INFLUENCE OF VARYING RATES OF LIME AND NITROGEN ON WINTER WHEAT PRODUCTION

By

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CHAPTER I

INTRODUCTION

Increased yields of winter wheat over the past twenty-five years can be directly related to the amount of nitrogen fertilizer applied. Nitrogen fertilization became necessary when organic matter content declined due to years of continuous cropping (Webb, Tucker, and Westerman, 1980). Intense management practices were used in order to optimize and increase economic returns. After years of success, yields began to decline and complete crop failures were reported. This problem was observed on a Pond Creek Silt Loam near Carrier, Oklahoma. Even though virgin soils in this area were slightly acidic (5.5-6.5), the surface soil pH (1:1 H_2O) declined to approximately 4.0 (Westerman, 1981). As a result, a field experiment was initiated in July 1978 by applying four rates of nitrogen in strips and five ag-lime rates (80% + $CaCO_3$ equivalent and 30% through 60 mesh screen) within each strip (four replications). Thus, there were four separate experiments (complete randomized block design). Nitrogen treatments continue to be applied annually.

Objectives for this experiment include the determination of soil constituents that have detrimental effects on yield and nutrient content of wheat forage, grain, and straw; secondly, to determine the effect of varying rates of lime and nitrogen on yield and nutrient content of forage, grain, and straw; third, to quantitatively assess the acidification effect of varying rates of urea-N in a winter wheat production system; and finally, to determine the contribution of removal of forage, grain, and straw and their equivalent excess base/N ratios on soil acidity.

CHAPTER II

LITERATURE REVIEW

The adverse effects of soil acidity on plant growth are documented (Blair and Prince, 1923; Fried and Peech, 1946; Wright, 1948; Schmehl et al., 1950; Foy and Brown, 1964) as well as the corrective management practice of lime application (Evans et al., 1970; White, 1970; Hutchinson and Hunter, 1970). The scope of this review is to discuss the development of soil acidity, adverse effects on plant growth, role of excess base/nitrogen ratios of plants, and application of ag-lime.

Development of Soil Acidity

The concept of soil pH is very complex. A chemist defines pH as the negative logarithm of the hydrogen ion concentration. Since soils react similar to buffered weak acids, the term must be redefined to describe hydrogen ion "activity". Hydrogen ion activity is related to several soil processes. These include, the addition of hydrogen ions by nitrification of ammonical nitrogen fertilizers (Abruna et al., 1958; Hiltbolt and Adams, 1960; Jolley and Pierre, 1977), and the hydrolysis of aluminum and iron compounds (Bhumbla and McLean, 1965). Decomposition of organic matter also increases soil acidity (Westerman, 1981). Increases in H^+ ion concentration along with declining base concentrations due to leaching and crop removal leave an exchange complex dominated with H^+ ions.

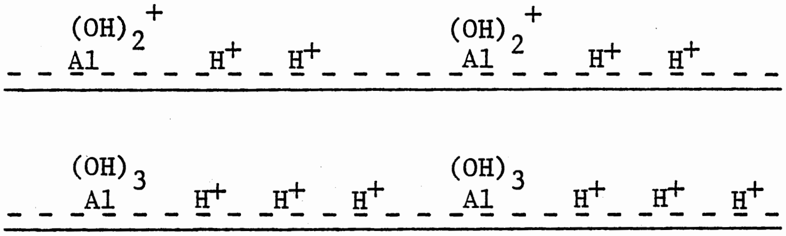
Nitrification of ammonical nitrogen fertilizers produce significant amounts of H^+ ions which can lead to increased soil acidity. All fertilizers containing ammonia or ammonium will undergo microbial processes which will oxidize these species to nitrate (Morrill, 1979).

$$\begin{array}{lll} \text{Reaction (1)} & \text{a.} & 2NH_3 + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2 + 2H^+ + 2H_2O \\ & \text{b.} & 2NH_3 + 3O_2 \xrightarrow{\hspace{6em}} 2NO_2 + 4H^+ + 2H_2O \\ \text{Reaction (2)} & & 2NO_2 + O_2 \xrightarrow{\text{Nitrobactor}} 2NO_3^- \end{array}$$

The acidity developed in the first reaction can become a major problem on soils that are slightly acidic with the continued use of ammonium fertilizers unless agricultural lime is applied to neutralize this acidity.

The role of aluminum in soil acidity has been debated for over fifty years. Early workers believed aluminum ions would replace basic ions that were on the exchange complex thereby increasing soil acidity (Jenny, 1961). Then Sorenson (1909) defined the concept of pH, and researchers redefined soil pH as adsorption of H ions on clay surfaces. The H-clay theory was upheld until 1947 when Chernov (1947) stated that aluminum-oxide-hydroxy polymers were more strongly adsorbed by clays than aluminum ions, and these more strongly than H^+ ions. He added, Al-clays would yield titration curves similar to weak acids. Schwertman and Jackson (1964) made it apparent that charges resulting from isomorphous substitution often are neutralized by hydroxy complexes of aluminum ions, which in turn donate protons. A model for surface hydrolysis was proposed by Jenny (1961):

$$\begin{array}{c} \overset{OH^{++}}{Al}\quad H^{+}\qquad\qquad\qquad\qquad \overset{OH^{++}}{Al}\quad H^{+} \\ \hline \text{Clay surface} \end{array}$$



Hence, $Al(OH)_3$ would coexist with H-Clay. Today, researchers believe that under acid conditions aluminum adsorbed to clay particles becomes soluble and is in equilibrium with aluminum in the soil solution. The aluminum ions are then hydrolyzed and form aluminum hydroxide as indicated by the following reactions (Tisdale and Nelson, 1975):

$$Al^{+++} + H_2O \longrightarrow Al(OH)^{++} + H^+$$
$$Al(OH)^{++} + H_2O \longrightarrow Al(OH)_2^{+} + H^+$$
$$Al(OH)_2^{+} + H_2O \longrightarrow Al(OH)_3 + H^+$$

Each aluminum ion in soil solution could produce three H^+ ions when hydrolyzed. Further, addition of salts, such as those contained in fertilizers, increases the hydrolysis of non-exchangeable aluminum resulting from release from the soil mineral complex by weathering or by the addition of salts to the soil, generates soil acidity (Heddleson et al., 1960).

Another important aspect of soil acidity is soil organic matter. Carboxyl, phenolic and amino groups contained in organic matter have H^+-saturated groups which will behave as weak acids. The acidity produced can vary depending on the amount of organic matter in the soil and its distribution. Significant amounts of acidity can be produced in mineral soils containing large amounts of organic matter.

The final segment on soil acidity development will pertain to the removal of basic cations (Ca, Mg, K, and Na) from the soil rooting zone by leaching and crop removal. Leaching can have a significant effect on soil acidity especially on sandy soils where high intensity rainfall often occurs. This occurs in conjunction with application of fertilizers when elements, either by mass action or by the principle of the lyotrophic series, replace basic cations on the exchange complex. These ions are leached from the effective rooting zone by high intensity rainfall. This again contributes to an exchange dominated by H^+ and Al ions.

Basic cation removal in the forage, grain and straw is a major factor to soil acidity. Increased yields due to fertilizer applications have increased the rate of basic cation removal from the soil complex. Straw contains large amounts of basic cations, and with continued removal can deplete the soil of large quantities of bases. Forage or grain removal is not as detrimental as straw removal due to lower base contents. Thus, under intense management practices, such as heavy fertilization, straw removal, and continuous cropping, large quantities of bases are depleted from the soil thereby lowering base saturation and increasing soil acidity.

