IMPACT OF SOIL ACIDITY ON CROP PRODUCTION

BY

KENDRA WISE

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

2000

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2002

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Thesis Approved:

Eugene G. Krenzer, Jr.

Thesis Advisor

Hailin Zhang

John L. Caddel

Timothy J. Pettibone

Dean of the Graduate College

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to my major advisors, Dr. Gene Krenzer and Dr. Hailin Zhang, for their constructive guidance, scientific insight, inspiration, and willingness to help. My sincere appreciation extends to my other committee member Dr. John Caddel whose guidance and assistance are also invaluable.

Many thanks also to my colleagues Randy Davis, Yan Tang, and Josh Pittman for assisting me with my research. I would also like to thank Clemn Turner, Robert Mullen, Libby Dayton, and Jamie Patton for their assistance and advice over the past two years.

Lastly, I would like to thank Mike Kress, Barbara McCray and the staff at the OSU Soil, Water, and Forage Analytical Laboratory for their day-to-day advice and laboratory contributions.

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Chapter I

Relationship of Soil Aluminum Saturation and Winter Wheat Production

Abstract

Soil acidity is a major problem in north central Oklahoma an area that is primarily used for grain or forage and grain winter wheat production. This field study was conducted at the Agronomy Research Station near Perkins, OK, to determine the critical level of soil aluminum (Al) saturation for winter wheat on production induced acid soils. Soil, forage, and grain samples were collected and analyzed to establish relationships between chemical and physical properties of soil, such as soil pH, Al concentration, base cation concentration and winter wheat forage and grain yields. Soil pH ranged from 4.2 to 4.7, and Al saturation ranged from 13 to 37% of the effective cation exchange capacity. The soil texture was sandy loam with approximately 1% organic matter. Forage yields ranged from 50 to 2400 lbs/A in 2001 and 2002. Grain yields ranged from 0 to 66 bu/A in 2001, and 0 to 31 bu/A in 2002. Forage and grain yields were highly correlated with soil pH and Al saturation for both years. This suggests that winter wheat forage and grain yields are severely impacted by Al concentration in soil, and this could be used as an indicator to estimate production levels. However, this relationship

changes with respect to changes in soil texture, organic matter content, and other soil properties. More research is needed to pinpoint a critical Al saturation level for winter wheat.

Literature Review

Soil acidity is a major problem in the southern Great Plains region that is primarily used for grain, or forage and grain winter wheat production. Winter wheat (*Triticum aestivum L.*) in Oklahoma (6.1 million acres) ranked fourth in total area planted in the United States in 2000 (USDA- NASS, 2000). Over 1 million acres of hard red winter wheat suffers from possible production losses due to soil acidity in Oklahoma (Carver and Ownby, 1995). Similar problems have been reported in Kansas and Texas.

Dual-purpose wheat production enables producers to harvest forage by grazing cattle and grain from the same planting in one growing season. If nutrient requirements are met by proper fertilizer use then growth of dual-purpose wheat is affected by other soil properties, such as pH, and climatic conditions (Brensing and Lynd, 1962). With dual-purpose wheat production, forage yields in late fall and early winter could be affected more than grain yields at harvest by low soil pH.

Production induced soil acidity is a predominate issue throughout central and western parts of Oklahoma. Production induced acid soil profile suggests the higher soil acidity found at the surface is a result of high production, since the surface layer is more acidic then the subsurface layer. A statewide soil survey unveiled that 39% of the total area cropped in wheat had a soil pH below 5.5 in the surface layer (Carver and Ownby, 1995). Soil pH has declined to 4.0 or below in some areas of Oklahoma. At around soil pH 4.3, there have been reports of complete crop failure. Western Australia, Europe, South Africa, and other parts of the world have all reported areas of critically acid soils below pH 5.0 (Carver and Ownby, 1995).

Acid soils

Numerous researchers have studied different aspects of soil acidity and crop production. Soil acidity increases with time due to nitrogen fertilization, harvest of high yielding crops, rainfall and leaching of base cations, acidic parent material, and organic matter decay (Westerman, 1981). Nitrogen fertilizer containing ammonium (NH_4^+) when applied to soil will nitrify and produce H^+, which will increase soil acidity. This process could be detrimental to crop yields with continued use of these fertilizers without lime application (Westerman, 1981). Harvest of high yielding crops removes basic cations (Ca, Mg, K, and Na), which increases the acidification effect of N fertilizer use. High rainfall leads to leaching of base cations. Soils that form from granite parent material acidify faster then calcareous parent materials (Carver and Ownby, 1995). Organic matter decomposition produces carbon dioxide (CO_2), which combines with water to from carbonic acid. Then carbonic acid dissociates into bicarbonate and H^+, which increases soil acidity (Westerman, 1981).

As soil pH decreases below 5.5, aluminum (Al) and manganese (Mn) become more soluble in soil. Aluminum toxicity limits root growth thus reducing nutrient uptake, and hindering plant growth. Toxicity affects seedling development of wheat plants, and is a major source of crop failure at extremely low soil pH (<4.3) in Oklahoma (Sloan et al., 1995). Roots may eventually grow past the more acidic surface soil into less acidic subsurface and recover (Sloan et al., 1995). Manganese toxicity is caused by excess available Mn. Visual symptoms include stunting and stiffness of leaf tissue, purpling of leaves, white flecking, tip burn, and chlorosis (Ohki, 1984). It reduces dry weight production, photosynthesis, and chlorophyll (Carver and Ownby, 1995). Manganese toxicity is considered a problem in parts of eastern Oklahoma, because of the presence of Mn-oxide parent material.

Management practices that alleviate yield reducing impacts of low soil pH are lime application, use of Al tolerant wheat varieties, or banding P fertilizer with seeds. Lime application is sometimes not practiced due to lack of availability, or restrictions on leased land (Boman et al., 1993). Wheat genotypes tolerant to acidic soils and banding phosphorus fertilizers are temporary practices used to increase yields when liming is not an economical option (Bona et al., 1994; Boman et al., 1992). Eventually, acidity could reach a level beyond what Al tolerant species can accommodate (Guertal and Westerman, 1993). Boman et al. (1992) reported that banding at or below seed rather than broadcasting P fertilizer increased wheat yields even when soil test P was adequate for plant growth on a soil with a pH of 4.8 or lower. Banded phosphorus (P) precipitates

Al, and normal crop yields are achieved by reducing the reactive Al concentration in the immediate zone of application (Guertal and Westerman, 1993; Sloan et al., 1995).

Aluminum

Soil pH controls dissolution of Al hydroxy compounds in soil. Aluminum toxicity becomes a problem in soils with a pH less then 5.5 (Srivastava and Gupta, 1996). Acid forming N fertilizers exacerbates the problem of decreasing pH in intensely farmed soils. Further reduction of soil pH by any acid producing process solubilizes Al and pH becomes more acidic very rapidly and may drop to as low as 4.0 (Westerman, 1981).

The concentration of base cations (Ca, Mg, Na, K) found in soil affects how Al impacts growth of different plant types. Aluminum saturation is the percent Al that occupies cation exchange sites. Field sites with similar soil pH may produce different yields depending on Al saturation and other chemical or physical properties (Johnson et al., 1997).

Aluminum toxicity causes blunt tips on roots, premature death of leaves, lack of tillering, and purpling of leaves (Krenzer, 2000). In soils with occluded Al on clay minerals, reduction of soil pH brings Al into solution and pH drops rapidly due to the ability of Al^{+3} to produce 3 H^+ ions when hydrolyzed (Westerman, 1981). Not much is known about exact forms of Al that contribute to the toxicity. Monomeric forms of soluble Al include: Al^{3+}, $[Al(OH)]^{2+}$, and $[Al(OH)_2]^+$.

Polynuclear hydroxy-Al or "Al_{13}" is an Al species that is 10 times more rhizotoxic than monomeric forms (Guertal and Westerman, 1993).

Aluminum toxicity in winter wheat is identified by either soil analysis or identification of waning crop production (Bouma et al., 1981). However, in more tolerant crops, such as subterranean clover, Al toxicity can be identified by analyzing Al concentration in dry matter (Bouma et al., 1981). This method is useless in finding Al critical levels in winter wheat, because reactive Al affects roots not shoots (Carver and Ownby, 1995).

Researchers have studied the inverse correlation between plant growth and exchangeable Al levels, however it is hard to assume a value for this relationship. Critical Al saturation level is defined as a range or threshold above which a decrease in yield has occurred (Bouma et al., 1981). One reason for the difficulty in defining critical Al saturation is the lack of consistency in research, and variance between species tolerance and location. Several researchers have reported critical levels using different units and methods. Exchangeable Al (1 M KCl) critical to cotton is 0.1- 2.5 cmol kg^{-1} (Kapland and Estes, 1985) depending on soil characteristics. Critical level of Al saturation for alfalfa is 3 to 20 percent of the CEC (Lanyon and Griffith, 1988; Hutchinson and Hunter, 1970). Johnson et al. (1997) found that an Al tolerant variety of winter wheat was favorable at sites with an Al saturation level above 12%.

Studies have indicated that soils classified in different Great groups respond differently to liming because differences in clay mineralogy cause a variance in buffer capacity (Chartres, 1990). There is not much known on how soil factors affect Al toxicity to crops whether or not critical levels of exchangeable Al or Al saturation are different for each soil is not well documented for winter wheat. Characterizing different soil types by percent Al saturation may show a correlation between exchangeable Al and wheat yields. Therefore, several factors affecting Al solubility in soils need to be addressed including soil pH, base cation concentration, organic matter, and texture.

Soil organic matter influences the concentration of soluble Al that is in soil. Studies showed that an increase in soil organic matter led to a decrease in exchangeable Al (Evans and Kamprath, 1970; Kapland and Estes, 1985), because organic acids (e.g., humic acid) chelate with Al at a soil pH between 3.8 and 5.0 which decreases exchangeable Al in soil (Srivastava and Gupta, 1996). Kapland and Estes (1985) showed that the critical Al level of alfalfa correlated with soil organic matter levels, and as soil organic matter increased critical Al level also increased, but at Al levels greater than 15 ppm, organic matter did not reduce effects of Al stress.

Soil texture affects concentration of exchangeable Al in soil. Clayey soils have a higher cation exchange capacity (CEC) than sandy soils; therefore, clayey soils retain a greater concentration of exchangeable Al (Srivastava and Gupta, 1996). In low pH soils, Al^{+3} has the potential to produce 3 H^+ when hydrolyzed. Aluminum (Al^{3+}) can react with water and form aluminum hydroxide ($(Al(OH)^{2+}$) and hydrogen acidity (H^+) which can be hydrolyzed two more times to form $Al(OH)_3$ and two more H^+ ions (Westerman, 1981).

Thus far, studies have shown that Al concentration in soil affects continuous winter wheat growth and that as pH decreases Al concentration increases. In addition, studies have shown that Al saturation is a better indication of possible damage to winter wheat crop production then Al concentration alone, because base cation concentration influences to what degree Al concentration affects roots. However, it is unclear by how much forage and grain yields are affected by the degree of Al saturation, or if there is a critical level that can be identified to aid in lime recommendations. Additionally, it is unknown how various soil chemical or physical properties affect Al saturation and winter wheat yields.

Objectives

1. To characterize a production induced acid soil in Oklahoma by its soil chemical and physical properties such as pH, Al saturation, base cation concentration, organic matter content, and texture;
2. To establish a relationship between acid soil properties and winter wheat forage and grain yields;
3. To identify the critical Al saturation level for wheat production.

Materials and Methods

Site Identification

This study was conducted on a Teller fine sandy loam soil (fine, loamy, mixed, active, thermic, Udic Argiutolls) planted with winter wheat at Agronomy Research Station near Perkins, OK. The field was chosen because of spatial variability in wheat growth possibly due to variable and low soil pH in the study area. Fertilizer, 100-0-30, was broadcasted pre-plant and incorporated in 2001 and 2002. 'Custer' was planted at a rate of 120 lbs/A on September 12, 2001 and on October 5, 2002. Normalized Difference Vegetative Index (NDVI) was measured in March of 2001 to show variability of wheat growth in the field (Lukina, 2000). Winter wheat growth ranged from very poor (nearly no vegetation) to normal with no apparent pattern on the field (Figure 1.1).

In 2001, 15 areas (about 100 square feet each) in the field were sampled based on visual ratings of crop growth (poor, moderate, and good) to identify the problem (Figure 1.2). In 2002, transects in the field were selected, based on early plant growth, ranging from 6 to 46 feet long and 2 rows (8 inches) wide (Figure 1.2). Transects were placed in the field to follow the growth gradient from normal to poor (Figure 1.1). Soil, forage, and grain samples were taken in 3-foot increments.

