

DISSERTATION

**EFFECTS OF LIME AND CHICKEN MANURE ON NUTRIENT CYCLING, SOIL
PROPERTIES AND PLANT RESPONSE IN ACID SOUTH AFRICAN ULTISOLS**

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**In partial fulfillment of the requirements
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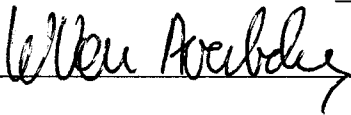
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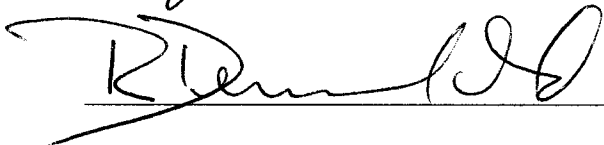
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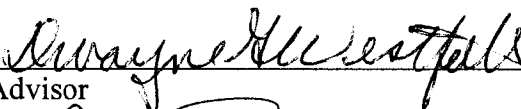
WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY GCINUHLANGA GOODMAN JEZILE ENTITLED EFFECTS OF LIME AND CHICKEN MANURE ON NUTRIENT CYCLING, SOIL PROPERTIES AND PLANT RESPONSE IN ACID SOUTH AFRICAN ULTISOLS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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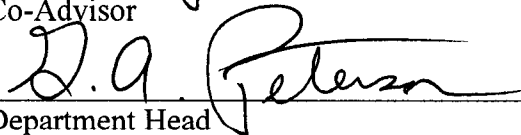




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ABSTRACT OF DISSERTATION

EFFECTS OF LIME AND CHICKEN MANURE ON NUTRIENT CYCLING, SOIL PROPERTIES AND PLANT RESPONSE IN ACID SOUTH AFRICAN ULTISOLS

In South Africa's Eastern Cape Province, little information is available from which the influence of soil acidity and liming on organic matter decomposition, nutrients cycling and plant growth responses can be predicted. Accordingly, the laboratory studies described herein were conducted to obtain information on the effects of soil liming on amounts of carbon (C) and nitrogen (N) released during the decomposition of chicken manure applied to soils. Additionally, liming, organic and/or inorganic N fertilizers were compared for their effects on maize growth, N uptake, added N recovery and selected soil properties. The two soils used in these studies were collected from two sites (Magusheni and Nikwe) in the Eastern Cape Province. Both soils are classified as Humic Hapludults. A comparison of chemical properties of virgin topsoil (0-15 cm) indicated that the soils differ in fertility and potential productivity, with the experimental soil from Magusheni site being the poorer of the two. The Magusheni soil had a $\text{pH}_{(\text{KCl})}$ of 4.78, exchangeable (Al + H) acidity was $1.40 \text{ cmol}_c \text{ kg}^{-1}$ and acid saturation was 24.7%. The percentage Ca, Mg and K saturation levels were 30.1, 41.4 and 3.9 %, respectively. In comparison, the Nikwe soil had a $\text{pH}_{(\text{KCl})}$ of 5.06, exchangeable (Al + H) acidity was $0.38 \text{ cmol}_c \text{ kg}^{-1}$ and acid saturation was 4.3%. The percentage Ca, Mg and K saturation levels were 46.6, 34.0 and 15.0 %, respectively. Results of the 56-day soil laboratory incubation experiment (chapter 1) indicated that the effects of liming on microbial activity and N mineralization varied between the soils. In the low acid saturated (Nikwe) soil, total CO_2 evolution and N mineralization increased as the rate of chicken manure application increased. However, liming and the accompanying increase in soil pH (5.0 to 5.9) had no apparent effect on total CO_2 evolution and N mineralization rates. The results indicated that microbial activity and N mineralization were limited by C and N supply and not by soil acidity in the Nikwe soil. The lack of a liming effect on microbial activity and N

mineralization in the Nikwe soil can be attributed to the relatively high initial soil base status (95.7 %), high % Ca^{2+} saturation (47 %) and the low percent acid saturation (4.3 %). In the Nikwe soil, there would be no appreciable benefit on microbial activity nor N mineralization by liming soil when the base saturation is high and the soil acid saturation percentage is low. In the high acid saturated (Magusheni) soil, total CO_2 evolution increased as both lime and chicken manure application rates increased. However, among all chicken manure rates, the total amount of CO_2 evolved was lower in the unlimed than in the lime amended treatments. The results indicate that N mineralization decreased as lime application rate and soil microbial activity increased. The decrease in the accumulation of inorganic N in lime amended treatments as soil respiration rates increases, suggest a rapid immobilization of mineralized N by an active microbial population. Therefore, liming is essential to supply Ca^{2+} and correct the acidity in the Magusheni soil. However, addition of large amounts of lime, especially when combined with broiler chicken manure, are expected to stimulate greater microbial activity and are likely to cause an initial N immobilization or a longer lag period in N mineralization. The long-term effect under field conditions, however, is expected to be a net increase in N availability. The results of this study do show that the short-term effects of lime on microbial activity and N mineralization varies among soils and highlight the influence of chemical soil properties other than soil pH on microbial activity and N mineralization in organic waste amended soils. The findings presented in chapter 1 agreed with the results obtained in the greenhouse pot experiment reported in chapter 2. Results of another greenhouse pot experiment (chapter 3) also showed that the effect of lime x N fertilizer interaction on maize plant height, biomass production, total N uptake and N concentration varied between the Magusheni and Nikwe soils. In the Magusheni soil, the lime x N fertilizer interaction was positive in that lime enhanced plant growth responses to N application. Based on soil analysis results, responses in plant height, aboveground biomass production, and total N uptake to N application were lower in the unlimed than in limed soil due to the higher levels of soil acidity in the former soil. In the unlimed soil, the percent soil acid saturation was 47%, which is more than double the critical 20% permissible acid saturation level for a maize crop. The percent base saturation and Ca^{2+} saturation were also much lower than in limed soil. In the limed soil, the percent base

saturation, Ca²⁺ saturation, and soil acid saturation were 91%, 50%, and 9.3%, respectively. These greatly improved soil conditions may have contributed to the positive plant responses to N application in the limed soil. Therefore, soil acidification must be corrected in order to optimize maize response to applied N fertilizer in the Magusheni soil. In the Nikwe soil, the plant height, aboveground belowground biomass production and total N uptake was either similar or lower in limed than in the limed soils. Soil analysis results, indicated that chemical characteristics of the unlimed and limed soils were similar. In both the unlimed and the limed soils, the percent base saturation, Ca²⁺ saturation, and soil acid saturation were 95%, 50%, and 5.0%, respectively. Therefore, lime had little or no effect on soil chemical properties in the Nikwe soil. The results presented, suggest that as long as the soil base status remains high and acid saturation levels low, there would be little or no benefit to total N uptake, maize growth and development due to lime application in the Nikwe soil. However, the fact that large responses to applied N were obtained in the Nikwe and Magusheni soils confirms that N was the limiting nutrient in the control treatments.

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GENERAL INTRODUCTION

The Eastern Cape is the second largest of South Africa's provinces (Figures 1.1 and 1.2), with an area of approximately 169, 580 square kilometres (km²). It constitutes about 13.9% of total area of South Africa. The Eastern Cape is subdivided into 7 districts. The Oliver Tambo District covers much of the former Transkei including most of the Wild Coast and Pondoland (Eastern Cape Development Corporation, 2006). This District has an area of 15,535 km². It is well watered. It counts many rivers and has a mean annual rainfall in excess of 700mm in most parts. Pondoland is one of the most fertile areas of South Africa, with warm temperatures, frost-free conditions and good soils (Eastern Cape Development Corporation, 2006). The studies reported in this dissertation were conducted using two soils that were collected near Bizana, one of the major towns in the Pondoland region.

Soil acidity has been recognized as an important crop production problem in the high rainfall areas of the Eastern Cape Province, including Bizana and surrounding areas. There is a need to apply agricultural lime to the soils to improve their productivity. To date, there is a general lack of soil liming, particularly in areas farmed by smallholders (Mandiringana et al., 2001). In addition, information on the lime requirement and appropriate liming practices for the wide range of soils occurring in the Eastern Cape is limited. Of importance are information on agricultural liming materials, the methods of use, and the potential benefits accruing from their use, before lime use is adopted. Research is needed to elucidate the effects of liming on soil acidity and soil fertility on crop productivity. Such information for important crops and for different soils is likely to be of value for small-scale farmers in the Eastern Cape who struggle to achieve food security partly due to low crop yields.

In sub-Saharan Africa, manures and chemical fertilizers are increasingly being used in combination rather than as separate applications. Small-scale farmers recognize that, chemical fertilizers are too expensive to be used on their own and only limited amounts of manure are available. On their own, neither of these types of fertilizers are adequate to redress the decline in soil fertility, but combined they may be effective. In the Eastern Cape Province, there is very little information about the optimum use of small amounts of mineral fertilizers to supplement nutrients in locally obtained organic materials. Therefore, research on the efficient use of organic resources supplemented with mineral fertilizers is needed.

The first chapter of this dissertation describes a soil laboratory incubation study designed to evaluate the effect of liming to raise soil pH on soil microbial activities and N mineralization in broiler chicken manure amended soils. The second chapter reports on a greenhouse pot study designed to evaluate the effect of liming to lower percent soil acid saturation to levels of less than 20% on plant growth, nutrient uptake, N mineralization and soil chemical properties in soils amended with broiler chicken manure. The third chapter reports on a greenhouse pot study designed to quantify dry matter yield, N uptake and N recovery by maize in two previously limed soils that were amended with broiler chicken manure N and urea-N alone or combined.

CHAPTER 1

EFFECTS OF LIME AND CHICKEN MANURE ON SOIL pH, MICROBIAL ACTIVITY AND N MINERALIZATION IN TWO ACID SOUTH AFRICAN ULTISOLS

ABSTRACT

Alterations in soil environmental conditions (e.g. pH, bioavailable Al, base cation supply) associated with use of agricultural lime are particularly important for both crop growth and soil microorganisms. In cropping systems where N mineralized from organic matter is expected to contribute a major proportion of soil N available to plants, it is essential to understand how environmental conditions will alter the rate and extent of N mineralization. A 56 day laboratory study was conducted to determine the effects of liming to raise soil pH on microbial activity and N mineralization in South African Ultisols amended with broiler chicken manure. The soils with widely varying acid saturation percentage (4.0 – 25%) and base saturation (75 – 96%) were sampled from the Eastern Cape Province. The soils were amended using a factorial combination of 4 rates of lime and 3 rates of manure. The lime rates were (1) a full-lime rate to raise the soil $\text{pH}_{(\text{water})}$ to 6.0, (2) 66% of the full-lime rate, (3) 33% of the full-lime rate; (4) a control without lime. The broiler chicken manure rates were (1) 10 Mg ha^{-1} , (2) 5 Mg ha^{-1} and (3) a control without manure. The soil pH increased with lime application and ranged from 4.5 to 5.7 and from 5.0 to 5.9 for the Magusheni and Nikwe soils, respectively. Effects of liming on microbial activity and N mineralization varied between the soils. In the low acid saturated (Nikwe) soil, total CO_2 evolution and N mineralization increased

as the rate of chicken manure application increased. However, liming and the accompanying increase in soil pH (5.0 to 5.9) had no apparent effect on total CO₂ evolution and N mineralization rates. The rates of total CO₂ evolution ranged from 191.3 µg C g⁻¹ in the 10 Mg ha⁻¹ manure only treatment to 194.2 µg C g⁻¹ in the full-lime rate + 10 Mg ha⁻¹ manure treatment. Similarly, net N mineralization rates ranged from 30 mg N kg⁻¹ in the 10 Mg ha⁻¹ manure only treatment to 32 mg N kg⁻¹ in the full-lime rate + 10 Mg ha⁻¹ manure treatment. A similar response in CO₂ evolution and N mineralization was observed in other lime and manure treatments. The lack of a liming effect on microbial activity and N mineralization in the Nikwe soil can be attributed to the relatively high initial soil base status (95.7 %), high % Ca²⁺ saturation (47 %) and the low percent acid saturation (4.3 %). The results indicated that microbial activity and N mineralization seems to be limited by C and N supply and not by soil acidity in the Nikwe soil.

In the high acid saturated (Magusheni) soil, total CO₂ evolution increased as both lime and chicken manure application rates increased. However, among all chicken manure rates, the total amount of CO₂ evolved was lower in the unlimed than in the lime amended treatments. The rates of total CO₂ evolution ranged from 201.0 µg C g⁻¹ in the 10 Mg ha⁻¹ manure only treatment to 282.0 µg C g⁻¹ in the full-lime rate + 10 Mg ha⁻¹ manure treatment. Net N mineralization rates ranged from 29 mg N kg⁻¹ in the 10 Mg ha⁻¹ manure only treatment to 13 mg N kg⁻¹ in the full-lime rate + 10 Mg ha⁻¹ manure treatment. The stimulating effect of lime on soil microbial activity was due to either increased availability of C or a more favourable environment to the soil microorganisms or both. The decrease in the accumulation of inorganic N in limed treatments as soil respiration rates increase, suggest a rapid immobilization of mineralized N by an active microbial population. The higher percent soil acid saturation (25%) in the Magusheni soil may have slowed down microbial activity in unlimed treatments. Therefore, liming is essential to supply Ca²⁺ and correct the acidity in the Magusheni soil. However, an addition of a large amount of lime, especially when combined with broiler chicken manure, is expected to stimulate greater microbial activity and may cause an initial N

immobilization. Under field conditions, the long-term effect of liming in the Magusheni soil is expected to be a net increase in N availability.

INTRODUCTION

The time needed to complete the processes of decomposition and mineralization of crop residues or manure ranges from days to years, depending mainly on two broad factors: (1) the quality of the added residues as food source for soil organisms, and (2) the environmental conditions in the soil (Brady and Weil, 1999). Factors that determine the quality of the residues as a food source for microbes include the physical condition of the residues, their carbon:nitrogen (C:N) ratio and their content of lignins and polyphenols. The environmental conditions in the soil conducive to rapid decomposition and mineralization include water availability, aeration, temperature regime, and soil pH (Fu et al., 1987; Brady and Weil, 1999). The effects of pH adjustment by adding lime on C and N mineralization in soils amended with organic waste are the focus of this chapter.

Research on N mineralization has focused on N transformations occurring in soils. Some of the early studies by Harmsen and van Schreven (1955), Alexander (1961), Scarsbrook (1965) report that soil acidity limits the mineralization of soil N, implying that low pH soils release less mineral N than high pH soils. Moreover, liming not only increased N mineralization, it also prolonged it. Similarly, in a 28-day incubation study Nyborg and Hoyt (1978) found that liming acid surface soils (pH 4.0-5.6) doubled N mineralization. More recently, Persson et al., (1989) observed that liming (with CaCO_3) increased net N mineralization in the Fexboda humus (C:N = 31) and tended to increase net N mineralization in the Jadrass humus (C:N = 44). Similar results were obtained by Lyngstad (1992) when a powdered liming material (CaO) was applied to 12 soils to attain pH levels to about 7.

Other investigators have reported that enhanced N mineralization caused by liming is short-lived and decreases with time. Clay et al., (1993) reported that liming acidified

soils increased soil pH, which in turn enhanced N mineralization during the first 14 days of incubation. However, the increase in N mineralization was only temporary. After the initial 14-day period, the limed and unlimed treatments had similar amounts of NO_3 leaching through the soil columns. Nyborg and Hoyt (1978) also reported a temporary stimulation in N mineralization following the application of lime to low pH soils. In a 16-week incubation study, Haynes and Swift (1988) found that net N mineralization was increased by additions of both lime and phosphate during the first 4 – 8 weeks of incubation, but after 8 weeks, the mineralization-immobilization turnover was in balance (equilibrium) and there was no more net accumulation of mineral N. Black (1968) suggested that the effect of liming on N mineralization in acid soils was due to increased susceptibility of a portion of the organic N to mineralization, and that this effect diminished or disappeared over time. Clay et al. (1993) also suggested that the enhanced mineralization of N, which only occurred during the early part of incubation, could be due to a lime-induced increase in soil pH, which in turn could have increased the amount of soluble organic matter in the soil solution. This explanation was supported by evidence from a previous study by Clay et al. (1988) in which an increase in soil pH from 4.1 to 6.0 by applying $\text{Ca}(\text{OH})_2$ increased the water soluble organic matter content from 36 to 51 mg C liter⁻¹.

Other research reports indicate that liming has little or no influence on the rate of N mineralization in soils (Thompson et al., 1954; Weier and Gilliam, 1986), whilst some claim that soil acidity by itself does not affect the rate of N mineralization (Nyborg and Hoyt, 1978; Clay et al., 1990). Thompson et al. (1954) determined the N mineralization during laboratory incubation of 50 soils varying in pH values from 5.2 - 8.1. They found that N mineralized per unit of organic N did not increase with increase in soil pH. Dancer et al. (1973) also investigated the long-term effect of lime on N mineralization using soil samples collected from previously limed field plots which varied in soil pH from 4.7-6.6. After a 35 day incubation period they concluded that soil pH had no appreciable effect on N mineralization. Similarly, Tabatabai and Al-Khafaji (1980) and Simard and N'dayegamiye (1993) noted that soil acidity does not necessarily restrict the

mineralization of organic N. Simard et al. (1994) observed no lime effect on organic C, total N concentration or microbial C and N mineralization. Weier and Gilliam (1986) observed that none of the six acidic Atlantic Coastal Plain Histosols they studied showed a significant net N mineralization increase between the very acid initial pH value (3.4 to 4.5) and the pH value (pH 4.8 – 5.2) recommended for crop production on Histosols. Similarly, studies by Lyngstad (1992) and Clay et al. (1993) challenged the generally accepted view that N mineralization is restricted by soil acidity.

Numerous studies have reported that mineralized N varies among soils. For instance, Fu et al. (1987) reported that when expressed as a percentage of N mineralized in untreated soils at pH 4, pH 6, and pH 8, the amounts of N mineralized in corn residue amended soils were 8.2 %, 44.7 % and 63.6 % for the Luther, Lester and Nicollet soils, respectively. Similarly, Nyborg and Hoyt (1978) noted that the amount of organic N mineralized during 120 days of incubation varied markedly among 40 soils. Net mineralization ranged from -1 to 136 mg kg⁻¹ in unlimed soil samples while in limed samples N mineralization ranged from 3 to 212 mg kg⁻¹. Using 12 acid surface soils ranging in texture from sandy loam to silty clay, Lyngstad (1992) also reported that the amounts of organic N mineralized during a 4-week incubation period of soil samples taken once a year from a 6 year pot experiment varied greatly among soils. Net mineralization ranged from 24 - 41 and 94 - 114 mg kg⁻¹ in unlimed soils while in limed soils N mineralization was between 37 – 57 and 111 - 176 mg kg⁻¹. The author also noted that the duration of lime effects on mineralization was not related to any soil chemical or physical characteristics. When six organic soils were selected to give a range of organic matter (OM) contents from 28 to 850 mg kg⁻¹, there was no apparent relationship between OM, OM/N ratio and N mineralized (Weier and Gilliam, 1986). However, Serna and Pomares (1993) concluded that N mineralized and total N of organic amendments were closely correlated.

A limited amount of research has been conducted on the effect of pH on N mineralization in plant residue and animal manure amended soils. Fu et al. (1987) in a laboratory study, compared N mineralization in three soils amended with various crop residues, with the soil pH adjusted to pH 4, pH 6 and pH 8 with dilute sulphuric acid (H₄SO₄) or potassium

hydroxide (KOH). The mineralization of N in these crop residue amended soils was significantly correlated with soil pH and the amount of N mineralized was high at pH 8, intermediate at pH 6 and low at pH 4. However, it has been shown that decomposition rates vary considerably from one type of organic amendment to another (Ajwa and Tabatabai, 1994) and among soils. For example, Chae and Tabatabai (1986) compared the percentage of organic N mineralized from chicken manure added to five soils (with pH values ranging from 5.1 to 7.6) and found that mineralization varied widely between soils. For soils with a pH > 6.0 the percentage of organic N mineralized from the added chicken manure ranged from 54 % to 67 % while those soils with a pH < 6.0 the percentage of organic N mineralized was about 21%. Therefore, more research on the effects of pH on soil microbial activity and N mineralization in various soil-organic waste systems particularly in the Eastern Cape Province (South Africa) is needed, for better prediction of crop N requirements.

Nitrogen in solid animal manure is mainly in the organic form and microbial decomposition is essential for transforming organic N to inorganic N. Without this transformation the available plant nutrient supply would soon be used up and the soil would become infertile (Troeh and Thompson, 1993). In aerobic decomposition, microorganisms feed upon the organic matter and in the process use N, P, C, and other required nutrients. Much of the C serves as an energy source for the organisms and is respired as carbon dioxide (CO₂). It has been estimated that under aerobic conditions about 20 – 40 % of the substrate C is assimilated by microorganisms and the rest is released as CO₂ (Wagner and Wolf, 1999). Therefore, CO₂ evolution is a good indicator for measuring microbial activity and substrate decomposition in soils. According to Cortassa et al. (2001) microbial CO₂ production is a function of not only the density of microorganisms but also of their metabolic status, which in turn, depends on soil physico-chemical conditions such as O₂, soil water availability, temperature, and soil pH.

Excessive acidity in soil can slow down the general bacterial and biological life in the soil (Francis 1982; FSSA 1989). The decrease in microbial activity may slow down the rate of organic matter decomposition and hence the cycling and overall availability of

nutrients (e.g. N, P, S) in the soil-plant system (Condrón et al., 1993). Studies by several researchers (Adams and Cornforth, 1973; Lohm et al., 1984; Haynes and Swift, 1988) indicated that the addition of lime to acid soils increased CO₂ evolution. Persson et al. (1989) also observed that liming stimulated CO₂ evolution, but noted that the increase was mainly due to an initial flush in CO₂ evolution followed by a decline, rather than a general increase over an extended time period (55 days). These authors also noted that liming resulted in an increase of approximately 3 pH units, from pH 4.5 – 7.5 (Fexboda series) or pH 3.8 – 6.9 (Jadraas series). Similarly, Condrón et al. (1993) reported that liming increased soil microbial activity over the control soil, as shown by the increase in CO₂ evolved, although the difference in CO₂ evolution rate between the control and limed soils decreased with time over the 17-week incubation period. The pH values of the control, litter only, lime only and lime + litter amended soils were 4.46, 4.86, 6.56, and 6.63, respectively, indicating that liming increased soil pH and created a conducive soil environment for the survival and growth of microorganisms.

A substantial part of the Eastern Cape Province of South Africa has good agricultural potential, much of which is situated in former Transkei and Ciskei where small-scale farmers hold most of the land under various forms of communal tenure (Mkile, 2001). Mixed crop-livestock farming is commonly practiced and is mostly for subsistence purposes. Over the last 100 years the per hectare yield of cereal crops has declined and food security has become a problem. For example, Bembridge (1984) estimated that during the period 1918 to 1927 the average maize yields in OR Tambo district was 636 kg ha⁻¹, and between 1974 to 1980, the average yield declined by approximately 60% to 252 kg ha⁻¹. A survey study in two villages in Central Eastern Cape, suggested that the contribution of local economic activities, including agriculture, trade, and locally supplied services towards the average household income was much less in comparison that derived mainly from external sources such as remittances, claims against the state, salaries and wages (Van Averbeke et al., 1998). Hence, in many areas of the Eastern Cape, including Bizana, increase agricultural production is considered necessary to ensure better household food security.

The few studies carried to assess the fertility status of soils from fields of small-scale farmers in the Eastern Cape have shown that these soils have inherently low soil fertility and also have an acid soil pH (Laker, 1976; Mkile, 2001; Mandiringana, et al., 2001). Mkile, 2001 reported that garden and field soils collected from three districts of the former Transkei were highly acidic with mean soil pH values of 4.7 and 4.3, respectively. Data obtained from liming experiments that formed part of the Bizana LandCare project, also indicate that naturally acidic soils occur in the Bizana area, Eastern Cape Province. For example, Fyfield et al., (2000 and 2002) collected topsoil and subsoil samples across two field research plots ranging in size from 0.2 ha (Nikwe site) to 1.3 ha (Magusheni site), respectively, for physical and chemical analysis. Chemical analysis revealed that virgin topsoil collected from the Magusheni research site had a $\text{pH}_{(\text{KCl})}$ of 4.38, exchangeable Ca, Mg and K were 119.0, 147.3 and 54.7 mg kg^{-1} , respectively, exchangeable (Al + H) acidity was 1.70 $\text{cmol}_c \text{kg}^{-1}$ plus 45.4% acid saturation. In comparison, the Nikwe research site soil had a $\text{pH}_{(\text{KCl})}$ of 4.56, exchangeable Ca, Mg and K were 675.7, 292.5 and 238.8 mg kg^{-1} , respectively, exchangeable (Al + H) acidity of 1.15 $\text{cmol}_c \text{kg}^{-1}$ plus 15.9% acid saturation. Such acidic reaction renders nutrients from the soil and added amendments such as manures less available to crops (Van Averbek et al., 2005, personal communication). For this reason, liming to correct soil pH and increase available Ca has been recommended as the first step towards addressing the general problem of poor soil fertility in the Eastern Cape soils (Mandiringana, et al., 2001).

Studies in the rural areas of the Eastern Cape have demonstrated that small-scale farmers incorporate livestock manure into the soil to help maintain soil fertility (Mkile, 2001). Other farmers combine livestock manure with small quantities of mineral fertilizer in an effort to improve the efficiency of both types of input. While manure of large animals has been studied extensively for its use as a fertilizer for crops (Herron and Erhart, 1965; Pomares-Garcia and Pratt, 1978; Sawyer and Hoef, 1990; Rubiez et al., 1992), much fewer studies have evaluated chicken manure. It is widely known that the types and amounts of nutrients in manure vary considerably from one type of animal to another (e.g. broiler chicken manure compared to cattle manure). The factors that contribute to

this variation include (a) composition of the rations fed to livestock; (b) method of waste collection and storage; (c) amount of feed, bedding and/or water added; (d) method and time of land application, including use of additives which preserve nutrient value.

Therefore, one has to be cautious in interpreting general statements about the value and use of manure. Laboratory incubation studies indicate that the organic N is more easily mineralized in poultry manure than hog and cattle manures (Hadas et al., 1983; Chae and Tabatabai, 1986; Chadwick et al., 2000).

Efficient management of poultry manure as a N source requires knowledge of the rate of net N mineralization as well as the timing within the growing season of N release from the organic fraction of the manure. Growers who supplement chicken manure (or other manures) with chemical fertilizer N must know when the N mineralized in the manure will be available in order to maximize the efficiency of fertilizer use (Sims, 1986).

Currently, quantitative data on N mineralization potential of acidic soils in the Bizana and other areas of the Eastern Cape as well as the basic N transformations in poultry manure-amended soils are lacking. Changes in the availability of N, and the characteristics of mineralization or immobilization after organic fertilizers have been applied to strongly acidic soils, need to be studied as a basis for developing suitable management strategies for these soils. Dick et al. (2001) stated that an important ecological process that is mediated by microorganisms is the decomposition and mineralization of nutrients, which are central functions in vegetatively or biologically based low-input cropping systems. Knowledge about the mineralization potential of the soil, including the acid humic soils of the Eastern Cape, will be helpful in optimizing the timing and magnitude of N applications (Agenbag and Vlassak, 2000). Additionally, due to the wide variation in N mineralization response by different soils, mineralization studies conducted on one type of soil cannot be assumed to apply directly to all soils (Weier and Gilliam, 1986).

The specific questions addressed in the incubation study were as follows:

- (1) What is the effect of broiler chicken manure and lime rates (CaCO_3) on pH of these soils and is there a relationship to soil microbial activity.

(2) How will the effects of broiler chicken manure and lime rates (CaCO_3) on soil pH and soil microbial activity affect N mineralization.

In response to the scientific questions posed above, a short term soil incubation laboratory experiment was conducted with the objective of determining the effects of calcitic lime and broiler chicken manure application on soil pH, microbial activity and N mineralization in two acid South African Ultisols. This study was designed to test the following hypothesis: Liming low-pH soils increases microbial activity and stimulates the mineralization of manure N.