Adverse Effects on Plant Growth

Soil acidity can have a major impact on plant growth. Several nutrients (Ca, Mg, K, P, Cu, Zn, N, Mo, and S) essential for plant growth are less available on low pH soils (Foth and Turk, 1972). Also, microorganisms necessary for nitrification are inhibited (Foy et al., 1978). The major reduction in growth, however, is caused by increased levels of aluminum and manganese which can become toxic to plants.

It was stated earlier that as H^+ ion concentration increases, and as basic cations are removed from the exchange complex, aluminum ions move into the soil solution. These ions reach the root-soil interface where they passively diffuse across the plasmalemma (Rhue, 1976; Foy et al., 1978). Foy et al. (1978) reported that Henning (1975) found

> . . . the aluminum absorbed by wheat roots penetrated the boundary between root apex and root cap and accumulated in the nuclei and cytoplasm of cells adjacent to this zone. Considerable amounts are retained in the cortical cells since the endodermis prevents movement of aluminum into the central cylinder (p. 516).

The root system, suffering from aluminum toxicity, contains stubby, brittle roots without fine branching. Such roots are inefficient in absorbing nutrients and water (Foy et al., 1978). Aluminum has been shown to interfere with cell division in plant roots, fix P in less available forms in the soil and in the plant root, decrease root respiration, interfere with enzymes, increase cell wall rigidity (by cross-linking pectins), and interfere with the uptake, transport and use of several elements (Ca, Mg, P, and K) and water by plants (Foy et al., 1978). This increases the susceptibility to drought which often occurs in the great plains.

Manganese also becomes soluble as the soil pH decreases (White, 1970). This situation is compounded in soils that are waterlogged for short periods. Waterlogging of soil promotes the reduction of manganese to the divalent (available) form (Foy et al., 1978). Manganese toxicity is not as straight-forward as aluminum toxicity. Unlike aluminum, excess manganese affects plant tops more severely than roots. "Manganese accumulates in the foliage in proportion to injury" (Foy et al., 1978). Symptoms of manganese toxicity are diverse among plant species. "Plant symptoms include marginal chlorosis and necrosis of leaves (alfalfa, Kale, lettuce), leaf puckering (cotton, soybean, snapbean), and necrotic spots on leaves (barley, lettuce, soybeans)" (Foy et al., 1978, p. 523). Morgan et al. (1976) found that manganese excess increased in vitro destruction of auxin by increasing indole acetic acid (IAA) oxidase activity in cotton. Symptoms of auxin deficiency include IAA oxidase activity, leaf abscission, and internode length. Manganese toxicity is an important factor in acid soils; but, when aluminum and manganese toxicity occur simultaneously, aluminum toxicity is the more important of the two factors (Foy et al., 1978).

Role of EB/N Ratio on Soil Acidity

Plants can have a significant effect on the base status of soils and the acidity resulting from the use of nitrogen fertilizers (Pierre and Banwart, 1973). The effect of plants results from their cation-anion balance, and it can be determined quantitatively from the excess base (EB) and nitrogen content of the harvested crop (Pierre et al., 1973). The EB/N ratio is used as a tool to estimate the contribution of crop production to soil acidity. Excess base to N ratio is defined as the total cations minus the total anions divided by total N expressed as milliequivalents/100 g of plant material:

$$\text{Excess Base/N ratio} = (\text{Ca+Mg+K+Na}) - (\text{Cl+S+P+NO}_3\text{-N})/\text{Total N}$$

EB/N ratio relates the effect of plants on soil acidity in terms of the total N taken up (Pierre et al., 1970). Comparisons of the plant effect on soil acidity per unit N taken up can be made between different crop species or different plant parts that are harvested under different environmental conditions (Pierre and Banwart, 1973). Plants with an EB/N ratio greater than 1 would enhance the acidity production by nitrification of ammonical fertilizers, and plants with an EB/N ratio less than 1 would decrease the acidity produced by nitrification. An EB/N ratio of 0.30 means that the EB in the plant is equivalent to only 30% of the total NO_3-N uptake. Thus, when N is taken up as nitrate from the soil, an amount of base equivalent to 70% of the total plant N is taken up without bases, leaving the soil more basic (Banwart and Pierre, 1975).

> In case of winter wheat production, forage removal by grazing and removal of grain at harvest will tend to reduce the amount of lime required for neutralization of the acidity produced by fertilizers, whereas removal of straw will increase the lime requirement (Westerman, 1981, p. 65).

Both forage and grain have EB/N ratios less than 1, whereas EB/N ratio of wheat straw is greater than 1. In forage and grain removal, considerable N is removed without an uptake of equivalent amount of bases leaving behind in the soil residues of Ca, Mg, K, and Na that can neutralize the acidity produced by nitrification of nitrogen fertilizers (Westerman, 1981).

Liming of Acid Soils

The management practice required for acid soils is the application of agricultural lime. Lime is broadcast uniformly and mixed into the rooting zone. The basic equation is as follows:

$$CaCO_3 + 2H^+ \longrightarrow Ca^{++} + CO_2 + H_2O$$

The rate of reaction is dependent on the purity of lime, fineness factor, time, pH, moisture, and type of soil. As H^+ ions are neutralized and bases from the lime are combined with the exchange complex, aluminum and manganese become less soluble. Also, Kamprath (1970, p. 252) asserted, "The beneficial effects of a pH near neutrality on availability of soil phosphorus, molybdenum, calcium, and magnesium, and increased activity of microorganisms have been given as reasons for liming a soil to a given pH." The amount of lime required depends on soil pH, buffer index, purity of the lime, grind factor, crops grown, and management practices.

CHAPTER III

MATERIALS AND METHODS

Part I: Field Experiments

The experiment was conducted on a Pond Creek Silt Loam (Udic Arguistoll). The site is located 1.6 km North and 1.6 km East of Carrier, Oklahoma in Sec. 12, T. 23, N. R.8.W. of Garfield County.

The field was divided into four strips (121.9 m by 22.9 m) which included four separate experiments (complete randomized block design). Four ag-lime rates were applied randomly with four replications within each N strip (Table I). The experiment was initiated in July 1978, and the N treatments continue to be applied annually during September.

On September 14, 1979, winter wheat (Tam-101) was seeded. One month later soil samples were taken from the top six inches and processed for laboratory analysis. Each plot was sampled at 10 locations and combined. During March of 1980, forage samples were collected by sampling five locations within each plot. The top 6 inches of plant material was removed. On June 21, 1980, grain and straw yields were determined by harvesting with an A-type Gleaner combine. The middle 3.05 m of each plot was harvested, and grain samples were collected in burlap bags and weighed. The straw was collected from a 10 foot section behind the combine and weighed in a large plastic container. Laboratory samples of grain and straw were taken from the yield samples.

TABLE I

LOCATION, SOIL TYPE, RATES OF LIME AND NITROGEN

Location	Soil Type	Treatment Rates Lime (metric tons/ha)	Treatment Rates Nitrogen (kg/ha)
Carrier	Pond Creek (Udic Arguistoll)	0	0
		2.69(¼x)	224
		5.38(½x)	448
		10.76(x)*	896
		21.52(2x)	

*Recommended Lime Rate

Part II: Laboratory Experiments

Soil Procedures

Soil samples were air-dried for 24 hours. Samples were thoroughly mixed before a smaller sample was weighed for analysis. The soil analysis included tests for pH, CEC, NO_3^--N, P, Mg, Ca, K, Na, Mn, and Al.

pH (1:1) was determined by adding 15 ml deionized water to 15 g of dry soil. The soil and water were mixed and allowed to equilibrate for 30 minutes, stirred again, and pH values were read on an Orion Research 701 which had been standardized at pH 4.0, 7.0, and 10.0.