Soil Sampling and Analysis

In 2001, depth soil samples (0-6, 6-12, 12-18, 18-24 inches) were taken at three areas and remaining areas were surface samples (0-6"). In March 2002, soil samples (0-6") were collected within transects in 3 foot segments. Soil samples were oven dried at 65°C and ground to pass a 2-mm sieve. Soils were extracted with appropriate extract, and shaken on a rotary shaker (~210 rpm) then filtered.

Exchangeable Al was extracted with 1.0 M KCl and analyzed using inductively coupled argon plasma (ICAP) atomic emission spectroscopy. The soil to solution ratio was 1:15 (Bertsch and Bloom, 1996). Extractable Al was extracted with 0.01 *M* $CaCl_2$ and analyzed using ICAP. Soil to solution ratio was 1:2. Base cations (Ca, K, Mg, Na) and Mn concentrations were determined using 1.0 M ammonium acetate extraction with a 1:10 soil to solution ratio, and quantified by ICAP. Effective cation exchange capacity (ECEC) was determined by equation [1] (Sumner and Miller, 1996).

$$\text{ECEC (meq./ 100g)} = [\text{Ca}] + [\text{Mg}] + [\text{K}] + [\text{Na}] + [\text{Al}_{KCl}] \qquad [1]$$

Al saturation was calculated using equation [2] (Sumner and Miller, 1996):

$$\%\ \text{Al saturation} = (\text{Al}_{KCl} / \text{ECEC}) * 100 \qquad [2]$$

Soil pH was determined by using a pH meter and combination electrode in 1:1 soil to water suspension (Thomas, 1996). Soil nitrate nitrogen (NO_3-N) was measured on a flow-injection analyzer by using 0.008 M $(Ca)_3(PO_4)_2$ extracting solution in a 1:2.5 soil to extract ratio (Mulvaney, 1996). Plant available potassium (K) and phosphorus (P) were analyzed using Mehlich 3 extractant at a 1:10 soil to extract ratio (Mehlich, 1984). Soil texture was determined using the Hydrometer method (Gee and Bauder, 1996). Soil organic matter was determined by using the dry combustion method (Nelson and Sommers, 1996).

Wheat Forage and Grain Harvesting and Analysis

Forage was collected once in March 2001. Yield was determined by harvesting an 8 in. by 39 in. visibly uniform region by clipping to soil surface. All samples were dried in an oven at 85°C and ground to pass through a 1mm screen. Nitrogen concentration in forage was determined by dry combustion (NFTA, 1993). Grain yield was determined by combining a 5 ft. by 25 ft. area from a visually uniform region including forage sampling sites.

In March 2002, forage was collected by clipping to the soil surface in 16 in. by 39 in. segments. Grain was harvested by hand in June 2002, heads of wheat were cut off in the same segments where forage was previously harvested.

Relative winter wheat yield of each sampling unit were calculated by dividing the actual yield by the maximum yield in the respective year, and multiplying by 100. Relative yields were used to correlate with pH and Al saturation.

Statistical Analysis

Simple linear regression was used to correlate many soil characteristics with each other as well as soil pH and percentage of Al saturation with forage and grain yields. The significance of correlations were expressed by coefficient of determination, r^2 value.

RESULTS AND DISCUSSION

Soil pH Changes with Depth

Soil pH can change several ways throughout the profile. The pH could be constant throughout the profile, pH could be higher in the surface soil than the subsurface, or the surface soil pH could be lower then the subsurface. Figure 1.3 shows the typical change in soil pH with increasing depth for three scenarios. Production induced acidity is recognized by its unique drop in pH within the first 6 inches of the soil profile. Then soil pH increases gradually to the native pH as depth increases. This relationship between soil pH and depth in this situation is different from other naturally occurring acidic soils where subsoil has a lower pH then surface soil or pH is constant throughout the profile. This illustrates the importance of knowing the nature of pH change in the soil profile to enable identification of the depth roots would have to reach to possibly recover from negative effects of low soil pH (Sloan et al., 1995).

Payne County Soil Survey documents for a Konawa and Teller soil a native surface pH of 5.1-6.5 at the research site. The present subsoil pH of 5.7 corresponds to the native pH. However, the lowest surface soil pH found at this site was 4.2, far below native pH. The difference in native pH and present pH suggests that over time soil pH has dropped significantly probably due to removal of cations and fertilizer use. The change in pH with depth is what would be expected with production induced soil acidity.

Relationship between Soil pH and Aluminum

Exchangeable Al (Al_{KCl}) and extractable Al (Al_{CaCl_2}) were highly correlated with soil pH (r^2=0.85 and r^2=0.81, p<0.01) (Figure 1.4). Soil pH ranged from 4.2 to 4.7, exchangeable Al ranged from 100 to 50 mg kg^{-1}. This is a significant decrease in exchangeable Al concentration with only a five-tenths increase in pH.

There was a highly significant (r^2=0.82 and r^2= 0.86, p<0.01) linear relationship between soil pH and Al saturation for 2001 and 2002 (Figure 1.5). As soil pH increased, percent Al saturation decreased. This relationship between percent Al saturation and soil pH is similar to results from past studies (Chartres et al., 1990; Evans and Kamprath, 1970; Hutchinson and Hunter, 1970). There was a shift in pH from 2001 to 2002; this is probably due to a natural decrease in pH over time and different sampling methods. The relationship between soil pH and Al changes depending on chemical and physical properties of soil such as texture, base cation concentration, and organic matter content. Therefore, Al concentration must be analyzed for every location.

Impact of Acid Soil Properties on Forage and Grain Yields

The varying Al saturation levels may be affected by different soil chemical and physical properties such as pH, texture, base cation concentration, and organic matter content. The variation of soil properties is the source of difficulty in determining a critical Al saturation level effect on winter wheat production. Soil samples were collected and analyzed to determine the effect of these properties on Al saturation.

At this site, the range in pH had a significant impact on winter wheat forage and grain yields. In 2002, as pH ranged from 4.7 to 4.2, Al saturation ranged from 15 to 30%, and this caused a decrease in forage yields from 2400 lbs/A to 60 lbs/A and grain yields from 31 bu/A to 0 bu/A.

Calcium and Mg largely affected percent Al saturation. Exchangeable Ca had a highly significant correlation (r^2=0.43, p<0.01) with relative forage yields for 2002 (Figure 1.6), and with Al (r^2=0.27, p<0.01) (Figure 1.7). This shows that at a low soil pH, as Ca concentration increased Al concentration decreased and yields increased. Similar to Ca, exchangeable Mg had a highly significant relationship with relative forage yields (r^2=0.58, p<0.01) (Figure 1.6). Figure 1.8 shows a highly significant (r^2=0.61, p<0.01) linear correlation between Mg and Al concentration in soil. This demonstrates that at a low soil pH, as Mg concentration increased Al concentration decreased and forage yields increased. However, there is no significant relationship between relative forage yields and exchangeable K or Na. Further investigation is needed to determine if Ca or Mg measurement could be used to estimate Al saturation at low soil pH, since Ca and Mg are much easier to determine in a laboratory than Al saturation.

Organic matter contributes additional exchange sites to soil. When organic acids chelate with Al at low soil pH, concentration of soluble Al in soil decreases. This site had 1% organic matter, which is considered low. This could be a reason why percent Al saturation is so high. Evans and Kamprath (1970) found that organic soils, with greater than 25% organic matter, had an Al saturation of 16 to 32% when compared to a mineral soil with 2 to 4% organic matter with around 70% Al saturation. However, more research is needed to find a correlation between organic matter and Al saturation for a given soil pH. Therefore, these results suggest that a production induced acid soil with sandy texture, low base cation concentration, and low organic matter could have a high Al saturation level, which may affect production of winter wheat more than wheat grown in heavy soils.

Effect of soil pH and Al on Winter Wheat Production

A digital picture of the site (Figure 1.2) shows variation in plant growth in the field caused by soil pH. Soil, forage, and grain samples were analyzed to find trends between soil pH, Al saturation, and crop yield. The results show a highly significant correlation (r^2=0.35, $p<0.01$) between soil pH and relative forage yields for 2001 and 2002 (Figure 1.9a). As the pH range increased from a low of 4.2, forage yields increased also. This demonstrates that yields are dependent on soil pH, as other studies have shown (Westerman, 1981; Boman et al., 1993).

As pH decreased, Al saturation increased causing decreased forage yields. As percent Al saturation increased, relative forage yield for 2001 and 2002 decreased linearly (r^2= 0.69, $p<0.01$) (Figure 1.10a). This suggests that winter wheat forage yields are affected by the amount of active Al in soil, and this is consistent with what other studies have shown (Boman et al., 1992).

The effect of soil pH on grain yields was similar to forage yields. Figure 1.9a shows a highly significant correlation (r^2=0.24, p<0.01) between soil pH and relative grain yields for 2001 and 2002. As the soil pH increased from a low of 4.2, grain yields increased also. Therefore, this demonstrates that grain yields are dependent on soil pH as other studies have shown (Westerman, 1981; Boman, 1993).

Aluminum saturation had a similar effect on winter wheat grain yields (Figure 1.10b), Al saturation increased and caused grain yields to decrease for 2001 and 2002 (r^2=0.56, p<0.01). This suggests that winter wheat grain yields are also affected by Al saturation. However, due to differences in soil physical and chemical properties, and their effect on Al saturation it is difficult to determine a critical Al saturation level for winter wheat forage.

Conclusion

Production induced acid soils are common in Oklahoma, and are characterized by a drop in soil pH within plow layer of soil. The use of a soil pH profile could be useful to production farmers to identify appropriate management practices to remediate soil acidic problem. The soil used in this study was a production induced acid soil with sandy texture, low base cation concentration, and a low organic matter (around 1%). A soil with these same soil properties is likely to have a winter wheat production problem at a soil pH below 5.0 due to Al toxicity.

At this site, a range in pH from 4.7 to 4.2 was associated with Al saturation from 15 to 35% in 2002. The increase in percent Al saturation caused a decrease in forage yields from 2500 to 50 lbs/A and a 31 to 0 bu/A decrease in grain yields. This is a significant drop in production caused by a five-tenths drop in pH.

In this study, concentration of Ca and Mg seemed to be an important soil chemical property controlling Al saturation. Results show that as exchangeable Ca and Mg increased winter wheat forage and grain yields increased. Therefore, because other soil properties, texture and organic matter, were more uniform throughout the site they did not have a great impact on variation. More research is needed to pinpoint their role in this problem. This information may be useful to future field experiments on Al saturation and winter wheat. It is difficult to pinpoint a critical Al saturation level due to physical properties of soils in question.