MATERIALS AND METHODS

The experimental materials (soils, chicken manure, and agricultural lime samples) used in the present study were collected from the Eastern Cape Province of South Africa, packaged with due attention to import control regulations and shipped to Colorado State University (Fort Collins, Colorado USA).

Soils

Soils used in this experiment were collected from the surface layer (0-15 cm) at two experimental sites of the Agricultural Research Council – Institute of Soil, Climate and Water (ARC – ISCW) in the Bizana Magisterial District (Eastern Cape Province, South Africa). Each soil sample was obtained from an uncultivated area adjacent to an established lime/fertilizer/chicken manure field research plot. The two soils were classified as a Magwa Connemara series, and a Sweetwater Newton series, according to the South African Soil Classification System (Soil Classification Working Group, 1991). The approximate equivalent name according to USDA Soil Taxonomy classification (Soil Survey Staff, 1992) is Humic Hapludult for both soils. The Magwa and Sweetwater soil series will hereafter be referred to as Magusheni and Nikwe soils, respectively. The Magusheni soil has a humic A horizon extending to a depth of 300 mm and has a yellow-brown apedal B horizon. The Nikwe soil has a humic A horizon extending to a depth of

500 mm and has a neo-cutanic B horizon (Booyens, 2001). In the analyses reported in Table 1.1, pH values was determined on 10-g samples using a 1:1 (w/v), soil:water ratio. Mineral N (NH₄-N and NO₃-N) was extracted with 2 M KCl solution (1:5 soil dry weight basis) and determined by steam distillation (Keeney and Nelson, 1982). Total C and N were determined by a dry combustion procedure using a LECO CHN 1000 Auto-Analyzer. The exchangeable Ca, Mg, and K were extracted with 1 M ammonium acetate at pH 7.0 and determined by atomic absorption spectrometry. The 1 M KCl extraction was used for exchangeable acidity (Al + H) and exchangeable Al (Non-affiliated Soil Analysis Working Group, 1990). Exchangeable acidity (Al + H) in the extract was determined by titration to a phenolphthalein endpoint with NaOH and exchangeable Al by atomic absorption. Acid saturation was calculated as: exchangeable Al + H (cmol_c kg⁻¹) x 100 / exchangeable Ca + Mg + K + Al + H (cmol_c kg⁻¹). Base saturation was calculated as exchangeable Ca + Mg + K (cmol_c kg⁻¹) x 100 / exchangeable Ca + Mg + K + Al + H (cmol_c kg⁻¹) (FSSA 1989). The % saturation with any cation was calculated in a similar fashion. For example, from Table 1.1, % Ca saturation = (1.71 cmol_c kg⁻¹ Ca/5.70 cmol_c kg⁻¹ ECEC) x 100 = 30 % in the Magusheni soil. Effective cation exchange capacity (ECEC) was estimated through the summation of exchangeable bases (Ca, Mg, and K) and exchangeable acidity (Al + H). Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986). Soil water content at field capacity was determined by the moisture retention plate method (Topp et al., 1993).

Broiler chicken manure

The chicken manure used in this study is known as GROMOR¹ in the Bizana area and is widely used by farmers in the region as an organic fertilizer. GROMOR chicken manure which is a product of National Plant Food CC in South Africa, is marketed and registered as an organic fertilizer (Reg. No. B124) under Act 36 of 1947 (NPF, 2000). Broiler chickens are grown on bedding material (sunflower husks, wood shavings or wheat straw) placed on the floor of environmentally controlled houses. At the end of a six week period, the houses are cleared and the litter sent to NPF for processing (NPF, 2000). After the chicken manure was brought to the laboratory, it was spread on a polyethylene

plastic sheets and air dried at room temperature for 1 week prior to shipment. Table 1.2 shows the composition of the manure used in this study. In these analyses, chicken manure pH was determined with a manure:water ratio of 1: 2.5 (w/v). Total C, total N and inorganic N (NH₄-N and NO₃-N) were analyzed by the same procedures as the soil samples. Moisture was determined from loss in weight after drying at 65 °C for 48 h. The moisture content of the chicken manure was taken into account when different rates were applied to each soil.

Lime requirement determination

The specific objectives of liming the soils were to neutralize soil acidity and raise soil pH to 6.0. The lime requirement was determined by using the SMP buffer method (Shoemaker et al., 1961). With this method, the pH of a soil-buffer system was determined after equilibrating 10 mL (p-nitrophenol-triethanolamine-chromate-acetate) with 5 g of soil for 30 min and the lime requirement values were taken from a table prepared by Shoemaker et al., 1961. Approximately 18.7 and 24.4 Mg calcitic lime ha⁻¹ were the recommended application rates to raise the soil pH to 6.0 for the Nikwe and Magusheni soils, respectively. Calcitic limestone was then applied at rates designed to represent 0, 33%, 66% and 100% of the recommended rate to raise soil pH to approximately 6.0. The agricultural limestone used in this study was analytical reagent grade calcium carbonate, known as Kulu-CAG¹. Kulu-CAG is a product of Idwala (the Zulu word for rock or stone) Industrial Holdings in South Africa. Kulu-CAG is mined from a white calcitic limestone deposit in the Port Shepstone area of KwaZulu-Natal (adjacent to the Umzimkhulu River). The mining operation entails quarrying, crushing, further milling, screening and upgrading of the limestone through flotation and fine milling/micronising (Mkhize, 2005. personal communication). Particle size analysis was conducted by dry sieving 20g lime samples Sieve openings were (8-mesh) and (60-mesh).

¹ Trade names and company names are included for the benefit of the reader and do not constitute endorsement or preferential treatment of the product.

Treatments and experimental design

For each soil, a 4 x 3 complete factorial experiment with three replicates was used in a completely randomized design. Details regarding the treatments imposed on each soil are given in Table 1.4. The manure application rates used in the present study were similar to chicken manure application rates applied on field research trials conducted in the Bizana area by Fyfield et al. (2000 and 2002).

Incubation procedure

About 100 g (oven dry basis) of air dried sieved soil (2 mm) was placed into plastic sample cups (10-cm tall x 10 cm diameter). Lime was applied at rates of 0, 4.1, 8.2 and 12.2 g CaCO₃ kg⁻¹, which is equivalent to field applications of 0, 8.1, 16.3 and 24.4 Mg lime ha⁻¹ (assuming 1 ha weighs 2x10⁶ kg of soil in the 15 cm surface layer) for the Magusheni soil. The lime application rates for Nikwe soil were 0, 3.1, 6.2 and 9.4 g CaCO₃ kg⁻¹, which is equivalent to field applications of 0, 6.2, 12.5 and 18.7 Mg lime ha⁻¹. For each soil, the lime rates are equivalent to 0, 33, 66 and 100 % full-lime rate application to raise soil pH to 6.0, respectively. As noted by Persson et al. (1989), the amount of CO₂ measured in the limed treatments can be partitioned into microbial CO₂ evolution and the chemical reaction between the carbonate added and the acids produced during the process of organic matter decomposition. Separate cups which were treated with the same amount of CaCO₃ as in the ordinary samples were prepared in order to estimate the contribution of abiotic CO₂ evolution to the observed total CO₂ evolution. The extent of this of abiotic CO₂ evolution was measured by estimating the difference in CO₃-C before and after the experimental period in the latter samples. On both soils, chicken manure was added at rates of 0, 2.5 and 5 g (oven dry basis) manure kg⁻¹ soil, which corresponds to 0, 5 and 10 Mg ha⁻¹ containing 0.12 kg H₂O kg⁻¹. The 2.5 and 5 g manure kg⁻¹ rates contained about 85 and 170 mg N kg⁻¹, respectively. The equivalent amounts of C added were 850 and 1700 mg, respectively. An unamended treatment (control) of each soil was also included. All treatments were mixed thoroughly before moistening. Soil water potential was adjusted to 75% field capacity (-0.1 bar) with

addition of deionized water at the beginning of the incubation study. Field capacity corresponds to gravimetric water contents of 46 and 39% for the Magusheni and Nikwe soils. The plastic cups were placed in 1L glass jars (containing 15 mL deionized water to maintain humidity), sealed airtight and incubated in the dark for 8 weeks in a controlled environment chamber at 25 ± 1 °C. The weight of the cups was monitored weekly to ensure constant water content during the incubation period. Each treatment was replicated 3 times. Carbon dioxide evolved (an index of microbial activity), was determined at 0, 2, 4, 7, 14, 21, 28, 35, 42, 49 and 56 days after initiation of incubation. Direct analysis of headspace CO₂ concentrations in gaseous samples was performed using infrared gas analysis (IRGA) method. After each sampling, the incubation jars were aerated (10 min). The incubation was continued for 56 days and at the completion of the incubation period, the soils were mixed thoroughly and air-dried before chemical analysis. Soil pH and mineral N (NH₄-N and NO₃-N) were measured as described previously.

Calculations

Mineralization rates in the incubated soils were determined as described by Kaboneka et al. (1997). Net N mineralization was calculated as the difference between soil inorganic N (NH₄⁺-N + NO₃⁻-N) in amended and unamended soils.

a)
$$\text{Net } N_m = N_{m \text{ amended soil}} - N_{m \text{ unamended soil}}$$

Where $N_m = N$ mineralization (mg N kg⁻¹ soil)

b) The percent N mineralization was calculated as follows:

$$\% \text{ N mineralization} = [(X-Y) / Z] \times 100$$

where: X = mg of N mineralized from amended soil, Y= mg of N mineralized from unamended soil, and Z=mg of N added in chicken manure amendments.

Statistical analysis

Table 1.5 shows sources of variation and their degrees of freedom. All statistical analyses were performed using Statistical Analysis Software General Linear Model (SAS GLM) procedure (SAS Institute, 2005). Treatment means were compared using the least significant difference (LSD) at the 5% level of significance Steel et al. 1997).

Correlation was determined by Pearson's correlation coefficient. Values presented in tables and figures are arithmetic means.

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) was conducted to test the effect of lime and broiler chicken manure treatments on soil pH, total CO₂, total inorganic N, net inorganic N, NH₄-N, NO₃-N. Table 1.6 shows all the significant and non significant tests.

Manure characteristics

As demonstrated in Table 1.2, the broiler chicken manure sample used in our study was slightly acidic (pH 6.31), with a narrow C:N ratio (1:10). The narrower the C:N ratio of freshly added decomposable materials, the sooner N will be mineralized (Troeh and Thompson, 1993). Total N content was 34 g kg⁻¹ and the inorganic N content was low, and mainly consisted of NH₄-N. The characteristics of the manure used in our study differed from those reported in other studies. Poultry manure samples used in the study by Sims (1986) were alkaline (pH ≥ 8.5), and the C:N ratio varied from 12 to 15:1. Total N ranged from 40.4 to 49.3 g kg⁻¹, NH₄-N ranged from 10 460 to 15 020 mg kg⁻¹, and NO₃-N varied from 230 to 3110 mg kg⁻¹. In the study of Tyson and Cabrerra (1993) composted broiler litter had a C:N ratio of 10:1 whilst uncomposted broiler litter varied from 5 to 7:1. Total N ranged from 12.5 to 14.1 for composted litter and for uncomposted litter it varied from 50.6 to 65.4 g kg⁻¹. Inorganic N content was lower in the composted litter. Ammonium-N ranged from 0.04 to 0.10 g kg⁻¹ while NO₂⁻+ NO₃⁻-N

ranged from 0.30 to 0.39 g kg⁻¹. In the uncomposted litter NH₄-N contents were between 3.0 and 3.6 g kg⁻¹ whereas the NO₂⁻+ NO₃⁻-N contents were between 1.45 and 1.53 g kg⁻¹.

Soil pH

The average pH_(water) values of lime and/or broiler chicken treated soils at the end of a 56 day laboratory incubation period are given in Figures 1.3 – 1.4 and Table 1.7. The soil pH data indicates that the full lime rates did not bring the soil pH to 6.0 in either soil as had been predicted by the SMP buffer lime requirement, although the pH of 5.94 in the Nikwe soil was close. Based on our own observations and the work of Haynes and Swift (1988), it seems possible that the slightly lower than expected pH values could be partly due to the effect of nitrification on soil pH. These authors observed during 16 weeks of laboratory incubation that when an acid soil (initial pH of 4.3) was limed at rates of 0, 1.8 and 4.3 mg Ca(OH)₂ g⁻¹ soil, soil pH increased in limed and unlimed treatments to values between pH 5.2 – 7.0 during the first 2 – 3 weeks. Thereafter, as nitrification increased soil pH decreased drastically in the lower lime rates to values similar to the original pH (Haynes and Swift, 1988). The results of the present study suggest that on both soils, NO₃-N was the dominant inorganic nitrogen form in most of the treatments after the 6 - weeks incubation period. Nitrification is an acidifying process, since during nitrification two hydrogen ions (H⁺) are released per mole of ammonium oxidized to nitrate (Helyar, 1976; Wong and Swift, 2003; Tyson and Cabrera, 1993). On the other hand, on both soils statistical analysis of soil pH data has shown small, but statistically significant responses in the lime plus chicken manure treatments than in the lime only treatments. Small but statistically significant differences were also observed in the chicken manure only treatments and the unamended controls. According to Edwards and Beegle (1988) “for purposes of normal agronomic soil recommendations, pH changes less than 0.5 units are usually not considered to be “practical” pH changes with respect to soil management practices, sampling and analytical uncertainty”.

An examination of the data in Figures 1.3 – 1.4 and Table 1.7 indicates liming resulted in a linear increase in soil pH on both soils as application rate increased. For the Magusheni

soil, the pH among all treatments varied from 4.50 to 5.74. Soil pH was approximately 1.0 pH unit higher in the 24.4 Mg ha⁻¹ lime only and 24.4 Mg ha⁻¹ lime plus chicken manure treatments than in the chicken manure alone and control treatments. The pH among all treatments varied from 4.99 to 5.94, in the Nikwe soil. Soil pH was approximately 0.8 or more pH units higher in the 18.7 Mg ha⁻¹ lime only or 18.7 Mg ha⁻¹ lime plus chicken manure treatments than in the chicken manure alone and control treatments. The question then is how would the observed increase in soil pH impact C and N turnover? The next section discusses the C and N mineralization in the Magusheni and Nikwe soils.

Carbon and Nitrogen mineralization

There was a significant lime x manure interaction (Table 1.6) on total and net inorganic N in the Magusheni soil. Among all chicken manure rates, the accumulation of total and net inorganic N was higher in the unlimed than in the lime amended treatments (Figures 1.5 – 1.6 and Table 1.8). After 6 weeks of incubation, the total inorganic N content ranged from 74.7 mg N kg⁻¹ in the control treatment to 69.9 mg N kg⁻¹ of soil in the 24.4 Mg ha⁻¹ lime only treatment. The total inorganic N content ranged from 87.2 mg N kg⁻¹ in the 5 Mg ha⁻¹ manure only treatment to 80.3 mg N kg⁻¹ of soil in the 24.4 + 5 Mg ha⁻¹ treatment. The total inorganic N content ranged from 103.9 mg N kg⁻¹ in the 10 Mg ha⁻¹ manure only treatment to 87.5 mg N kg⁻¹ of soil in the 24.4 + 10 Mg ha⁻¹ treatment (Table 1.8). The trends in net inorganic N were similar to those observed for total inorganic N. After 6 weeks of incubation, the results show that in the lime only treatments a complete immobilization took place (Table 1.8). In contrast, values of net inorganic N for the combined lime and chicken manure treatments ranged from 2.84 to 5.57 mg N kg⁻¹ in the 5 Mg ha⁻¹ manure rate and from 12.8 to 18.9 mg N kg⁻¹ in the 10 Mg ha⁻¹ manure rate. Values of net inorganic N for the 5 and 10 Mg ha⁻¹ manure only treatments were 12.4, and 29.2 mg N kg⁻¹, respectively. Table 1.11 shows the percentages of organic N mineralized from chicken manure amended treatments. In the 5 and 10 Mg ha⁻¹ chicken manure only treatments about 15% and 18% of added organic N was mineralized, respectively. For the rest of the treatments, the percentage of

mineralized organic N showed a declining trend. For the combined lime and manure treatments, the percentage of added organic N mineralized ranged between 3.5 to 6.8% for the lime + 5 Mg ha⁻¹ manure rate and between 7.7 to 11.3% for the lime + 10 Mg ha⁻¹ manure rate. The lower N mineralization in the limed compared to the unlimed treatments could be partly due to N immobilization by the growing microbial biomass, which was stimulated by favourable soil environmental conditions and the availability of readily oxidizable C. The trends in CO₂ production lend support to this inference.

The total CO₂ evolution in the Magusheni soil is given in Table 1.9 and the cumulative evolution of CO₂ is shown in Figures 1.7 (a-e). In the Magusheni soil, the results indicate that total CO₂ evolution increased as lime and chicken manure application rates increased. However, among all chicken manure rates, the total amount of CO₂ evolved was lower in the unlimed than in the lime amended treatments (Table 1.9). The rates of total CO₂ evolution ranged from 76.3 μg C g⁻¹ in the control treatment to 150.5 μg C g⁻¹ in the 24.4 Mg ha⁻¹ lime only treatment. The rates of total CO₂ evolution ranged from 135.2 μg C g⁻¹ in the 5 Mg ha⁻¹ manure only treatment to 210.4 μg C g⁻¹ in the 24.4 + 5 Mg ha⁻¹ manure treatment. Similarly, CO₂ evolution rates ranged from 201.0 μg C g⁻¹ in the 10 Mg ha⁻¹ manure only treatment to 282.0 μg C g⁻¹ in the 24.4 + 10 Mg ha⁻¹ manure treatment. These findings indicate that addition of lime, separately or in combinations with chicken manure, increased soil microbial activity than in the unlimed treatments. In this soil the % Ca²⁺ saturation (Table 1.1) was lower amounting to about 30% of the ECEC, while percent soil acid saturation was more than 5 times than in the Nikwe soil. Hence, the lower rates of soil microbial activity in the unlimed treatments can be attributed to higher levels of bioavailable Al in the Magusheni soil. Therefore, liming and the reduction in the exchangeable Al concentrations and percent soil acid saturation may have produced a more favourable environment for soil microorganisms. The conducive environment and the increased availability of C to the soil microorganisms, especially in the chicken manure amended treatments, lead to an increase in microbial activity and perhaps population growth, which in turn increased the microbial demand for N. Therefore, it seems most likely that immobilization of N was the primary source for loss of mineralized N in the limed treatments. The reduction in net N mineralization in

the Magusheni soil as a result of liming is contrary to the findings of many workers, for example, Nyborg and Hoyt (1978), Edmeades et al. (1981), Fu et al. (1987), Haynes and Swift 1988, Lyngstad (1992) who noted increased N mineralization in soils following lime additions.

In contrast to the Magusheni soil, the lime x manure interaction on total or net inorganic N accumulation and also the main effects of lime were not significant in the Nikwe soil (Table 1.6.). However, the main effects of chicken manure were significant. The results indicate that the total and net inorganic N increased as chicken manure rate increased, however, lime application and the corresponding increases in soil pH (pH 5.0 to 6.0) had no apparent effect on N mineralization (Figures 1.8–1.9 and Table 1.8.). The total inorganic N contents between the control and lime only treatments (6.2 Mg ha⁻¹, 12.5 Mg ha⁻¹, and 18.7 Mg ha⁻¹), ranged from 28.8 to 30.4 mg N kg⁻¹. Similarly, the total inorganic N contents in soils amended with 5 Mg ha⁻¹ chicken manure (with or without lime) ranged from 42.0 to 45.3 mg N kg⁻¹. Additionally, the total inorganic N content in soils amended with 10 Mg ha⁻¹ chicken manure (with or without lime) ranged from 58.6 to 60.8 mg N kg⁻¹. The trends in net inorganic N were similar to those observed for total inorganic N. After 6 weeks of incubation, the results show that in the lime only treatments net inorganic N values were generally below 2.0 mg N kg⁻¹ (Table 1.8). Values of net inorganic N for the 5 and 10 Mg ha⁻¹ chicken manure only treatments were 15.2 and 29.9 mg N kg⁻¹, respectively. Similarly, values of net inorganic N for the combined lime plus chicken manure treatments ranged from 13.2 to 16.5 mg N kg⁻¹ in the 5 Mg ha⁻¹ chicken manure rate and from 30.5 to 32.0 mg N kg⁻¹ in the 10 Mg ha⁻¹ manure rate (Table 1.8). Apart from the lack of response to liming, these data clearly show that in the Nikwe soil, net mineralized N increased as the chicken manure rate increased, and was twice as high in the 10 Mg ha⁻¹ manure treatments than in the 5 Mg ha⁻¹ treatments. Expressed as percentages of added organic N, net N mineralized ranged from 17 to 18% in the 10 and 5 Mg ha⁻¹, respectively (Table 1.11). For the combined lime plus chicken manure treatments, the mineralization rate ranged between 15 to 19% of the added organic N in the lime plus 5 Mg ha⁻¹ manure rate and between 18 to 19% in the lime plus 10 Mg ha⁻¹ manure rate. As noted earlier, the soil pH was nearly 0.8 or more pH units

higher in the 18.7 Mg ha⁻¹ lime only or 18.7 Mg ha⁻¹ lime plus chicken manure treatments compared to chicken manure alone and in the control treatments. If N mineralization was limited by soil pH, the increases in soil pH following the application of lime should have enhanced N mineralization. However, because this increase did not occur, it was concluded that N mineralization may not have been limited by soil acidity in the Nikwe soil. The trends in CO₂ evolution rates were consistent with those observed for N mineralization.

The rate of CO₂ production for Nikwe soil is given in Table 1.10 and the cumulative evolution of CO₂ is shown in Figures 1.10 (a-e). Similarly to N mineralization, the results showed that the total CO₂ evolved increased as chicken manure application rates increased. However, liming and the associated increase in soil pH had no apparent effect on total CO₂ evolution in the Nikwe soil (Table 1.10). In the lime only treatments, the total CO₂ evolution rates ranged from 54.0 to 60.8 μg C g⁻¹ soil. In the lime + 5 Mg ha⁻¹ manure treatments, the rates of total CO₂ evolution ranged from 131.7 to 136.5 μg C g⁻¹ soil. In the lime + 10 Mg ha⁻¹ manure treatments, total CO₂ evolution rates ranged from 191.3 to 201.1 μg C g⁻¹ soil. Thus, the results indicate that microbial activity and N mineralization seems to be limited by C and N supply and not by soil acidity in the Nikwe soil. In general, the patterns of total CO₂ evolution and N mineralization followed the order of 10 Mg > 5 Mg > 0 Mg ha⁻¹ chicken manure, regardless of lime rate or final soil pH values. This is consistent with the theory that soil microbial activity increases after manure application (Martyniuk and Wagner, 1978; Paul and Beauchamp, 1995). The most likely reasons for the observed lack of a stimulating effect of lime on microbial activity and N mineralization rates in the Nikwe soil include the high soil base status, percentage Ca²⁺ saturation in the exchange complex and low percent soil acid saturation. The initial soil chemical analysis results (Table 1.1) showed that the exchange complex in the low acid saturated Nikwe soil was dominated primarily by Ca²⁺ and other base forming cations even prior to liming. According to Havlin et al. (1999) high percentage base saturation and Ca²⁺ saturation indicate a favourable pH for plant growth and microbial activity and usually mean low concentrations of exchangeable Al in acidic soils. In the case of the Nikwe soil, the percent base saturation, Ca²⁺ saturation, and soil

acid saturation were about 95.6 %, 47 %, and 4.3 %, respectively. Research shows that most crops respond to Ca^{2+} applications when % Ca saturation is <25% (Havlin et al., 1999). Since the soil environmental conditions that affect plant growth are similar to those that affect microbial activity, it is hypothesized that microbial activity did not respond to liming because the % Ca^{2+} saturation was nearly twice as much as the 25% saturation level and the exchange complex was nearly saturated (95.6 %) with base forming cations. The lack of stimulation of N mineralization in soil despite increases in soil pH from liming has been reported previously (Dancer et al., 1973; Weier and Gilliam, 1986).

If the net inorganic N is partitioned into $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$, the results suggest that in both Magusheni and Nikwe soils, there was a rapid increase in $\text{NO}_3\text{-N}$ which coincided with a rapid drop in $\text{NH}_4\text{-N}$ levels (Table 1.12). A closer evaluation of the data showed that in the Magusheni soil, the $\text{NH}_4\text{-N}$ contents in the chicken manure alone treatments were significantly higher than in the lime + chicken manure treatments. These data suggest that to some extent the nitrifier population in unlimed chicken manure only treatments was limited by low pH. Nevertheless, nitrification in these treatments (with pH values well below 5.0) was appreciable, suggesting that this soil probably contains a low pH tolerant nitrifier population. Nitrification at pH 4.50 or below has been reported elsewhere (Clay et al., 1993, Sarathchandra, 1978, Myrold, 1999). In the Nikwe soil, there were low levels of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ was the dominant form of inorganic N at all rates of lime and chicken manure. This was probably related to the presence of adequate levels of available Ca^{2+} and Mg^{2+} in this soil (Table 1.1). According to Brady and Weil (1999) acidity itself seems to have less influence on nitrification when adequate base forming cations (particularly available Ca^{2+}) are present in soil. Our results lend support to this inference. Simple correlation analyses showed that $\text{NO}_3\text{-N}$ was not correlated to soil pH in the Nikwe soil whereas in the Magusheni soil $\text{NO}_3\text{-N}$ was significantly related ($r^2 = 0.45$; $P < 0.001$) to soil pH (Figure 1.11).

Fractionation of the total amounts of CO_2 evolved revealed that the non-microbial CO_2 evolution accounted for < 1% of the total CO_2 evolution observed in the lime only and

lime + chicken manure treatments, respectively (Table 1.9 and 1.10). Thus, most of the CO₂ evolved in the limed treatments emanated from microbial respiration.

Correlation between net N mineralized and selected soil chemical properties

The linear correlations between net mineralized N in the two soils and selected soil chemical properties are presented in Table 1.13. Statistical analysis indicated that the amount of N mineralized was significantly correlated with amount of CO₂ evolved in both the Magusheni ($r^2 = 0.63$; $P < 0.05$) and Nikwe soils ($r^2 = 0.95$; $P < 0.001$). The relationship of CO₂ evolved as a function of N mineralized is shown in Figures 1.12 and 1.13. However, mineralized N was not correlated with soil pH, soil total C, soil total N, and C:N ratio. Tabatabai and Al-Khafaji (1980) also found that the mineralization of organic N in Iowa soils was not significantly correlated with organic C, total N, and total S. Similarly, Weier and Gilliam (1986) found no apparent relationship between organic matter (OM) content, OM/N ratio and N mineralized in soils with a wide range (2.8 to 85%) of soil organic matter contents. Simard and N'dayegamiye (1993) also found no significant relationship between N mineralization parameters and soil pH values of 20 meadows soils collected from pastures in different regions of Quebec. Lyngstad (1992) reported that in limed soils mineralization of organic N was not significantly related to the total N concentration nor original pH. Dancer et al. (1973) found that effects of liming to modify soil pH did not appreciably affect ammonification rates in soils that ranged in pH from 4.7 to 6.6. Nevertheless, some researchers have observed that the increases in N mineralization due to liming correlated with soil pH (Edmeades et al., 1981; Nyborg and Hoyt, 1978). Singh and Beauchamp (1986) investigated the effects of liming on N mineralization in lime and urea-N amended acid soils from southern Ontario. They observed that an appreciable increase in N mineralization due to liming occurred only when the soil pH rose above 6.0. In this study, results indicate that the net N mineralization after liming was related more with microbial activity than with soil chemical properties that are commonly used to quantitatively predict N availability. Microbial activity appears to be a useful variable to measure when attempting to predict

the effects of lime and broiler chicken amendments on short-term N availability. Similar conclusions have been drawn from a number of short-term laboratory incubation studies using soils amended with various organic amendments (Iratini and Arnold 1960; Agbim et al., 1977; Castellanos and Pratt, 1981).

CONCLUSIONS

Compared with other investigations the amounts of mineralizable organic N determined in this laboratory incubation study were generally low. Castellanos and Pratt (1981) found that approximately 48% of the organic N in chicken manure and 30% in composted chicken manure was mineralized in 10 weeks at 23 °C, while Sims (1986) reported that 25, 37, and 40% of the organic N in three broiler manures mineralized in 150d at 25 °C. However, direct comparisons of the amounts of mineralizable organic N values obtained in this study with previous research is not strictly valid, due to variations in soil environmental factors (soil moisture, pH) as well as soil and chicken manure properties.