Cation exchange capacity (CEC) was determined by sodium saturation. This procedure was modified from Bower et al. (1952). Soil (5.00 g) was placed in a 50 ml round bottom centrifuge tube and 33 ml of 1.0 N sodium acetate (NaOAc) solution was added. The tube was stoppered and placed on a mechanical shaker for 5 minutes, after which the sample was placed in a Servall Superspeed Centrifuge at 4000 rpm for 5 minutes. The clear supernatant was decanted, and the extraction repeated three more times. The sample was then washed in an identical manner with three 33 ml portions of 99% isopropyl alcohol. The adsorbed Na was replaced by using the same shaking and centrifuging procedure with three 33 ml portions of 1.0 N Ammonium acetate (NH_4OAc) reagent. Each washing was decanted into a 100 ml volumetric flask and brought to volume with 1.0 N NH_4OAC. Sodium was determined on a Perkin-Elmer 403 Atomic Absorption Spectrophotometer and results recorded in meq per 100 g of soil.

Soil NO_3^--N was determined by extracting 10.0 g of soil with 25 ml 0.015 N $CaSO_4$. The solution was placed on a rotary shaker for 30 min utes. Nitrogen levels were read on an Orion Research 901 Ionalyzer which had been calibrated with standards made from a 1000 ug NO_3^-/ml stock solution of KNO_3. This was prepared by accurately weighing 7.2202 g of dry KNO_3 and quantitatively transferring to a 1 L volumetric flask. The solution was diluted to volume with extracting solution. From this a 100 ug NO_3^-/ml stock was made. Standard solutions containing 100, 50, 25 ml of 100 ug NO_3^-/ml stock were added to three 500 ml volumetric flasks and brought to volume with extracting solution. These were used to standardize the 901 equipped with nitrate and double junction reference electrodes to read 112, 56, and 28 kg NO_3/ha.

Soil P was determined by a modified Bray P-1 method (0.03 N NH_4F in 0.025 N HCl) using a 1:20 soil solution extraction ratio (Bray and Kurtz, 1945). The extracting solution was prepared by adding 41.7 ml of concentrated HCl to 22.22 g of NH_4F in 5 liters of water; then, brought to 20 liters final volume. One gram of soil was transferred into a 50 ml Erlenmeyer flask with 20 ml of Bray extraction solution and placed on a shaker for 5 minutes. The sample was filtered through Whatman #2 filter paper. Five ml of each sample and 5 ml of each standard were placed in 50 ml tubes along with 5 ml of extracting solution used as a blank. Ten ml of 1% boric acid (20.0 g H_3BO_3 in 2 L water) was added and mixed. Next, 5 ml of ascorbic acid:ammonium molybdate-antimony potassium tartrate solution (prepared daily) was added. This solution was made by dissolving 24.0 g of ammonium molybdate in 500 ml of deionized water, and then transferring to a 2 L volumetric flask. Next, antimony potassium tartrate (0.58 g) was dissolved in 200 ml of deionized water and transferred to the 2 L volumetric flask. Concentrated H_2SO_4 (296 ml) was added to 1500 ml of deionized water in a second 2 L volumetric flask. Both 2 L flasks were mixed and stored. Finally, 1.06 g L-ascorbic acid was mixed with 200 ml of the stored solution to develop the color complex which requires 45 minutes. Standards were prepared from 1000 ug P/ml stock (4.4042 g KH_2PO_4/1 L Bray extract) and readings were taken on a Coleman 55 Spectrophotometer at 840 m.

Potassium, Na, Mn, Ca, Mg, and Al were determined by extracting with 1 N NH_4OAc (pH 4.8). This solution was prepared by adding 58 ml of glacial acetic acid to 400 ml of water in a 1 L volumetric flask. Next, 70 ml of concentrated NH_4OH was added through a funnel which extended into the acid, and the solution was brought to volume. Then, the solution was transferred to a 2 L beaker where the pH was adjusted to 4.8 with 1.0 N HOAc (approximately 1 L is required). Ten grams of soil and 250 ml of extracting solution were placed in a 500 ml Erlenmeyer flask.

Samples were placed on a wrist action shaker for 30 minutes and allowed to stand overnight. The samples were filtered with a 55 mm Buchner funnel using Whatman #2 filter paper (light suction). An additional amount (50 ml) of extracting solution was placed in the flask and then allowed to leach through the sample to insure complete Ca removal. A 25 ml aliquot was taken from the 300 ml of solution and stored in test tubes to be analyzed on a Perkin-Elmer 403 Atomic Absorption Spectrophotometer. Potassium, Na, Mn, Ca, and Mg were determined with an air-acetylene flame. For Ca and Mg determinations, a 4 ml aliquot was taken and 1 ml of 5% La_2Cl_3 was added to neglect ionization interferences. This solution was prepared by dissolving 58.65 g of La_2O_3 in 500 ml of water in a 1 L flask, then 250 ml of concentrated HCl and dilute to volume. The presence of other easily ionized elements in the sample will add free electrons to the flame and supress ionization of Ca and Mg thereby increasing absorption of these elements (Hosking et al., 1979). Aluminum was determined by using an acetylene-nitrous oxide flame. The flame was used in the reducing (fuel-rich) condition, in which a large red feather secondary reaction zone was present. Refractory elements such as Al react with O and OH species in the flame and produce thermally stable metal oxides and hydroxides. These are decomposed by using high temperature flames. All standards were made from Fisher 1000 ug/ml stock solutions. Twenty ml of 5% La_2Cl_3 solution was added to the Ca and Mg standards. All samples were diluted in the linear working range of the Perkin-Elmer 403.

Plant Procedures

Plant samples were dried at 60°C for 12 hours and ground to pass through a 100 mesh sieve.

Forage, straw, and grain samples were analyzed for total N, Ca, Mg, Na, K, P, Cl, S, NO_3-N, Mn, and Al. Duplicate samples were run; however, if the first two were not within 5%, a third sample was tested. Duplicate samples of NO_3-N were not run due to the expense of the extracting reagent, $AgSO_4$.

A modified microkjeldahl procedure was used to determine total plant N by placing 250± 3 mg of dry plant material in the bottom of a BD-40 digestion tube and adding 2.1 g catalyst mixture (100 g K_2SO_4, 10 g $CuSO_4$, and 1 g Se mixed and finely ground) and 7 ml of concentrated H_2SO_4. After the sample was thoroughly wet, 1 ml of 30% H_2O_2 was added, and the tubes were placed in a Tecator BD-40 block digestor that had been preheated to 420°C. After the samples had digested for 1 hr, they were removed and cooled. Twenty to 25 ml of water was added, and the contents were quantitatively transferred to a 100 ml microkjeldahl flask. If salt crystals formed in the bottom of the tubes, heat was applied (bunsen burner) and stirred before transferring to the 100 ml flask. Twenty-five ml of 10 N NaOH was added to each flask before steam distillation was performed (Bremner, 1965). Thirty-five ml was distilled into 50 ml Erlenmeyer flasks which contained 5 ml of boric acid indicator. This solution was prepared by placing 50 g of boric acid in 1900 ml of deionized water in a 2 L volumetric flask. It was necessary to heat and stir the solution. After cooling, 40 ml of mixed indicator solution was added and brought to volume. Indicator solution was prepared by dissolving 0.099 g bromocresol green and 0.066 g of methyl red in 100 ml of 95% ethanol. Sodium hydroxide (0.1 N) was cautiously added until the solution assumed a reddish purple tint (pH = 5.0). The samples were titrated with standardized 0.0100 N HCl to a light pink endpoint. Two blanks were run with each set of 40 samples, and the mean subtracted from the total N.