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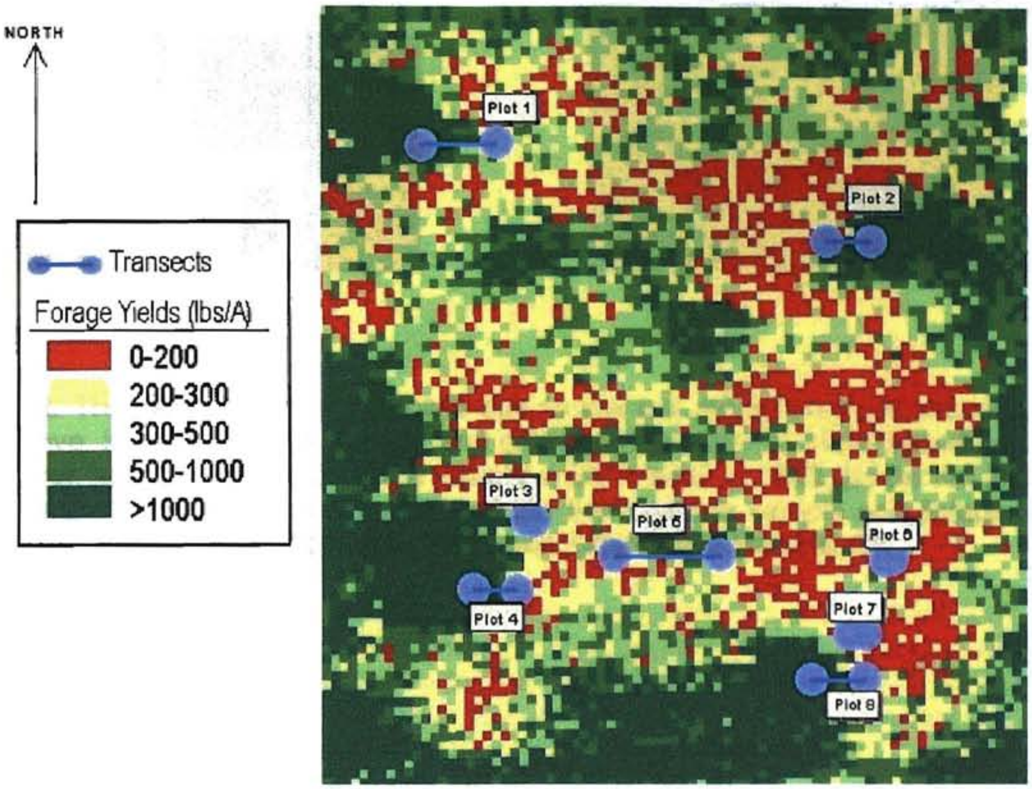
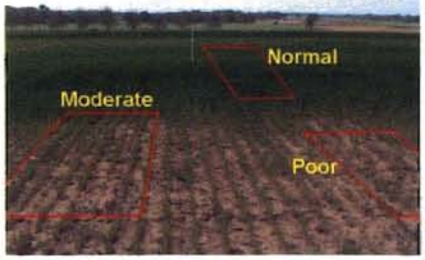


Figure 1.1. Digital picture of Perkins site showing variability in stand growth and locations of sampled transects. Normalized Difference Vegetative Index (NDVI) sensors were used to find variability in field. The transects are located in areas from normal growth to poor growth.

a) 

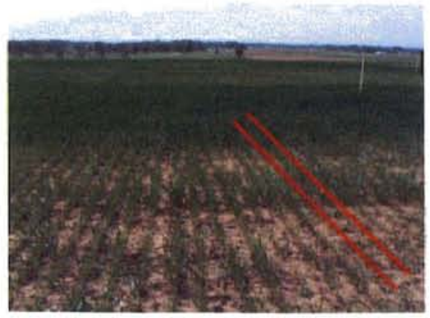
b) 

Figure 1.2. The variability in crop growth due to low soil pH and high Al saturation is shown above. In 2001, (a) soil, forage, and grain were sampled in areas based on crop growth (poor, moderate, and good) in a visually uniform area. In 2002, (b) the red lines in the picture are an example of a transect of the field used to sample soil, forage, and grain in 3 foot increments at Agronomy Research Station near Perkins, OK.

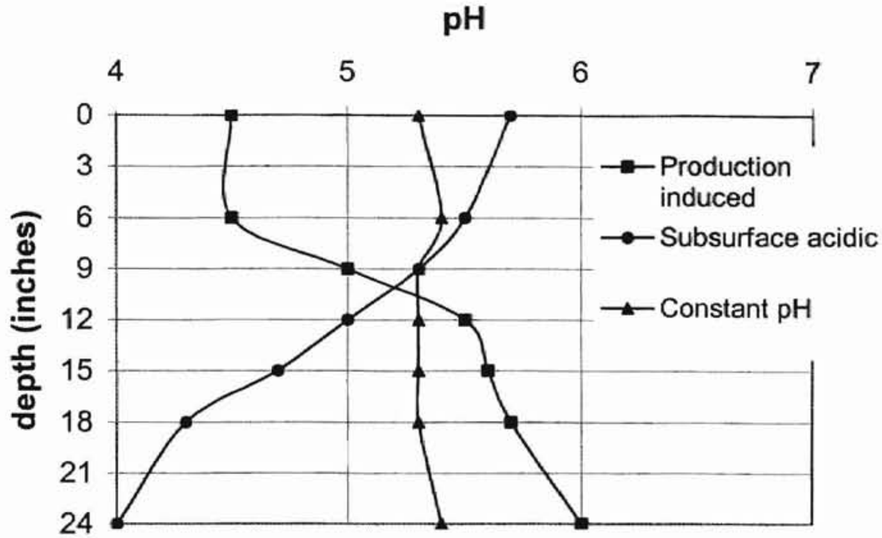


Figure 1.3. Typical profiles of soil pH. The production induced acid soil profile suggests soil acidity found at the surface is a result of high production, since the surface layer is more acidic than the subsurface layer (results from Perkins, OK. March 2001). This relationship is different from other naturally occurring acidic soils where subsoil has a lower soil pH then surface soil or soil pH is constant throughout the profile.

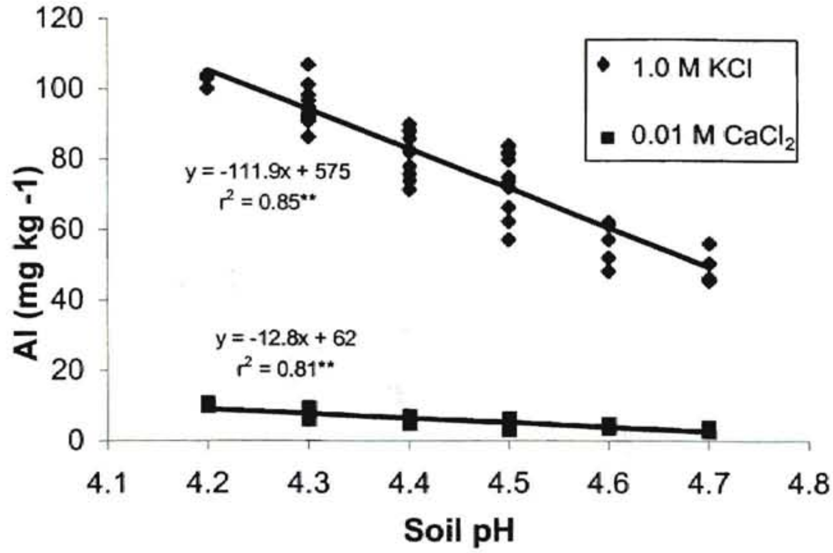


Figure 1.4. Relationships between Al extracted with 1.0 *M* KCl and with 0.1 *M* $CaCl_2$, and soil pH, Perkins, OK. 2002

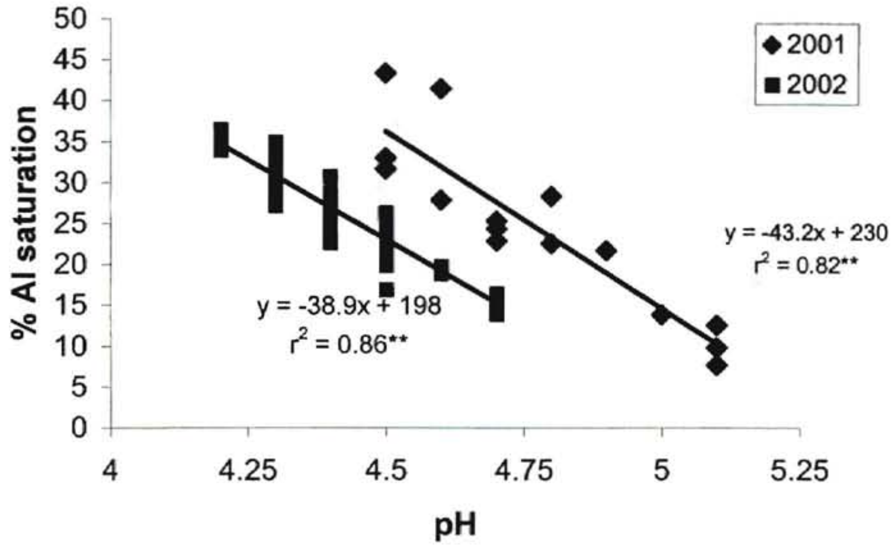


Figure1.5. Relationships between percent Al saturation and soil pH, Perkins, OK. 2001-2002.

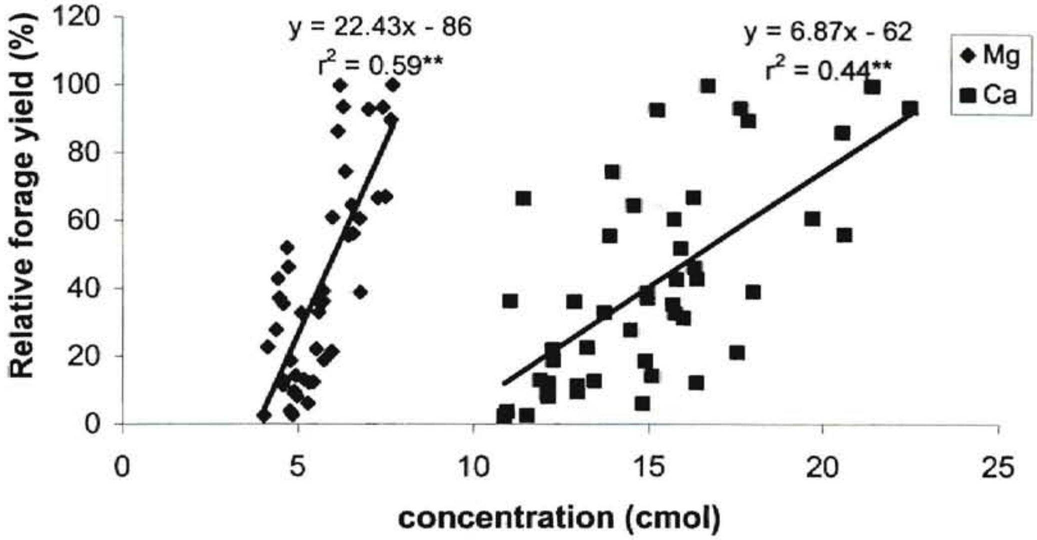


Figure 1.6. In low pH soils, as availability of base cations, such as Ca and Mg, increase forage yields also increase, Perkins, OK. 2002.

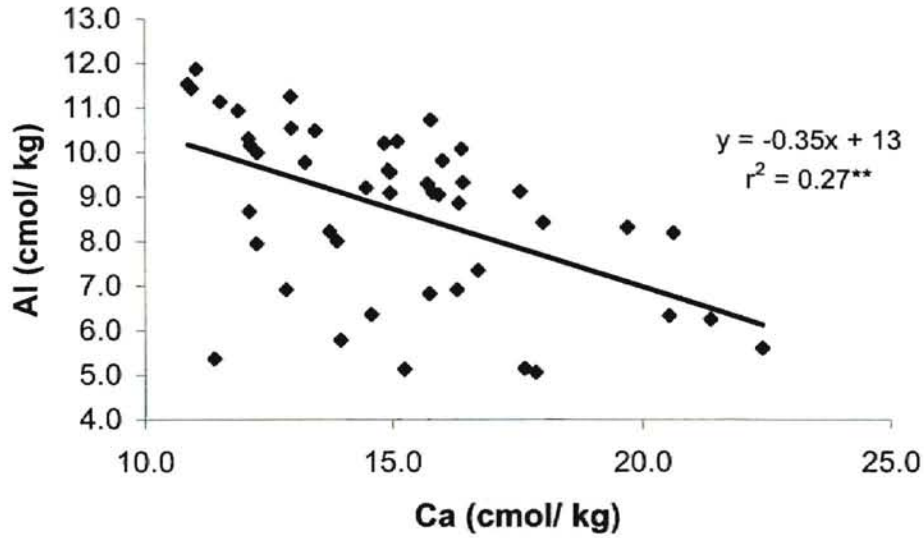


Figure 1.7. Relationship between exchangeable Ca and exchangeable Al, Perkins, OK. 2002.

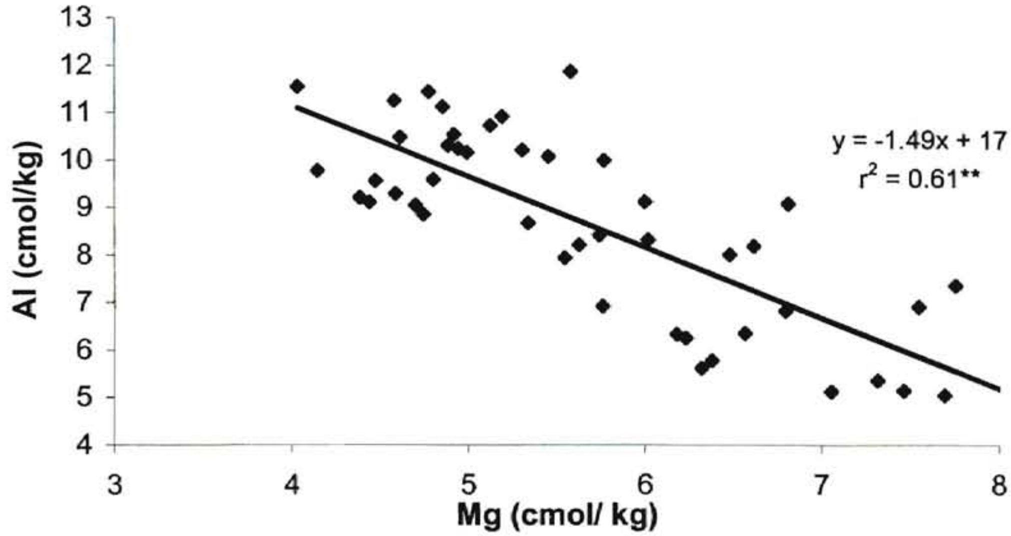


Figure1.8. Relationship between Mg and Al concentrations in soil, Perkins, OK. 2002.