The hypothesis that liming low pH soils increases microbial populations and/or their activity and stimulates N mineralization was not supported by the results from this investigation. Liming and the associated increase in soil pH had no apparent effect on microbial activity and N mineralization in the Nikwe soil. However, microbial activity and N mineralization increased as chicken manure application rates increased. The results indicate that microbial activity and N mineralization seems to be limited by C and N supply and not by soil acidity in the Nikwe soil. In the Magusheni soil, the effects of liming on microbial activity and N mineralization differed from those observed for the Nikwe soil. The stimulating effect of lime on CO₂ evolution suggests that the higher percent soil acid saturation (25%) in the Magusheni soil had an inhibitory effect on microbial activity in unlimed treatments. Therefore, liming is essential to supply Ca and correct the acidity in the Magusheni soil. However, an addition of a large amount of lime, especially when combined with broiler chicken manure, is expected to stimulate greater microbial activity and are likely to cause an initial N immobilization or a longer

lag period in N mineralization. It is hypothesized that, under field conditions the long-term effect of liming would be a net increase in N availability. If this were the case, the question arises as to how net immobilization of mineral N followed eventually by net mineralization would affect crop response in the field? Chapter 2 of this dissertation reports on the influence of lime and chicken manure on mineralization of N under greenhouse conditions.

Some studies have shown that N mineralization in organic waste treated soils was highly pH dependent, and increased as the soil pH was raised. In the experiment described herein, the chemical properties of the soils studied, particularly the levels of bioavailable Al (as indicated by the percent acid saturation) or the abundance of exchangeable Ca and other base forming cations had a significant influence on how the soil microbial population responded to lime addition. This in turn affected mineralization-immobilization turnover in soil. These data suggest the importance of paying attention also to soil chemical properties other than just soil pH, when studying the effect of lime on microbial activity and N mineralization in organic waste amended soils.

Recommendations for further study

- 1) Results of the experiment highlighted the effects of lime on N mineralization after 56 days of laboratory incubation. The need to investigate the long-term effects of lime on N mineralization was identified.

- 2) The information reported in this study was obtained from soils incubated without plants and comparison of these values with those obtained in the presence of plants is desirable.

- 3) In the present study the highest lime rates (18.7 and 24.4 Mg/ha) were applied in order to raise soil pH to 6.0. It is now widely accepted that high levels of bioavailable Al are the primary cause for adverse effects (Al toxicity) on plant growth and soil microbial activity. Therefore, for highly weathered soils (in which the hydrous oxides of Al and Fe are predominant) lime sufficient to neutralize exchangeable aluminum is all that is needed to create a favourable environment for microbial activity and plant growth. Future research efforts should concentrate on assessing the effects of liming to reduce percentage soil acid saturation to levels <20% of effective CEC on microbial activity, N mineralization, and plant growth.

- 4) Studies in other parts of the world have shown that N mineralization in animal manure treated soils vary with type or composition of manure and the physical and chemical properties of the soil receiving the manure. More local studies on mineralization-immobilization turnover in soil (selected to include a wide range of chemical and physical properties) treated with various animal manures are needed.

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Table 1.1. Selected chemical and physical properties of the Magusheni and Nikwe soils used in this study.

Soil Property	Magusheni soil	Nikwe soil
Total C (%)	4.6	3.4
Total N (%)	0.3	0.2
NH ₄ -N (mg kg ⁻¹)	21.5	5.9
NO ₃ -N (mg kg ⁻¹)	4.7	5.9
ECEC (cmol _c kg ⁻¹)	5.70	8.75
Ca saturation (%)	30.1	46.6
Mg saturation (%)	41.4	34.0
K saturation (%)	3.9	15.0
Base saturation (%)	75.3	95.7
Acid saturation (%)	24.7	4.3
Exch. Al (cmol _c kg ⁻¹)	1.27	0.20
Exch. Al+H (cmol _c kg ⁻¹)	1.40	0.38
Soil pH (KCl)	4.78	5.06
Sand (%)	27	30
Silt (%)	28	26
Clay (%)	45	44
Moisture @ Field Capacity (g g ⁻¹ soil)	0.47	0.39

Table 1.2. Selected properties of broiler chicken manure (Gromor¹) used in this study.

pH (KCl)	Total N (g kg ⁻¹)	Total C (g kg ⁻¹)	C:N ratio	NH ₄ -N (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	Moisture (g g ⁻¹)
6.31	34	340	1:10	2.7	<0.01	0.12

¹ Trade names and company names are included for the benefit of the reader and do not constitute endorsement or preferential treatment of the product.

Table 1.3. Characteristics of the calcitic lime (CaCO₃) used in this study.

Trade name	CCE	-----% on Mesh size-----		
	(%)	8	60	<60
Kulu-CAG ¹	100	0	47	53

¹ Trade names and company names are included for the benefit of the reader and do not constitute endorsement or preferential treatment of the product.

Table 1.4. Calcitic lime and broiler chicken manure rates used in this study.

Treatments	Magusheni soil	Nikwe soil
Lime rates (Mg/ha)	0, 8.1, 16.3, 24.4	0, 6.2, 12.5, 18.7
Manure Rates (Mg/ha)	0, 5, 10	0, 5, 10

Table. 1.5. Analysis of variance (ANOVA) table showing sources of variance.

Source	Degrees of Freedom
Lime	3 (4-1)
Manure	2 (3-1)
Lime x Manure	6 (4-1) x (3-1)
Error	By Subtraction=24
Total	35 ((4x3x3)-1)

Table 1.6. Significance of the calcitic lime and broiler chicken manure effects and their interaction for the soil pH, total CO₂ evolved, total inorganic N, net inorganic N, NH₄-N and NO₃-N (Magusheni and Nikwe soils).

<u>Magusheni soil</u>			
Source of variation			
-----P < F-----			
Parameters	Lime	Manure	Lime x Manure
Soil pH (H ₂ O)	< 0.0001	< 0.0001	0.0031
Total CO ₂ evolved	< 0.0001	< 0.0001	0.8915
Total Inorganic N	< 0.0001	< 0.0001	0.0112
Net Inorganic N	< 0.0001	< 0.0001	< 0.0208
NH ₄ -N	< 0.0001	< 0.0001	< 0.0001
NO ₃ -N	< 0.0001	< 0.0001	0.0005

<u>Nikwe soil</u>			
Source of variation			
-----P < F-----			
Parameters	Lime	Manure	Lime x Manure
Soil pH (H ₂ O)	< 0.0001	0.0008	0.0378
Total CO ₂ evolved	0.6071	< 0.0001	0.7091
Total Inorganic N	0.3843	< 0.0001	0.9667
Net Inorganic N	0.4364	< 0.0001	0.9396
NH ₄ -N	0.5024	0.0532	0.8995
NO ₃ -N	0.4225	< 0.0001	0.9477

Table 1.7. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on soil pH after 56 days of laboratory incubation (Magusheni and Nikwe soils).

Lime rate (Mg ha ⁻¹)	Manure rate (Mg ha ⁻¹)		
	0	5	10
Magusheni soil	pH (H ₂ O)		
0	4.50	4.67	4.72
8.1	4.94	4.94	5.06
16.3	5.31	5.34	5.36
24.4	5.66	5.72	5.74
LSD _{0.05}		0.034	
Nikwe soil			
0	5.09	5.06	4.99
6.2	5.40	5.32	5.31
12.5	5.68	5.64	5.65
18.7	5.91	5.94	5.91
LSD _{0.05}		0.028	
Analysis of Variance			
Source of variation			
	P < F		
Magusheni soil	Lime	Manure	Lime x Manure
Soil pH (H ₂ O)	< .0001	< .0001	0.0031
Nikwe soil			
Soil pH (H ₂ O)	< .0001	0.0008	0.0378

Table 1.8. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on total inorganic N (NH₄-N + NO₃-N) and net inorganic N after 56 days of laboratory incubation (Magusheni and Nikwe soils).

Lime rate (Mg ha ⁻¹)	Manure rate (Mg ha ⁻¹)					
	0			5		
Magusheni soil	-----Total Inorganic N----- (mg N kg ⁻¹)			-----Net Inorganic N----- (mg N kg ⁻¹)		
0	74.7	87.2	103.9	---	12.4	29.2
8.1	73.6	79.5	93.6	-1.05	4.78	18.9
16.3	73.9	77.5	89.1	-0.82	2.84	14.4
24.4	69.9	80.3	87.5	-4.81	5.57	12.8
LSD _{0.05}		2.76			2.90	
Nikwe soil						
0	28.8	44.0	58.6	---	15.2	29.9
6.2	28.0	42.0	59.8	-0.80	13.2	31.0
12.5	29.9	43.4	59.2	1.08	14.6	30.5
18.7	30.4	45.3	60.8	1.63	16.5	32.0
LSD _{0.05}		2.35			2.59	

Analysis of Variance

Source of variation

----- P < F -----

	Lime	Manure	Lime x Manure
Magusheni soil			
Total Inorganic N	< .0001	< .0001	0.0112
Net Inorganic N	< .0001	< .0001	<0.0208
Nikwe soil			
Total Inorganic N	0.3843	< .0001	0.9667
Net Inorganic N	0.4364	< .0001	0.9396

Table 1.9. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on total CO₂ evolved and biotic CO₂ evolved after 56 days of laboratory incubation (Magusheni soils).

Lime rate (Mg ha ⁻¹)	Manure rate (Mg ha ⁻¹)					
	0	5	10	0	5	10
	Total CO ₂ evolved (µg C g ⁻¹ soil)			Biotic CO ₂ evolved (µg C g ⁻¹ soil)		
0	76.3	135.2	201.0	76.3	135.2	201.0
8.1	102.8	160.0	231.6	98.0	154.2	226.8
16.3	129.9	184.9	257.6	120.4	175.2	247.9
24.4	150.5	210.4	282.0	136.2	196.1	268.7

Table 1.10. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on total CO₂ evolved and biotic CO₂ evolved after 56 days of laboratory incubation (Nikwe soils).

Lime rate (Mg ha ⁻¹)	Manure rate (Mg ha ⁻¹)					
	0	5	10	0	5	10
	Total CO ₂ evolved (µg C g ⁻¹ soil)			Biotic CO ₂ evolved (µg C g ⁻¹ soil)		
0	55.3	135.3	191.3	55.3	135.3	191.3
6.2	54.0	131.7	191.6	51.7	130.2	190.1
12.5	57.9	133.1	195.9	54.1	127.3	192.1
18.7	60.8	136.5	201.1	54.0	127.6	194.2

Table 1.11. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on percent N mineralization (+) and immobilization (-) after 56 days of laboratory incubation (Magusheni and Nikwe soils).

Lime rate (Mg ha ⁻¹)	Manure rate (Mg ha ⁻¹)	
	5	10
Magusheni soil	-----% N mineralized [†] -----	
0	+15.1	+17.5
8.1	+5.80	+11.3
16.3	+3.50	+8.60
24.4	+6.80	+7.70
Nikwe soil		
0	+18.5	+17.9
6.2	+16.0	+18.5
12.5	+17.7	+18.2
18.7	+20.1	+19.1

[†] (N mineralized in chicken manure amended soil minus N mineralized in unamended (control) soil / organic N added in chicken manure) x 100.

Table 1.12. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on NH₄-N and NO₃-N contents after 56 days of laboratory incubation (Magusheni and Nikwe soils).

Lime rate (Mg ha ⁻¹)	Manure rate (Mg ha ⁻¹)					
	0	5	10	0	5	10
Magusheni soil	NH ₄ -N ------(mg N kg ⁻¹)-----			NO ₃ -N ------(mg N kg ⁻¹)-----		
0	6.96	24.2	40.9	67.7	62.9	62.9
8.1	1.87	7.70	13.8	71.7	71.8	79.8
16.3	1.85	2.71	9.19	72.0	74.8	79.9
24.4	1.52	2.18	4.57	68.4	78.10	82.9
LSD _{0.05}		3.46			2.64	
Nikwe soil						
0	1.41	1.46	1.66	27.4	42.5	56.9
6.2	1.29	1.59	1.59	26.7	40.4	58.2
12.5	1.27	1.45	1.64	28.6	41.9	57.6
18.7	1.29	1.93	1.89	29.1	43.4	58.9
LSD _{0.05}		NS			2.21	

Analysis of Variance

Source of variation

	-----P < F-----		
Magusheni soil	Lime	Manure	Lime x manure
NH ₄ -N	< .0001	< .0001	< .0001
NO ₃ -N	< .0001	< .0001	0.0005
Nikwe soil			
NH ₄ -N	0.5024	0.0532	0.8995
NO ₃ -N	0.4225	< .0001	0.9477

Table 1.13. Relationships between N mineralization (N min) and selected soil characteristics (Magusheni and Nikwe soils).

Soils	NO ₃ -N	NH ₄ -N	Soil pH	Total Soil C	Total Soil N	C:N ratio	CO ₂ evolved
Magusheni	-----r ² -----						
N min	0.08ns	0.75***	-0.28ns	0.32ns	-0.29ns	-0.08ns	0.63***
Nikwe							
N min	0.99***	0.49**	-.017ns	0.33ns	-0.08ns	0.30ns	0.95***

*, **, *** significant at P<0.05, P<0.01, P<0.001, respectively; ns, not significant.



Figure 1.1. Map of the world showing the location of the Republic of South Africa.
(http://www.places.co.za/maps/free_state_map.html)

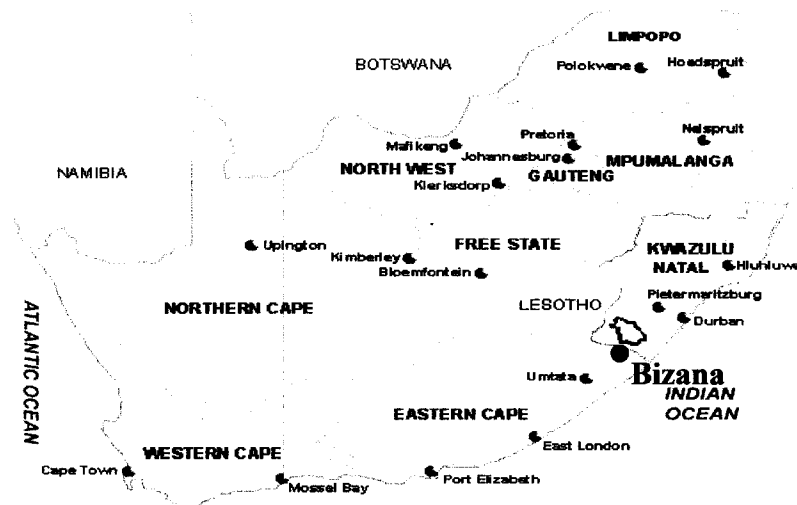


Figure 1.2. Map of South Africa showing the location of the Eastern Cape province.
(http://www.places.co.za/maps/free_state_map.html)

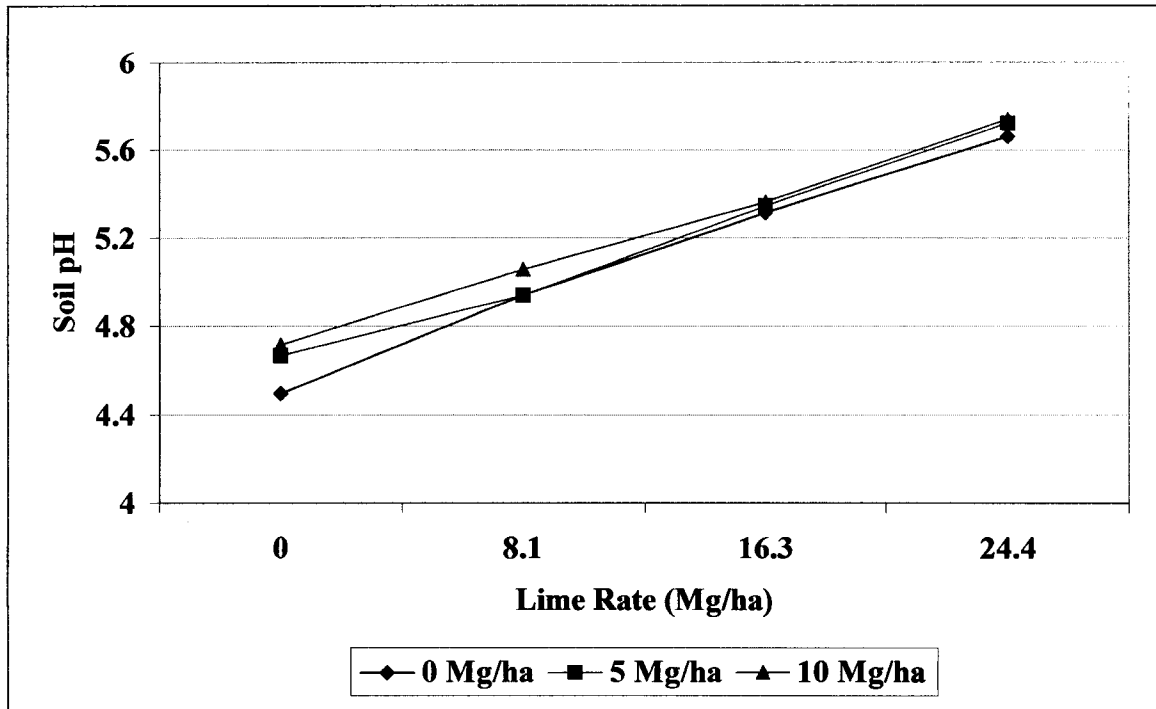


Figure 1.3. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on the soil pH after 56 days of laboratory incubation (Magusheni soil).

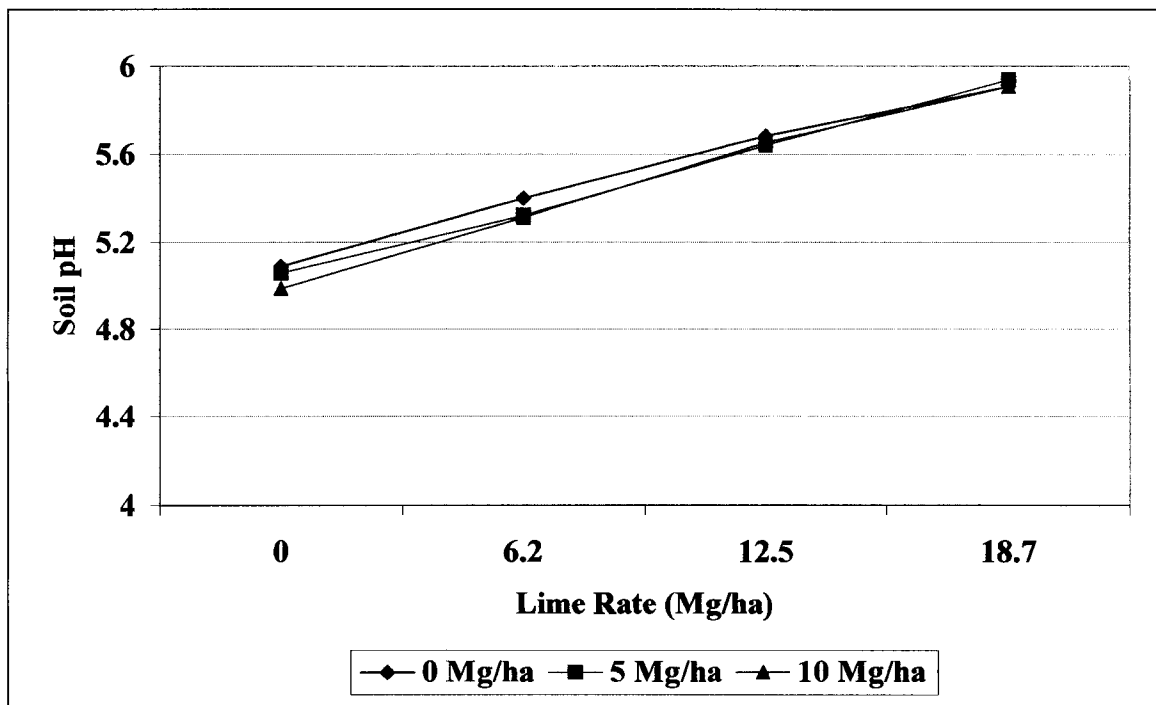


Figure 1.4. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on the soil pH after 56 days of laboratory incubation (Nikwe soil).

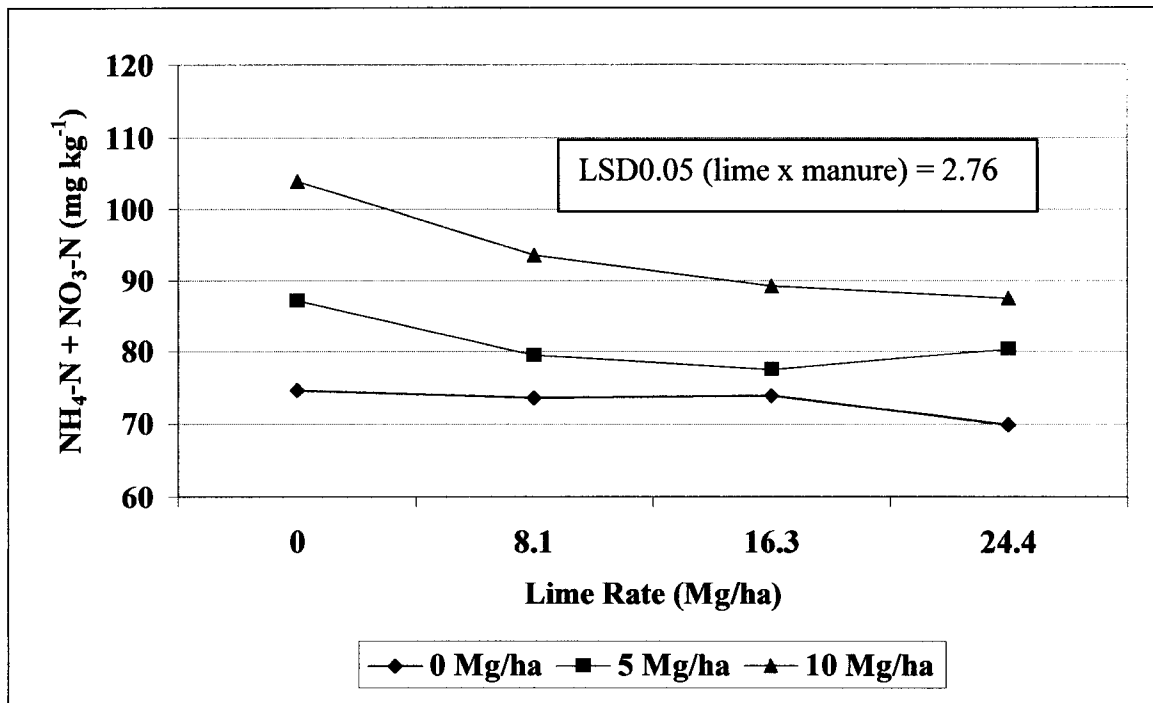


Figure 1.5. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on inorganic N ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) contents after 56 days of laboratory incubation (Magusheni soil).

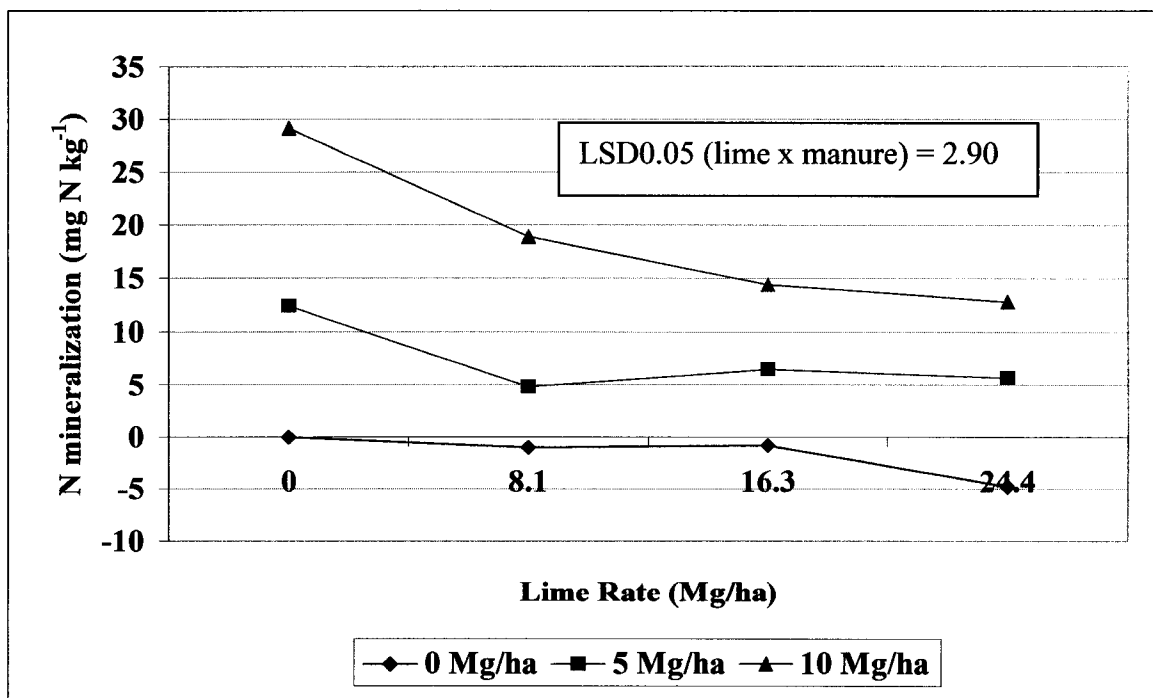


Figure 1.6. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on net N mineralization after 56 days of laboratory incubation (Magusheni soil).

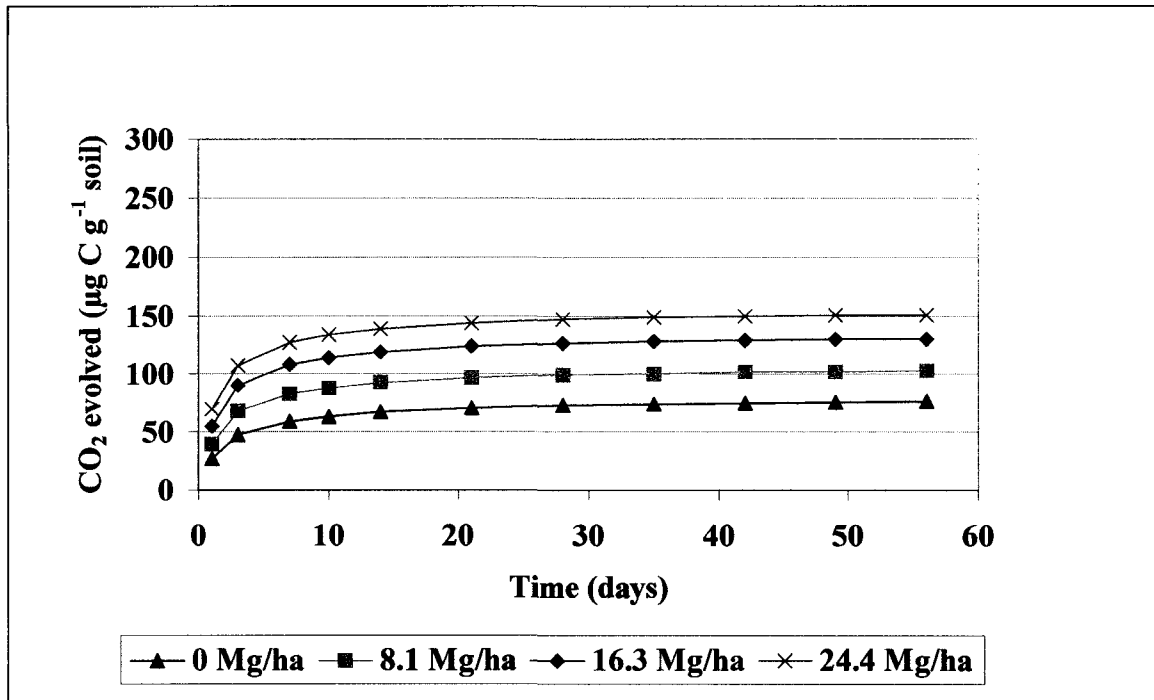


Figure 1.7(a). Effects of calcitic lime on rates of CO₂ production during 56 days of laboratory incubation (Magusheni soil).