Plant contents of P, Ca, Mg, Na, K, Mn, and Al were determined by nitric-perchloric digestion. Dried plant material (0.200 g) was placed into calibrated 50 ml test tubes, and 5 ml of concentrated HNO_3 was added. After the sample was thoroughly wet, 2 ml of concentrated $HClO_4$ was added. The tubes were placed on a Tecator BD-40 digestion block at 100°C for 30 minutes, 175°C for 1 hr, and then 265°C until approximately 0.5 ml remained in the tubes (approximately 3½ hrs total). The tubes were cooled and diluted to 50 ml. Calcium, Mg, Na, K, Mn, and Al were determined on a Perkin Elmer 403 Atomic Absorption Spectrophotometer with the same techniques described in the soil procedures section. Plant P was determined by pipetting a 5 ml aliquot from the 50 ml tube into a 200 ml tall form beaker. Fifty ml of water and 5 ml sodium molybdate were added. Sodium molybdate was prepared by dissolving 20 g in 500 ml water with 400 ml $HClO_4$ and diluting to 1 L. Five ml hydrazine sulfate (20 g/L) was added, and the beakers were placed on a hot plate until boiling. The samples were cooled and diluted to 100 ml. The samples were analyzed with a Bausch and Lomb Spectronic 20 coupled with a Fisher Concentration Computer. The Spectronic 20 was standardized with 2, 4, 6, 8, and 10 ml aliquots of 25 up P/ml stock. These were placed in 200 ml tall form beakers and processed as samples. The 25 ug P/ml stock was prepared by diluting 25 ml of 100 up P/ml stock (4.394 g KH_2PO_4 + 10 ml H_2SO_4/ L) to 1 L. The Concentration Computer was standardized with 0.00, 0.50, 1.00, 1.50, 2.00, and 2.50 up P/ml.

Plant NO_3-N was determined by weighing 0.400 g of dry plant tissue into 125 ml Erlenmeyer flasks. Fifty ml of extracting solution was added, and the samples were placed on a wrist action shaker for thirty minutes. The extracting solution was prepared by placing 33.32 g aluminum sulfate, 18 H_2O, 2.48 g boric acid, and 9.34 g silver sulfate into a 2 L volumetric flask. All chemicals were dissolved in 1800 ml water and brought to volume. Next, the pH was adjusted to 3.0± 0.1 with concentrated H_2SO_4. The solution was stored in the refrigerator between uses. The samples were filtered through Whatman #40 filter paper into 100 ml beakers. Analysis was performed with an Orion Research 901 Ionalyzer coupled with nitrate (model 93-07-01) and double junction reference electrodes (model 90-02). Extracting solution was placed in the outside jacket of the double junction reference electrode. Standards were made by placing 0.1044 g KNO_3 into a 200 ml volumetric flask which was brought to volume with extracting solution and labeled 320 ug NO_3/ml. Then 0, 25.0, 50.0, and 100.0 ml aliquots were taken from the stock solution and placed into 100 ml volumetric flasks which were diluted to volume with extracting solution and labeled 0.0, 16.0, 80.0, and 160.0 ug NO_3/ml. These standards were used to calibrate the Ionalyzer. Readings were converted to ug NO_3-N/g plant tissue.

Plant Cl content was determined (modified from LaCroix et al., 1970) by weighing 0.500 g oven dried plant tissue into a 100 ml plastic cup and adding 50 ml 0.1 N HNO_3 and 1 ml ionic strength adjustor (ISA:5 M $NaNO_3$). These were placed on a rotary shaker for 15 minutes along with a blank. Chloride content was determined with an Orion Research 901 Ionalyzer coupled with chloride (model 94-17) and double junction reference electrodes. The outer jacket of the reference electrode was filled with 10% KNO_3. The Ionalyzer was checked daily for an adequate slope. This was accomplished by placing electrodes in 100 ml deionized water plus 2 ml ISA and pressing clear/read mv. Then, 1 ml 1000 ug Cl/ml (1.65 g NaCl/L) was dispersed into the solution and SET CONC was pressed. Ten more ml of 1000 ug Cl/ml was added and mv reading recorded. Correct operation was indicated by a difference of 53-59 mv. The sample was vigorously stirred while being titrated with 0.02800 N $AgNO_3$:0.1 N HNO_3 using the Cl electrode to indicate the endpoint. The Ionalyzer was set for mv reading, and the endpoint was seen as the change in mv per ml of titrant added. Silver nitrate was titrated at 0.05 ml increments and mv reading recorded every 10 seconds. The endpoint is calculated by plotting the first derivative (delta mv per 0.05 ml titrant vs total titrant added). Chloride amounts were then calculated from the total ml of titrant at the endpoint.

Plant S was determined turbidimetrically with $BaCl_2$ using a Technicon AutoAnalyzer II modified with a Dual probe conversion kit (Part Number 930-1112-01). Modules used with the Auto-Analyzer included: Sampler IV with 30/hr, 1:1 cam, proportioning pump II, AAII single channel colorimeter with 1.5 (id) x 20 mm tubular flowcell, 420 nm interference filter, and recorder. A different nitric-perchloric digestion method (modified from Blancher et al., 1965) was utilized for total plant S. Samples (0.250 g) were placed in 50 ml digestion tubes along with three glass beads. Five ml of concentrated HNO_3 were added and a 25 ml funnel placed in the mouth of each tube. Samples were allowed to stand overnight. Then the samples were placed in a preheated Tecator BD-40 digestion block (150^{o}C) for 30 minutes. The tubes were removed and the block turned to 215^{o}C. After 5 minutes, 2 ml concentrated $HClO_4$ was added, and the samples digested for 1½ hours. Then the funnels were removed and digestion continued until all nitric fumes had evolved (20 min.). Approximately 0.5 ml remained in the tubes. The samples were then removed and cooled, after which 10 ml of water was added, and they were placed on the block until boiling occurred. The tubes were then removed and diluted to 35 ml. Plant S was then determined using the modified Technicon AutoAnalyzer as described by Wall et al. (1980).

Treatment effects and interactions were determined by using analysis of variance, stepwise linear regression, and correlation programs of Statistical Analysis Program (SAS) 79.

CHAPTER IV

RESULTS AND DISCUSSION

Soil Analysis

Results of chemical analysis of soils are listed in Table II. Significant increases in pH were observed for each lime rate except between ¼X and ½X for 0, 448, and 896 kg N/ha. In the 224 kg N/ha plot, significant increases occurred between each lime rate except X and 2X. Due to the increase in pH, Al concentrations significantly decreased between 0X and ¼X, ½X, X, and 2X at all four N rates. Similar decreases were expected with Mn; however, this occurred only at 896 kg N/ha between 0X and ¼X, ½X, X, and 2X. In 224, and 448 kg N/ha plots Mn significantly decreased between 0X and ¼X, ½X, and X; but, a significant increase occurred at 2X.

Application of ag-lime influenced the base status of the soil. Calcium increases were observed between 0X and X in 0 and 448 kg N/ha plots, whereas, in the 224 kg N/ha plot a significant increase occurred between 0X and 2X. There were no significant differences in the 896 kg N/ha plot using a protected FLSD at 0.05 or 0.10 level. Magnesium increases occurred between each lime rate except ¼X and ½X in 0, 448, and 896 kg N/ha. In 224 kg N/ha significant increases occurred between each lime rate except 0X and ¼X. Soil Na and K levels were not affected by lime application. Due to the addition of Ca and Mg, base saturation