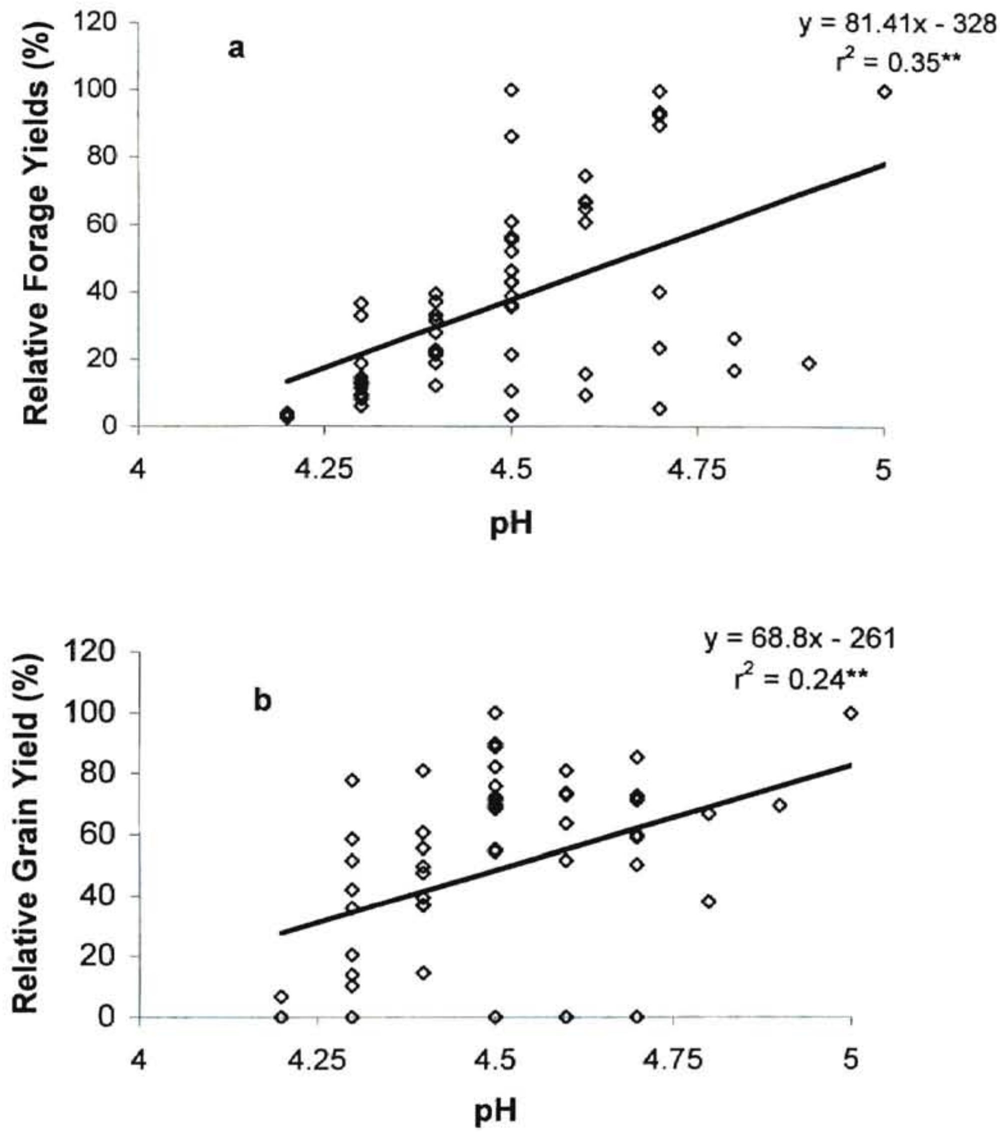


Figure1.9. The relationship between relative winter wheat forage yield (a) and grain yield (b) and soil pH for 2001 and 2002, Perkins, OK.

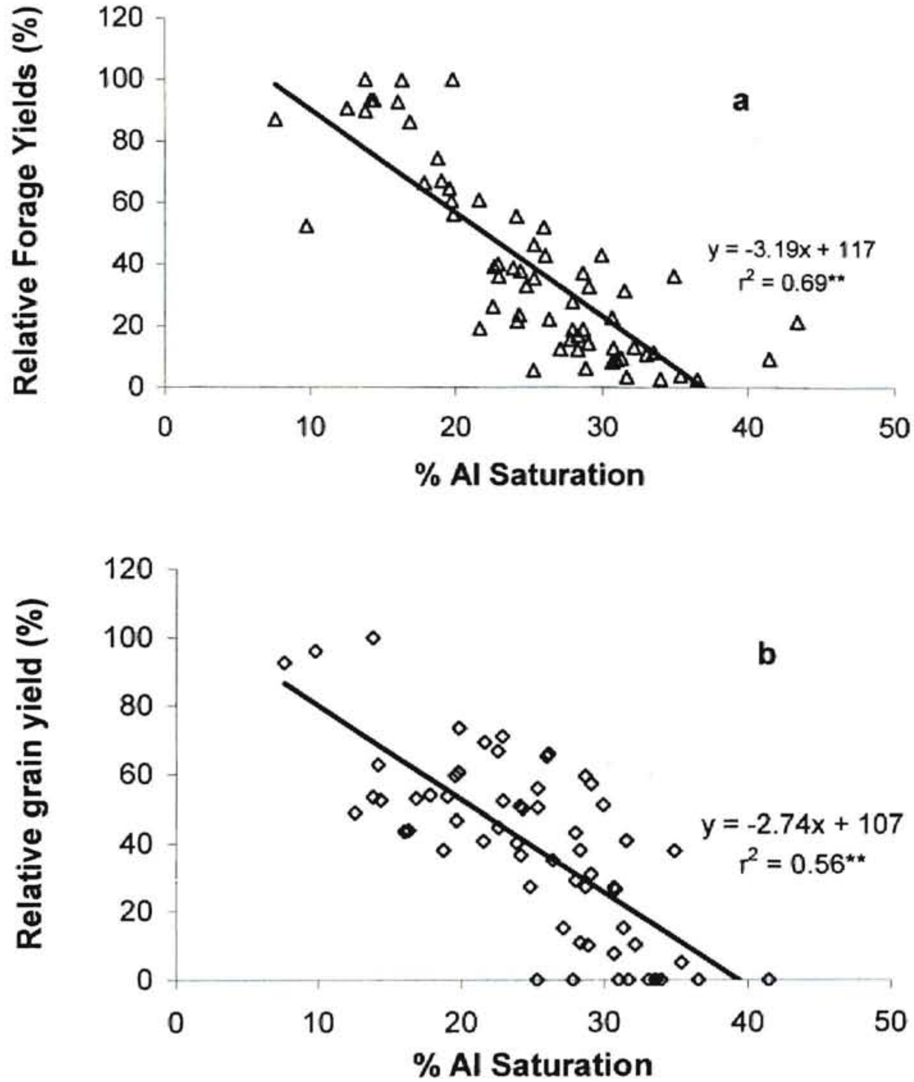


Figure 1.10. Relationship between percent Al saturation and relative winter wheat forage yields (a) and grain yields (b) for 2001 and 2002, Perkins OK.

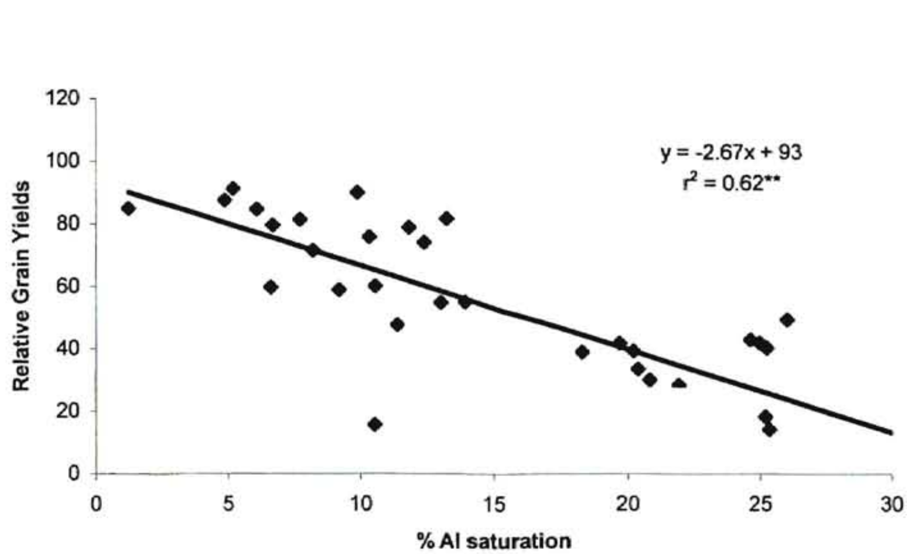
Appendixes

Appendix A. Soil pH, Al saturation, forage, and grain yield results for the first year at Perkins, OK., 2001.

Sample Location	pH	Al saturation	Forage	Grain
		%	lbs/A	bu/A
1	4.8	28.4	431	25
2	4.5	31.7	85	0
3	5.1	7.6	2245	61
4	5.1	12.6	2337	32
5	4.6	41.4	237	0
6	4.8	22.6	678	44
7	4.5	33.0	274	0
8	4.6	27.9	401	0
9	4.7	24.3	605	33
10	4.7	25.3	140	0
11	4.5	43.4	550	36
12	5.1	9.8	1352	63
13	5.0	13.9	2581	66
14	4.7	22.9	1035	47
15	4.9	21.7	493	46
Mean	4.8	24	896	30

Appendix B. Soil pH, Al saturation, forage, and grain yield results for the second year at Perkins, OK, 2002.

Sample Location	pH	Al saturation	Forage	Grain
		%	lbs/A	bu/A
101	4.7	14.4	2214	22
102	4.7	16.4	2365	18
103	4.5	16.9	2043	22
104	4.5	21.6	1444	17
105	4.5	19.9	1332	31
106	4.4	22.6	930	19
107	4.4	24.2	507	15
108	4.3	29.1	777	24
109	4.3	27.1	294	6
110	4.3	28.9	143	4
201	4.4	28.3	287	5
202	4.4	26.4	522	15
203	4.5	22.9	856	22
204	4.6	19.6	1531	25
205	4.6	18.8	1766	16
206	4.7	16.1	2196	18
301	4.3	34.9	862	16
401	4.5	19.8	2369	25
402	4.6	19.1	1588	23
403	4.5	24.1	1316	21
404	4.5	23.9	919	17
405	4.4	28.7	445	11
416	4.3	32.1	309	4
501	4.3	31.3	224	6
502	4.3	29.1	340	13
503	4.3	28.0	441	18
504	4.4	28.7	880	25
505	4.4	31.5	746	17
506	4.5	30.0	1018	22
507	4.5	26.0	1233	27
508	4.5	25.4	1097	21
509	4.5	26.1	1016	28
510	4.5	25.3	840	23
511	4.4	28.0	658	12
512	4.4	30.7	538	11
513	4.3	30.8	303	11
514	4.3	15.7	270	0
601	4.2	36.5	59	0
701	4.2	33.9	64	0
702	4.2	35.3	90	2
801	4.7	14.2	2209	26
802	4.6	17.9	1577	23
803	4.7	13.9	2126	22
804	4.6	19.7	1437	20
805	4.4	24.8	781	11
806	4.3	30.7	193	3
807	4.3	31.0	215	0
Mean	4.4	25	965	16



Appendix C. Relationship between relative winter wheat grain yields and percent Al saturation near Lahoma, OK. North Central Research Station on a Grant silt loam (fine-silty, mixed, thermic, Udic Argiustoll). 2002.