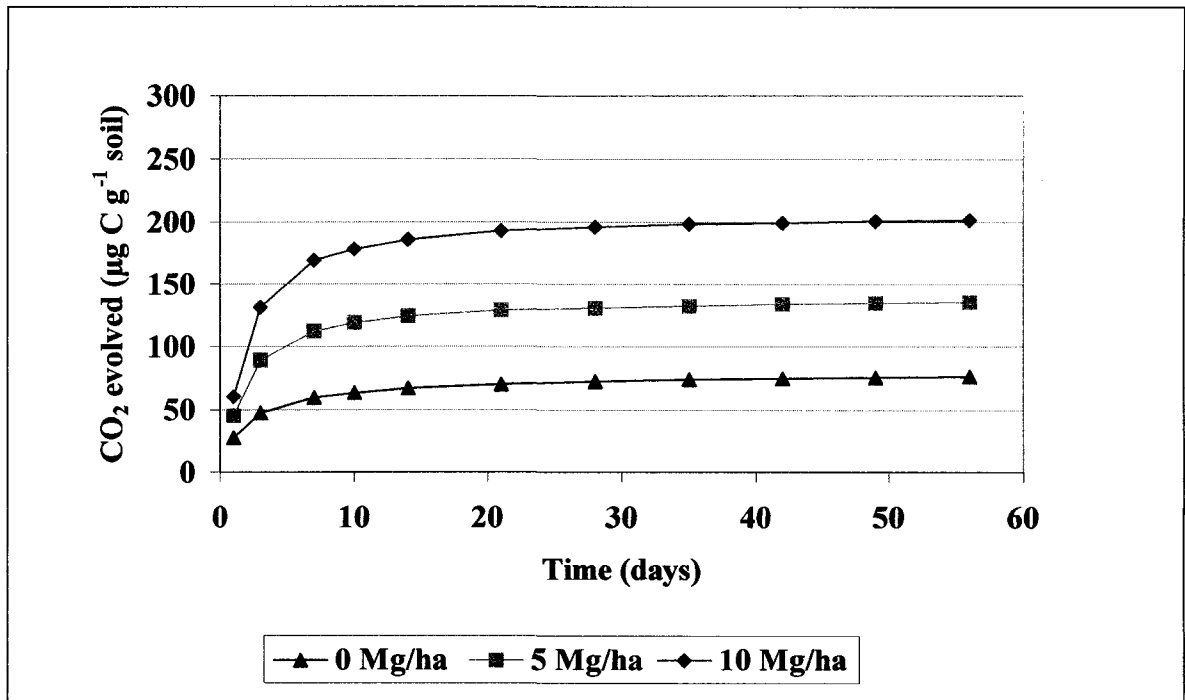


Figure 1.7(b). Effects of broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Magusheni soil).

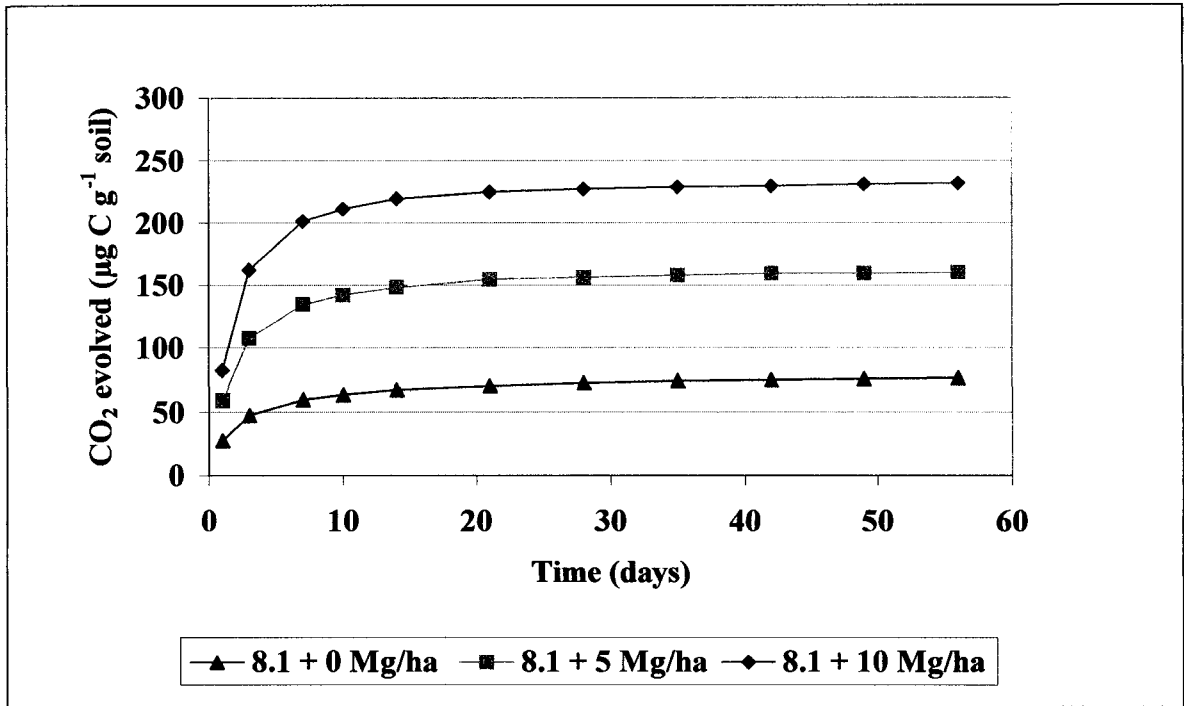


Figure 1.7(c). Effects of factorial combinations of calcitic lime and broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Magusheni soil).

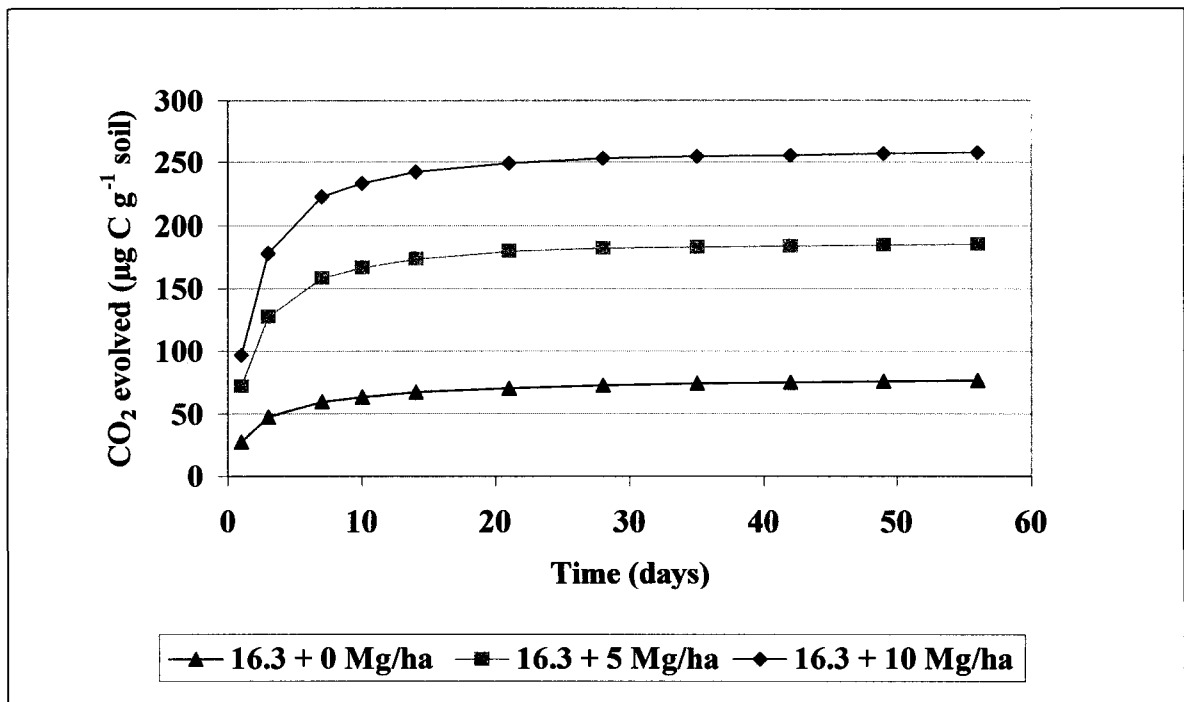


Figure 1.7(d). Effects of factorial combinations of calcitic lime and broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Magusheni soil).

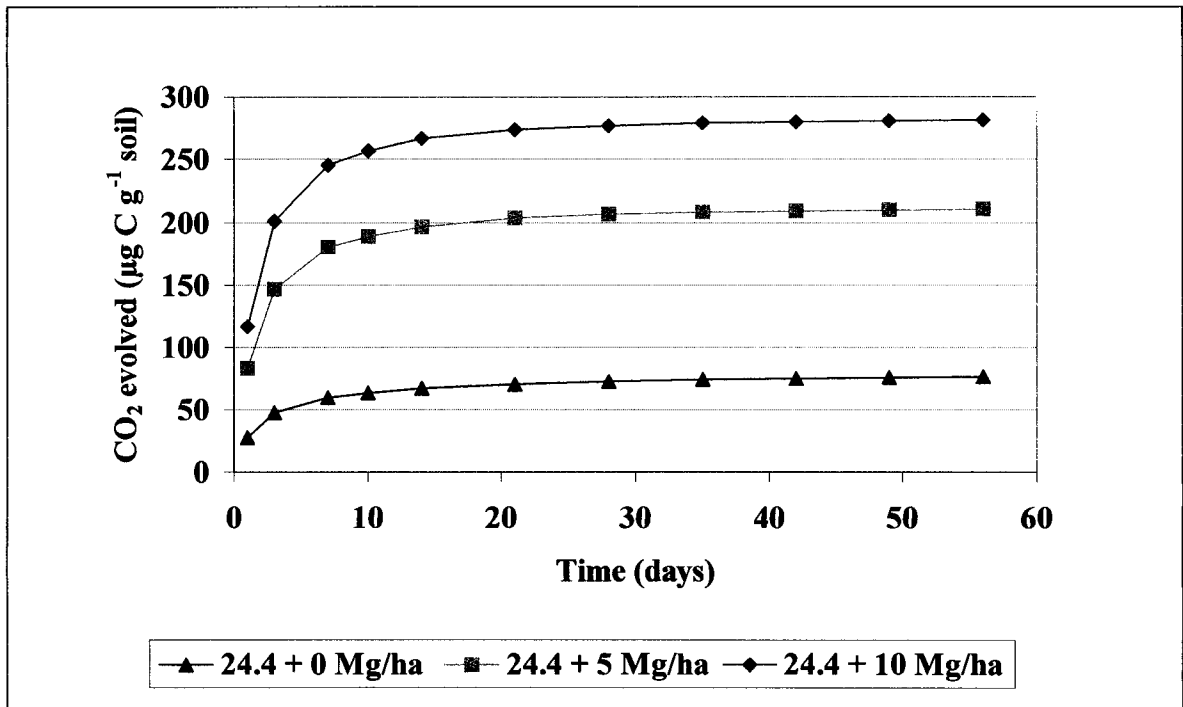


Figure 1.7(e). Effects of factorial combinations of calcitic lime and broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Magusheni soil).

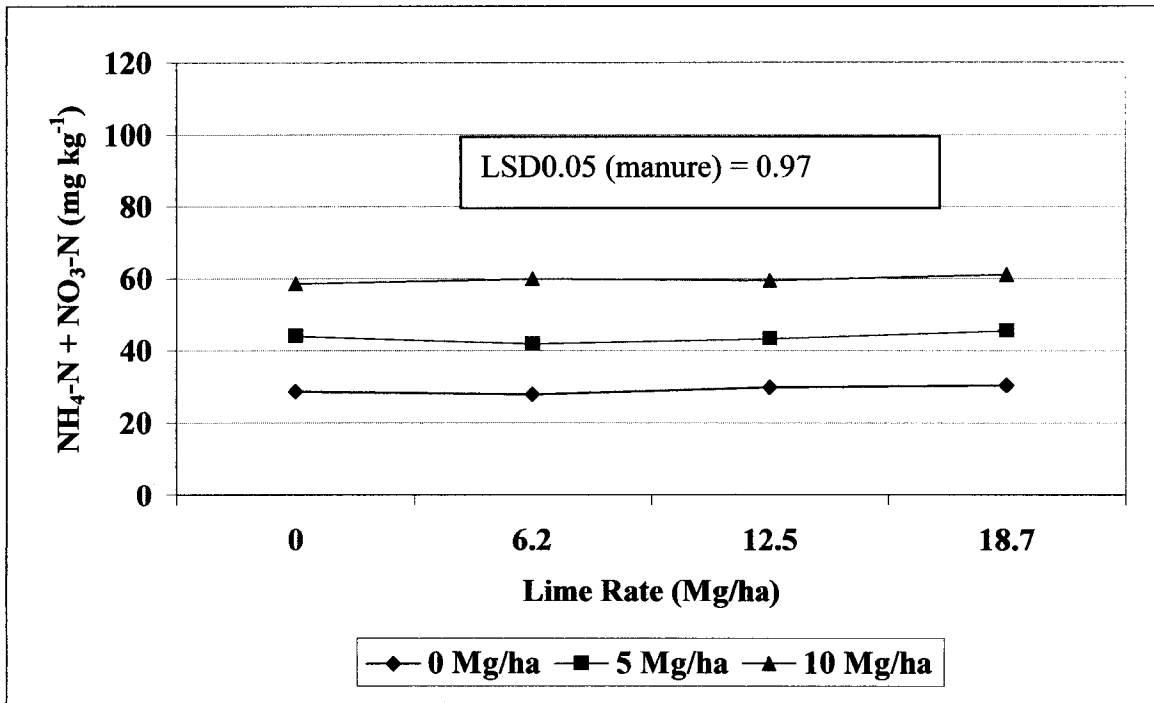


Figure 1.8. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on inorganic N (NH₄-N + NO₃-N) contents after 56 days of laboratory incubation (Nikwe soil).

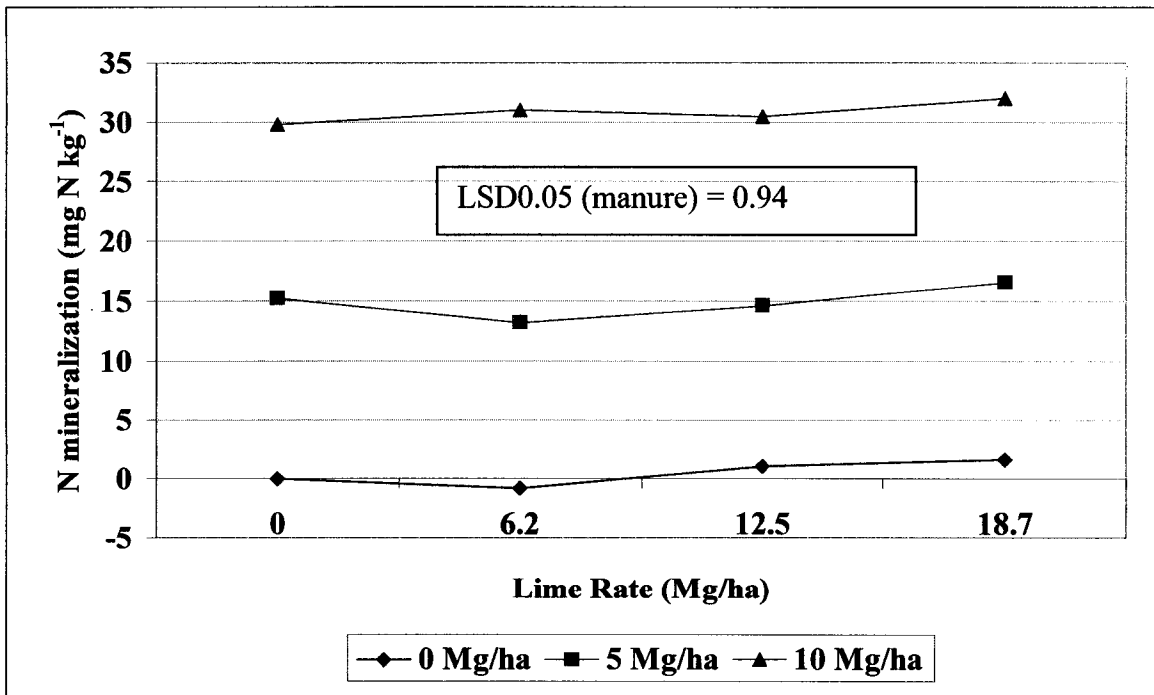


Figure 1.9. Effects of factorial combinations of calcitic lime and broiler chicken manure rates on net N mineralization after 56 days of laboratory incubation (Nikwe soil).

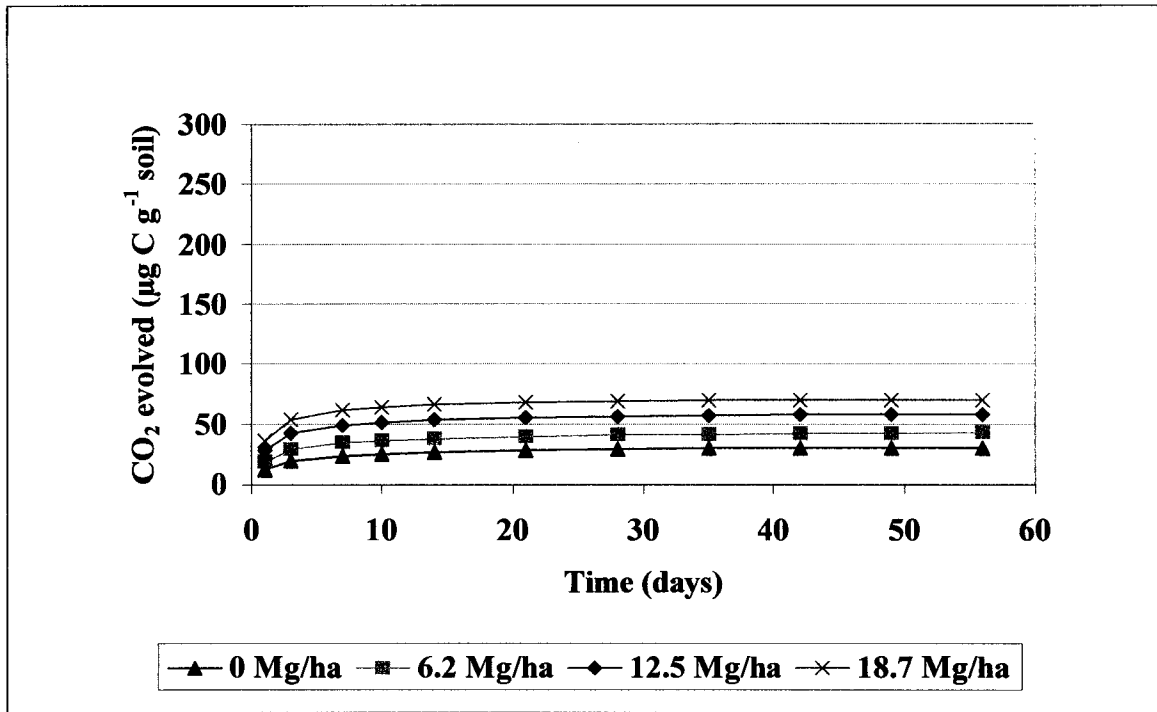


Figure 1.10(a). Effects of calcitic lime on rates of CO₂ production during 56 days of laboratory incubation (Nikwe soil).

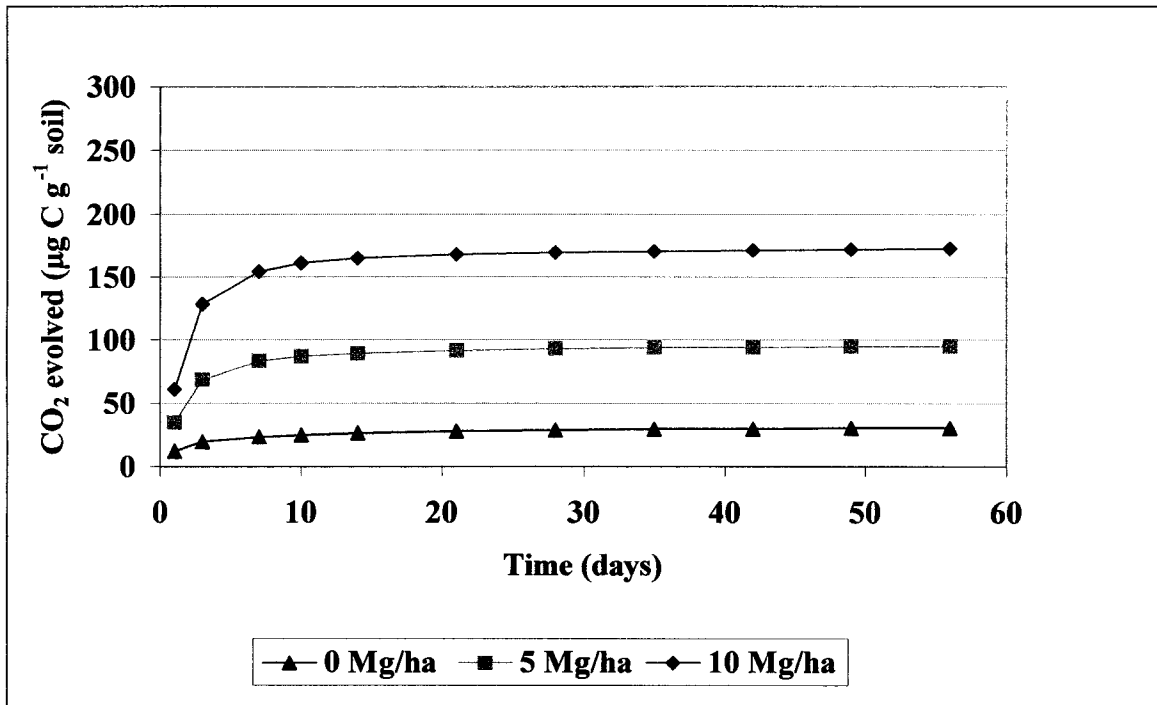


Figure 1.10(b). Effects of broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Nikwe soil).

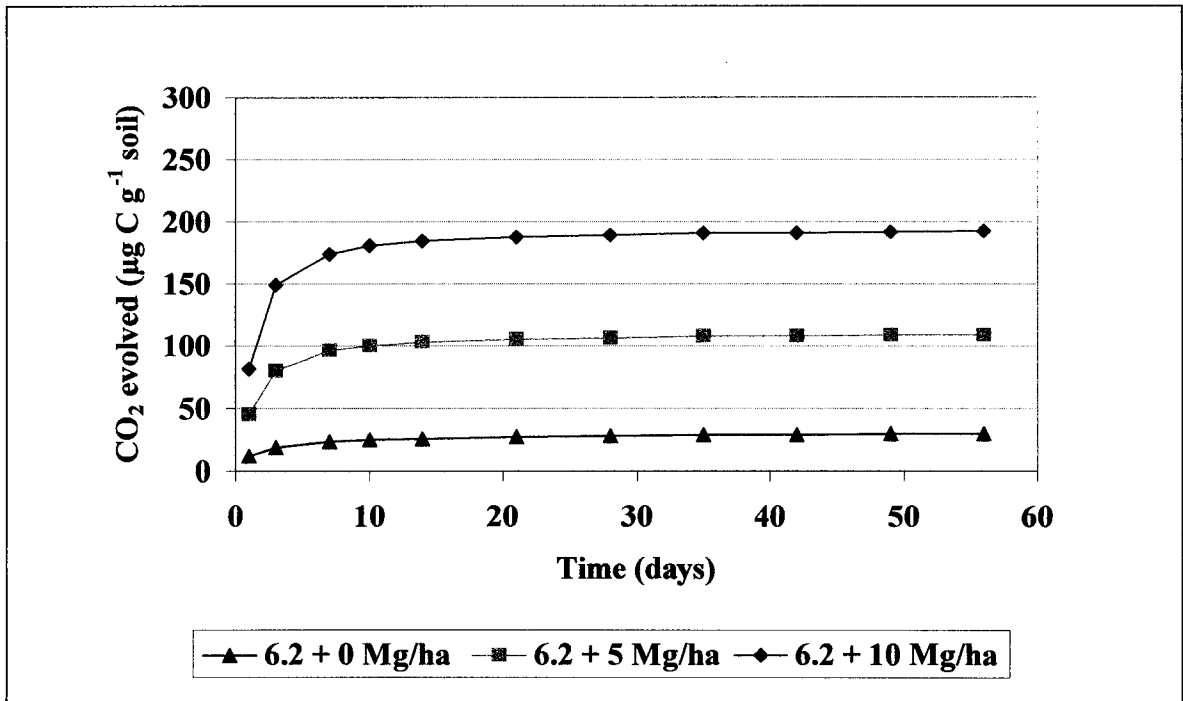


Figure 1.10(c). Effects of factorial combinations of calcitic lime and broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Nikwe soil).

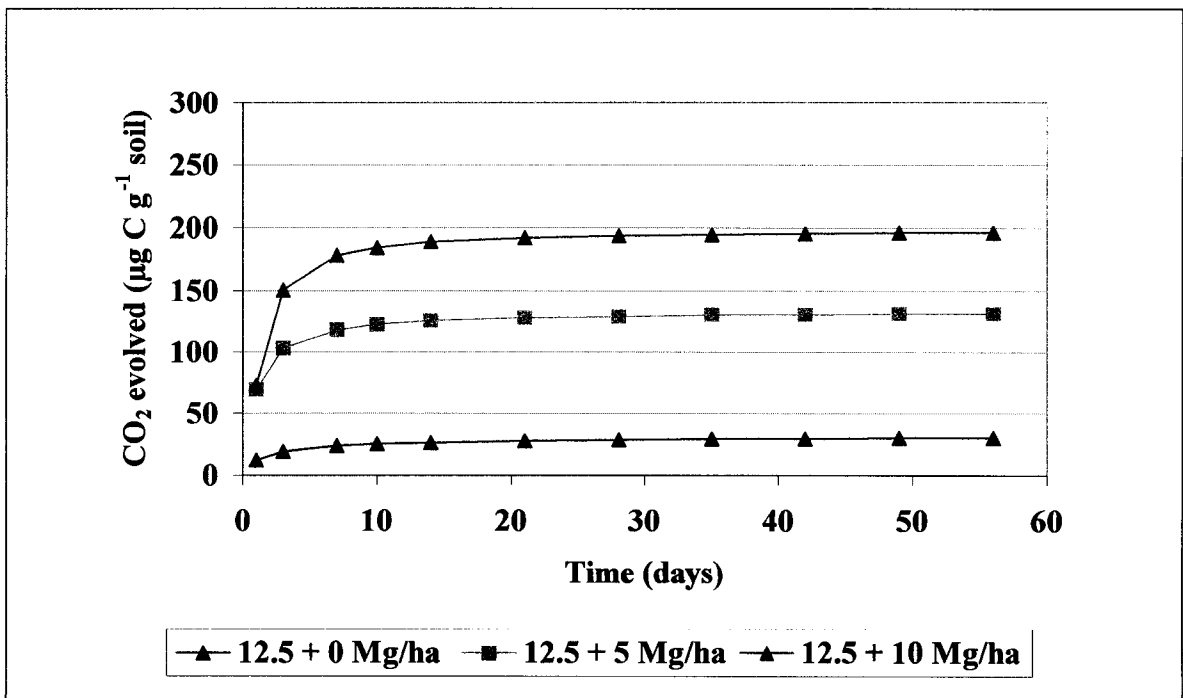


Figure 1.10(d). Effects of factorial combinations of calcitic lime and broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Nikwe soil).