TABLE II

CHEMICAL ANALYSIS OF POND CREEK SILT LOAM TREATED WITH FIVE LIME RATES AT FOUR N LEVELS*

	Lime	pH	NO_3-N	P	Na	K	Ca	Mg	Mn	Al	CEC	BS
			----ug/g-----		----------------meq/100 g						----------------------------	%
						N Rate 0 kg/ha						
	0X	5.2	7.6	44.6	0.17	1.06	4.7	1.31	0.33	1.6	18.3	40
	¼X	6.0	19.0	37.5	0.19	1.07	6.4	2.60	0.27	1.0		56
	½X	6.2	22.1	37.3	0.15	1.05	6.2	3.03	0.27	0.9		57
	X**	6.7	28.5	40.0	0.18	1.05	9.5	4.80	0.31	0.9		85
	2X	7.0	30.5	40.8	0.21	1.10	10.5	7.28	0.44	0.8		104
FLSD	(0.05)	0.3	10.3	4.0	n.s.	n.s.	2.9	0.76	0.04	0.2		17
						N Rate 224 kg/ha						
	0X	5.0	14.5	48.1	0.12	0.98	6.2	1.17	0.39	1.6	19.0	45
	¼X	5.5	21.3	42.9	0.13	0.99	5.0	1.83	0.33	1.1		42
	½X	6.0	28.3	38.5	0.15	0.99	7.0	2.80	0.31	0.9		58
	X**	6.5	31.1	41.6	0.14	0.94	7.7	4.11	0.30	0.7		68
	2X	6.7	40.6	42.0	0.16	0.99	10.6	6.91	0.40	0.7		98
FLSD	(0.05)	0.3	6.8	5.4	n.s.	n.s.	3.3***	0.73	0.03	0.2		19
	(0.10)***											

TABLE II (Continued)

	Lime	pH	NO_3-N	P	Na	K	Ca	Mg	Mn	Al	CEC	BS
			----ug/g-----		-----------------	-----------------	meg/100 g	-----------------	-----------------	-----------------	-----------------	%
						N Rate 448 kg/ha						
	OX	4.4	19.0	50.6	0.13	1.09	4.9	0.90	0.48	1.6	20.3	34
	¼X	5.4	24.3	43.9	0.13	1.05	6.3	2.26	0.38	1.0		48
	½X	5.5	24.5	39.8	0.14	1.03	6.7	3.24	0.37	0.8		55
	X**	6.0	39.0	43.6	0.13	1.12	7.8	4.90	0.36	0.6		69
	2X	6.5	41.1	44.5	0.12	1.01	10.2	7.10	0.43	0.6		91
FLSD	(0.05)	0.5	12.5	n.s.	n.s.	n.s.	2.8	1.00	0.05	0.1		17
						N Rate 896 kg/ha						
	OX	4.9	24.0	48.1	0.13	1.11	7.0	1.34	0.58	1.2	21.2	45
	¼X	5.4	30.9	38.8	0.14	0.97	7.7	2.07	0.50	0.9		52
	½X	5.5	32.6	39.5	0.18	1.03	7.5	2.60	0.44	0.9		53
	X**	6.1	44.9	38.8	0.13	1.03	8.3	3.73	0.40	0.7		63
	2X	6.5	46.4	41.9	0.14	1.03	10.1	5.55	0.41	0.7		79
FLSD	(0.05)	0.3	9.4	n.s.	n.s.	n.s.	n.s.	0.58	0.03	0.1		14

* Fifteen months after lime application and two nitrogen applications.

** Recommended lime rate (10.76 metric tons/ha).

significantly increased at ½X, X, and 2X compared to OX in 0 and 448 kg N/ha. Also, increases occurred between OX and X in 224 and 896 kg N/ha.

Soil nitrate levels increased with increasing lime rates. Microorganisms necessary for nitrification are more active in a neutral pH range than in very acidic conditions. Significant increases were observed between OX and ¼X, ½X, X, and 2X in 0 and 224 kg N/ha. In 448 and 896 kg N/ha significant increases occurred between OX and X.

Phosphorus availability should increase in an acid soil when lime is applied. This is due to the low solubility of Al, Fe, and Mn phosphates present in an acid soil. However, in 0 and 224 kg N/ha significant decreases in P were observed between OX and ¼X, ½X, X, and 2X. This is due to the inability of the Bray extraction method used to detect Ca phosphates formed by lime application. There were no significant differences in P levels in 448 and 896 kg N/ha.

Prediction equation were formed for pH, Al, and Mn by using Stepwise Linear Regression Max R^2 option of SAS 79 (Table III). The variables included eleven chemical analyses along with seventeen created variables listed in Table IV. The variables are listed in order as they appeared in the equation. This program enables variables to leave and re-enter the equation until the best one variable model, the best two variable model, etc., is formulated. The sign and size of beta values are not significant because each variable influences the other. The important observation is which variables are included and their order in the equation.

In 0 kg N/ha pH was related to $Mg^{\frac{1}{2}}/P$, NO_3-N, P, Mg/Al+Mn+Ca+Mg+Na+K, and $Al^{1/3}/P$. An R^2 value of 0.97 was established. The pH prediction equation at 224 kg N/ha indicated that pH was related to Al, Ca, Mg/Al+

TABLE III

STEPWISE LINEAR REGRESSION MAXIMUM R^2 FOR DEPENDENT SOIL VARIABLES pH, Al, AND Mn AT FOUR NITROGEN RATES

N Rate kg/ha	Y=	b_0	+ b_1x_1	+ b_2x_2	+ b_3x_3	+ b_4x_4	+ b_5x_5	+ b_6x_6	+ b_7x_7	+ b_8x_8	+ b_9x_9	R^2
0	pH	9.26	45.7G*	0.0193NO_3-N	-0.0389P	-3.75Q*	-111F*					0.97
	Al	-1.32	-0.0400pH	-0.0523Mg	-1.92Q*	1100*	0.0344P					0.99
	Mn	0.312	0.0803Mg	0.187Al	-6.72G*	-0.0068P	-0.0042Ca	0.0224pH				0.99
224	pH	7.40	0.959Al	0.137Ca	9.63Q*	0.0219NO_3-N	-0.0740P	-1860*	-0.161Mg			0.96
	Al	-1.01	-3.05Q*	0.0435P	-0.0402Ca	-0.953J*	92.40*	1.10B*				0.98
	Mn	0.368	0.00654Ca	0.184K*	0.0527Mg	0.157Al	-0.0288pH	-0.0049P	-2.73G*			0.93
448	pH	2.98	273L*	-61.2B*	-0.398Mg	12.9A*	0.019NO_3-N	0.401Ca	13.6Q*	0.559Al	29.2F*	0.93
	Al	-0.788	-2.65Q*	27.1B*	-6.78K*	5.41J*	-154L*	3.00Mn	-0.0787Ca			0.97
	Mn	-0.175	-1.15E*	0.104Mg	0.490J*	-1.62Q*	-0.0317Ca	17.7F*	0.007P			0.92
896	pH	5.19	0.191Mg	0.015NO_3-N	-0.0153P	0.0521Ca	-0.918Mn					0.96
	Al	-4.27	8.39G*	2.45Mn	49.5B*	0.0952Ca	211L*	1190*	-0.0397P	-1.39J*		0.97
	Mn	0.590	0.143Al	4.44G*	-1.59I*	0.492K*	-1.36Q*	0.0525Mg	-0.081pH			0.94

* Refer to Table IV.

