the optimal level of nitrogen was found to be small (<= 3lbs or 1.3kg /acre). This result implies that the rate of acidification due to nitrogen fertilizer from year to year is small to adversely affect farm returns. Acidification potential due to nitrogen was estimated to be equivalent to 174.3 kg of 100% ECCE per 100kg of nitrogen fertilizer applied as ammonium nitrate (34-0-0). Nitrogen acidification was found to be more severe with nitrogen application amounts above recommended rates than with nitrogen that is used by the plant.

Model predictions found in this study compared well with theoretical predictions. Although predictions from this study seem practical, they should be considered as near-optimal. A short coming of this study is that optimal lime rates are different for different initial pH levels, and conditions that determine soil pH are specific for different soils.

Table 1. Parameter estimates for regressions of rye-ryegrass response to nitrogen and soil pH using the quadratic yield function

Dependent variable: Yield/1000		
Parameter	Estimate	Std Error
Intercept	-19.79	5.86
Nrate	1.71	0.17
Nrate*Nrate	-0.35	0.03
pH	7.85	2.03
pH*pH	-0.69	0.17
Cropyear random effect	3.23	
Variance of error term	1.48	
pH* at max yield	5.73	
Optimal N (100lbs/acre)	2.12	
-2Log Likelihood	1505.80	

Table 2. Parameter estimates for regressions of rye-ryegrass response to nitrogen and soil pH using the linear response plateau yield function

Dependent variable: Yield/1000	**Non-Stochastic LRP**		**Stochastic LRP**	
Parameter	Estimate	SE	Estimate	SE
Intercept w/Nrate	5.26	0.13	4.46	0.16
Nrate linear slope	2.41	0.21	3.45	0.25
Intercept w/pH	1.57	1.43	-3.88	1.02
pH linear slope	1.07	0.28	2.46	0.22
Plateau yield	8.22	0.16	8.21	0.31
Cropyear random effect	19.77	0.65	17.23	0.64
Variance of error term	0.41	0.04	0.27	0.04
Plateau random effect			6.95	1.62
pH* at plateau yield	6.20	0.35	5.10	0.93
N* (100lbs/acre) at plateau	1.23		1.57	
-2Log Likelihood	7358.60		7349.80	

Table 3. Parameter Estimates of the Regression of Soil pH change

Dependent variable: pHt+1		
Parameter	Estimate	SE
Intercept	3.333*	0.589
Lime	0.138*	0.042
Nrate	-1.2E-4*	4.41E-5
Nrate squared	-1.39E-6*	5.2E-7
Initial pH	0.543*	0.091
Time trend	-0.039	0.053
Variance of error term	0.104	
Year random effect	0.246	
-2Loglikelhood value	314.400	

*Significant at 99% confidence level

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