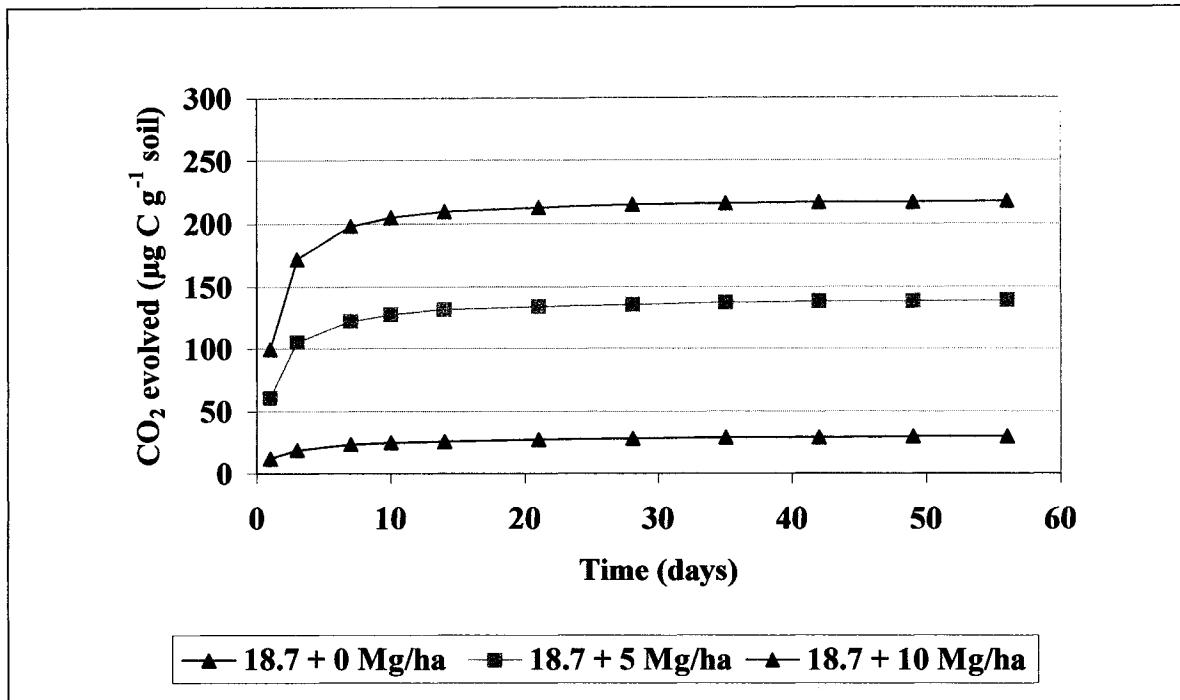


Figure 1.10(e). Effects of factorial combinations of calcitic lime and broiler chicken manure on rates of CO₂ production during 56 days of laboratory incubation (Nikwe soil).

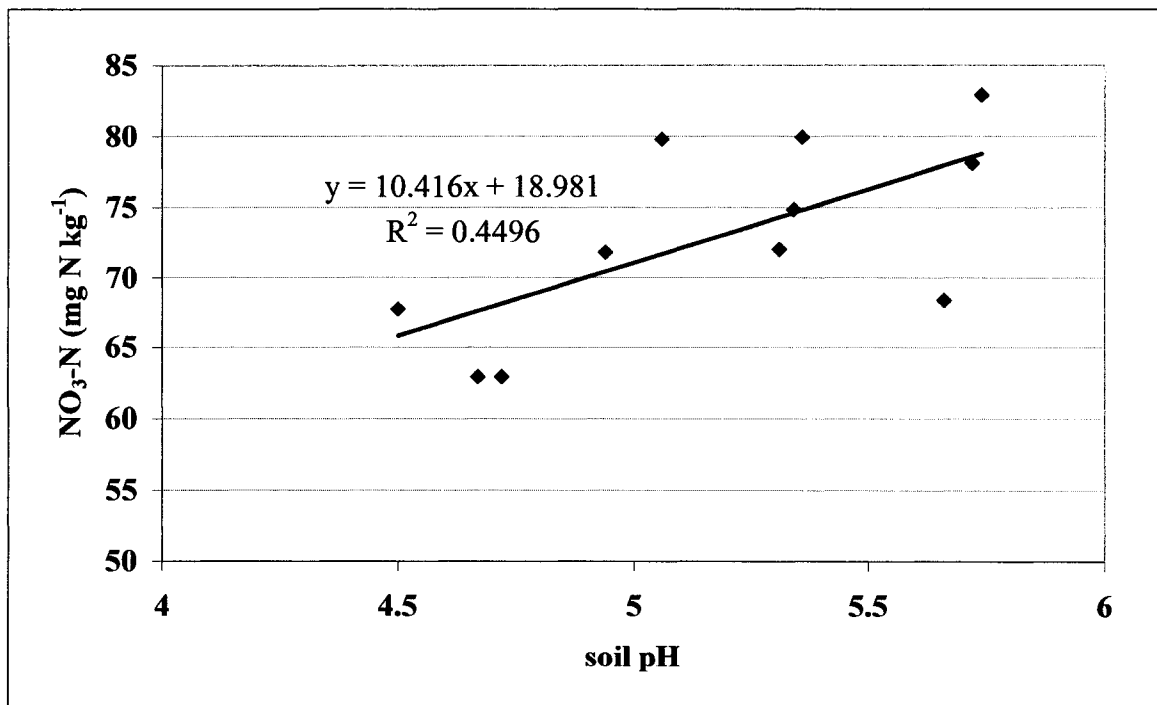


Figure 1.11. Relationship between soil pH_(water) and NO₃-N after 56 days of laboratory incubation (Magusheni soil).

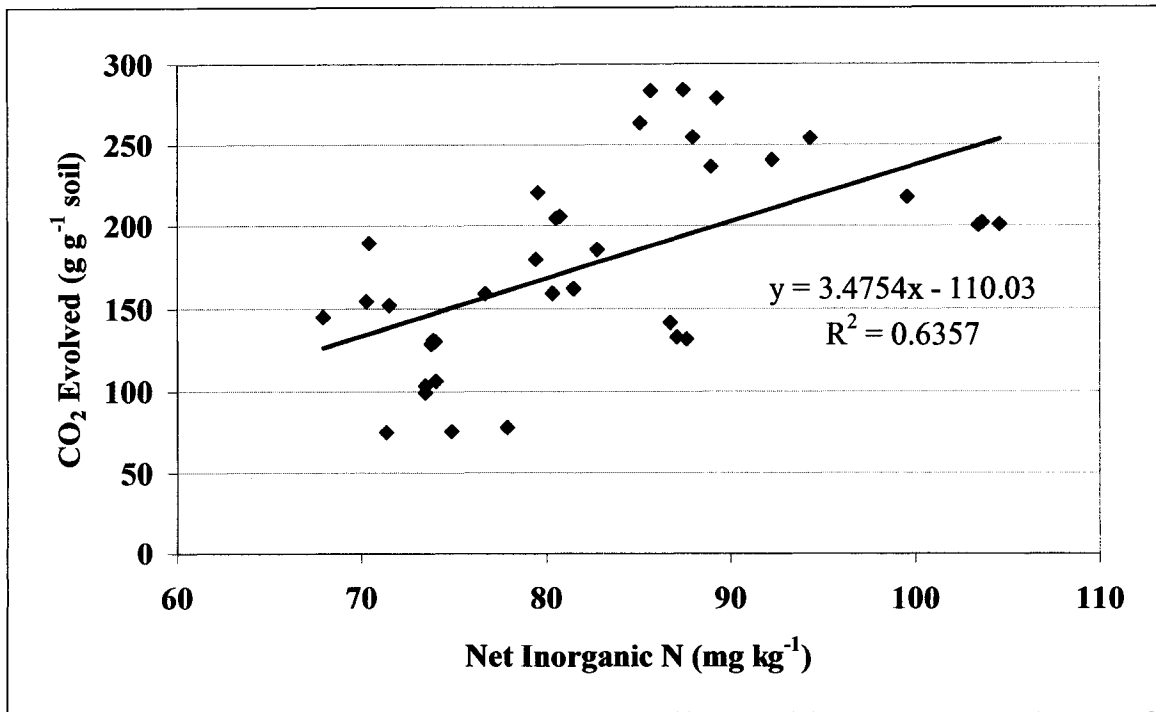


Figure 1.12. Relationship between total CO₂ evolution and total inorganic N mineralized in soils after 56 days of laboratory incubation (Magusheni soil).

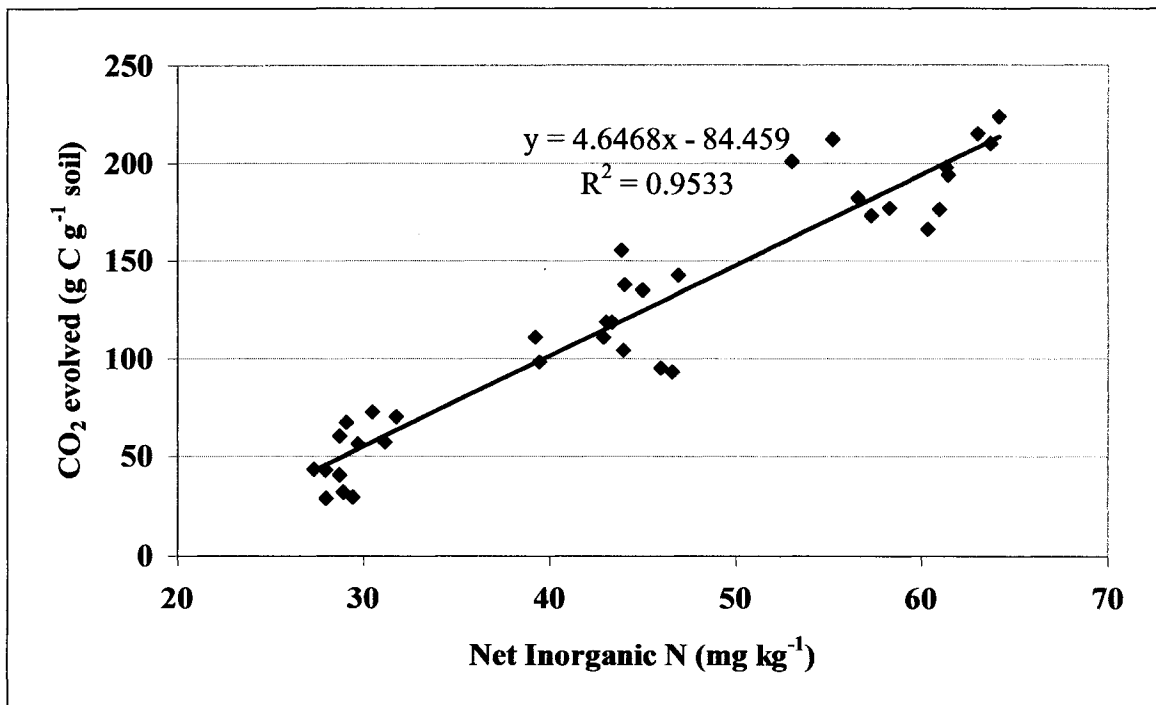


Figure 1.13. Relationship between total CO₂ evolution (μg C g⁻¹ soil) and total inorganic N mineralized in soils after 56 days of laboratory incubation (Nikwe soil).

CHAPTER 2

EFFECTS OF LIME AND CHICKEN MANURE INTERACTIONS ON SOIL PROPERTIES, N AVAILABILITY, N UPTAKE AND MAIZE GROWTH IN TWO ACID SOUTH AFRICAN ULTISOLS

ABSTRACT

The effects of calcitic lime and chicken manure application and their interaction on soil chemical properties, N availability, N uptake and maize growth were studied in the greenhouse. Two soils with varying percent acid saturation (4.0 – 25%) and base saturation (75 – 96%) were sampled from the Eastern Cape Province. The soils were amended with a factorial combination of 2 rates of lime and 3 rates of manure. The lime rates were (1) 1.0 Mg ha⁻¹ full-lime rate to lower the soil acid saturation to levels below 20%; (2) a control without lime. The broiler chicken manure rates were (1) 10 Mg ha⁻¹, (2) 5 Mg ha⁻¹ and (3) a control without manure. The results showed that the Magusheni soil, which had higher initial soil acid saturation (>20%), had lower N mineralization, total N uptake, plant height, and aboveground biomass production rates than the Nikwe soil which had lower initial soil acid saturation (<5%). In the Nikwe soil, N mineralization, total N uptake, biomass yield responses increased as chicken manure increased. However, lime had no apparent effect on N mineralization, total N uptake, aboveground biomass production and the soil chemical properties of the Nikwe soil. In the unlimed treatments, the mean soil pH (KCl), soil acid saturation and base saturation values were 4.39, 3% and 97 %, respectively. In the limed treatments, the mean soil pH (KCl), soil acid saturation and base saturation values were 4.31, 6% and 94%, respectively. The results demonstrate that in the Nikwe soil, the levels of soil acidity were relatively low, therefore, N mineralization, total N uptake, maize growth and development were mainly limited by the N supply. In the Magusheni soil, N

mineralization, total N uptake, and aboveground biomass production among the 5 and 10 Mg ha⁻¹ chicken manure rates was similar between limed and unlimed treatments, even though the soil data indicates that on average the soil acid saturation levels were more than 3 times higher in the unlimed compared to the limed treatments. In the unlimed treatments, the mean soil pH (KCl), soil acid saturation and base saturation values were 3.85, 41% and 59%, respectively. In the limed treatments, the mean soil pH (KCl), soil acid saturation and base saturation values were 4.27, 13% and 87%, respectively. Based on soil analysis results, there is little doubt that the lower responses in N mineralization, total N uptake, and aboveground biomass production observed in unlimed treatments were caused by soil acidity. However, in the limed treatments microbial N immobilization rather than soil acidity seems responsible for the reduction in N mineralization, total N uptake, and aboveground biomass production. It is hypothesized that the long-term effect of lime under field conditions would be a net increase in N availability and improved crop growth.

INTRODUCTION

Research by Clay et al. (1993) showed that the influence of lime on mineralization of N was not definitive. Indeed the soil laboratory incubation experiment in chapter 1 showed liming enhanced microbial activities in a high acid saturated (Magusheni) soil amended with or without broiler chicken manure, and lead to a decrease in N concentration in the soil solution (N immobilization) in comparison to unlimed treatments. In contrast, results showed that broiler chicken manure application doubled N mineralization whereas liming had little or no influence upon N mineralization in a low acid saturated (Nikwe) soil. On the strength of such observations, the present greenhouse study was undertaken to evaluate the validity of the findings under greenhouse conditions. The results of a 6-weeks study on the effects of calcitic lime and chicken manure interaction on soil chemical properties, N availability, N uptake and maize growth on two acid South African Ultisols are therefore reported in this study, with focus on the following questions:

- What are the effects of rate of broiler chicken manure application and liming (CaCO_3) to reduce percent acid saturation to $<20\%$ on soil properties, N availability, N uptake and maize growth for a soil that has $>20\%$ acid saturation?
- What are the effects of rate of broiler chicken manure application and liming (CaCO_3) a soil that already has $<20\%$ acid saturation on soil properties, N availability, N uptake and maize growth?

MATERIALS AND METHODS

Soils

Soils used in this experiment were collected at a depth 0 to 15 cm from the same locations as the soil samples used for the soil laboratory incubation experiment discussed in Chapter 1. Soil chemical properties vary between the two soils, especially the soil acidity levels (Table 2.1). The soil from Magusheni demonstration site (Magusheni soil)

is classified as Magwa connemara series (Humic Hapludult), and contains 270 g sand kg⁻¹, 280 g silt kg⁻¹, 450 g clay kg⁻¹, 46% total C, 0.3% total N, 75% base saturation, 25% acid saturation, and a soil pH of 4.78. The soil from Nikwe demonstration site (Nikwe soil) is classified as Sweetwater newton series (Humic Hapludult), and contains 300 g sand kg⁻¹, 260 g silt kg⁻¹, 440 g clay kg⁻¹, 3.4% total C, 0.2% total N, 96% base saturation, 4.0% acid saturation, and a soil pH of 5.0.

Broiler chicken manure

Table 2.2 shows the composition of the manure used in this study. In these analyses, chicken manure pH was determined with a manure:water ratio of 1: 2.5 (w/v). Total C, total N and inorganic N (NH₄-N and NO₃-N) were analyzed by the same procedures as the soil samples. Moisture was determined from loss in weight after drying at 65 °C for 48 h. The moisture content of the chicken manure was taken into account when different rates were applied to each soil.

Lime requirement determination

There are many methods available for the determination of soil lime requirement (LR), but no single method is suitable for all soils under all conditions (Quigley 1998). In South Africa, the two most prominent methods for measuring lime requirement are (1) liming to achieve an arbitrary desired pH, (2) liming to neutralize acidity and to lower Al toxicity (FSSA, 1989). The latter method is widely in KwaZulu-Natal Province where most lime recommendations are based on percent acid or Al saturation (Farina et al., 1981; Manson 1997; Sumner and Yamada 2002). The acid saturation method is justified by the argument that Al toxicity is the most limiting factor for plant growth in acid soils (Norton and Zhang, 1998). Several studies in the KwaZulu-Natal Province have found that acid saturation was a good indicator of likely aluminum toxicity over a variety of soils (Miles 1986; Farina & Channon 1991; Farina et al., 1993). Farina et al., (1981) found that for maize there was a better correlation with percentage acid or aluminum saturation than with soil pH. Field research, such as that of Farina and Channon (1991), and Miles (1986) has been used to determine the permissible (or target) acid saturation (PAS) of important crops in the KwaZulu-Natal Province. If soil acid saturation exceeds

the PAS of the crop to be grown, an application of lime is recommended to neutralize the excess acidity (Manson, 1997). In the field trials conducted as part of the Bizana LandCare project, lime was applied to lower soil acid saturation to levels below 20% because a PAS of 20% or lower was considered necessary to ensure optimum growth for a maize crop (Fyfield et al., 2000 and 2002).

In the present study, lime was therefore applied to lower the soil acid saturation to levels below 20%. Preliminary soil analysis results demonstrated that for the Magusheni soil (acid saturation 25%) the amount of lime required to achieve this objective was 5.0 g $\text{CaCO}_3 \text{ pot}^{-1}$, which is equivalent to 1.0 Mg ha^{-1} . In the Nikwe soil, soil acid saturation was already at levels lower than 20%, nonetheless, lime was applied to this soil at rates similar to those for Magusheni soil in order to validate those observations made from chapter 1 which indicated that liming had no apparent influence upon N mineralization in the Nikwe soil. For a faster reaction rate, the calcitic lime was ground to powder ($<2500 \mu\text{m}$) prior to use (Table 2.3).

Treatments and experimental design

A 2 x 3 complete factorial experiment with four replicates was used in a completely randomized design for each soil. Details regarding the treatments imposed on each soil are given in Table 2.4. The calcitic lime and broiler chicken manure used in the present study were also similar to those used in the soil incubation experiment reported in Chapter 1. The present experiment was conducted over a 6 week period in a greenhouse located at the experimental farm of the University of Pretoria (26° 12' S; 28° 10' E), concurrently with the pot experiment discussed in Chapter 3.

Experimental procedure

About 10 kg (on an oven-dry soil basis) of air dry and sieved ($< 4 \text{ mm}$) soil was placed into plastic pots (27 cm height x 30 cm diameter). To ensure proper aeration, three holes, each 10 mm in diameter, were drilled in the bottom of each pot and covered with nylon screen. All pots (excluding control treatments) containing the Magusheni soils received 1.2 g P per pot as triple super-phosphate, 3.0 g K per pot as potassium chloride, and 0.12

g Zn per pot as zinc oxide. The pots containing the Nikwe soils only received 1.2 g P per pot as triple super-phosphate, because soil analysis results indicated that the other elements were available in adequate quantities in soil. A control without any fertilizer or chicken manure addition was also included. The potted soils were thoroughly mixed, moistened with deionized water to field capacity, a loose-fitting lid applied to retard water loss, and preincubated for 7 days to allow the soil in each pot to equilibrate with its amendments. After 7 days, five seeds of maize were planted into each pot and thinned to three uniform plants per pot after emergence. The greenhouse temperature was 32 °C during the day-time and 19 °C at night-time. Soil moisture was kept at approximately 90% field capacity in all treatments by daily watering to the same weight. The pots were rotated each week. Plant height from the soil surface to the plant tip was measured 7 days prior to harvest.

Plant analysis

At the termination of the experiment, the maize plants were cut off at ground level and the cut stalks were thoroughly rinsed with distilled water, placed in a labeled paper bag, dried in a forced draught oven at 60 °C for 48 h and weighed. Total N content was run on these plant samples using the Kjeldhal procedure. Plant N uptake was calculated by multiplying the aboveground biomass (as determined by weighing plant samples) by N concentration.

Soil Analysis

At the conclusion of the trial, homogenized soil samples were collected from each pot and the following chemical properties were determined: soil pH, exchangeable bases (Ca, Mg, and K), exchangeable acidity (Al + H), exchangeable aluminum (Al), NH₄-N and NO₃-N (Non-affiliated Soil Analysis Working Group, 1990). Base saturation was calculated as $\text{exchangeable Ca} + \text{Mg} + \text{K} \text{ (cmol}_c \text{ kg}^{-1}) \times 100 / \text{exchangeable Ca} + \text{Mg} + \text{K} + \text{Al} + \text{H} \text{ (cmol}_c \text{ kg}^{-1})$ (FSSA, 1989). Acid saturation was calculated as $\text{exchangeable Al} + \text{H} \text{ (cmol}_c \text{ kg}^{-1}) \times 100 / \text{exchangeable Ca} + \text{Mg} + \text{K} + \text{Al} + \text{H} \text{ (cmol}_c \text{ kg}^{-1})$.

Calculations

Nitrogen mineralization (N_m) was calculated for all treatments as follows (Edmeades et al., 1981):

$$N_m = N \text{ uptake} + \text{soil mineral } N_{\text{final}} - \text{soil mineral } N_{\text{initial}}$$

where

$N \text{ uptake}$ = total N uptake by aboveground biomass

soil mineral N_{final} = $\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$ at the end of study period (6 weeks)

soil mineral N_{initial} = $\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$ at the beginning of study period

Statistical analysis

Table 2.5 shows sources of variation and their degrees of freedom. All statistical analyses were performed using Statistical Analysis Software General Linear Model (SAS GLM) procedure (SAS Institute, 2005). Treatment means were compared using the least significant difference (LSD) at the 5% level of significance (Steel et al., 1997).

RESULTS AND DISCUSSION

Plant height and aboveground biomass production

Analysis of variance for plant height and aboveground biomass production indicated a significant lime x chicken manure interaction (Tables 2.6) on both Magusheni and Nikwe soils. Among the 0 Mg ha⁻¹ chicken manure rates, liming significantly increased plant height and aboveground biomass production compared to the unlimed treatment on both soils (Tables 2.7). On both Magusheni and Nikwe soils, there were significant differences in plant height for 10 Mg ha⁻¹ chicken manure rates between unlimed and limed treatments. In the Magusheni soils, plant height among the 10 Mg ha⁻¹ chicken manure rates was significantly lower in limed than in unlimed treatments. However, in the Nikwe soils, plant height among the 10 Mg ha⁻¹ chicken manure rates was significantly higher in limed than in unlimed treatments. Nonetheless, these differences in plant height did not have any noticeable effects on aboveground biomass production (Tables 2.7). On both Magusheni and Nikwe soils, the aboveground biomass production among the 5 and 10 Mg ha⁻¹ chicken manure rates was generally not significantly different between unlimed and limed treatments. Additionally, the results suggest that there were steady increases in aboveground biomass production and plant height from 0 to 5 Mg ha⁻¹ chicken manure, in both limed and unlimed treatments. But a relatively smaller further increase in aboveground biomass production and plant height was seen from 5 to 10 Mg ha⁻¹ chicken manure rates. The results show that doubling the chicken manure application rate from 5 to 10 Mg ha⁻¹ significantly increased aboveground biomass production and plant height in the Nikwe soil only. The only exception was observed in unlimed soil where the differences in plant height between 5 to 10 Mg ha⁻¹ chicken manure treatments were not significant.

Interestingly, the results indicate that the plant height and aboveground biomass production varied between the Magusheni and Nikwe soils. In all the treatments plant height and aboveground biomass production were consistently higher in the Nikwe soil than in the Magusheni soil. For example, at the end of the pot experiment the aboveground biomass in the Magusheni soil was about 50% of that observed in the

Nikwe soil (Tables 2.7). These data suggest that in the Nikwe soil the conditions may have been more favourable for plant growth compared to Magusheni soil.

Nitrogen mineralization

In the Magusheni soil, the lime x chicken manure interaction (Table 2.6) for N mineralization was significant. The effects of lime and chicken manure rates on N mineralization are presented in Table 2.8. Among the 0 Mg ha⁻¹ chicken manure rates, N mineralization was significantly higher in the limed than in the unlimed treatments. However, for the 5 and 10 Mg ha⁻¹ chicken manure rates, N mineralization was not significantly different between unlimed and limed treatments. Additionally, our data suggest that there were steady increases in N mineralization from 0 to 5 Mg ha⁻¹ chicken manure, in both unlimed and limed treatments. But a relatively smaller further increase in N mineralization was seen from 5 to 10 Mg ha⁻¹ chicken manure rates. Results show that mineralization of N between 5 and 10 Mg ha⁻¹ chicken manure rates was not significantly different in unlimed treatments, however in limed treatments, differences in N mineralization between these chicken manure rates were significant (Tables 2.8).

In the Nikwe soil, analysis of variance for the N mineralization data indicated that the lime x chicken manure interaction effects and main effects of lime on N mineralization were not significant (Tables 2.8). The results suggest that, among all chicken manure rates lime had no noticeable effect on N mineralization. However, the main effects of chicken manure were significant and the results indicate that N mineralization increased as chicken manure application rate increased. The pattern of N mineralization followed the order of 10 Mg > 5 Mg > 0 Mg ha⁻¹ chicken manure.

Interestingly, in agreement with earlier observations made on plant height or aboveground biomass production, the results indicate that the amount of N mineralized varied between the Magusheni and Nikwe soils. In all the treatments more N was mineralized in the Nikwe soil than in the Magusheni soil. This suggests the presence of a more favourable environment for microbial activity and accelerated mineralization of N from organic matter in the Nikwe soil. The most likely reasons for the apparent differing

effects of liming on N mineralization between in the Magusheni and Nikwe soils seem to be related to the two soils chemical properties. Hence, some additional explanation about the observed N mineralization responses in the present study is given in the following soil chemical properties section of this chapter.

A further point of interest which deserves mentioning is that the lime and chicken manure effects on mineralization of N in the present study are consistent with those observed in the short-term (56 days) soil laboratory incubation experiment reported in Chapter 1, even though liming objectives, hence the quantities of lime added, and laboratory incubation conditions varied between the two studies. In the soil incubation study, liming had little or no noticeable effect on soil biological activity and N mineralization in the Nikwe soil, whereas in the Magusheni soil, liming contributed to an increase in microbial activities and resulted in a decrease in N concentration in the soil solution from microbial immobilization.

Aboveground Biomass N concentration and uptake

In both the Magusheni and Nikwe soils, the concentration of N in the aboveground biomass was highest in the control treatments (Table 2.9 and 2.10), which had lower biomass production than the other treatments. These data suggest that N concentration correlated negatively with aboveground biomass production. A dilution effect of plant biomass on nutrient concentrations was responsible for the lower N concentrations in plants with higher biomass production. Whilst, the higher N concentrations in the control treatments could be the result of continuing accumulation of nutrients in plants under stress. A similar response on nutrient concentrations in plant tissues and dry matter yield has also been recorded in other investigations (Mortvedt et al., 1981; Ernst and Stivers, 1982; Prochnow et al., 2001).

The trends in the aboveground biomass total N uptake were in accordance with those observed for N mineralization. In the Magusheni soil, the lime x chicken manure interaction (Table 2.6) for total N uptake was significant. The effects of lime and chicken manure rates on total N uptake are presented in Table 2.9. Among the 0 Mg ha⁻¹ chicken

manure rates, total N uptake was significantly higher in the limed than in the unlimed treatments. However, for the 5 and 10 Mg ha⁻¹ chicken manure rates, total N uptake was not significantly different between unlimed and limed treatments. Additionally, there were steady increases in total N uptake from 0 to 5 Mg ha⁻¹ chicken manure, in both unlimed and limed treatments. But a relatively smaller further increase in total N uptake was seen from 5 to 10 Mg ha⁻¹ chicken manure rates. Results show that total N uptake between 5 and 10 Mg ha⁻¹ chicken manure rates was not significantly different in unlimed treatments, however in limed treatments, the observed differences were statistically significant (Tables 2.9).