TABLE IV

ADDITIONAL VARIABLES CREATED FOR
STEPWISE LINEAR REGRESSION

$A = \mathrm{Al}^{1/3} / (\mathrm{Ca} + \mathrm{Mg} / 2)^{\frac{1}{2}}$

$B = \mathrm{Mn}^{\frac{1}{2}} / (\mathrm{Ca} + \mathrm{Mg} / 2)^{\frac{1}{2}}$

$C = \mathrm{Al}^{1/3} + \mathrm{Mn}^{\frac{1}{2}} / (\mathrm{Ca} + \mathrm{Mg} / 2)^{\frac{1}{2}}$

$D = \mathrm{Al} / \mathrm{CEC}$

$E = \mathrm{Al} / \mathrm{Al} + \mathrm{Mn} + \mathrm{Ca} + \mathrm{Mg} + \mathrm{Na} + \mathrm{K}$

$F = \mathrm{Al}^{1/3} / \mathrm{P}$

$G = \mathrm{Mg}^{\frac{1}{2}} / \mathrm{P}$

$H = \mathrm{Al}^{1/3} + \mathrm{Mn}^{\frac{1}{2}} / \mathrm{P}$

$I = \mathrm{Na} / (\mathrm{Ca} + \mathrm{Mg} / 2)^{\frac{1}{2}}$

$J = \mathrm{K} / (\mathrm{Ca} + \mathrm{Mg} / 2)^{\frac{1}{2}}$

$K = \mathrm{Na} + \mathrm{K} / (\mathrm{Ca} + \mathrm{Mg} / 2)^{\frac{1}{2}}$

$L = \mathrm{Mn} / \mathrm{Al} + \mathrm{Mn} + \mathrm{Ca} + \mathrm{Mg} + \mathrm{Na} + \mathrm{K}$

$M = \mathrm{Al} + \mathrm{Mn} / \mathrm{Al} + \mathrm{Mn} + \mathrm{Ca} + \mathrm{Mg} + \mathrm{Na} + \mathrm{K}$

$N = \mathrm{Al} + \mathrm{Mn}$

$O = \mathrm{Mn}^{\frac{1}{2}} / \mathrm{P}$

$Q = \mathrm{Mg} / \mathrm{Al} + \mathrm{Mn} + \mathrm{Ca} + \mathrm{Mg} + \mathrm{Na} + \mathrm{K}$

$R = \mathrm{Ca} + \mathrm{Mg} + \mathrm{Na} + \mathrm{K} / \mathrm{CEC}$

Mn+Ca+Mg+Na+K, NO_3-N, P, $Mn^{1/2}$/P, and Mg. At the third N rate pH was related to Mn, Mg, Al, NO_3-N, and Ca. In 896 kg N/ha the pH prediction equation included Mg, NO_3-N, P, Ca, and Mn.

The prediction equations for Al included pH, Mg, Mn, Ca, and P and other variables. Manganese equations included Mg, Al, P, Ca, and pH along with ratios of these variables.

Forage Analysis

Results of the chemical analysis of forage tissue are listed in Table V. Decreasing Al concentrations were recorded at 0, 224, and 448 kg N/ha. There were significant decreases between 0X and ½X, X, and 2X in 0 kg N/ha and between 0X and ¼X, ½X, X, and 2X in 224 and 448 kg N/ha. Also, significant decreases in Mn were observed in the first three N rates between 0X and ¼X, ½X, X, and 2X. In 896 kg N/ha there were significant decreases between 0X and ½X, X, and 2X.

Total N content increased in 0 kg N/ha between 0X and ½X, X, and 2X because of increased nitrification. However, this trend did not appear in the other N treatments. Nitrate levels tended to increase with increasing lime rates, but variations within each replication due to the method of analysis indicated no significant treatment effects. The only significant increases occurred in 448 kg N/ha between 0X and ¼X, ½X, X, and 2X. Phosphorus levels increased in 0 kg N/ha and decreased in 896 kg N/ha with increasing lime rates. There were no significant differences in 224 and 448 kg N/ha.

Forage base contents were affected by the addition of bases to the soil. Although there were no treatment effects observed in Ca or Na contents, K and Mg increases were observed. Significant increases in K

TABLE V

CHEMICAL ANALYSIS AND EXCESS BASE/NITROGEN RATIOS OF WHEAT FORAGE TREATED WITH FIVE LIME RATES AT FOUR NITROGEN RATES*

	Lime	N	P	K	Ca	Mg	Na	Cl	S	NO_3-N	Al	Mn	EB/N
		%	meq/100 g								ug/g		
						N Rate 0 kg/ha							
	OX	2.99	8.50	82.5	18.3	12.5	2.55	7.77	8.08	2.25	193	136	0.30
	¼X	3.07	8.30	84.6	20.3	12.8	2.71	7.55	7.10	2.78	166	87	0.31
	½X	3.19	8.42	83.1	16.3	13.0	2.11	7.60	7.53	2.88	149	84	0.28
	X**	3.30	9.23	84.7	21.8	14.0	2.80	8.18	7.75	3.23	118	75	0.29
	2X	3.39	10.00	87.1	18.0	14.5	2.73	7.43	9.50	3.53	136	71	0.27
FLSD	(0.05)	0.16	0.77	n.s.	n.s.	0.7	n.s.	n.s.	n.s.	n.s.	43	10	n.s.
						N Rate 224 kg/ha							
	OX	3.36	8.69	76.2	20.7	10.3	2.61	5.10	11.50	2.34	236	334	0.25
	¼X	3.33	8.53	85.2	19.7	12.0	2.19	5.83	7.64	4.20	158	142	0.28
	½X	3.20	8.42	84.9	20.4	12.7	3.21	5.95	8.52	3.72	149	110	0.30
	X**	3.38	8.82	86.3	18.0	13.2	3.10	6.08	8.95	3.98	140	85	0.27
	2X	3.44	9.64	87.4	20.7	13.8	2.69	5.75	9.28	4.56	140	82	0.28
FLSD	(0.05)	n.s.	n.s.	3.7	n.s.	0.7	n.s.	n.s.	1.46	n.s.	49	35	0.02

TABLE V (Continued)

	Lime	N	P	K	Ca	Mg	Na	Cl	S	NO_3-N	Al	Mn	EB/N
		%	meq/100 g								ug/g		
						N Rate 448 kg/ha							
	OX	3.36	9.68	76.2	22.2	11.3	2.43	3.85	14.50	2.19	276	595	0.25
	¼X	3.46	8.91	93.4	18.0	13.1	2.52	4.43	9.50	5.29	162	183	0.26
	½X	3.33	9.02	83.4	19.1	13.3	2.74	5.30	9.61	5.36	158	128	0.27
	X**	3.53	9.59	83.4	20.5	14.3	2.04	4.55	9.83	5.93	158	92	0.26
	2X	3.42	9.42	87.3	19.6	14.6	1.92	4.78	9.93	5.86	136	92	0.27
FLSD	(0.05)	n.s.	n.s.	4.7	n.s.	0.7	n.s.	1.08	3.31***	0.94	64	113	n.s.
	(0.10)***												
						N Rate 896 kg/ha							
	OX	3.61	10.80	77.5	23.8	13.4	2.87	2.95	11.80	8.81	162	441	0.23
	¼X	3.56	9.79	80.9	25.1	14.6	3.00	4.05	10.30	8.65	153	286	0.26
	½X	3.45	9.37	83.3	18.9	13.3	2.36	4.30	9.61	7.54	144	230	0.25
	X**	3.46	8.69	85.5	27.7	13.7	3.01	4.55	8.95	8.39	149	109	0.27
	2X	3.53	9.69	84.4	21.5	14.4	2.81	4.73	8.30	9.59	144	90	0.26
FLSD	(0.05)	n.s.	0.76	6.1***	n.s.	n.s.	n.s.	1.35***	n.s.	n.s.	n.s.	203***	n.s.
	(0.10)***												

*Fifteen months after lime application and two nitrogen applications.
**Recommended lime rate (10.76 metric tons/ha).

occurred in 224, 448, and 896 kg N/ha, whereas, increases in Mg occurred in 0, 224, and 448 kg N/ha.

Chloride concentrations increased in 448 and 896 kg N/ha. In 896 kg N/ha significant differences were observed between 0X and ½X, X, and 2X. No treatment effects were observed in 0 or 224 kg N/ha.

Sulfur analysis revealed decreases in concentration with increasing lime rates at 224 and 448 kg N/ha. Significant differences were observed between 0X and ¼X, ½X, X, and 2X in both plots. There were no treatment effects in 0 or 896 kg N/ha.