Chapter II
Relationship of Lime Treatments and Mo, Ca Fertilizer to Three Legume Species

Abstract

Legume crops are important forages for livestock production, but yield and quality of legume crops are affected by soil acidity. This study was conducted to determine the effect of lime on red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), and alfalfa (*Medicago sativa L.*) forage production on an acid soil. In addition, the effect of molybdenum and calcium fertilizer on alfalfa forage yields was examined. In April 2000, 0.40, 0.72, 1.20, 2.04, and 3.68 tons per acre (t/A) of effective calcium carbonate equivalent (ECCE) were applied to plots. Red clover (Kenland), white clover (Regal Ladino), and alfalfa (Cimarron VR) were planted in September 2000. Calcium chloride and sodium molybdate fertilizers were applied to the lowest lime treated (0.4 t/A) alfalfa plots. Soil samples were collected and analyzed for pH and other nutrients twice a year for two years. Lime increased soil pH for 14 months, and then pH stabilized or slowly declined. Lime application did not affect legume seedling density, but liming did suppress weed population. The legume species reacted differently to lime treatments. Red clover and alfalfa had a significant increase in yields with

increasing pH, but white clover did not respond to lime with an increase in yields above a pH of 5.2. Alfalfa yields did not increase with additions of Ca or Mo fertilizer.

Literature Review

Acidic Soils and Agriculture

An issue that is predominate throughout the central part of the state is production induced acidic soils. Soil acidity is damaging to crop production because it causes a decrease in plant growth, and deficiencies in calcium (Ca), magnesium (Mg), and molybdenum (Mo) (Carver and Ownby, 1995; Lanyon and Griffith, 1988). Soil pH decreases with time due to N fertilization, rainfall, leaching, acidic parent material, organic matter decay, and harvest of high yielding crops (Westerman, 1981).

The optimum pH for plant growth varies among crop species and soil types based on percent organic matter, soil texture, and other chemical properties of soil (Lanyon and Griffith, 1988). There are several benefits to maintaining proper soil pH for crop production by applying lime such as a decreased solubility of toxic elements, aluminum (Al) and manganese (Mn), improved nitrogen (N) fixation by legumes, and an increased availability of essential nutrients (Mo, Ca) and percent base saturation (Lanyon and Griffith, 1988; Haynes and Ludecke, 1981a and b). Lack of available Mo causes a decrease in rhizobium activity at low pH (Lanyon and Griffith, 1988). Legume yield reduction under different soil acidity was not well documented.

Aluminum and Mn toxicity is caused by an increase in solubility of these two elements at low pH. Studies have suggested Al levels at less than 20% of the CEC are ideal for alfalfa production (Mochler et al., 1960; Foy, 1964). Soils with higher Al saturation levels have to be managed differently to receive optimum yields. Hutchinson and Hunter (1970) found alfalfa growth was restricted in soils with Al levels at 25% of the CEC. Al toxicity limits root growth thus reducing nutrient uptake, and hindering plant growth. Visual symptoms of Mn toxicity include stunting and stiffness of leaf tissue, purpling of leaves, white flecking, tip burn, and chlorosis (Carver and Ownby, 1995).

Elevated Mn level in low pH soils generates deficiency in Ca, Mg and Iron (Fe) (Srivastava and Gupta, 1996), and produces toxicity (Giddens and Morris, 1982). Deficiencies in Ca can lead to a lower critical level for manganese toxicity than usually found, which will hinder growth of legumes (Munns and Fox, 1977). Manganese toxicity is a problem in eastern Oklahoma, because of Mn-oxide in the parent material in this area.

Red Clover Production

In eastern Oklahoma, red clover (*Trifolium pratense* L.) is grown in mixtures with grasses or small grains in areas that are generally too shallow or to acidic for alfalfa. This legume is used for hay and grazing, and is the highest yielding clover due to a long growing season (Redmon et al., 1996). Red clover is not tolerant to low phosphorus (P) or potassium (K) in soil. Inadequate P causes a reduction in yields and difficulty establishing a stand. Red clover could grow well at a pH of 5.0 to 6.0 if all nutrient needs are satisfied, but a pH above

6.0 and adequate Ca is needed for maximum yields (Taylor and Smith, 1995). This crop is sensitive to manganese toxicity, which is a concern when pH is below 5.7 in some soils.

White Clover Production

White clover (*Trifolium repens* L.) is one of the most useful forage legumes in Oklahoma. This legume is used with grasses for hay, silage, and in pastures. Optimum pH for white clover is 6.5 with adequate K and P, and if these needs are not met, stands are not productive. Research shows root growth, shoot growth, and N fixation increased as pH increased to 6.0 (Andrew, 1976). This would suggest that pH of 6.0 is adequate if other nutrient needs are met for white clover production. Haynes and Ludecke (1981b) determined that increasing lime application would increase N concentration and nodulation of white clover. Munns and Fox (1977) suggested that white clover needs less lime than alfalfa, and white clover is more tolerant to Mn toxicity than alfalfa (Andrew and Hegarty, 1969) due to the ability of white clover to not retain Mn in roots.

Alfalfa Production

Oklahoma had 352,000 acres of alfalfa (*Medicago sativa L.*) planted in 2000 (Oklahoma Agricultural Statistics Service, 2001). Alfalfa productivity is enhanced on deep, fertile, well-drained loamy or sandy loam soil found along creek and river bottoms. Alfalfa crops require large quantities of water so a soil with adequate clay and organic matter is needed to increase water-holding capacity of soil if irrigation is not available. However, this crop does not survive well in waterlogged soils due to poor aeration, root rot diseases, and inhibited N fixation (Caddel et al., 1993). The ideal pH range for alfalfa is between 6.6 and 7.5 (Lanyon and Griffith, 1988).

Soil characteristics and fertility levels are important factors for alfalfa yields and stand longevity (Lynd and Murphy, 1964). Alfalfa removes large amounts of nutrients, such as Ca, K, and P, from soil even at average yields, when compared to crops harvested for grain. Many nutrients require replenishing by fertilization before planting and after establishment to optimize alfalfa production (Lanyon and Griffith, 1988). Nutrient deficiencies and low soil pH decrease yields, shorten stand life of the crop, and reduce alfalfa competitiveness against weeds (Caddel et al., 1993).

Soil pH is important to legume establishment. Liming to a pH of 6.5 is not necessary when soils have a high buffer capacity and there is ample Ca and Mg (Hutchinson and Hunter, 1970). If the accepted optimum pH for alfalfa is 6.6 to 7.5, but there is no significant increase in yields above 6.1 then liming to 6.6 in not needed for production.

Molybdenum Fertilizer

Molybdenum is a micronutrient essential to alfalfa and other legume crops for N fixation process, and its availability decreases as soil pH decreases (Lanyon and Griffith, 1988). This nutrient is deficient in soils with pH below 5.5, course-textured soils, or soils with low organic matter content (Lanyon and Griffith, 1988; Srivastava and Gupta, 1996). The effects of Mo fertilizer on forage legume crop yields has not been thoroughly studied due to difficulty in distinguishing between Mo deficiencies and other fertility problems such as Al and Mn toxicity and Ca and Mg deficiencies (Adams, 1997), although it is known that clover and alfalfa respond to Mo (Gupta and Lipsett, 1981). Liming legumes increased yields partially due to an increase in Mo availability (Gupta and Lipsett, 1981).

Research showed Mo fertilizer increased yields of soybeans on unlimed acid soils (pH: 5.4 to 6.4). Using 0.2 pounds per acre of Mo on soybean plots was as effective on increasing yield as 2 tons of lime per acre (Parker and Harris, 1962). Scott (1963) observed that 1 oz. per acre of sodium molybdate with 500-1000 lbs. of lime produced similar clover yields to 2-3 tons of lime. Scott (1963) investigated the effect of sodium molybdate applied to a soil (pH of 5.7) on white clover and red clover yields over a period of seven years. The researcher found that maximum yields occurred for both crops at rates above the 1 oz. treatment, and recommended reapplication after 5 to 6 years. These studies suggest that adding Mo fertilizer to legumes grown in a low pH soil (eg., pH < 5.7) could increase yields.

Calcium Fertilizer

Alfalfa yielding 6 to 7 t/A takes up about 900 lbs/A of Ca. Calcium deficiencies exacerbate negative effects of soil acidity. Addition of Ca fertilizer may also benefit the crop by providing an essential nutrient that is deficient at low pH. Lynd and Murphy (1964) reported alfalfa plants could grow in a solution culture at a pH as low as 4.0 when Ca is adequate if no other nutrient deficiencies exist.

Lynd and Murphy (1964) studied alfalfa yield response to additions of K, Ca, and Mg to illustrate the importance of nutrient balance for alfalfa production, because limitations are evident when using soil pH as the single criteria for lime and fertilizer application. The Waynesboro Loam soil (pH 6.0) showed a slight increase in yields with additions of Ca. Alfalfa grown on a Port loam soil (pH 5.0) received highest yields with high Ca treatments. This suggests that at a low soil pH additions of Ca fertilizer could increase yields, but more research is needed to quantify benefits of Ca fertilization under field conditions.

Research has shown optimum environmental conditions for legume growth. However, it is unknown how legume growth responds to different acidic pH levels, for example, if yields are similar at a pH of 5.0 and 6.0. Other studies have suggested that at a low pH, fertilizer can be added to soil to make up for nutrient deficiencies, like Ca or Mo, causing yields to increase (Lynd and Murphy, 1964; Scott, 1963; Parker and Harris, 1962). However, this method is not well defined and it is not known at what pH adding additional Ca or Mo fertilizer increases yields.

Objectives

1. To determine the effect of lime rates on alfalfa, white clover, and red clover forage production on an acid soil;
2. To study the effects of Ca and Mo fertilizers on alfalfa forage yields at pH below 5.5;

Materials and Methods

Lime and Fertilizer Treatments

Experiments were conducted on a Taloka silt loam soil (Fine, mixed, active, thermic Mollic Albaqualfs) with a mean initial pH ranging from 4.1 to 5.4 at the Eastern Research Station near Haskell, OK. The five treatments were replicated four times (Figure 2.1). The plot size was 24 X 33 feet with 15-foot wide alleys running North-South and 20 feet wide running East-West.

On April 14, 2000 the following rates of granulated bagged lime: 0.40, 0.72, 1.20, 2.04, and 3.68 tons effective calcium carbonate equivalent (ECCE) per acre was applied to plots with a fertilizer spreader and incorporated to a depth of about 6 inches. These lime application treatments became the mainplots of a split-plot design experiment. On September 29, 2000, red clover (Kenland), white clover (Regal Ladino), and alfalfa (Cimarron VR) were planted as subplots in each mainplot at 12, 5, and 18 lbs/A, respectively. At the time of planting, additional treatments of sodium molybdate (1 lbs/acre Mo), and calcium chloride (50 lbs/acre Ca) were added to the lowest lime treatment plot (0.4 t/A lime) of alfalfa. Mo and Ca fertilizer was incorporated into the top 0.5 inches of soil. For the second year of the study, calcium chloride fertilizer was hand broadcasted onto the plot once, 10 days after the first cutting of 2002. Sodium molybdate was dissolved in deionized water and applied using a hand-held sprayer to the lowest treatment of alfalfa (Segars, 1981), approximately 10 days after the first, second, and third cutting.

In March 2001, weeds and legume seedlings were counted in each plot. Weeds were identified in three 8 x 18 inch areas per plot as Italian ryegrass (*Lolium multiflorum* Lam.), rattail fescue (*Vulpia myuros* (L.) K.C.Gmel), henbit (*Lamium amplexicaule* L.), mustard (*Brassica* spp.), cutleaf evening primrose (*Oenothera laciniata* Hill), stickychick weed (*Cerastium glomeratum* Thuill.), and miscellaneous. Legume seedling samples were collected in three 8 x 18 inch areas inside each plot by removing the top 1 inch of soil with the plant, cleaned, and weighed.

Soil Sampling and Analysis

Soil samples consisted of 15-20 core samples to a depth of 0-6 inches and were collected from individual plots. Soil samples were oven dried at 65°C and ground to pass a 2-mm sieve. Soils were extracted with the appropriate extract, and shaken on a rotary shaker (~210 rpm) then filtered.

Exchangeable Al was extracted with 1.0 M KCl and analyzed using an inductively coupled argon plasma atomic emission spectroscopy (ICAP). Soil to solution ratio was 1:15 (Bertsch and Bloom, 1996). Base cations (Ca, K, Mg, Na) and Mn concentrations were determined using 1.0 M ammonium acetate (NH_4OAc) buffered at pH 7.0 with a 1:10 soil to solution ratio, and quantified on

ICAP. Effective cation exchange capacity (ECEC) was estimated using the method from Sumner and Miller (1996).