In the Nikwe soil, analysis of variance indicated that the lime x chicken manure interaction effects and main effects of lime (Table 2.6) on total N uptake were not significant. The results suggest that, among all chicken manure rates lime had no noticeable effect on total N uptake. However, the main effects of chicken manure were significant and the results indicate that total N uptake increased as chicken manure application rate increased (Tables 2.10). The pattern of total N uptake followed the order of 10 Mg > 5 Mg > 0 Mg ha⁻¹ chicken manure.

Furthermore, in accordance with earlier observations made on plant height, aboveground biomass and N mineralization, results show that the amount of total N uptake varied between the Magusheni and Nikwe soils. In all treatments, total N uptake was higher in the Nikwe soil than in the Magusheni soil, indicating better N availability in the former soil.

Soil chemical properties

Tables 2.11 and 2.12 presents some chemical characteristics of the soils at the beginning and at the end of the 6 weeks greenhouse pot trial. In the Magusheni soil, changes in soil chemistry were noted between unlimed and limed treatments. Soil pH (KCl) values in unlimed treatments were strongly acidic ranging from 3.80 to 3.90 (with a mean value of 3.85). In limed treatments, soil pH (KCl) ranged from 4.21 to 4.30 (with a mean value of 4.27). The percentage acid saturation in unlimed treatments varied from 35 to 47% (with a mean value of 41%) and exchangeable Al was between 1.63 to 2.37 cmol_c kg⁻¹ (with a

mean value of $1.96 \text{ cmol}_c \text{ kg}^{-1}$). In limed treatments, percentage acid saturation varied from 10 to 17% (with a mean value of 13%) and exchangeable Al ranged from 0.50 to $0.51 \text{ cmol}_c \text{ kg}^{-1}$ (with a mean value of $0.51 \text{ cmol}_c \text{ kg}^{-1}$). The percentage base saturation in unlimed treatments varied from 53 to 65% (with a mean value of 59.3%), whilst in limed treatments, it ranged from 83 to 88% (with a mean value of 86.6%). The percentage Ca^{2+} saturation in unlimed treatments varied from 25 to 32% (with a mean value of 29%), whilst in limed treatments, it ranged from 52 to 57% (with a mean value of 54%). The results indicate that liming reduced soil acidity and increased the soil base status in the Magusheni soil. For instance, in limed treatments the percent soil acid saturation, had drop below the 20% threshold for all limed treatments. Meanwhile, in unlimed treatments the percent soil acid saturation averaged about 41%. Since, the percent soil acid saturation was about 25% at the beginning of the present study, these data suggest that soil acidity increased with time in the unlimed treatments. This probably related to the release of Al from organo-Al complexes during rapid organic matter decomposition. Further support for this inference comes from Buhman et al. (2006), who studied soil acidity related parameters including extractable and soil organic matter bound Al (SOM-bound Al) in the highly-weathered soils of the Lusikisiki area of the Eastern Cape Province and found that soil organic matter was an important source of Al on decomposition and controlled Al mobility/toxicity. In the present study, the differing soil chemical properties between no-lime and limed chicken manure amended treatments were expected to be reflected in plant growth, total N uptake, biomass yield and N mineralization responses but for most indicators lime had no effect. Based on the soil analysis results presented here, there is little doubt that the lower plant growth, total N uptake biomass yield and N mineralization rates observed in unlimed treatments were caused by soil acidification. However, some other factor than soil acid saturation must have contributed to the lower responses observed in limed Magusheni soil compared to those observed in the Nikwe soil. The most likely factors include microbial immobilization of N, denitrification, volatilization of ammonia and leaching of N. Giddens and Rao (1975) in studies with incorporated and surface applied poultry manure, found that losses of inorganic N by means of volatilization ammonia (NH_3) were unlikely with incorporated manure. As the manure was incorporated, the soil was not watered in

excess of pot capacity (therefore leaching did not occur) and gas exchange was not restricted in this experiment, it seems most likely that immobilization of N was the primary source for the decrease in the N mineralization when lime was applied in conjunction with chicken manure. The soil analysis results show that in the limed treatments the soil acid saturation percentage and exchangeable acidity decreased whereas the soil pH and soil base status increased. The improvement soil environmental conditions coupled with the presence of readily oxidizable carbon from chicken manure could contribute to an increase in soil microbial population. Then, a decrease in readily available N in the soil solution may result as N is used by soil microorganisms during decomposition. Therefore, biological immobilization of N due to an increase in the number and activity of heterotrophic organisms may have also contributed to the reduced total N uptake, vigour and aboveground biomass production in the limed treatments because it temporarily renders nitrogen and other nutrients unavailable for plants. According to Havlin et al. (1999) soil microorganisms compete very effectively with plants for inorganic N ($\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$) during immobilization, and plants can readily become N deficient.

In the Nikwe soil, soil pH (KCl) values ranged from 4.38 to 4.39 (with a mean value of 4.39) and from 4.25 to 4.41 (with a mean value of 4.31) in unlimed soil and limed soil, respectively. The percentage acid saturation in unlimed soil varied from 3.08 to 4.27% (with a mean value of 3.49%) and exchangeable Al was between 0.18 to 0.19 $\text{cmol}_c \text{kg}^{-1}$ (with a mean value of 0.18 $\text{cmol}_c \text{kg}^{-1}$). In limed soil, percentage acid saturation varied from 3.65 to 8.13% (with a mean value of 6.39%) and exchangeable Al ranged from 0.24 to 0.45 $\text{cmol}_c \text{kg}^{-1}$ (with a mean value of 0.37 $\text{cmol}_c \text{kg}^{-1}$). The percentage base saturation in unlimed treatments varied from 96 to 97% (with a mean value of 96.5%), whilst in limed treatments, it ranged from 92 to 96% (with a mean value of 94.0 %). The percentage Ca^{2+} saturation in unlimed treatments varied from 49 to 52% (with a mean value of 50.6%), whilst in limed treatments, it ranged from 51 to 54% (with a mean value of 52.8%). The similarities between the soil pH, base saturation and other soil chemical properties in unlimed and limed treatments indicates that, liming had little or no effect on the measured soil chemical properties of the Nikwe soil. This may explain why in the

present study lime had no noticeable influence on N mineralization, total N uptake, and the aboveground biomass production in the Nikwe soil. The apparent lack of a liming effect on plant growth and yield in the Nikwe soil, has been reported in previous studies. For example, results from South African field research studies (Fyfield et al., 2000) where the soils used in the present study were collected showed that liming and fertilization resulted in small differences in maize grain yields during the first growing season with no significant treatment effects. Grain yields were 2680, 4100 Mg ha⁻¹ for zero manure (unlimed) and 5 Mg ha⁻¹ manure only, 3610, 3510 Mg ha⁻¹ for 250 kg ha⁻¹ fertilizer only and 250 kg ha⁻¹ fertilizer + 1.50 Mg ha⁻¹ lime, 4130, 4190 Mg ha⁻¹ for 677 kg ha⁻¹ recommended fertilizer only and 677 kg ha⁻¹ recommended fertilizer + 1.50 Mg ha⁻¹ lime, respectively (Fyfield et al., 2000). The average grain yield responses among treatments followed a similar trend even in succeeding years. In the present study, the lack of a noticeable effect of liming on N mineralization, total N uptake, and the aboveground biomass production in the Nikwe soil may be linked to the high base saturation (95.6 %) and even more importantly to the % Ca²⁺ saturation (47 %) (Table 3.1). According to Havlin et al. (1999) a Ca²⁺ saturation of approximately 25 % appears to be adequate for supplying the Ca requirements of most plants. Furthermore, these authors also noted that a high Ca²⁺ saturation indicates a favourable pH for plant growth and microbial activity and usually mean low concentrations of exchangeable Al in acidic soils. In the Nikwe soil, the % Ca²⁺ saturation was nearly twice as much as the 25% saturation level and the soil base status was high, which strongly suggest that the initial soil chemical environment was favourable for microbial activity and plant growth. Under these circumstances, liming broiler chicken manure treated soil is not expected to be of benefit to N mineralization and maize growth in the Nikwe soil.

CONCLUSIONS

The results from this investigation showed that the Magusheni soil, which had higher initial soil acid saturation (>20%), had lower N mineralization, total N uptake, plant height, and aboveground biomass production rates than the Nikwe soil which had lower initial soil acid saturation (<5%).

In the Magusheni soil, N mineralization, total N uptake, and aboveground biomass production among the 5 and 10 Mg ha⁻¹ chicken manure rates was similar between limed and unlimed treatments, even though the soil data indicates that on average the soil acid saturation levels were more than 3 times higher in the unlimed compared to the limed treatments. Based on soil analysis results, there is little doubt that the lower responses in N mineralization, total N uptake, and aboveground biomass production observed in unlimed treatments were caused by soil acidity. However, in the limed treatments microbial N immobilization rather than soil acidity seems responsible for low responses in N mineralization, total N uptake, and aboveground biomass production. It is concluded from the results, that for the optimum growth of maize liming essential in the Magusheni soil. However, when both lime and chicken manure are applied to the Magusheni soil, a temporary immobilization of N may take place and this N immobilization can potentially reduced N mineralization, total N uptake and delay maize growth and development. It is hypothesized that the long-term effect of lime under field conditions would be a net increase in N availability and improved crop growth.

In the Nikwe soil, N mineralization, total N uptake, biomass yield responses increased as chicken manure increased, however, lime had no apparent effect on N mineralization, total N uptake, and the aboveground biomass production. The similarities between the soil pH, base saturation and other soil chemical properties in unlimed and limed treatments also indicated that, liming lime had no apparent effect on the measured soil chemical properties of the Nikwe soil. It is concluded from the results that for the Nikwe soil, as long as the soil base status remains high and acid saturation levels low, there would be little or no benefit to N mineralization, total N uptake, maize growth and

development due to lime application. However, chicken manure incorporation by itself is expected to improve the available nutrient content of the soil, maize growth and development due to rapid initial mineralization in this soil. Chicken manure should be taken into account in fertilizer recommendations because of its ability to supply N and other plant nutrients.

The findings in the present study are in agreement with the data in the soil laboratory incubation experiment in chapter 1, where liming has no apparent effect on microbial activity and N mineralization in the chicken manure amended Nikwe soil, whereas liming stimulated microbial activity and induced a temporary immobilization of N in the chicken manure amended Magusheni soil.

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Table 2.1. Selected chemical and physical properties of the Magusheni and Nikwe soils used in this study.

Soil Property	Magusheni soil	Nikwe soil
Total C (%)	4.6	3.4
Total N (%)	0.3	0.2
NH ₄ -N (mg kg ⁻¹)	21.5	5.9
NO ₃ -N (mg kg ⁻¹)	4.7	5.9
ECEC (cmol _c kg ⁻¹)	5.70	8.75
Ca saturation (%)	30.1	46.6
Mg saturation (%)	41.4	34.0
K saturation (%)	3.9	15.0
Base saturation (%)	75.3	95.7
Acid saturation (%)	24.7	4.3
Exch. Al (cmol _c kg ⁻¹)	1.27	0.20
Exch. Al+H (cmol _c kg ⁻¹)	1.40	0.38
Soil pH (KCl)	4.78	5.06
Sand (%)	27	30
Silt (%)	28	26
Clay (%)	45	44
Moisture @ Field Capacity (g g ⁻¹ soil)	0.47	0.39

Table 2.2. Selected properties of the broiler chicken manure (Gromor¹) used in this study.

pH (KCl)	Total N (g kg ⁻¹)	Total C (g kg ⁻¹)	C:N ratio	NH ₄ -N (g kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	Moisture (g g ⁻¹)
6.68	36.9	405	1:11	7.9	n.d.	0.07

¹ Mention of trade names does not constitute endorsement of this product by Colorado State University or by the agricultural Research Council-Institute for Soil, Climate and Water.

n.d. (not detected)

Table 2.3. Characteristics of the calcitic lime (CaCO₃) used in this study.

Trade name	CCE	-----% on Mesh size-----		
	(%)	8	60	<60
Kulu-CAG ¹	100	0	0	100

¹ Mention of trade names does not constitute endorsement of this product by Colorado State University or by the agricultural Research Council-Institute for Soil, Climate and Water.

Table 2.4. Calcitic lime and broiler chicken manure rates used in this study.

Treatments	Magusheni / Nikwe soil (Mg/ha)
Lime rates	0, 1
Manure rates	0, 5, 10

Table 2.5. Analysis of variance (ANOVA) table showing sources of variance.

Source	Degrees of Freedom
Lime	1 (2-1)
Manure	2 (3-1)
Lime x Manure	2 (2-1) x (3-1)
Error	By Subtraction=18
Total	23 ((2x3x4)-1)

Table 2.6: Significance of the calcitic lime and broiler chicken manure effects and their interaction for plant height, aboveground biomass production, N concentration, N uptake and N mineralization (Magusheni and Nikwe soil).

Plant parameter	Magusheni soil		
	Lime	Manure	Lime x Manure
Plant height	0.0020	< 0.0001	< 0.0001
Aboveground biomass	0.0202	< 0.0001	0.0001
N Concentration	< 0.0001	< 0.0001	< 0.0001
N uptake	0.0128	< 0.0001	0.0026
N mineralization	0.0330	< 0.0001	0.0040
Plant parameter	Nikwe soil		
	Lime	Manure	Lime x Manure
Plant height	< 0.0001	< 0.0001	0.0038
Aboveground biomass	0.0003	< 0.0001	< 0.0001
N Concentration	< 0.0001	< 0.0001	< 0.0001
N uptake	0.4277	< 0.0001	0.3858
N mineralization	0.4722	< 0.0001	0.3179

Table 2.7. Effects of factorial combinations of lime and broiler chicken manure treatments on maize plant height and aboveground biomass production under greenhouse conditions (Magusheni and Nikwe soils).

Magusheni soil	Lime rate (Mg/ha)			
	No Lime	Lime	No Lime	Lime
Manure rate (Mg/ha)	Plant height (cm)		Aboveground biomass (g/pot)	
0	35.0	57.3	4.6	14.7
5	67.7	67.0	21.6	19.0
10	69.8	63.2	22.4	22.3
LSD _{0.05}	5.1	5.1	3.6	3.6

Nikwe soil	Lime rate (Mg/ha)			
	No Lime	Lime	No Lime	Lime
Manure rate (Mg/ha)	Plant height (cm)		Aboveground biomass (g/pot)	
0	55.9	82.4	14.8	27.9
5	97.8	100.8	40.6	41.7
10	105.8	118.2	50.7	49.7
LSD _{0.05}	9.0	9.0	3.6	3.6

Table 2.8. Effects of factorial combinations of lime and broiler chicken manure treatments on N mineralization under greenhouse conditions (Magusheni and Nikwe soils).

Manure rate (Mg/ha)	Magusheni soil		Nikwe soil	
	Lime rate (Mg/ha)			
	No Lime	Lime	No Lime	Lime
	N mineralization		N mineralization	
	------(mg/pot)-----		------(mg/pot)-----	
0	161	362	396	457
5	545	506	663	640
10	585	605	911	922
LSD _{0.05}	95.35	95.35	80.52	80.52

Table 2.9. Effects of factorial combinations of lime and broiler chicken manure treatments on N concentration and uptake by the aboveground biomass under greenhouse conditions (Magusheni soil).

Manure rate (Mg/ha)	Lime rate (Mg/ha)			
	No Lime		Lime	
	N Concentration ------(%)-----		N uptake ------(mg/pot)-----	
0	4.29	2.88	195.1	421.2
5	2.89	3.10	623.4	589.4
10	3.06	3.21	680.9	711.9
LSD _{0.05}			97.90	97.90

Table 2.10. Effects of factorial combinations of lime and broiler chicken manure treatments on N concentration and uptake by the aboveground biomass under greenhouse conditions (Nikwe soil).

Manure rate (Mgha ⁻¹)	Lime rate (Mg/ha)			
	No Lime		Lime	
	N Concentration ------(%)-----		N uptake ------(mg/pot)-----	
0	2.83	1.73	417.6	481.1
5	1.73	1.64	700.1	684.8
10	1.91	1.97	967.3	975.7
LSD _{0.05}			84.76	84.76

Table 2.11. Effects of lime and broiler chicken manure rate on soil chemical properties as measured at the end of a 6 week greenhouse experiment (Magusheni soil), together with initial soil properties.

Soil Parameters	Initial soil properties	Lime rate (Mg/ha)					
		No Lime			Lime		
		Manure rate (Mg/ha)					
		0	5	10	0	5	10
pH (KCl)	4.78	3.90	3.90	3.80	4.21	4.29	4.30
Acid Saturation (%)	24.7	47.2	40.1	34.9	17.4	10.8	11.9
Base Saturation (%)	75.3	52.8	59.9	65.1	82.6	89.2	88.1
Ca Saturation (%)	30.1	25.8	28.7	32.4	57.0	52.0	52.1
Exch. Acid (cmol _c /kg)	1.40	2.47	2.00	1.71	0.72	0.72	0.79
Exch. Al (cmol _c /kg)	1.27	2.37	1.88	1.63	0.51	0.51	0.50

Table 2.12. Effects of lime and broiler chicken manure rate on soil chemical properties as measured at the end of a 6 week greenhouse experiment (Nikwe soil), together with initial soil properties.

Soil Parameters	Initial soil properties	Lime rate (Mg/ha)					
		No Lime			Lime		
		Manure rate (Mg/ha)					
		0	5	10	0	5	10
pH (KCl)	5.06	4.39	4.39	4.38	4.41	4.28	4.25
Acid Saturation (%)	4.3	4.3	3.1	3.1	3.6	7.4	8.1
Base Saturation (%)	95.7	95.7	96.9	96.9	96.4	92.6	91.9
Ca Saturation (%)	46.6	49.1	50.9	51.7	51.5	53.6	53.4
Exch. Acid (cmol _c /kg)	0.39	0.28	0.28	0.33	0.64	0.71	0.39
Exch. Al (cmol _c /kg)	0.19	0.18	0.18	0.24	0.43	0.45	0.19

CHAPTER 3

MAIZE GROWTH, N UPTAKE AND N RECOVERY AS AFFECTED BY UREA AND CHICKEN MANURE INTERACTIONS AND PREVIOUS LIME TREATMENTS

ABSTRACT

Alterations in soil environmental conditions (e.g. pH, bioavailable Al, base cation supply) associated with use of agricultural lime are particularly important for both crop growth and soil microorganisms. The residual effects of liming and interactions between (organic and inorganic N inputs) urea-N fertilizer and broiler chicken manure on maize growth, N uptake, and N recovery were evaluated under greenhouse conditions, using soil samples from lime experiments that were established in 1999 and 2000. The complete factorial set of treatments included two lime rates (no lime and with lime) and six fertilizer N rates (0, 0.2-F, 0.6-M, 0.6-F+M, 1.2-M, and 1.2-F+M g N pot⁻¹) in all possible combinations. The results showed that the effect of lime x N fertilizer interaction on maize plant height, biomass production, total N uptake and N concentration varied between the Magusheni and Nikwe soils. In the Magusheni soil, the lime x N fertilizer interaction was positive in that lime enhanced plant growth responses to N application. When averaged across all N rates, the aboveground and belowground biomass production in unlimed soil averaged about 23.4 and 7.56 g dry matter pot⁻¹ whereas in the limed soil the corresponding values were 65.5 and 18.2 g dry matter pot⁻¹, respectively. The aboveground biomass N uptake in unlimed soil averaged about 0.480 g N pot⁻¹, whereas in the limed soil N uptake averaged about 0.791 g N pot⁻¹. The belowground biomass N uptake in unlimed soil averaged about 0.180 g N pot⁻¹ whereas in the limed soil N uptake averaged about 0.326 g N pot⁻¹. Based on soil analysis results, responses in plant height, aboveground biomass production, and total N uptake to N application were

lower in the unlimed than in limed soil due to the higher levels of soil acidity in the former soil. In the unlimed soil, the percent soil acid saturation was 47%, which is more than double the critical 20% permissible acid saturation level for a maize crop. The percent base saturation and Ca^{2+} saturation were also much lower than in limed soil. In the limed soil, the percent base saturation, Ca^{2+} saturation, and soil acid saturation were 91%, 50%, and 9.3%, respectively. These greatly improved soil conditions may have contributed to the positive plant responses to N application in the limed soil. Therefore, soil acidification must be corrected in order to optimize maize response to applied N fertilizer in the Magusheni soil. In the Nikwe soil, the plant height, aboveground belowground biomass production and total N uptake was either similar or lower in unlimed than in the limed soils. When averaged across all N rates, the aboveground biomass and belowground biomass production in unlimed soil averaged about 39.1 and 12.9 g dry matter pot^{-1} whereas in the limed soil the corresponding values were 35.0 and 11.6 g dry matter pot^{-1} , respectively. The aboveground biomass N uptake in unlimed soil averaged about 0.687 g N pot^{-1} , whereas in the limed soil N uptake averaged about 0.709 g N pot^{-1} . The belowground biomass N uptake in unlimed soil averaged about 0.303 g N pot^{-1} whereas in the limed soil N uptake averaged about 0.189 g N pot^{-1} . Soil analysis results, indicated that chemical characteristics of the unlimed and limed soils were similar. In both the unlimed and the limed soils, the percent base saturation, Ca^{2+} saturation, and soil acid saturation were 95%, 50%, and 5.0%, respectively. Therefore, lime had little or no effect on soil chemical properties in the Nikwe soil. The results presented, suggest that as long as the soil base status remains high and acid saturation levels low, there would be little or no benefit to total N uptake, maize growth and development due to lime application in the Nikwe soil. However, the fact that large responses to applied N were obtained in this soil confirms that N was the limiting nutrient in the control treatments. The results showed that the net effects of the combined use of chicken manure plus urea and chicken manure alone on plant growth responses varied between the two soils and at times lacked consistency. Therefore more research especially field studies are needed to elucidate these effects.

INTRODUCTION

Plant growth on acidic soils is limited by ion toxicity (H, Al, or Mn), nutrient deficiency (Ca, Mg, K, P, N, or Mo), reduced nutrient cycling from soil organic matter and decreased growth/water/nutrient uptake by plant roots (Mohebbi and Mahler, 1988; Marschner, 1991; Edmeades et al., 1995). Liming removes one or more of these limiting factors and increases crop growth on acid soils (Edmeades et al., 1981; Haynes, 1984; Arshad and Gill, 1996). However, it has been noted that liming may also cause negative effects in plant growth and soil properties.

Phosphorus and Mn deficiencies can be induced by lime applications (Foy, 1974; Kamprath, 1970; Munns, 1965). Farina et al. (1980) also noted a reduction in uptake of P, Zn, B, and Mn by corn (*Zea mays* L.) plants as liming raised soil pH to neutral values. Liming has been found to decrease Mg content of plants (Pavan et al., 1984), and some acid soils in the tropics appear not to respond to liming (Zakaria et al., 1978). Kemper and Sorensen (1974) in a greenhouse study investigated the comparative effects of N and S fertilization and liming on three crops (corn, soybeans, and bromegrass) on four Nebraska soils, which were selected to represent a wide range of properties. These four soils, which ranged in soil pH from 5.3 to 7.3 and in organic matter content from 0.3 to 3.9%, received 7 rates of CaCO₃ lime ranging from 0 to 6 Mg ha⁻¹. The authors noted that CaCO₃ applications had a minimal impact on crop growth.

Extensive areas of the humid regions of eastern Pondoland (Eastern Cape, study area) are covered by Ultisols and Oxisols. Two common characteristics of these soils are their relatively high organic matter content and an acidic soil pH. In spite of these common properties, marked differences in several other soil properties have been observed. For example, Fyfield et al. (2000 and 2002) studied the chemical properties of soils from two locations in Bizana. He found that the Magusheni soil has a pH(KCl) value of 4.38, exchangeable Ca, Mg, and K were 99, 140 and 51 mg kg⁻¹ respectively, exchangeable acidity (Al + H) of 1.68 cmol_c kg⁻¹ plus 47% acid saturation. The Nikwe soil has a pH(KCl) value of 4.56, exchangeable Ca, Mg, and K were 676, 293 and 239 mg kg⁻¹ respectively, exchangeable acidity (Al + H) of 1.15

cmol_c kg⁻¹ plus 16% acid saturation. The Magusheni soil has a high level of acidity and a relatively low base saturation, while the Nikwe soil has lower levels of acidity and is high in base saturation. Previous studies on liming of acid soils in the two localities of Bizana showed that liming improved crop yields at Magusheni, whereas no beneficial effects of lime were observed at Nikwe (Fyfield et al., 2000 and 2002). However, none of these studies combined organic and inorganic nutrient inputs, which is practiced extensively by small scale farmers in the region and similar farming systems of SubSaharan Africa (SSA). Additionally, while livestock manure has been studied for its use as a fertilizer for crops in the Eastern Cape (Mkile, 2001; Yoganathan et al., 1998), much fewer studies have evaluated poultry manure.

Integrated nutrient management or the combined application of organic and inorganic fertilizers is currently a major area of interest in SSA. Research from SSA and other parts of the world has shown that combinations organic nutrient inputs (crop residues, agroforestry litter, animal wastes and compost) with modest levels of inorganic fertilizers can maintain or even increase yields (Goyal et al., 1992; Rees et al., 1993; Singh and Singh 1994; Gachengo 1996; VanLauwe 2001a). The literature on integrated nutrient management can be separated into two broad groups. The first group of studies have made comparisons between yields from a given amount of inorganic fertilizer (F), an organic material (M), and their combination (F+M) whereby the latter treatment (F+M) has received more total nutrients than in F or M alone. For example in Zimbabwe, Nyamangara et al. (2005) studied the effectiveness of aerobically composted solid cattle manure, mineral N fertilizer (as ammonium nitrate), and their combined application on maize in terms of N uptake and grain yield. Combined applications of cattle manure with mineral N (12.5 Mg cattle manure + 60 kg N, 12.5 Mg cattle manure + 120 kg N, 37.5 Mg cattle manure + 60 kg N, 37.5 Mg cattle manure + 120 kg N) increased total N uptake and grain yield compared to sole manure or chemical fertilizer treatments (12.5 Mg cattle manure only, 37.5 Mg cattle manure only, 60 kg N ha⁻¹ only, 120 kg N ha⁻¹ only) in both the first and third seasons. The greatest percentage increase in total N uptake and maize grain yield was recorded when manure (12.5 Mg ha⁻¹ and 37.5 Mg ha⁻¹) was

combined with 60 kg N ha⁻¹ mineral N, and a relatively smaller further increase was recorded when mineral N was doubled to 120 kg N ha⁻¹. The increase in N uptake with increasing mineral N fertilizer rate indicated that the mineral N was readily absorbed by the maize crop (Nyamangara et al., 2005). The poor N recovery from manure only treatments compared to N fertilizer implied that aerobically composted cattle manure was not adequate to supply the N requirement for maize production in the short term because of the low rate of N mineralization. The improvement in N uptake and grain yield in combined manure/mineral N fertilizer treatments was attributed to nutrients supplemented by the manure (e.g. Ca and Mg) and increased N recovery from mineral N fertilizer (Nyamangara et al., 2005).

Rees et al. (1993) examined the efficiency of N uptake by spring barley from field plots amended with poultry manure (at rates 0 and 10 Mg ha⁻¹), ammonium nitrate (0, 30, 60 and 120 kg NH₄NO₃ ha⁻¹), and combinations of poultry manure and ammonium nitrate. The field experiment was performed on a clay loam soil with a soil pH of 6.5. They found significant responses in dry matter production and N uptake to added mineral N, both in the manured and unmanured plots. However, the N uptake in plots receiving poultry manure (10 Mg ha⁻¹) was consistently higher than that from unmanured plots at comparable rates of inorganic N application (0, 30, 60, and 120 kg N ha⁻¹). For example, in manured plots, the uptake of N was 11 kg ha⁻¹ greater than in unmanured plots where no inorganic N was applied and 23 kg ha⁻¹ greater where inorganic N was applied at the highest rate (120 kg ha⁻¹). Additionally, in the pot experiment Rees et al. (1993) found that N uptake and yield of barley showed little response to applications of poultry manure only or manure in combination with 24 and 48 mg N pot⁻¹. However, where poultry manure was applied in combination with the top rate of inorganic N (96 mg N pot⁻¹), uptake and yield were significantly increased. One of the main limitations of studies investigating the interaction of organic and inorganic nutrients is that, in many cases the combination of manure and inorganic fertilizer (F+M) does better (produces higher yields) because more total nutrients had been added than when the inorganic and organic nutrient inputs were applied separately (Palm et al., 1997).