Excess base N ratios were determined by subtracting the total cations from the total anions and dividing by the total N content. Results generally indicated that the EB/N ratio was not affected by lime treatments. However, in 224 kg N/ha a significant increase in EB/N was observed between 0X and ¼X, ½X, X, and 2X.

Straw Analysis

Results of chemical analysis of straw tissue are listed in Table VI. There were no treatment effects on Al content in straw. However, Mn data revealed significant decreases at all four N rates. At 0, 448, and 896 kg N/ha significant decreases were observed between 0X, ¼X, ½X, X, and 2X.

Total N of straw increased only in 224 kg N/ha plot between 0X and 2X. Nitrate significantly increased in 224 and 896 kg N/ha between 0X and 2X. Phosphorus data did not indicate any treatment effects.

Increases in base content of straw were observed in Mg data. Significant increases occurred in the first three N rates. The only K increase occurred in the 224 kg N/ha plot between 0X and X. Treatment

TABLE VI

CHEMICAL ANALYSIS AND EXCESS BASE/NITROGEN RATIOS OF WHEAT STRAW TREATED WITH FIVE LIME RATES AT FOUR NITROGEN RATES*

Lime	N	P	K	Ca	Mg	Na	Cl	S	NO_3-N	Al	Mn	EB/N
	%	meq/100 g								ug/g		
						N Rate 0 kg/ha						
OX	0.261	1.02	22.9	6.92	6.57	0.295	4.26	2.14	0.891	152	45	1.19
¼X	0.218	0.79	23.0	8.05	6.73	0.285	3.34	2.37	0.177	143	25	1.25
½X	0.335	0.99	27.0	8.09	7.45	0.280	3.12	2.37	0.183	95	22	1.14
X**	0.362	1.19	26.1	7.35	7.10	0.297	3.05	2.44	0.245	102	28	1.00
2X	0.353	1.24	24.9	6.78	8.29	0.337	2.38	2.65	0.495	172	24	0.95
FLSD (0.05) (0.10)***	n.s.	n.s.	n.s.	n.s.	1.21***	n.s.	0.74	n.s.	n.s.	n.s.	15***	n.s.
						N Rate 224 kg/ha						
OX	0.389	0.88	28.7	8.08	6.43	0.284	2.75	2.65	0.829	95	92	0.99
¼X	0.298	1.12	29.9	8.00	6.10	0.296	3.86	2.65	0.624	156	45	1.29
½X	0.383	0.85	32.4	7.02	7.34	0.318	4.31	2.82	1.330	164	27	0.99
X**	0.477	1.16	38.9	7.24	8.30	0.450	3.93	3.26	1.830	158	21	0.97
2X	0.550	1.70	31.6	7.33	8.93	0.389	3.93	3.54	2.990	153	26	0.66
FLSD (0.05) (0.10)***	0.095	n.s.	3.9	n.s.	0.92	n.s.	0.34***	0.54	0.016***	n.s.	21	0.37***

TABLE VI (Continued)

	Lime	N	P	K	Ca	Mg	Na	Cl	S	NO_3-N	Al	Mn	EB/N
		%	meq/100 g								ug/g		
						N Rate 448 kg/ha							
	0X	0.437	1.58	29.5	8.99	6.23	0.334	2.90	2.83	3.50	148	145	0.80
	¼X	0.575	1.42	34.1	9.07	7.92	0.308	2.75	2.98	3.45	141	70	0.80
	½X	0.493	1.69	35.4	9.06	7.57	0.376	2.75	3.10	2.07	179	53	0.94
	X**	0.557	1.73	40.0	8.46	7.93	0.434	3.78	3.58	4.18	159	25	0.78
	2X	0.533	2.16	35.6	8.99	8.37	0.518	4.23	3.65	4.09	159	26	0.77
FLSD	(0.05) (0.10)***	n.s.	n.s.	n.s.	n.s.	0.38***	n.s.	n.s.	0.74***	n.s.	n.s.	34	n.s.
						N Rate 896 kg/ha							
	0X	0.651	1.64	40.2	9.54	7.18	0.408	3.37	3.49	5.09	221	224	0.70
	¼X	0.580	1.37	44.0	9.83	8.18	0.541	4.01	3.58	4.96	249	154	0.86
	½X	0.625	1.52	44.2	10.30	6.61	0.498	3.57	3.74	7.67	191	70	0.73
	X**	0.534	1.25	40.3	8.07	7.49	0.492	4.38	3.61	5.08	172	43	0.78
	2X	0.568	2.06	37.4	8.55	7.98	0.760	4.23	3.96	8.17	179	37	0.71
FLSD	(0.05)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	2.23	n.s.	51	n.s.

* Fifteen months after lime application and two nitrogen applications.

** Recommended lime rate (10.76 metric tons/ha).

effects were not observed in Ca or Na analysis.

Chloride analysis of straw tissue indicated two trends. At 0 kg N/ha a decrease was observed between 0X and ¼X, ½X, X, and 2X. Conversely, an increase occurred between 0X and ¼X, ½X, X, and 2X in the 224 kg N/ha plot. There were no significant treatment effects in the two higher N rates; but, the trend indicated an increase in chloride with increasing lime treatments. Sulfur analysis revealed a significant increase between 0X and X in 224 and 448 kg N/ha.

Again, the only treatment effect on EB/N occurred in 224 kg N/ha between ¼X and 2X.

Results of straw yields are listed in Table VII. Lodging occurred in the high fertility plots (high lime and high N). Significant increases in straw yields occurred in 0 and 224 kg N/ha plots between 0X and ¼X, ½X, X, and 2X. There were trends in the higher N rates of increased yields with lime, but the F value was not significant at 0.05 or 0.10 level.

Grain Analysis

Results of the chemical analysis of grain are listed in Table VIII. There were no treatment effects on Al content in grain. Also, there were no treatment effects on Mn in the first three N rates; however, at 896 kg N/ha there was a significant decrease between 0X and 2X.

Total N analysis revealed significant treatment effects in 224, 448, and 896 kg N/ha. An increase in total N was noted between 0X and X in all three plots. Increases did not occur in the NO_3-N analysis, where all treatments were insignificant. Results of P content in wheat grain indicated that liming an acid soil actually improved P uptake by

TABLE VII

THE EFFECT OF LIME ON STRAW YIELDS* IN A POND CREEK SILT LOAM FERTILIZER WITH VARYING NITROGEN RATES

	Nitrogen (kg/ha)			
Lime	0	224	448	896
0	2280	2500	3510	5260
¼X	3700	4230	5280	5180
½X	3460	4380	5500	6700
X**	4330	4390	5180	5950
2X	4830	3850	4540	4300
FLSD(.05)	916	461	n.s.	n.s.