Soil pH was determined by using a pH meter and combination electrode 1:1 soil to water suspension (Thomas, 1996). Soil nitrate nitrogen (NO_3-N) was measured on a flow-injection auto analyzer by using 0.008 M $(Ca)_3(PO_4)_2$ extracting solution in a 1:2.5 soil to extract ratio (Mulvaney, 1996). Plant available potassium (K) and plant available phosphorus (P) was analyzed using Mehlich 3 extractant at a 1:10 soil to extract ratio (Mehlich, 1984). Molybdenum was analyzed on ICAP after extraction using the resin ball method (Segars, 1981). Soil organic matter was estimated using a dry combustion method (Nelson and Sommers, 1996) (Appendix B).

Forage Sampling and Analysis

Red clover and white clover was harvested three times in 2001 and four times in 2002. Alfalfa was harvested four times in 2001 and 2002. Yield was determined by harvesting an area of 24 by 3 feet. Harvested forage from the third cutting was sub-sampled for moisture and protein determination (Appendix A). Samples were dried in an oven at 85°C and ground to pass through a 1mm screen. Crude protein content was calculated by multiplying percent N in forage by 6.25 (NFTA, 1993).

Statistical Analysis

Treatments were arranged as a split plot with lime treatments as main plots in a randomized complete block design with four repeated measures. Legume species (subplots) were randomized within each lime treatment. Correlations were analyzed using an autoregressive covariance structure for intra plot correlations. A Tukey's test (alpha< 0.05) or a protected LSD was used as mean separation tests.

Results and Discussion

Soil pH Changes over Time

Soil samples were collected and tested for pH every spring and fall starting from before lime was applied in April 2000 until October 2002. The soil pH gradually increased for 14 months after lime was applied, and then pH was stabile or slowly declined for the following months (Figure 2.2). Three treatments, 0.7, 1.2, 2.0 t/A, had an initial pH of 4.3. The two highest treatments (2.0 and 3.7 t/A) increased the fastest, while the lowest treatment (0.4 t/A) increased the slowest. After lime was applied pH increased to 6.2, 6.5, and 6.9, respectfully. Table 2.1 shows mean pH and standard deviation for all lime treatments.

Relationship between Seedling Weeds and pH

Numbers of weed seedlings that emerged during stand establishment were counted to determine if there was a relationship between lime treatment and weed infestation. Forage legume stand establishment problems are often associated with weed problems. However, it is unknown if the number of weed seedlings causes legume establishment problems, or if it is due to non-vigorous legume seedlings. Table 2.2 shows mean number of weeds found in samples taken from each treatment for all three species. Lime application decreased prevalence of certain weeds ($p<0.05$) (Table 2.3). This could be due to the fact that as some weeds are more prevalent at a low pH due to the decrease in legume competitiveness.

Rattail fescue was the most prevalent weed seedling found at this site. There was a significant relationship ($r^2= 0.97$, $p<0.01$) between pH and number of rattail fescue plants in a square foot (Figure 2.3). As pH increased from 5.1 to 7.0, rattail fescue weed decreased from about 20 to 5 plants per square foot. No other weed species at this site had this relationship with pH, and there was no significant difference ($p<0.05$) in weed count for different species of legumes (Table 2.3). There is no species-lime interaction ($p<0.05$), which suggests rattail fescue could be used as an indicator for acidic soils (Table 2.3).

Relationship between Seedling Legumes and pH

Seedlings were collected and weighed from each plot in March 2001 to show the effect of lime treatments on legume stand establishment (Table 2.4). There was a species-lime interaction for seedling number ($p<0.05$), but not for seedling weight ($p<0.05$) (Table 2.3). There was a significant difference in seedling numbers ($p<0.05$) and seedling weight ($p<0.05$) between species, which is expected due to species establishing at different rates (Table 2.3).

There was no significant difference in seedling number ($p<0.05$) or seedling weight ($p<0.05$) between lime treatments (Table 2.3). This suggests that seedling numbers and weights were not increased as a result of higher lime treatments. The pH might not be low enough at 5.0 to have a significant impact on seedling numbers or growth (Table 2.9). If pH was below 5.0, then Al toxicity could become a concern (Mochler et al., 1960; Foy, 1964).

In this case, seedling weeds did not seem to affect legume establishment success. Legume seedling population and weight did not react to different soil pH like rattail fescue population. This suggests that stand establishment was determined by how vigorous legume seedlings were, not by competition with weed seedlings.

Relationship between Lime Treatments and Legume Yields

Forage dry matter weights were collected and analyzed to find a relationship between crop yields and lime treatments. Lime treatment effects (Table 2.5) on yield were significant in 2001, 2002, and total yields for both years ($p<0.05$). This suggested that there was a change in yield caused by lime treatments for at least one legume, which was expected.

Differences in yield among species were significant in 2001, 2002, and total yields for both years ($p<0.05$) (Table 2.5). Alfalfa had highest yields followed by red clover and white clover. There was significant interaction between legume species and lime treatments in 2001 and total for both years ($p<0.05$), but not in 2002 (Table 2.5). This suggested that these legume species responded differently to lime treatments the first year and overall, but not during the second year. These are useful findings since lime recommendations to correct low pH are normally the same regardless of the legume species.

To illustrate yield of each legume species, soil pH was averaged for the period the forage was harvested. For example, in 2001 and 2002 mean legume yields were correlated with the average of pH from the spring and fall sampling of that year.

Total yields

The legume yields for 2001 and 2002 were added together to find the relationship between total yield and lime treatment (Table 2.6). Total yields are important because when growing a perennial crop, years are not independent of each other. Therefore, significance in yields with respect to lime treatments or pH must be considered over growing periods.

There was a significant difference ($p<0.05$) in total alfalfa yields between the lowest (0.4 t/A) lime treatment and the two highest (2.04 and 3.7 t/A) lime treatments (Table 2.6). There were no other significant differences in total alfalfa yield. Figure 2.4 demonstrates the relationship between total alfalfa yields and soil pH. As pH increased from 5.2 to 7.0, alfalfa yields increased by 2t/A.

When red clover yields for 2001 and 2002 were considered together there was a significant difference ($p<0.05$) in yields between the lowest lime treatment and the highest lime treatment (Table 2.6). Figure 2.5 illustrates the relationship between total red clover yields and soil pH. As pH increased from 5.2 to 7.0, red clover yields increased by 1 t/A.

Total yields for white clover showed no significant differences among lime treatments (Table 2.6). This suggests that above a pH of 5.2, white clover yields do not increase.

2001

In this study, there was a significant difference ($p<0.05$) in total alfalfa yield for 2001 between the lowest (0.4 t/A) treatment and all other treatments (Table 2.6). Statistical analysis showed a significant yield difference between the 1.2 t/A lime treatment and the highest (3.68 t/A) lime treatment, and there were no other significant differences (Table 2.6). The results suggest that above a pH of 6.0 no additional lime was needed for alfalfa production, because negative effects of soil acidity were absent.

Statistical analysis showed no significant differences ($p<0.05$) in red or white clover yield between lime treatments for 2001 (Table 2.6). This suggests that above a pH of 5.2 no additional lime was needed for clover production.

2002

In 2002, no significant difference ($p<0.05$) was found in total alfalfa, red clover, or white clover yield between treatments (Table 2.6). Results suggest that above a pH of 5.2 there were no increased yields.

The optimum pH range for legumes is generally reported to be between 6.6 and 7.5 (Lanyon and Griffith, 1964; Andrew, 1976; Taylor and Smith, 1995), but current soil test recommendations for legume production do not call for lime application when soil pH is above 6.1. The results from this study come to a different conclusion. For alfalfa, the first year showed no increased yields above a soil pH 6.0, however, in 2002 yields were not increased above pH 5.2. Total alfalfa yields increased 2 t/A when pH was increased from 5.2 to 7.0. Total red clover yield increased 1 t/A when pH increased from 5.2 to 7.0. White clover showed no substantial increase in yield, therefore, a pH of 5.2 was satisfactory for white clover production.

The increase in overall yields in the second year for all legumes can be explained by the fact that the first year after establishment is typically hardest and this can cause lower yields. In addition, total amount of precipitation received during the season was same for both years, but the second year rainfall was better distributed to meet the needs of these species. For example, in July of 2001 there was a total of 0.04 inches as opposed to about 3.5 inches in 2002. Therefore, this could have led to a more favorable growing season for 2002.

Effect of Calcium and Molybdenum Fertilizer on Alfalfa Yields

Calcium and Mo were applied to part of the lowest lime treated alfalfa plots. There were no significant differences in alfalfa yields ($p<0.05$) between the area that received Ca fertilizer and the control (Table 2.7) for 2001, 2002, or total yields for both years. This suggests that when pH is 5.2, supplementary amounts of Ca were not needed to overcome a deficiency.

Lynd and Murphy (1964) concluded that additions of Ca fertilizers to two low pH (5.0 and 6.0) soils increased legume yield. However, this study led to different conclusions. At a pH of 5.2, there was no increase in alfalfa yields with additions of Ca fertilizer. Therefore, Ca was not deficient at a pH of 5.2, and it was not necessary to apply additional fertilizers containing Ca.

Alfalfa did not respond to Mo fertilizer additions either. One year after Mo was applied to soil, it was tested below detection limits (Table 2.8). No significant differences ($p<0.05$) were found in alfalfa yield between areas that received Mo fertilizer additions and control (Table 2.7) for 2001, 2002, or total yield for both years. This suggests that when pH is 5.2, Mo fertilizer applied to soil or foliarly does not increase alfalfa yields.

Parker and Harris (1962) and Scott (1963) suggested that at a soil pH below 5.7, an addition of Mo fertilizer increased legume yields. However, this study did not agree with previous conclusions. Molybdenum was below detection limits for the present study, but additions of Mo fertilizer to soil or by foliar application did not increase yields for alfalfa either year. Therefore, at a pH above 5.2, Mo was not deficient in this soil and alfalfa did not benefit from additional Mo fertilizer.

Nutrient Requirements

Soil samples were collected and analyzed to determine if there were adequate levels of N, P, K, and other nutrients that are needed for legume production. Table 2.1 and 2.8 show levels of essential nutrients analyzed. For alfalfa and other legumes in pasture, P was sufficient for production. Potassium was about 90% sufficient for legume production. Nitrogen was not needed for production after establishment. For optimum growth, Ca and Mg should be at soil test index of 700 and 100 lbs/A, respectively, which was satisfied. This suggests that even at a soil pH of 5.2 it was possible to have decent crop production if P, K, Ca, and Mg were sufficient.

Soil samples were analyzed to find the relationship between Al and Mn concentrations and forage yields. Studies have shown that at 20% Al saturation there was a reduction in alfalfa yields due to Al toxicity (Mochler et al., 1960; Foy, 1964). However, excess Al was not a problem in this study because Al saturation was less then 3.5% (Table 2.9). Mn concentration for the lowest lime treatment was 16ppm, and then decreased to 3 ppm with increased pH (Table 2.9). Therefore, Mn toxicity was not an issue during this study because the minimum amount of lime applied was sufficient to overcome damaging effects of excess Mn.

Conclusion

Forage legumes are important to Oklahoma agriculture, because they improve the quality of soil while providing high quality forage for livestock. Legume growth is adversely affected by low pH. Soil acidity is damaging to crop production because it causes deficiencies in calcium (Ca), magnesium (Mg), molybdenum (Mo), and a decrease in plant growth.

Overall, legumes showed a positive response to increased pH caused by lime treatments. Lime application did not affect seedling density, and legume species reacted differently to lime treatments. White clover did not have a significant increase in yields above a pH of about 5.2. Red clover and alfalfa had a significant increase in yields with increased pH. In 2002, alfalfa, red clover, and white clover yields increased twofold over the first year probably due to more favorable growing season. Alfalfa yields did not increase as a result of additional Mo or Ca fertilizer at the lowest lime treatment.

This information can be useful to future researchers interested in finding an economically sound liming practice for a soil with low Al saturation and Mn concentration. The Oklahoma Cooperative Extension Service recommends lime for legume production when soil pH is below 6.1, but this study showed white clover did not benefit from liming above a 5.2, when all other nutrient needs were satisfied and Al saturation was low.

Of the weeds found at this site, rattail fescue was the predominate weed, and it was most prevalent in areas of low pH. The population of rattail fescue decreased as pH increased. This weed could be used as an indicator weed, which could aid producers in identifying areas of low pH. This suggests liming reduces weeds and improves forage quality.