In the second group of studies, researchers made comparisons between treatments in which the total amount of nutrients added was the same, but the proportion of organic-to-inorganic fertilizers varied. For example, Singh and Singh (1994) studied N and P availability and mineralization from reduced tillage cultivation in a dryland farming system. The treatments were (a) control, (b) chemical fertilizer (NPK: 80 kg N ha⁻¹, 40 kg P ha⁻¹, 30 kg K ha⁻¹; for N urea, for P single super phosphate, for K muriate of potash were used), (c) wheat straw (2 kg m⁻²) with the amount of N equivalent to that under treatment (b), (d) wheat straw + fertilizer [wheat straw 1 kg m⁻² + chemical fertilizer 50% of (b)]. They found that wheat straw + fertilizer application substantially increased available nutrient pools as well as the rate of N mineralization. Similarly, Gachengo (1996) reported that the application of a high quality organic material, tithonia leaves, combined with inorganic P in a pot experiment resulted in greater maize biomass and P uptake than from equal amounts of nutrients added from inorganic fertilizers. The dry matter yields were 1.09, 6.04, 4.58, 10.30, and 6.23 g pot⁻¹ for control, tithonia leaves, N-P-K fertilizer, tithonia leaves + inorganic P, N-P-K fertilizer + P, respectively. In on-station field experiments at four locations in West Africa (Ivory Coast, Togo, Benin, Nigeria), VanLauwe et al. (2001b) investigated the impact of sole and combined applications of organic matter and urea on maize grain yield. They observed substantial added benefits (positive interactions) at two out of the four sites, one site showed no interaction, and at the fourth site there was no N response at all. In the two N-responsive sites, the maize in the mixed treatments, receiving 45 kg urea-N ha⁻¹ mixed with 45 kg N ha⁻¹ as organic inputs, produced similar amounts of grain (1557 kg ha⁻¹ in Benin and 3673 kg ha⁻¹ in Ivory Coast) as the treatment receiving 90 kg urea-N ha⁻¹ (1507 kg ha⁻¹ in Benin and 4085 kg ha⁻¹ in Ivory Coast). However, in the third site (Nigeria), maize yields in the mixed treatments were significantly lower (1773 kg ha⁻¹) than in the treatment receiving the 90 kg ha⁻¹ as urea (3391 kg ha⁻¹). The added benefits in Benin and Ivory Coast were shown to be mainly caused during the grain filling period, which was characterized by a severe lack of rainfall. VanLauwe et al. (2001b) concluded that although no unequivocal evidence could be provided, the most likely cause for the positive interaction was improved soil water

availability in the mixed treatments compared with the treatments which received the same quantity of N as urea, leading to a more efficient utilization of the applied N. The authors contended that the subsurface placed residues might have improved soil moisture conditions by interrupting the capillary conductivity between the soil above and the residues, thus reducing evaporative losses. Brady and Weil (1999) noted that while the mechanism responsible for the yield increases are not yet established, there appear to be synergistic effects of organic and inorganic inputs such as those concerned with the supply of water, activities of soil organisms, and rhizodeposition.

The question of whether combining organic and inorganic nutrient inputs produces higher yields than when the same inputs are supplied separately is of importance in the Eastern Cape Province. Farmers in the rural areas of the Eastern Cape (and similar farming systems of SSA) are combining organic manures with modest levels of inorganic sources of nutrients to meet crop demands. However, research studies on the combined application of organic and inorganic nutrient inputs in the Eastern Cape are rare. There is increasing concern that crop yields have fallen far below their potential (Mkile, 2001). The probable causes for the decline in average crop yields per unit of land include inadequate amounts of nutrient added, the low quality of the organic materials, and inappropriate or inefficient combinations and loss of soil fertility (Palm et al., 1997). Further work is required to elucidate the nutrient management aspects of combining organic and inorganic inputs in order to maximize the N supply from both inputs.

Nitrogen supply to cereal crops is one of the major constraints to agricultural productivity in the Eastern Cape and elsewhere in Africa (Ssali et al., 1986; Woomeer and Muchena, 1996; Sanchez et al., 1997). Not all N applied to the soil is immediately available. Even if the fertilizer is in mineral form, its availability might be delayed by various soil processes. Organic matter (composts, manures etc.) needs mineralization and urea needs hydrolysis. Once the N comes in the soil solution, a number of dynamic equilibrium reactions occur. Processes such as sorption and desorption, precipitation and dissolution, immobilization and mineralization and

transformation into gaseous forms or translocation out of the rooting zone are in competition with plant uptake (Van Cleemput and Boeckx, 2000). Studies on the recovery of applied fertilizer N by crops are scarce in the Eastern Cape. Various international studies conducted with ^{15}N -labelled inorganic fertilizers have shown that the amount of N recovered in arable crops is between 30% and 80% of that originally applied (Smith et al., 1988; Powlson, 1988; Recous et al., 1988). Comparable studies using ^{15}N -labelled as well as other unlabelled organic inputs suggest that N recovery is lower than that from inorganic fertilizers. In a pot trial, Kirchamnn (1989) found that the recovery of ^{15}N -labelled poultry manure by barley over 3 years was less than 30% of that originally applied. Muller and Sundman (1988) examined the release of N from decomposing ^{15}N -labelled legumes and grass. They found that between 6% and 25% of the input was recovered in a subsequent barley crop. In field studies Myers and Paul (1971) studied N release from ^{15}N -labelled oat straw and found that only 11.2% of the added N was taken up in two successive crops. Similar N recovery (by the first crop) from applied organic inputs has been noted in other studies (Giller and Cadisch, 1995; Mafongoya and Nair, 1997; Palm et al., 2001; Gioacchini et al., 2006). Dalal (1986) in a field experiment observed that the apparent N recovery by corn was considerably lower when the field was limed than without liming. They found that apparent N recoveries from lime treatments were 42%, 22%, and 13% as compared to 68%, 41% and 25% from unlimed treatments from surface applied urea at the rate of 50, 100, and 200 kg N per ha, respectively. In summary, these experiments suggest that the recovery of applied fertilizer N and organic residue-N by crops varies considerably and is often low. Improving the efficiency of fertilizer use is therefore an important challenge for modern agriculture (Gioacchini et al., 2006). To guide research on how the efficiency from combined use of N sources can be maximized in the Eastern Cape, more information is needed on the recovery of N from sole and mixed applications of organic and mineral nutrient sources. The investigation described herein was designed to evaluate the residual effects of liming and interactions between urea-N fertilizer and broiler chicken manure by measuring maize growth, N uptake, and N recovery, using soil samples from lime experiments that were established in 1999 and 2000. This study also tested the hypothesis that an

acidic soil reaction renders nutrients from the soil and added amendments, such as manures or inorganic fertilizers, less available to crops.

MATERIALS AND METHODS

Field plot history

Lime, chicken manure and fertilizer experiments under continuous maize (*Zea mays*) were initiated in 1999 (Magusheni site) and 2000 (Nikwe site) as part of Bizana LandCare project. The Bizana LandCare project was conducted by the Agricultural Research Council – Institute for Soil, Climate and Water, together with Keypoint Rural Development Support Services, in collaboration with the Eastern Cape Department of Agriculture and Land Affairs (Fyfield et al., 2000). The Magusheni site was initially virgin grassland while the Nikwe site had previously been cropped (>10 years). At both sites, the trials were designed to demonstrate the benefits of applying recommended quantities of inorganic fertilizer and/or agricultural lime on maize production, or of applying chicken manure as an alternative organic fertilizer and/or liming agent. At the Magusheni site, the experimental treatments comprised three levels of lime application (0, 5 and 10 Mg calcitic limestone ha⁻¹), with (409 kg ha⁻¹ monoammonium phosphate plus 268 kg ha⁻¹ limestone ammonium nitrate) and without fertilizer, as well as additional plots supplied with chicken manure (0, 5 and 10 Mg broiler chicken manure ha⁻¹). At the Nikwe site, the experimental treatments comprised two levels of lime application (0 and 1.5 Mg calcitic limestone ha⁻¹), with recommended (545 kg ha⁻¹ monoammonium phosphate plus 300 kg ha⁻¹ potassium chloride plus 214 kg ha⁻¹ limestone ammonium nitrate) and fertilizer application rate based on farmer practice (250 kg ha⁻¹ 2N: 3P: 2K (22) compound fertilizer), as well as additional plots supplied with chicken manure (0 and 5 Mg chicken manure ha⁻¹). The lime and recommended fertilizer applications were based on the requirements indicated by the initial soil chemical analysis. The 1.5 or 5 metric tons ha⁻¹ lime rate was determined to be an amount of calcitic lime needed to lower soil acid saturation

to levels below 20%. The recommended fertilizer application rates were based on a target dryland maize grain yield of 7 M ha⁻¹ (Fyfield et al., 2000).

Soils

The four bulk soil samples used in the present study were collected from the top 0 – 15 cm of the two demonstration sites described above. The soils from the two areas have been classified as Humic Hapludults. Two samples were collected from the unlimed or limed maize demonstration plots at the Magusheni site and the other two were taken from unlimed or limed demonstration plots at the Nikwe site. The unlimed samples were taken from plots which had not received fertilizer or chicken manure application (designated M0 plots) while the limed plots had also been amended annually with 250 kg ha⁻¹ 2:3:2 (22) fertilizer since year 2000. After collection, the soil was air-dried and one portion was used to determine soil physical and chemical properties and the remaining soil was sieved to pass a 4-mm screen for use in the greenhouse study. Pertinent properties of the experimental soils are given in Table 3.1. Soil pH values were determined by a combination glass electrode (1:2.5 soil:solution ratio). Organic carbon content was determined by the Walkley-Black procedure (Allison, 1965) and total N was measured by Kjeldahl digestion (Bremner, 1965). The exchangeable Ca, Mg, and K were extracted with 1 M ammonium acetate at pH 7.0 and determined by atomic absorption spectrometry. Exchangeable acidity (Al + H) and Al was extracted by shaking the soil samples with 1 M KCl for 1 h and determined by titration using methyl orange and phenolphthalein indicators (Non-affiliated Soil Analysis Working Group, 1990). Base saturation was calculated as exchangeable Ca + Mg + K (cmol_c kg⁻¹) x 100 / exchangeable Ca + Mg + K + Al + H (cmol_c kg⁻¹) (FSSA, 1989). Acid saturation was calculated as exchangeable Al + H (cmol_c kg⁻¹) x 100 / exchangeable Ca + Mg + K + Al + H (cmol_c kg⁻¹). Effective cation exchange capacity was determined by summation of exchangeable bases (Ca, Mg, and K) and exchangeable acidity (Al + H).

Broiler chicken manure

The chicken manure used in this a study is known as GROMOR and small-scale farmers in the Eastern Cape sometimes apply it to the soil in combination with crushed livestock manure and other mineral fertilizers (Mkile, 2001). The manure was a mixture of chicken droppings and sawdust or wood shavings. Organic waste application rates (animal and green manure and crop residue) should be based on crop yield goals and estimates of N release from the waste during a growing season (King, 1984). In this experiment, we used a manure N model proposed by Bitzer and Sims (1988) in order to estimate the amount of manure N that will be available to plants (Equation 1). In turn, these data were used to determine the rates of chicken manure application, either alone or in combination with urea fertilizer.

$$\text{Predicted Available N (PAN)} = 80\% N_i + 60\% N_o \quad [\text{Equation 1}]$$

$$N_i = \text{inorganic N} = (\text{NH}_4\text{-N} + \text{NO}_3\text{-N})$$

$$N_o = \text{Organic N} = (\text{Total N} - N_i).$$

This equation assumes that 20% of the inorganic N in the manure will be lost between time of sampling and actual incorporation into the soil and that 2 days would be required to transfer, apply, and incorporate the manure. The PAN equation also assumes that 60% of manure organic N (N_o) will be mineralized during 4 to 5 months of the normal growing season for corn. Similarly, Westerman et al., (1987) found that 59 to 66% of the total N applied in three broiler manures was in the inorganic form after 39-week incubation. Chae and Tabatabai (1986) observed that the quantity of N_o eventually released after 26 weeks varied from the equivalent of 13% with cow manure to 67% with chicken manure. Other investigators have suggested greater quantities of organic n will be mineralized. For instance, Van Faasen and Van Dijk (1987), studied manure as a source of nitrogen in soils and found that the rate of manure organic N in poultry manure mineralized during 6 months of incubation ranged from 70 – 100%. Selected chemical characteristics of the broiler chicken manure used in the present study are summarized in Table 3.2. Fertilizer was added

at a rate of 40 kg N ha⁻¹ in the form of urea (CONH₂)₂. This is the recommended amount of N to be applied in order to attain a target dryland maize grain yield of 4 Mg ha⁻¹ (Manson et al., 2000).

Treatments and experimental design

The experiment attempted to evaluate the effect of supplementing manure with fertilizer N in no-lime and limed soils by using chicken manure and urea fertilizer, singly or in combination. Treatments consisted of two lime rates (no-lime and with lime) and six N rates (0, 0.2-F, 0.6-M, 0.6-F+M, 1.2-M, and 1.2-F+M g N pot⁻¹) in all possible factorial combinations (Table 3.3). The N rates were: (a) control, (b) 0.2 g N pot⁻¹ (as urea fertilizer only), (c) 0.6 g N pot⁻¹ (as chicken manure only), (d) 0.6 g N pot⁻¹ (as chicken manure + urea fertilizer), (e) 1.2 g N pot⁻¹ (as chicken manure only) and (f) 1.2 g N pot⁻¹ (as chicken manure + urea fertilizer). As demonstrated in Table 3.3, in the manure plus urea fertilizer treatments (F+M), various proportions of chicken manure and urea fertilizer were applied, such that 17% and 33% of the predicted available N (PAN) was added as urea and the remainder added as chicken manure. Therefore, manure plus urea fertilizer treatments contained similar amounts of PAN as in equivalent treatments amended with chicken manure alone. The treatments were arranged in a completely randomized design with four replications.

Experimental procedure

This research was conducted at the University of Pretoria experimental farm (26° 12' S; 28° 10' E) simultaneously with the pot experiment reported on in chapter 2. About 10 kg (on an oven-dry basis) of air dry and sieved (< 4 mm) soil was placed into plastic pots (27 cm height x 30 cm diameter). To ensure proper aeration, three holes, each 10 mm in diameter, were drilled in the bottom of each pot and covered with nylon screen. In addition to the lime, chicken manure and urea amendments, all pots (excluding control treatments) containing the Magusheni soils received 1.2 g P pot⁻¹ as triple super-phosphate, 3.0 g K pot⁻¹ as potassium chloride, and 0.12 g Zn pot⁻¹ as zinc oxide. The pots containing the Nikwe soils only received 1.2 g P pot⁻¹ as triple

super-phosphate, because soil analysis results indicated that the other elements were available in adequate quantities in soil. Amendments were thoroughly mixed with the soil. The pots were arranged and watered as described in chapter 2. Plant height from the soil surface to the plant tip was measured 1 week prior to harvest.

Plant analysis

At the termination of the experiment, the maize plants were cut off at ground level and the harvested plant materials were thoroughly rinsed with distilled water, placed in a labeled paper bag, dried in a forced draft oven at 60 °C for 48 h and weighed. The dried plant samples were finely ground (<1 mm mesh screen), dry ashed and digested for elemental analysis. After the maize plants were harvested, the soil in the pots was air-dried and the coarse roots were removed. The roots were washed, bagged, dried, weighed and ground as described for plant samples. Total nitrogen content of the above and belowground plant biomass was determined by the Kjeldhal procedure. Plant N uptake was calculated by multiplying plant biomass (dry matter) production by the N concentration.

Calculations

Apparent N recovery of applied available manure or fertilizer N was calculated by comparing N uptake on pots receiving manure or fertilizer with that of the check pots (no manure, no fertilizer) as described in Olson and Swallow, (1984), Paul and Beauchamp (1996), and Kanneganti and Klausner (1994).

$$ANR = (N_{TRT} - N_{CHK}) / (N_{TOT}) \times 100$$

N_{TRT} = N uptake from manure or fertilizer amended pots

N_{CHK} = N uptake from control (check) pots

N_{TOT} = Total available N applied

ANR = apparent N recovery

Statistical analysis

Table 3.4 shows sources of variation and their degrees of freedom. Analysis of variance for the effect of the treatments on all variables (plant parameters) was performed using the general linear models procedure of the statistical analysis software (SAS, 2005). Treatment means were compared using the least significant difference (LSD) at the 5% level of significance (Steel et al., 1997). Orthogonal contrasts were used to perform specific comparisons between N (0.6 and 1.2 g N pot⁻¹) applied as broiler chicken manure only versus broiler chicken manure plus urea treatments on both unlimed and limed soils.

RESULTS AND DISCUSSION

Table 3.5 shows a summary of the results of analysis of variance (ANOVA) for the calcitic lime and N fertilizer effects and their interaction on plant height, aboveground and belowground biomass production, shoot:root ratio, N uptake and N recovery.

Plant height

Analysis of variance for plant height indicated that there was a significant lime x N interaction on both Magusheni and Nikwe soils (Table 3.5). However, the dynamics of lime x N interaction on plant height were different between the two soils. In the Magusheni soil, results show that the lime x N interaction was positive in that lime significantly enhanced plant height response to N compared to unlimed soil (Table 3.6, Fig. 3.1). When averaged across all N rates, maize plant height in unlimed soil averaged about 71.9 cm whereas in the limed soil plant height averaged about 109.3 cm. Additionally, in the Magusheni the largest increase in plant height was obtained by increasing N application from 0 to 0.6 g N pot⁻¹ as chicken manure-N only (M) or chicken manure plus urea-N (F+M) treatments on both unlimed and limed soils. But a relatively smaller further increase in plant height was observed from 0.6 to 1.2 g N pot⁻¹ on both chicken manure-N only (M) or chicken manure plus urea-N (F+M) treatments. For example, in unlimed soil the percentage increase in plant height from

the 0 to 0.6 g N pot⁻¹ rate was 88% and 98% for chicken manure-N only and chicken manure plus urea-N, respectively. The percentage increase in plant height from the 0.6 g N pot⁻¹ to 1.2 g N pot⁻¹ rate was 16% and 23% for chicken manure-N only and chicken manure plus urea-N treatments, respectively.

In the Nikwe soil results show that on most N rates, plant height tended to be lower in limed than unlimed soil. This indicates that the lime x N interaction was somewhat negative in the Nikwe soil. However, mean separation using least significant (LSD) values indicated that in most cases plant height responses to N application between limed and unlimed soil was similar (Table 3.6, Fig. 3.1). The only significant differences in plant height between limed and unlimed Nikwe soils occurred among control and 1.2 g N pot⁻¹ chicken manure-N only (M) treatments. In the control treatment, plant height in unlimed soil was significantly higher than in limed soil, while for 1.2 g N pot⁻¹ chicken manure-N only the opposite relationship existed. When averaged across all N rates, maize plant height in unlimed soil averaged about 94.8 cm whereas in the limed soil plant height averaged about 90.5 cm. These data indicate that lime had little or no effect on plant height to N treatments in the Nikwe soil. In both unlimed and limed soils, the largest increase in plant height was obtained by increasing N application from 0 to 0.6 g N pot⁻¹ as chicken manure-N only or chicken manure combined with urea-N. The higher rates of chicken manure-N only and chicken manure plus urea-N generally resulted in a relatively smaller further increase in plant height. For example, in limed Nikwe soil, the percentage increase in plant height from the 0 to 0.6 g N pot⁻¹ rate was 63% and 66% for chicken manure-N only and chicken manure plus urea-N treatments, respectively. By contrast, the percentage increase in plant height from the 0.6 g N pot⁻¹ to 1.2 g N pot⁻¹ rate was 13% and 8% for chicken manure-N only and chicken manure plus urea-N treatments, respectively. A similar effect was also noted for the Magusheni soil.

Orthogonal contrast comparisons showed that the plant height responses did not differ ($P < 0.05$) between chicken manure-N alone and chicken manure plus urea-N treatments in limed Magusheni soil, unlimed and limed Nikwe soils (Table 3.6).

However, significant differences in plant height between chicken manure-N alone and chicken manure plus urea-N treatments occurred in unlimed Magusheni soil, where the combination of chicken manure plus urea-N resulted in significantly ($P < 0.05$) larger plant height than the addition chicken manure-N only. The improvement in plant height in the combined urea plus chicken manure treatments suggest that in unlimed Magusheni soil the availability of N to plants might have been higher than in chicken manure only treatments. The immediate availability of N from urea could have contributed to the improvement in plant growth by increasing the N supply during the initial stages of plant growth.

Statistical analysis indicated that plant height was highly correlated with aboveground plant biomass of maize, the correlation coefficients being $r = 0.93$ and 0.96 for Magusheni and Nikwe soils, respectively (Fig. 3.2). This correlation shows that plants that were lower in height also had lower aboveground plant biomass and vice versa. According to Ahmad and Tan (1986) “taller plants with larger dry matter contents are indications for a good early start, and it is reasonable to expect that a good early start will be beneficial for proper development in later growth stages”.

Plant biomass production

In the Magusheni soil, the lime x N fertilizer interaction effects on belowground biomass (root DM) and aboveground:belowground biomass ratio (shoot:root ratio) were not significant (Table 3.5). However, the main effects of lime and N fertilizer in the belowground biomass (root DM) were significant at the 0.05 % probability level. Additionally, the lime x N interaction effects on aboveground biomass (shoot) were significant. In agreement with the plant height data, in limed soil aboveground biomass production was consistently higher ($P < 0.05$) than in unlimed soil, at all N rates (Table 3.7). When averaged across all N rates, in unlimed soil, the aboveground biomass, belowground biomass and shoot:root ratio averaged about 23.4 , 7.56 g dry matter pot^{-1} , and $3.12:1$ whereas in limed soil the corresponding values were 65.5 , 18.2 g dry matter pot^{-1} , and $3.58:1$, respectively. These data indicate that maize

growth response to N was significantly enhanced by the application of lime. A further indication of this was that in the limed soil the aboveground and belowground biomass production in the control treatment (0 g N pot^{-1}) was similar to that obtained from the 1.2 g N pot^{-1} chicken manure-N and chicken manure plus urea-N treatments in unlimed soil. Thus, in the highly acidic Magusheni soil, applied N could be used more effectively for plant growth when combined with lime application. Similar observations were made from lime research field studies in South Africa (Fyfield et al., 2000) that were conducted on the same soils as used in the present study. At the Magusheni research site, Fyfield et al., 2000 reported that maize grain yields were 3040 and 3700 kg ha^{-1} for the recommended fertilizer only and recommended fertilizer + 10 Mg ha^{-1} calcitic lime, respectively. The differences in yield seemed to be related to the percentage soil acid saturation, which amounted to 38.3% in the recommended fertilizer only and 1.6% in the recommended fertilizer + 10 Mg ha^{-1} calcitic lime, respectively.

In the Nikwe soil, the aboveground (shoot) and belowground (root) biomass responses to N treatments tended to be lower in the limed than in unlimed soils. However, comparison of mean values with the LSD test indicated that at equivalent rates of N application the aboveground and belowground biomass as well as the shoot:root ratio between limed and unlimed Nikwe soils were mostly similar (Table 3.8). When significant differences were observed, the aboveground and belowground biomass responses to applied N were higher in unlimed soil than in limed plots. Furthermore, in agreement with the observations on plant height, on both Magusheni and Nikwe soils the largest increase in aboveground and belowground biomass was obtained by increasing N application from 0 to 0.6 g N pot^{-1} as chicken manure-N only or chicken manure plus urea-N treatments. But a relatively smaller further increase in aboveground and belowground biomass production was observed from 0.6 to 1.2 g N pot^{-1} on both chicken manure-N only (M) or chicken manure plus urea-N (F+M) treatments (Table 3.7 and 3.8). When averaged across all N rates, in unlimed soil, the aboveground biomass, belowground biomass and shoot:root ratio averaged about 39.1 , $12.9 \text{ g dry matter pot}^{-1}$, and $3.0:1$ whereas in limed soil aboveground

biomass, belowground biomass and shoot:root ratio averaged about 35.0, 11.6 g dry matter pot⁻¹, and 3.0:1, respectively (Table 3.8). Thus the N treatments in unlimed soil resulted in a small but statistically significant average increase in aboveground biomass, but had no effect on belowground biomass and shoot:root ratios relative to limed soil. In agreement with the trends in plant height, liming showed little or no effect on aboveground biomass, belowground biomass and shoot:root ratio responses to N treatments in the Nikwe soil. Further support for this inference comes from lime research field studies (Fyfield et al., 2000) conducted in South African as mentioned previously. It was reported that at the Nikwe research site, the average grain yields among the recommended fertilizer only and recommended fertilizer plus lime (1.50 Mg ha⁻¹) treatments were similar. Grain yields were 4130 kg ha⁻¹ for recommended fertilizer only and 4190 kg ha⁻¹ for recommended fertilizer in combination with lime treatments (677 kg ha⁻¹ recommended fertilizer + lime), respectively. The percentage soil acid saturation was 18.1% and 10.4 % for the recommended fertilizer only and recommended fertilizer in combination with lime, respectively.

Contrast comparisons showed that on both unlimed and limed Nikwe soil the application of 0.6 and 1.2 g N pot⁻¹ as chicken manure-N only or chicken manure combined with urea-N resulted in comparable effects on aboveground biomass production and shoot:root ratio (Table 3.8). These results are in agreement with the observations on plant height measurements. Comparisons for the belowground biomass production were somewhat different in that in unlimed soil differences between chicken manure-N alone and chicken manure plus urea-N treatments were insignificant whereas in limed soil significant differences were observed. The belowground biomass was significantly higher in the chicken manure plus urea-N than in the chicken manure-N only treatments.

In the Magusheni soil, significant differences in plant biomass responses between chicken manure-N only and chicken manure plus urea-N treatments were only observed in limed soil. Chicken manure plus urea-N treatments had a significantly

stronger aboveground and belowground biomass response than on chicken manure-N alone treatments (Table 3.7).

N uptake and concentration

A significant lime x N interaction on N uptake (shoot and root) and N concentration was observed in both Magusheni and Nikwe soils (Table 3.5). In the Magusheni soil, the trends in total N uptake were similar to those observed on plant height and biomass production. In almost all the N rates, the uptake of N in shoots and roots was significantly higher in limed soil than in unlimed soil (Table 3.9). When averaged across all N treatments, the aboveground biomass N uptake in unlimed soil was about $0.480 \text{ g N pot}^{-1}$, whereas in the limed soil it was about $0.791 \text{ g N pot}^{-1}$. Similarly, in unlimed soil the belowground biomass N uptake averaged about $0.180 \text{ g N pot}^{-1}$ whereas in the limed soil N uptake averaged about $0.326 \text{ g N pot}^{-1}$. Highly acid soils (such as the Magusheni soil) may possess Al phytotoxicity or Ca-deficiency which can reduce water and nutrient uptake (Adams, 1984). These results indicate that in the Magusheni soil, liming may have created a favourable environment for increased N uptake by plant roots than in unlimed soil.

In the Nikwe soil the belowground biomass N uptake gave a more consistent trend than the aboveground biomass N uptake (Table 3.10). Consistently, total N uptake in the belowground biomass was significantly higher in unlimed soil than in limed soil, among all N rates. When averaged across all N rates, the belowground biomass N uptake in unlimed soil was about $0.303 \text{ g N pot}^{-1}$ whereas in limed soil N uptake was about $0.189 \text{ g N pot}^{-1}$. The reason for the lower N uptake in the below ground biomass is not clear. However, because of the much lower levels of acidity in the Nikwe soil, aluminum stress in limed soil can be excluded as a causal factor. The effects of lime and N fertilizer interactions on aboveground biomass N uptake responses were less consistent in the Nikwe soil. However, when averaged across all N rates, the aboveground biomass N uptake in unlimed soil was about $0.687 \text{ g N pot}^{-1}$ whereas in limed soil N uptake was about $0.709 \text{ g N pot}^{-1}$. The lack of marked

differences in aboveground biomass N uptake between unlimed and limed Nikwe soil is consistent with the plant height and biomass production results.