* (kg/ha)
** Recommended lime rate (10.76 metric tons/ha)

TABLE VIII

CHEMICAL ANALYSIS AND EXCESS BASE/NITROGEN RATIOS OF WHEAT GRAIN TREATED WITH FIVE LIME RATES AT FOUR NITROGEN RATES*

	Lime	N	P	K	Ca	Mg	Na	Cl	S	NO_3-N	Al	Mn	EB/N
		%	meq/100 g								ug/g		
	N Rate 0 kg/ha												
	OX	1.98	8.9	7.16	2.45	12.0	0.214	2.38	4.45	0.337	37	52	0.03
	¼X	2.05	11.1	7.35	3.48	13.8	0.157	2.23	4.08	0.358	31	55	0.03
	½X	2.06	10.5	8.38	6.34	12.6	0.209	2.08	4.37	0.316	34	49	0.05
	X**	2.00	11.8	8.42	2.63	13.5	0.181	2.08	4.56	0.354	25	58	0.03
	2X	2.00	12.3	8.64	4.37	14.6	0.165	2.38	2.80	0.318	63	50	0.05
FLSD	(0.05) (0.10)***	n.s.	1.3	1.24	n.s.	n.s.	n.s.	n.s.	1.22***	n.s.	n.s.	n.s.	n.s.
	N Rate 224 kg/ha												
	OX	1.99	9.4	8.80	3.17	11.0	0.140	2.28	4.54	0.421	44	50	0.03
	¼X	2.05	10.3	8.47	2.42	11.7	0.114	2.23	4.14	0.403	41	44	0.03
	½X	2.04	10.3	7.06	4.67	13.1	0.179	2.10	4.38	0.342	62	71	0.04
	X**	2.10	11.6	8.47	3.48	13.7	0.231	2.30	4.26	0.312	28	47	0.04
	2X	2.17	12.8	9.13	2.63	14.8	0.220	2.16	4.63	0.335	50	71	0.03
FLSD	(0.05)	0.10	1.3	n.s.	n.s.	2.3***	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

TABLE VIII (Continued)

	Lime	N	P	K	Ca	Mg	Na	Cl	S	NO_3-N	Al	Mn	EB/N
		%	meq/100 g								ug/g		
N Rate 448 kg/ha													
	OX	2.07	10.3	9.34	3.21	11.1	0.166	2.08	4.74	0.340	47	67	0.03
	¼X	2.12	10.2	7.75	3.64	12.9	0.205	2.05	4.69	0.382	79	80	0.03
	½X	2.14	11.0	8.65	6.79	12.7	0.177	2.23	5.05	0.371	31	61	0.04
	X**	2.20	13.7	10.30	3.13	14.9	0.181	2.01	3.81	0.356	65	43	0.04
	2X	2.18	11.6	9.39	3.95	15.2	0.213	2.23	4.16	0.366	40	58	0.05
FLSD	(0.05)	0.07	1.4	n.s.	n.s.	2.7***	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
N Rate 896 kg/ha													
	OX	2.12	12.6	9.05	4.74	14.5	0.228	2.01	4.67	0.327	12	98	0.04
	¼X	2.08	11.7	9.21	3.22	14.5	0.182	2.15	4.42	0.286	15	77	0.04
	½X	2.15	12.1	10.60	3.33	12.3	0.140	1.78	3.96	0.368	22	31	0.04
	X**	2.19	12.5	9.38	4.65	15.8	0.199	2.48	4.84	0.373	71	65	0.04
	2X	2.20	11.0	9.58	3.87	13.2	0.236	2.45	4.41	0.345	34	43	0.04
FLSD	(0.05) (0.10)***	0.06	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	43***	n.s.

* Fifteen months after lime application and two nitrogen applications.
** Recommended lime rate (10.76 metric tons/ha).

plants. Soil, forage, and straw data failed to indicate this. At 0 kg N/ha there were significant increases between 0X and ¼X, ½X, X, and 2X. In 224 and 448 kg N/ha there were significant increases between 0X and X, 2X. No significant treatment effects were observed at the highest N rate.

Base contents in grain were generally not affected by lime application. However, an increase in K was noted in 0 kg N/ha between 0X and X. Also, Mg increases were observed in 224 and 448 kg N/ha between 0X and X. Calcium and Na contents in grain were not affected by lime application.

Chloride and S contents in grain were generally not affected by lime treatments. However, S decreased in 0 kg N/ha between 0X and 2X.

The EB/N ratio of grain was not affected by lime treatments. The values obtained agree with Pierre and Banwart (1973).

Prediction equations for grain yield are listed in Table IX. As would be expected the equations are complex. But, the order of variables in 0 kg N/ha is significant. This indicates that base saturation, NO_3-N, pH, and several variables containing Al are related to grain yield. Variables in the remaining three equations included Mn, Al, P, pH, NO_3-N, and several ratios of these variables.

Grain yield results are listed in Table X. Grain yields were also affected by lodging in the high fertility plots. Significant increases in yield occurred in 0 and 224 kg N/ha. At 0 kg N/ha significant increases were between 0X and ½X, X, and 2X. At 224 kg N/ha differences occurred between 0X and ½X.

TABLE IX

STEPWISE LINEAR REGRESSION MAXIMUM R^2 FOR DEPENDENT VARIABLE GRAIN YIELD AT FOUR NITROGEN RATES

$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 + b_7x_7 + b_8x_8 + b_9x_9 + b_{10}x_{10} + b_{11}x_{11} + b_{12}x_{12}$	R^2
N = 0 kg/ha = $7340 - 395R* - 23.2NO_3\text{-}N - 910pH - 63900N* - 599000H* - 102000E* + 74300Al + 1.80X10^6O* + 2290Mg + 73300B* - 23000Q*$	$R^2 = 0.81$
N = 224 kg/ha = $2130 + 57100Mn + 361000F* + 620NO_3\text{-}N - 1980Mg - 6.08X10^5O* - 10200N* - 389000L* + 223pH + 90500E* + 19400Q* + 1900R*$	$R^2 = 0.77$
N = 448 kg/ha = $-2000 + 26.1NO_3\text{-}N + 105pH + 5.51X10^5L* + 507P - 73300Q* - 74200Mn - 153000M* + 8530Mg + 7510N* + 1.52X10^6O* + 1.00X10^5R* + 3490Ca$	$R^2 = 0.95$
N = 896 kg/ha = $668 + 5670F* - 1060pH + 13300N* + 4.96X10^5E* + 1330Ca - 20500R* + 22800Q* - 20800Al + 9.70NO_3\text{-}N - 3.84X10^5M* + 73600B* - 16600C*$	$R^2 = 0.76$

* Refer to Table IV.

TABLE X

THE EFFECT OF LIME ON GRAIN YIELD* IN A POND CREEK SILT LOAM FERTILIZED WITH VARYING NITROGEN RATES

	Nitrogen (kg/ha)			
Lime	0	224	448	896
0	2310	2560	2810	2390
$\frac{1}{4}$X	2760	2960	2830	2750
$\frac{1}{2}$X	2930	3360	3360	2530
X**	3425	2900	2370	2530
2X	3400	2370	2470	2550
$\text{FLSD}_{(.05)}$	611	460	n.s.	n.s.

* (kg/ha)

** Recommended lime rate (10.76 metric tons/ha)

CHAPTER V

SUMMARY AND CONCLUSIONS

The purposes of this study were to determine soil constituents that have a detrimental effect on yield and nutrient content of wheat forage, grain, and straw, and to determine the effect of varying rates of lime and nitrogen on yield and nutrient content of wheat forage, grain, and straw. Next, to establish prediction equations based on known soil constituents for pH, Al, Mn, and grain and straw yields. Finally, to quantitatively assess the acidification effect of varying rates of urea-N, and to determine the contribution of removal of wheat forage, grain, and straw and their equivalent excess base/N ratios on soil acidity.

Five lime treatments were applied at four N levels to a Pond Creek Silt loam. Soil, wheat forage, grain, and straw samples were analyzed. Also, grain and straw yields were determined.

Lime treatments significantly increased soil pH, NO_3-N, Ca, Mg, and base saturation while decreasing Al concentrations. Accurate models for soil pH, Al, and Mn can be formulated from known soil constituents. Also, lime treatments reduced forage Al and Mn concentrations while increasing K and Mg concentrations. Straw treatment effects included decreases in Mn content while Mg content increased. Lime treatments increased total N and P in grain. Straw and grain yields were increased by lime application under normal N fertilization. The acidification effect of urea-N cannot be determined until data collected over several years is analyzed. The EB/N ratios of forage and grain are less than 1. Consequently, removal of forage or grain would decrease the amount of lime needed to neutralize the theoretical potential acidity produced by nitrification. On the other hand, EB/N ratio of straw is greater than 1, and straw removal would increase the amount of lime required to neutralize the theoretical potential acidity of ammonium fertilizers.

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