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Table 2.1: Soil analysis for the forage legume-pH investigations from April 2000 to October 2002. Perkins, OK.

Lime	April 2000				November 2000				June 2001				November 2001				March 2002				October 2002			
(t/A)	pH†	NO_3-N‡	P§	K§	pH	NO_3-N	P	K	pH	NO_3-N	P	K	pH	NO_3-N	P	K	pH	NO_3-N	P	K	pH	NO_3-N	P	K
0.4	4.1(.21)¶	4	128	189	4.8(.28)	27	106	257	5.4(.35)	8	83	297	5.2(.22)	6	113	310	5.2(.24)	4	94	259	5.0(.23)	10	61	151
0.7	4.3(0.0)	4	117	179	5.3(.20)	33	95	237	6.2(.22)	6	74	255	5.9(.10)	9	99	277	5.8(.13)	4	84	205	5.4(.10)	12	57	148
1.2	4.3(.22)	5	121	190	5.6(.34)	27	94	250	6.5(.21)	7	78	265	6.2(.25)	7	102	275	6.0(.17)	4	80	225	5.9(.33)	12	58	159
2.0	4.3(.22)	4	117	186	6.3(.17)	26	92	247	6.9(.12)	7	66	252	6.7(.17)	7	103	283	6.6(.17)	5	80	224	6.5(.13)	11	52	154
3.7	4.7(.14)	5	111	169	6.7(.10)	23	86	241	7.2(.06)	6	63	249	7.2(.10)	10	100	280	6.8(.24)	4	74	225	6.9(.15)	10	51	139

†pH- 1:1 soil:water; ‡NO3-N- 0.008 M (Ca)3(PO4)2; §STP, K- Mehlich 3; ¶ standard deviation in parenthesis

Table 2.2: Mean number of weeds per square foot in each lime treatment for each legume, Haskell, OK. March 2001.

Weed	Lime t/A	Alfalfa	Red Clover	White Clover	Weed	Lime t/A	Alfalfa	Red Clover	White Clover
		---------weed per sq. foot---------					---------weed per sq. foot---------		
Ryegrass	0.4	0.0	0.1	0.1	Primrose	0.4	1.4	2.0	2.3
	0.7	0.0	0.1	0.1		0.7	0.6	0.8	0.6
	1.2	0.0	0.2	0.0		1.2	0.2	1.3	1.1
	2.0	0.1	0.0	0.0		2.0	0.1	0.7	0.1
	3.7	0.0	0.0	0.1		3.7	0.3	0.4	0.3
Rattail fescue	0.4	17.8	18.6	19.8	Stickychick	0.4	0.1	0.3	0.2
	0.7	8.9	7.8	7.0		0.7	1.6	2.3	0.8
	1.2	8.3	6.8	14.3		1.2	2.3	1.0	0.8
	2.0	6.3	7.8	7.4		2.0	0.7	0.7	0.3
	3.7	5.4	5.3	5.8		3.7	0.3	0.3	0.3
Henbit	0.4	0.1	0.0	0.1	Misc	0.4	2.4	4.0	3.0
	0.7	0.1	0.0	0.0		0.7	6.2	7.2	8.6
	1.2	0.0	0.0	0.3		1.2	6.2	8.3	9.2
	2.0	0.0	0.0	0.2		2.0	3.6	4.3	5.7
	3.7	0.7	0.4	0.1		3.7	5.1	4.8	6.8
Mustard	0.4	0.3	0.3	0.0	Total	0.4	22.1	25.3	25.5
	0.7	0.3	0.2	0.2		0.7	17.7	11.4	17.3
	1.2	0.0	0.2	0.1		1.2	17	17.8	25.8
	2.0	0.1	0.1	0.3		2.0	10.9	13.6	14
	3.7	0.0	0.2	0.1		3.7	11.5	11.4	13.5

Table 2.3 Analysis of variance for mean number and weights of legume seedlings and numbers of rattail fescue analyzed as a split plot with lime treatments as main plots in a randomized complete block design with repeated measures, Haskell, OK. 2001

		Legume Seedling		Rattail Fescue
		Number	weight	Number
Source	df	--------Mean Square Values--------		
lime treatment (A)	4	10	0.0001	324 **
species (B)	2	1074 **	0.0047 **	17
A x B	8	17 *	0.0001	14
		plant ft^{-2}	g/ plant	plant ft^{-2}
Mean		10.2	0.04	9.85
LSD		2.1	0.01	6.84
CV		24.3	41.97	84.32

* Significant at the 0.05 level

** Significant at the 0.01 level

Table 2.4. Mean number of legume seedlings and their weight per plant from three samples taken from the five treatments of lime for the three legumes, Haskell, OK. March 2001.

plot	Alfalfa	Red clover	White clover	Alfalfa	Red clover	White clover
	---------plants per sq. foot---------			-----------g per plant-----------		
0.4	16.0	7.3	3.3	0.047	0.046	0.025
0.4	20.3	9.0	4.3	0.035	0.032	0.013
0.4	11.7	5.0	4.0	0.030	0.016	0.023
0.4	25.0	7.3	3.3	0.068	0.111	0.036
0.7	16.3	15.3	2.0	0.042	0.061	0.018
0.7	16.0	17.0	4.0	0.047	0.040	0.015
0.7	19.0	15.7	3.3	0.046	0.085	0.024
0.7	15.0	12.7	0.7	0.047	0.037	0.012
1.2	16.3	9.0	1.0	0.047	0.046	0.023
1.2	14.7	9.0	3.3	0.031	0.046	0.018
1.2	14.7	11.0	2.0	0.030	0.032	0.033
1.2	15.7	14.3	2.0	0.028	0.060	0.007
2.0	17.3	11.7	1.7	0.079	0.049	0.024
2.0	21.3	11.3	3.0	0.028	0.045	0.008
2.0	10.0	6.7	0.3	0.024	0.065	0.017
2.0	18.0	14.3	1.7	0.049	0.055	0.027
3.7	17.0	7.3	1.7	0.079	0.034	0.022
3.7	18.7	10.3	4.0	0.045	0.046	0.023
3.7	18.3	16.0	3.0	0.043	0.049	0.029
3.7	22.0	11.0	2.7	0.042	0.044	0.024

Table 2.5: Analysis of variance for mean yields analyzed as a split plot with lime treatments as main plots in a randomized complete block design with repeated measures. Haskell, OK.2001-2002

		Yields per Cutting		Annual Yield		Total Yield
		-----------------------------Mean Square Values-----------------------------				
Source	df	2001	2002	2001	2002	
lime treatment (A)	4	0.102 **	0.027	1.94 **	0.4 *	4.02 **
species (B)	2	1.801 **	4.681 **	27.1 **	74.5 **	184.98 **
A x B	8	0.016	0.014	0.3 *	0.2	0.78 *
Mean (t/A)		0.61	1.07	2.41	4.20	6.61
LSD (t/A)		0.11	0.12	0.30	0.23	0.44
CV (%)		21.66	13.88	14.98	8.69	8.09

* Significant at the 0.05 level

** Significant at the 0.01 level

Table 2.6: Mean total yield for alfalfa, red clover, and white clover for five lime treatments in 2001 and 2002, Haskell, OK.

Treatment	Alfalfa			Red Clover			White Clover		
	---Yield---			---Yield---			---Yield---		
	2001	2002	Total	2001	2002	Total	2001	2002	Total
---t/A---	---t/A---			---t/A---			---t/A---		
0.4	2.3c	5.8a	8.1b	2.2a	3.7a	5.9b	0.93a	2.5a	3.4ab
0.7	3.3ab	6.2a	9.6ab	2.9a	3.7a	6.6ab	1.2a	2.3a	3.5ab
1.2	3.2b	6.4a	9.6ab	2.7a	4.0a	6.7ab	1.0a	2.2a	3.2b
2.0	3.7ab	6.1a	10.0a	2.9a	4.2a	7.1ab	0.98a	2.2a	3.2b
3.7	4.0a	5.9a	10.3a	3.4a	4.5a	7.9a	1.3a	2.7a	4.0a

alpha=0.05; Values reported as mean of four replications
Means with same letter are not significantly different in the same year

Table 2.7: Mean total alfalfa yield with molybdenum and calcium fertilizer treatments at the lowest lime rate (0.4t/A) Haskell, OK. 2001-2002.

Treatment	Alfalfa		
	---Yield---		
	2001	2002	Total
	---t/A---		
Molybdenum	2.3a	5.8a	8.2a
Calcium	2.3a	5.8a	8.0a
None	2.3a	5.7a	8.1a

t=3.948; alpha=0.05; Mean of 4 replications; Means with same letter are not significantly different in the same year

Table 2.8. The results from soil analysis of lowest lime treatment (0.4 t/A) for pH and essential nutrients for legume growth, Haskell, OK. November, 2001

check plot	pH†	N-NO_3‡	P§	K§	Ca	Mg	Fe	Zn	B	Mo¶
		------lbs/A------					------ppm------			
1	5.0	5	117	334	908	200	105	0.5	0.19	NA
2	5.2	6	95	288	1316	228	79	0.6	0.2	NA
3	5.1	7	131	366	1045	197	97	0.7	0.2	NA
4	5.5	6	108	253	1595	263	88	0.7	0.14	NA

†pH 1:1 (water); ‡ NO_3-N- 0.008 M $(Ca)_3(PO_4)_2$; §Mehlich 3 extractable P or K; ¶Mo below detection limit

Table 2.9. Average percent Al saturation and Mn concentration for all lime treatments, Haskell, OK. November, 2001.

Replication	0.4 t/A	0.72 t/A	1.2 t/A	2.04 t/A	3.68 t/A	0.4 t/A	0.72 t/A	1.2 t/A	2.04 t/A	3.68 t/A
	% Al saturation†					Mn (ppm)‡				
1	6.2	0.8	1.3	0.5	0.3	21.5	9.3	7.9	3.9	0.3
2	2.3	0.6	1.9	1.2	2.5	16.4	1.7	6.6	5.0	3.4
3	4.0	1.0	1.2	0.4	0.8	21.2	9.5	3.1	0.2	4.6
4	1.0	0.8	2.1	1.1	1.1	6.5	4.9	6.6	4.1	4.0
Mean	3.4	0.8	1.6	0.8	1.2	16.4	6.4	6.1	3.3	3.1

†% Al saturation=Al/(Al+Ca+Mg+K+Na); ‡Mn extract NH_4OAc

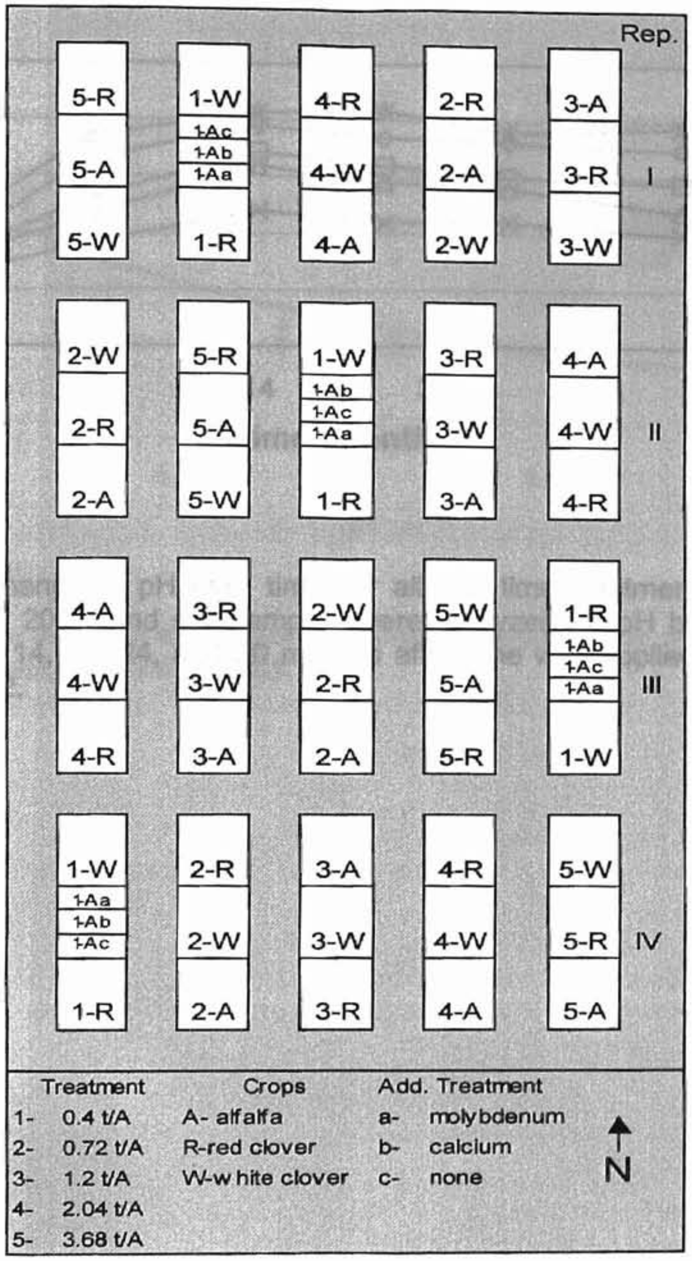

FIGURE 2.1. Plot plan for Legume-pH study near Haskell, OK. 2000-2002. Design is a randomized complete block with four replications. Alfalfa, red clover, and white clover yields were monitored under five different lime treatments. The lowest lime treatment for alfalfa had additional treatments of molybdenum fertilizer and calcium fertilizer.

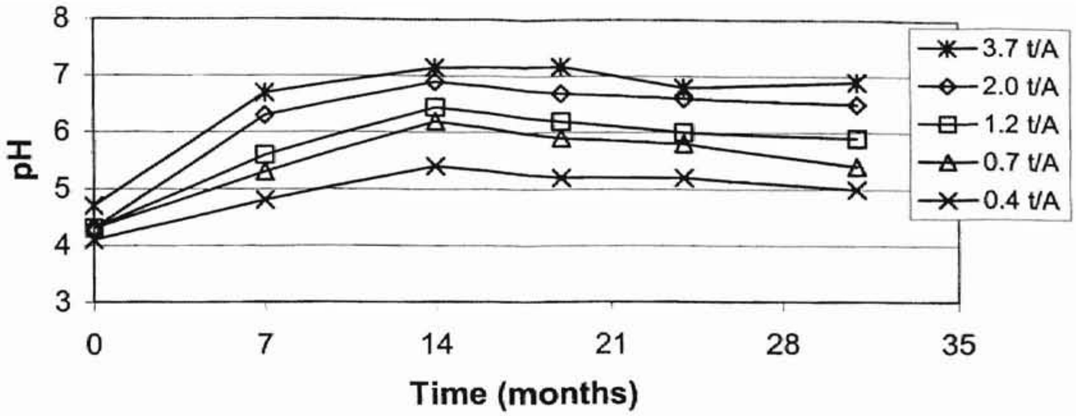

FIGURE 2.2. Change in pH over time for all five lime treatments. Lime was applied in April 2000, and soil samples were analyzed for pH before lime was applied and 7, 14, 18, 24, and 30 months after lime was applied near Haskell, OK. 2000-2002.

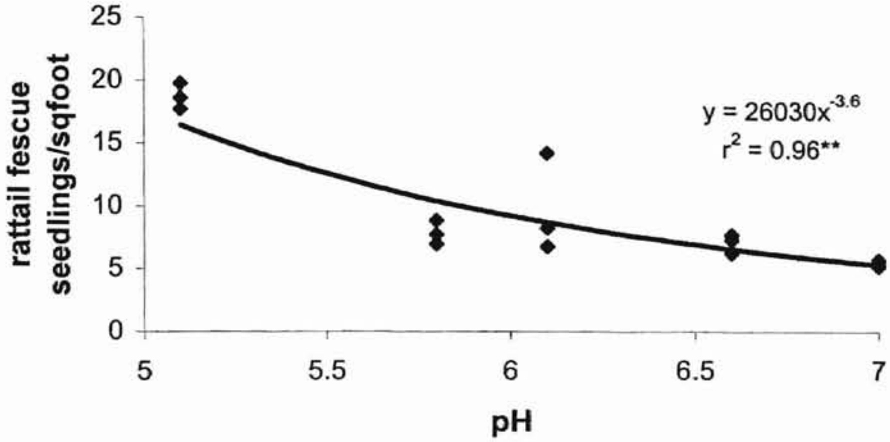

Figure 2.3. The relationship between numbers of rattail fescue seedlings per sq. ft. and pH, Haskell, OK. March 2001.

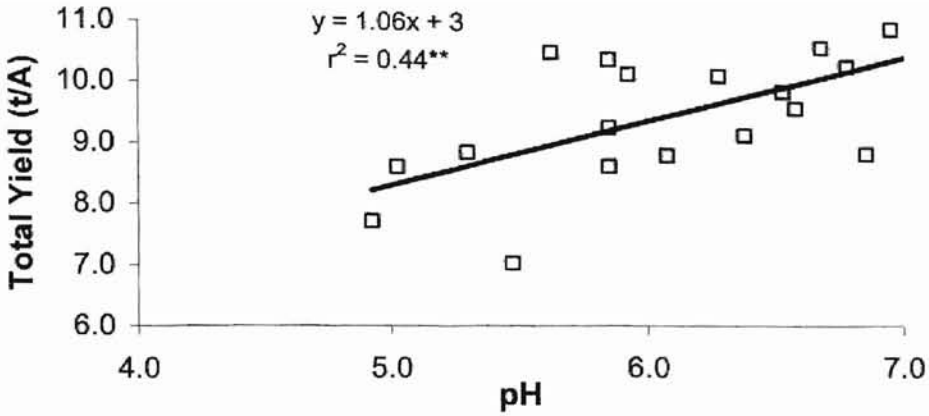

Figure 2.4. Relationship between total alfalfa yields (t/A) and pH for 2001 and 2002, Haskell, OK.

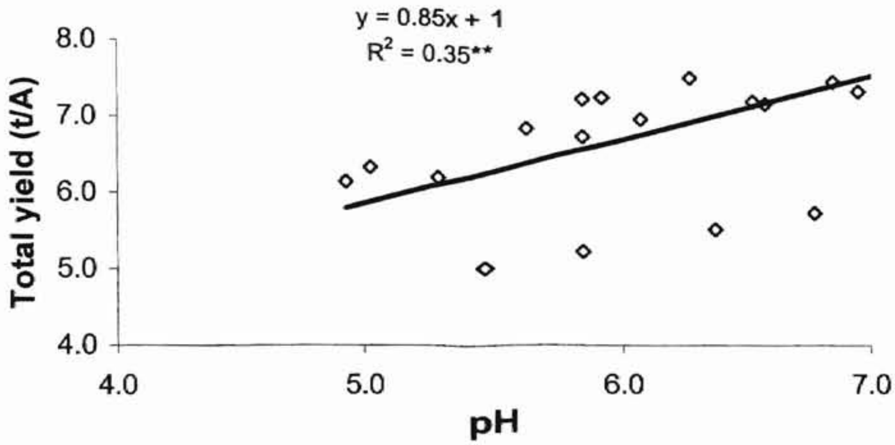

Figure 2.5. Relationship between total red clover yields (t/A) and pH for 2001 and 2002, Haskell, OK.

Appendixes

Appendix A. Protein analysis for all crops in 2001 and 2002. Harvested July 25, 2001 and July 11, 2002, Haskell, OK.

Lime Treatment	Alfalfa		Red Clover		White Clover	
t/A	2001	2002	2001	2002	2001	2002
	-----------------------------Protien (%)-------------------------					
0.4	17	22	22	24	18	26
0.4	19	21	18	22	19	23
0.4	20	16	25	25	19	24
0.4	19	22	19	21	17	26
0.7	20	22	19	22	21	24
0.7	20	21	24	19	20	27
0.7	17	20	22	23	19	24
0.7	17	22	14	23	19	29
1.2	20	20	21	21	18	26
1.2	18	21	17	23	19	25
1.2	20	20	22	23	19	29
1.2	15	20	22	21	21	24
2.0	19	20	22	22	20	22
2.0	22	22	23	26	18	27
2.0	19	22	18	22	18	30
2.0	19	21	16	22	18	29
3.7	18	21	18	22	18	28
3.7	20	22	19	23	22	30
3.7	19	21	18	20	19	24
3.7	23	18	18	22	17	24

Appendix B. Percent aluminum saturation and organic matter content for the different lime treatments, Haskell, OK. 2001.

Lime Treatment	Organic Matter†	Al Saturation‡
-------t/A-------	---------------------%------------------	
0.4	1.3	10.3
0.4	1.5	3.0
0.4	1.4	6.3
0.4	1.3	0.5
0.7	1.4	0.3
0.7	1.6	3.3
0.7	1.4	0.3
0.7	1.4	0.4
1.2	1.4	1.0
1.2	1.6	1.1
1.2	1.4	0.2
1.2	1.4	0.2
2.0	1.4	0.5
2.0	1.4	0.1
2.0	1.5	0.2
2.0	1.5	0.3
3.7	1.3	0.2
3.7	1.6	0.3
3.7	1.6	0.2
3.7	1.4	0.2

† organic matter by dry combustion method; ‡ Al extracted by 1.0M KCl

Appendix C. Mean yield for each cutting for red clover, white clover, and alfalfa. Haskell, OK. 2001-2002.

Species	Lime Treatment	5/9/2001	6/19/2001	7/25/2001	10/12/2001	Total
	-------t/A-------			-t/A-		
Alfalfa	0.4-a	0.60	0.77	0.46	0.47	2.30
Alfalfa	0.4-b	0.55	0.73	0.54	0.48	2.30
Alfalfa	0.4-c	0.54	0.81	0.45	0.80	2.60
Alfalfa	0.7	0.77	1.70	0.37	0.49	3.33
Alfalfa	1.2	0.60	1.61	0.46	0.55	3.22
Alfalfa	2.0	0.91	1.94	0.43	0.56	3.84
Alfalfa	3.7	1.16	1.99	0.35	0.54	4.04
Red Clover	0.4	0.65	1.00	0.55	0	2.20
Red Clover	0.7	1.02	1.46	0.45	0	2.93
Red Clover	1.2	0.85	1.29	0.51	0	2.65
Red Clover	2.0	0.96	1.46	0.51	0	2.93
Red Clover	3.7	1.27	1.70	0.41	0	3.38
White Clover	0.4	0.68	0.17	0.07	0	0.92
White Clover	0.7	0.81	0.35	0.06	0	1.22
White Clover	1.2	0.59	0.38	0.08	0	1.05
White Clover	2.0	0.59	0.30	0.09	0	0.98
White Clover	3.7	0.66	0.52	0.13	0	1.31

Species	Lime Treatment	4/29/2002	6/7/2002	7/11/2002	8/23/2002	Total
	-------t/A-------			-t/A-		
Alfalfa	0.4-a	1.2	2.1	1.1	1.5	5.8
Alfalfa	0.4-b	1.2	1.9	1.1	1.6	5.7
Alfalfa	0.4-c	1.7	2.0	1.1	1.5	5.8
Alfalfa	0.7	1.2	2.3	1.2	1.6	6.3
Alfalfa	1.2	1.2	2.2	1.3	1.6	6.4
Alfalfa	2.0	1.2	2.1	1.3	1.8	6.3
Alfalfa	3.7	1.2	2.0	1.2	1.9	6.2
Red Clover	0.4	0.8	1.4	0.9	0.5	3.7
Red Clover	0.7	0.8	1.5	1.2	0.4	3.7
Red Clover	1.2	1.0	1.4	1.1	0.5	4.0
Red Clover	2.0	1.1	1.6	1.1	0.4	4.1
Red Clover	3.7	0.7	1.6	1.5	0.7	4.5
White Clover	0.4	0.7	1.4	0.3	0.1	2.5
White Clover	0.7	0.7	1.2	0.4	0.1	2.3
White Clover	1.2	0.4	1.3	0.3	0.2	2.1
White Clover	2.0	0.4	1.2	0.4	0.2	2.2
White Clover	3.7	0.6	1.2	0.5	0.7	2.7

sodium molybdate; calcium chloride; no additional treatments

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VITA

Kendra J. Wise

Candidate for the Degree of

Master of Science

Thesis: IMPACT OF SOIL ACIDITY ON CROP PRODUCTION

Major Field: Plant & Soil Sciences

Biographical:

Education: Graduated from Owasso High School, Owasso, Oklahoma in May 1996; received Bachelor of Science degree in Environmental Sciences from Oklahoma State University, Stillwater, Oklahoma in December 2000. Completed the requirements for the Master of Science degree with a major in Plant & Soil Sciences at Oklahoma State University in December 2002.

Experience: Employed by Oklahoma State University Soil, Water, and Forage Laboratory as a laboratory technician; employed as a graduate research assistant for the Department of Plant & Soil Sciences, Oklahoma State University, 2001 to 2002.

Professional Memberships: American Society of Agronomy, Soil Science Society of America.