Additionally, our results show that the aboveground and belowground biomass N uptake increased as the N application rate increased in both Magusheni and Nikwe soils. But, the largest percentage increase in N uptake was obtained by increasing N application from 0 to 0.6 g N pot⁻¹ (as chicken manure-N alone or chicken manure plus urea-N). At 0.6 to 1.2 g N pot⁻¹, the percentage increase in N uptake was relatively small. This trend is consistent with that observed for plant height.

The effects of chicken manure-N alone versus chicken manure plus urea-N treatments on maize N uptake on both unlimed and limed soils were evaluated by means of orthogonal contrast comparisons (Table 3.9 and 3.10). Results show that in the Magusheni soil significantly more aboveground and belowground biomass N uptake occurred in chicken manure plus urea fertilizer (F+M) treatments than in chicken manure only (M) treatments. The improvement in N uptake in the combined urea plus chicken manure treatments suggests that the availability of N to plants might have been higher than on chicken manure only treatments. In the Nikwe soil, differences between chicken manure-N only and chicken manure plus urea-N treatments were not always consistent with regards to above and belowground biomass N uptake. In unlimed soil, chicken manure-N alone resulted in significantly greater aboveground biomass N uptake than chicken manure plus urea-N treatments. But, in limed soil chicken manure plus urea-N treatments resulted in significantly greater aboveground biomass N uptake than chicken manure-N alone treatments. Similarly, in unlimed soils belowground biomass N uptake was higher in soil amended with chicken manure plus urea-N than in chicken manure-N only treatments. In limed soil the effects of chicken manure-N only and chicken manure plus urea-N treatments were similar. These inconsistencies prevented the drawing of a conclusion on the effects of chicken manure-N only and chicken manure plus urea-N treatments on biomass N uptake for this soil.

The aboveground and belowground biomass production of maize were highly correlated with aboveground and belowground biomass N uptake for both soils. For the Magusheni soil, the correlation coefficients were $r = 0.72$ (shoots), 0.92 (roots) and for Nikwe soil the correlation coefficients were $r = 0.78$, (shoots), 0.65 (roots), respectively. Since, the relationship between biomass production and N uptake was similar for both soils, only the data for the Nikwe soil are presented in Fig. 3.3.

The data in Table 3.9 illustrate that, in the Magusheni soil, the N concentration in the aboveground and belowground biomass was inversely related to the total N uptake. In almost all the N rates, the concentration of N in aboveground and belowground biomass was significantly higher in unlimed than in limed Magusheni soil. In unlimed soil, aboveground biomass N concentration averaged about 2.15%, whereas in the limed soil N concentration averaged about 1.18%. Similarly, in unlimed soil, belowground biomass N concentration averaged about 2.37% whereas in the limed soil N concentration averaged about 1.79%. Furthermore, the relationship between aboveground or belowground biomass production and aboveground or belowground biomass N concentration clearly shows that N concentration decreased as biomass production increased (Figure 3.4). Therefore, the lower N concentration in plants with higher biomass production (limed soil) could be the result of a dilution effect of plant biomass on N concentrations, while the higher N concentration in plants with lower biomass production (unlimed soil) could be the result of N accumulation in plants under stress. This is in agreement with other studies that have examined the relationship between nutrient concentration in plants and biomass production. Kemper and Sorensen (1974) also found that total dry matter yields showed a negative relationship to total plant (maize) N concentration. In a field experiment with corn Liang and MacKenzie (1994) noted that stover N concentration correlated negatively with grain yield, indicating a higher grain yield was associated with lower stover N concentration.

The results indicate that in the Nikwe soil, the patterns for N concentration in the plant biomass responded somewhat differently from those observed in the Magusheni

soil. In most cases, the aboveground biomass N concentration was higher in the limed than in unlimed soil (Table 3.10). In unlimed soil, aboveground biomass N concentration averaged about 1.76% whereas in the limed soil N concentration averaged about 2.06%. In contrast, the belowground biomass N concentration was consistently higher in unlimed than in limed soil. In unlimed soil, belowground biomass N concentration averaged about 2.33% whereas in the limed soil N concentration averaged about 1.66%. The lack of consistency makes it difficult to conclude on the effect of lime and N fertilizer interactions on concentration of N in the plant biomass in the Nikwe soil. Additionally, the aboveground or belowground biomass production did not show significant correlation with the aboveground and belowground biomass N concentration for Nikwe soil ($r = 0.09$ (shoots), 0.04 (roots)). Taken as a whole, these results seem to lend support to those observed for plant growth responses that, soil acidity was a critical factor affecting plant growth in Magusheni soil, whilst in the Nikwe soil, soil acidity was not a growth limiting factor.

Apparent N recovery

The N recovery (Equation 1) represents the apparent amount of N recovered by the crop from fertilizer or manure (Kanneganti and Klausner, 1994). In the Magusheni soil, the lime x chicken manure interaction effects on apparent N recovery were not significant. However, the main effects of lime and chicken manure were significant. When average across N rates, the apparent N recovery was 89% and 104% for unlimed and limed soils, respectively (Table 3.11). This suggests that the liming improved apparent N recovery in the Magusheni soil. In the Nikwe soil, the lime x chicken manure interaction effects on apparent N recovery were significant. However, the trends in apparent N recovery varied markedly between the lime and N rates and this made it difficult to make a meaningful interpretation of these data. Therefore, the data was averaged across lime rates and the effects of N rates are given in Table 3.12. Results show that ANR as estimated by the difference method varied markedly between the N treatments. For Magusheni soil, ANR values ranged from 67% to 153% whereas in the Nikwe soil the ANR ranged from 56% to 101%. Thus,

ANR values for the Magusheni soil appeared to be relatively higher than those observed for Nikwe soil.

Additionally, there were trends showing a gradual decline in ANR between 0.6 g and 1.2 g N pot⁻¹ treatments, however these differences were not significant ($P < 0.05$) on both soils. Kanneganti and Klausner (1994) also observed that N recovery from manure diminishes with increasing rates of manure N application. In the present study, though values for ANR appeared slightly higher for chicken manure plus urea treatments than chicken manure alone treatments, the differences were not significant (Table 3.12). There is evidence from other studies which show that synchrony between N release and uptake can best be achieved in treatments receiving combinations of manure and fertilizer N (Murwira and Kirchmann, 1993). Rees et al., (1993), also noted that where inorganic fertilizers and manures are used simultaneously the uptake efficiency of both sources may increase.

Close examination of the ANR data revealed that the N recovered from the 0.2 g N pot⁻¹ treatments was higher than the initial amounts of fertilizer N applied. The surplus was equal to 1%, and 53% for the Nikwe soil and Magusheni soil, respectively (Table 3.12). The fact that N recovered from the 0.2 g N pot⁻¹ treatment was more than the initial amounts of fertilizer N applied was unexpected. However, similar effects have also been reported by other investigators studying the dynamics of soil N transformations the effects that the addition of fertilizers can have on these soil N transformations. Gioacchini et al. (2006) observed that the net accumulation of NO₃-N in a sandy loam soil amended with IBDU (fertilizer containing a synthetic organic N) and E26 (mineral fertilizer containing both nitrate and ammonium and a nitrification inhibitor) was significantly higher than the amount of N initially added. The surplus was equal to 58% and 89% for IBDU and E26, respectively, and was presumably, the result of an extra release of soil organic N. According to the authors an increased availability of this N form, which is preferentially assimilated by microorganisms, but normally rather limited in soil, enables an increase in activity of the soil microbial biomass. The consequent increase in microbial biomass activity

probably stimulated the SOM mineralization and the rate of soil N turnover (Gioacchini et al., 2006). Similarly, Alfaia et al. (2000) observed that applied fertilizer N represented only a small part of the total plant N uptake by rice and ryegrass grown in an Ultisol of central Brazilian Amazonia. However, the contribution of soil N to plant N uptake was very high amounting to 60-80% of total N uptake. The increased uptake of soil N by the plants was attributed to priming effects (the breakdown of some resistant soil organic matter due to intense microbial activity). The so-called priming effects or positive added N interaction was greater in the presence of urea than ammonium sulphate $(\text{NH}_4)_2\text{SO}_4$ fertilizer. The higher use efficiencies obtained in plants treated with urea were related to higher pH values caused by urea hydrolysis, which in turn might have favoured the activity of nitrifying bacteria in this acidic Ultisol. Thus, in the present study it is most likely that the additional N recovered in the urea amended treatments was mineralized by the priming effect.

The recovery of applied N in the present study seems high, especially when compared to published data obtained under field conditions. The results are not unusual, however, as studies by Rees et al. (1993) showed that the efficiency of N recovery from N-labelled manure in a pot experiment is generally greater than that in the field experiment because the volume of soil available for root exploration is limited, and N loss by leaching is usually prevented. From the field experiment they found that between 16 and 26% of the applied manure-N was recovered at harvest time. In contrast, the recovery of the applied manure-N in the pot experiment ranged from 54 to 60%.

CONCLUSIONS

The results showed that the effect of lime x N fertilizer interaction on maize plant height, biomass production, total N uptake and N concentration varied between the Magusheni and Nikwe soils. In the Magusheni soil, the lime x N fertilizer interaction was positive in that lime enhanced plant response to N application. Based on soil analysis results, responses in plant height, aboveground biomass production, and total N uptake to N application were lower in the unlimed than in limed soil due to the higher levels of soil acidity in the former soil. In the unlimed soil, the percent soil acid saturation was 47%, which is more than double the critical 20% permissible acid saturation level for a maize crop. The percent base saturation and Ca^{2+} saturation were also much lower than in limed soil. In the limed soil, the percent base saturation, Ca^{2+} saturation, and soil acid saturation were 91%, 50%, and 9.3%, respectively. These greatly improved soil conditions may have contributed to the positive plant responses to N application in the limed soil. Therefore, soil acidification must be corrected in order to optimize maize response to applied N fertilizer in the Magusheni soil.

In the Nikwe soil, the plant height, aboveground belowground biomass production and total N uptake was either similar or lower in limed than in the unlimed soils. Soil analysis results, indicated that chemical characteristics of the unlimed and limed soils were similar. In both the unlimed and the limed soils, the percent base saturation, Ca^{2+} saturation, and soil acid saturation were 95%, 50%, and 5.0%, respectively. Therefore, lime had little or no effect on soil chemical properties in the Nikwe soil. The negative lime x N interaction observed in this soil was unexpected, and we do not have a plausible explanation for the fact that lime reduced plant response to N application in this soil. The results presented, however, suggest that as long as the soil base status remains high and acid saturation levels low, there would be little or no benefit to total N uptake, maize growth and development due to lime application in the Nikwe soil.

The fact that large responses to applied N were obtained on both Magusheni and Nikwe soils confirms that N was the limiting nutrient in the control treatments. Additionally, the largest percentage increase in maize plant height, plant biomass production, and N uptake was obtained by increasing N application from 0 to 0.6 g N pot⁻¹ as chicken manure only or chicken manure plus urea fertilizer. The higher rates of chicken manure only or chicken manure plus urea fertilizer generally resulted in a relatively smaller further increase in plant growth responses on both Magusheni and Nikwe soils. A similar effect was observed among the 0 to 5 Mg ha⁻¹ and 5 to 10 Mg ha⁻¹ chicken manure rates in the greenhouse pot experiment reported in chapter 2. Additionally, Nyamangara et al. (2005) also noted a similar trend when manure rates of 12.5 and 37.5 Mg ha⁻¹ were applied in combination with 60 and 120 kg N ha⁻¹. In the present study, we do not know whether these trends in plant growth will continue until maturity and therefore this possibility should be investigated under field conditions. In field studies using the same soils and chicken manure as used in the present pot experiment, Fyfield et al. (2000) noted that there were visual symptoms of a slight N deficiency (i.e. yellowing of the older leaves which proceeds from the leaf tip down the midrib in a V-shaped pattern) later in the season (12 weeks after planting) for chicken manure amended plots (at a rate of 10 Mg ha⁻¹). However, despite this visual evidence of N deficiency symptoms the 10 Mg ha⁻¹ chicken manure treatment gave yields (2.44 Mg ha⁻¹) that were significantly higher than all the other treatments. This indicates that chicken manure mineralization can supply adequate amounts of N early in the growing season, however, some mineral N should be applied at about 6 weeks after planting to prevent N deficiency late in the season. The results of this study suggest that at least in the short term chicken manure mineralization can supply crop N requirements. However, since this study is based on a greenhouse experiment possible treatments effects at field level have to be inferred with some caution.

The results of this study show that the net effects of the combined use of chicken manure plus urea and chicken manure alone on (maize plant height, plant biomass production, N uptake and N concentration) varied between the two soils and at times

lacked consistency. In the Nikwe soil, plant biomass production (and plant height) was generally similar between chicken manure plus urea and chicken manure alone treatments. The trends in N uptake were inconsistent. Taken as a whole, the results suggest that in the Nikwe soil plant biomass production in the chicken manure plus urea treatments did not significantly differ from plant biomass production in the treatments which received the same quantity of N as chicken manure only. In the Magusheni soil, in some cases the effects of chicken manure plus urea and chicken manure treatments were similar. However, in other instances the chicken manure plus urea treatments tended to produce significantly higher plant biomass (N uptake and to a limited extent plant height) than chicken manure only treatments. These results do not enable definite conclusions to be drawn about the effects of organic and inorganic combinations. Instead they highlight the need to evaluate the benefits of these treatments under field conditions. A search of the literature revealed that the positive effects of combining inorganic fertilizers and manures observed in several studies are attributed to improved soil structure, aeration, water holding capacity, and availability of nutrients other than N (Rees et al., 1993, VanLauwe et al., 2001a, Nyamangara et al., 2005). In the present study, it is unlikely that the effects were due to improvements in soil physical properties or soil water availability, but could be due to better synchrony between N release and plant uptake.

The results of this study suggest that apparent N recovery was significantly higher in limed than in the unlimed Magusheni soil. However, in the Nikwe soil the lime x N interaction data lacked consistency. When average across lime rates, results show that ANR as estimated by the difference method varied markedly between the N treatments on both soils. Total ANR values ranged from 67% to 153% and from 56% to 101% for Magusheni and Nikwe soils, respectively. Additionally, there were trends showing a gradual decline in ANR between 0.6 g and 1.2 g N pot⁻¹ treatments, however these differences were not significant (P<0.05) on both soils. In agreement with previous observations in other soils, the results of this investigation provided evidence of a priming effect in urea fertilizer amended treatments. In summary, in the Magusheni and Nikwe soil, lime sufficient to neutralize percent acid saturation or

exchangeable Al to levels < 20% of the effective CEC will provide a chemical environment that encourages better uptake of nutrients, plant growth and productivity.

Recommendations for further study

- 1) Further testing of the impact of sole and combined applications of animal manure with mineral fertilizers on maize grain yield under field conditions is needed.
- 2) Long term experiments are needed to document how long lime additions will remain effective on acid soils.
- 3) The soils used in this study were collected in the top 0-15 cm, therefore our focus was on topsoil acidity. Future studies should also focus on how to reduce toxic levels of acidity in the subsoil.
- 4) Gypsum has been reported to be more effective than lime in reducing the amount of soluble aluminum in the subsurface layers because of its greater mobility. Local studies are needed to investigate the effects of gypsum amendments on subsoil acidity parameters.
- 5) There is evidence that organic residues from green and animal manures can increase the pH of acid soils. There is a need to investigate the use of organic residues to increase soil pH and improve crop production on acid soils from Eastern Cape.

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Table 3.1. Selected chemical and physical properties of soils used in this study.

Soil property	Magusheni soil		Nikwe soil	
	No Lime	Limed	No Lime	Limed
Organic C (%)	3.8	3.6	3.5	3.4
Total N (%)	0.24	0.23	0.22	0.21
Ca Saturation (%)	26	51	52	49
Mg Saturation (%)	23	37	32	36
K Saturation (%)	0.194	2.5	11	13
ECEC (cmol _(c) kg ⁻¹)	4.81	6.07	8.49	9.29
pH (KCl)	3.91	4.27	4.18	4.42
Exch. Al+H (cmol _(c) kg ⁻¹)	2.270	0.564	0.401	0.277
Exch. Al (cmol _(c) kg ⁻¹)	2.12	0.49	0.26	0.14
Base Saturation (%)	52.8	90.7	95.3	97.0
Acid Saturation (%)	47.24	9.28	4.74	2.98
Texture	Clay	Clay	Clay	Clay

Table 3.2. Selected properties of broiler chicken manure (Gromor¹) used in this study.

pH (KCl)	Total N (%)	Total C (%)	C:N ratio	NH ₄ -N (%)	Moisture (%)
6.68	3.69	40.5	1:11	0.79	6.6

¹ Trade names and company names are included for the benefit of the reader and do not constitute endorsement or preferential treatment of the product.

Table 3.3: Lime and N (urea fertilizer, chicken manure applied singly or in combination) treatments applied in this factorial pot study.

Lime rate	Chicken		¹ Chicken	
	Fertilizer N rate (g N pot ⁻¹)	manure N rate (g N pot ⁻¹)	Fertilizer N rate (kg N ha ⁻¹)	manure N rate (kg N ha ⁻¹)
No lime	0	0	0	0
No lime	0.2	0 (F)	40	0 (F)
No lime	0.2	0.4 (F+M)	40	79 (F+M)
No lime	0	0.6 (M)	0	119 (M)
No lime	0.2	1.0 (F+M)	40	198 (F+M)
No lime	0	1.2 (M)	0	238 (M)
With lime	0	0	0	0
With lime	0.2	0 (F)	40	0 (F)
With lime	0.2	0.4 (F+M)	40	79 (F+M)
With lime	0	0.6 (M)	0	119 (M)
With lime	0.2	1.0 (F+M)	40	198 (F+M)
With lime	0	1.2 (M)	0	238 (M)

¹ Manure rates were adjusted for moisture content.

Table 3.4. Analysis of variance (ANOVA) table showing sources of variance.

Source	Degrees of Freedom
Lime	1 (2-1)
Fertilizer	5 (6-1)
Lime x Fertilizer	5 (2-1) x (6-1)
Error	By Subtraction=36
Total	47 ((2x6x4)-1)

Table 3.5. Significance of the calcitic lime and N fertilizer effects and their interaction for plant height, aboveground (shoot) biomass, belowground (root) biomass, shoot:root ratio, N uptake and N recovery under greenhouse conditions (Magusheni and Nikwe soil).

Plant parameter	<u>Magusheni soil</u>		
	Lime	N Fertilizer	Lime x N Fertilizer
Plant height	< 0.0001	< 0.0001	0.0053
Shoot biomass	< 0.0001	< 0.0001	< 0.0001
Root biomass	< 0.0001	< 0.0001	0.1081 (NS)
Shoot:root ratio	0.036	0.774 (NS)	0.447 (NS)
N uptake	< 0.0001	< 0.0001	< 0.0001
N Recovery	0.036	< 0.0001	0.762 (NS)

Plant parameter	<u>Nikwe soil</u>		
	Lime	N Fertilizer	Lime x N Fertilizer
Plant height	0.005	< 0.0001	0.0025
Shoot biomass	< 0.0001	< 0.0001	< 0.0001
Root biomass	0.009	< 0.0001	0.021
Shoot:root ratio	0.949 (NS)	0.079 (NS)	0.035
N uptake	< 0.0001	< 0.0001	< 0.0001
N Recovery	0.365 (NS)	< 0.0001	0.028

Table 3.6. The effect of lime, fertilize N and available chicken manure N, and combinations chicken manure N plus fertilize N on maize plant height as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 1999 and 2000 (Magusheni and Nikwe soils).

N rate (g N pot ⁻¹)	Magusheni soil		Nikwe soil	
	Lime rate			
	No Lime	Lime	No Lime	Lime
	Plant height (cm)			
0	38.3	85.6	74	57.8
0.6 (M)	72.1	113.1	97.6	94.1
1.2 (M)	83.4	117.0	99.4	106.5
0.2 (F)	68.5	103.6	91.2	85.2
0.6 (F+M)	76	115.2	100.2	96
1.2 (F+M)	93.2	121.4	106.3	103.5
LSD _{0.05}	6.7	6.7	7.0	7.0
Average	71.9 B	109.3 A	94.8 A	90.5 A
Orthogonal Contrast				
Magusheni	Lime rate	0.6 & 1.2 (M) vs. 0.6 & 1.2 (F+M)		
Plant height	No Lime	0.0057		
	Lime	0.17 (NS)		
Nikwe				
Plant height	No Lime	0.06 (NS)		
	Lime	0.83 (NS)		

For a particular row, means followed by the same letter are not significant at the 5% level (t - test).

Table 3.7. The effect of lime, mineral and available manure nitrogen on maize aboveground (shoots) and below ground (roots) biomass and shoot:root ratio as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 1999 (Magusheni soil).

N rate	Lime rate					
	No Lime	Lime	No Lime	Lime	No Lime	Lime
(g N pot ⁻¹)	Shoot DM (g DM pot ⁻¹)		Root DM (g DM pot ⁻¹)		Shoot:root ratio	
0	4.5	34.3	1.38	10.1	3.3:1	3.4:1
0.6 (M)	26.6	69.8	9.00	18.6	3.0:1	3.8:1
1.2 (M)	31.2	76.7	11.0	19.5	2.9:1	3.9:1
0.2 (F)	18.8	59.5	6.58	18.5	2.9:1	3.2:1
0.6 (F+M)	26.1	68.8	8.13	20.4	3.2:1	3.4:1
1.2 (F+M)	33.4	83.7	9.33	22.1	3.6:1	3.8:1
LSD _{0.05}	3.42	3.42	2.74	2.74	0.9	0.9
Average	23.4 B	65.5 A	7.56 B	18.2 A	3.1:1 A	3.6:1 A
Orthogonal Contrast						
Parameter	Lime rate		0.6 & 1.2 (M) vs. 0.6 & 1.2 (F+M)			
Shoot DM	No Lime		0.48 (NS)			
	Lime		0.018			
Root DM	No Lime		0.20 (NS)			
	Lime		0.026			
Shoot:root ratio	No Lime		0.16 (NS)			
	Lime		0.39 (NS)			

For a particular row, means followed by the same letter are not significant at the 5% level (t - test).

Table 3.8. The effect of lime, mineral and available manure nitrogen on maize aboveground (shoots) and below ground (roots) biomass and shoot:root ratio as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 2000 (Nikwe soil).

N rate (g N pot ⁻¹)	Lime rate		Lime rate		Lime rate	
	No Lime	Lime	No Lime	Lime	No Lime	Lime
	Shoot DM (g DM pot ⁻¹)		Root DM (g DM pot ⁻¹)		Shoot:root ratio	
0	23.7	14.3	7.9	5.8	3.0:1	2.5:1
0.6 (M)	41.3	39.5	13.4	14.2	3.1:1	2.8:1
1.2 (M)	46.1	45.5	13.6	14.9	3.4:1	3.1:1
0.2 (F)	35.2	27.6	13.2	9.4	2.7:1	2.9:1
0.6 (F+M)	42.3	37.2	13.8	12.8	3.1:1	2.9:1
1.2 (F+M)	46.1	46.3	15.7	12.3	2.9:1	3.8:1
LSD _{0.05}	2.512	2.512	2.426	2.426	0.643	0.643
Average	39.1 A	35.0 B	12.9 A	11.6 A	3.0:1 A	3.0:1 A

Parameter	Lime rate	Orthogonal Contrast	
		0.6 & 1.2 (M) vs. 0.6 & 1.2 (F+M)	
Shoot DM	No Lime	0.59 (NS)	
	Lime	0.38(NS)	
Root DM	No Lime	0.16(NS)	
	Lime	0.0240	
Shoot:root ratio	No Lime	0.38(NS)	
	Lime	0.12(NS)	

For a particular row, means followed by the same letter are not significant at the 5% level (t - test).

Table 3.9. The effect of lime, mineral and available manure nitrogen on maize aboveground (shoots) and below ground (roots) biomass N uptake and concentration as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 2000 (Magusheni soil).

		Shoots			
		Lime rate			
N rate		No Lime	Lime	No Lime	Lime
(g N pot ⁻¹)		N uptake ----- (g/pot) -----		N concentration ----- (%) -----	
0		0.137	0.352	3.05	1.03
0.6 (M)		0.454	0.759	1.72	1.09
1.2 (M)		0.677	1.011	2.17	1.32
0.2 (F)		0.316	0.554	1.69	0.93
0.6 (F+M)		0.485	0.780	1.85	1.14
1.2 (F+M)		0.813	1.292	2.44	1.55
LSD _{0.05}		0.058	0.058	0.18	0.18
Average		0.480 B	0.791 A	2.15 A	1.18 B
		Roots			
N rate		N uptake ----- (g/pot) -----		N concentration ----- (%) -----	
(g N pot ⁻¹)					
0		0.035	0.185	2.52	1.81
0.6 (M)		0.227	0.329	2.52	1.79
1.2 (M)		0.287	0.347	2.61	1.80
0.2 (F)		0.147	0.305	2.26	1.64
0.6 (F+M)		0.153	0.379	1.87	1.86
1.2 (F+M)		0.228	0.409	2.45	1.85
LSD _{0.05}		0.064	0.064	0.34	0.34
Average		0.180 B	0.326 A	2.37 A	1.79 B
Parameter		Orthogonal Contrast			
Shoots	Lime rate	0.6 & 1.2 M vs. 0.6 & 1.2 F+M			
N uptake	No Lime	0.0002			
	Lime	<0.0001			
N concentration	No Lime	0.0025			
	Lime	0.0305			
Roots					
N uptake	No Lime	0.0054			
	Lime	0.0183			
N concentration	No Lime	0.0018			
	Lime	0.62 (NS)			

Table 3.10. The effect of lime, mineral and available manure nitrogen on maize aboveground (shoots) and below ground (roots) biomass N uptake and concentration as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 2000 (Nikwe soil).

		Shoots			
		Lime rate			
N rate		No Lime	Lime	No Lime	Lime
(g N pot ⁻¹)		N uptake ----- (g/pot)		N concentration ----- (%)	
0		0.444	0.359	1.88	2.52
0.6 (M)		0.702	0.629	1.70	1.60
1.2 (M)		0.924	0.927	2.01	2.05
0.2 (F)		0.534	0.512	1.52	1.86
0.6 (F+M)		0.654	0.749	1.55	2.02
1.2 (F+M)		0.865	1.076	1.88	2.33
LSD _{0.05}		0.051	0.051	0.15	0.15
Average		0.687 A	0.709 A	1.76 B	2.06 A
		Roots			
N rate		N uptake ----- (g/pot)		N concentration ----- (%)	
(g N pot ⁻¹)					
0		0.168	0.112	2.13	1.94
0.6 (M)		0.297	0.213	2.23	1.50
1.2 (M)		0.333	0.250	2.46	1.70
0.2 (F)		0.298	0.143	2.26	1.55
0.6 (F+M)		0.325	0.197	2.36	1.54
1.2 (F+M)		0.398	0.216	2.54	1.76
LSD _{0.05}		0.045	0.045	0.24	0.24
Average		0.303 A	0.189 B	2.33 A	1.66 B
Parameter		Orthogonal Contrast			
Shoots		Lime rate			
		0.6 & 1.2 M vs. 0.6 & 1.2 F+M			
N uptake		No Lime			
		Lime			
N concentration		No Lime			
		Lime			
Roots		No Lime			
N uptake		Lime			
N concentration		No Lime			
		Lime			

Table 3.11. The main effects of lime on apparent N recovery from a pot experiment with maize fertilized with broiler chicken manure (Magusheni and Nikwe soil)

N rate (g N pot ⁻¹)	Magusheni soil		Nikwe soil	
	No Lime	Lime	No Lime	Lime
	Lime rate			
	ANR (%)			
0.6 (M)	85	92	64	62
1.2 (M)	66	68	54	59
0.2 (F)	146	160	110	92
0.6 (F+M)	78	104	61	79
1.2 (F+M)	72	97	54	68
LSD _{0.05}	12.6	12.6	16.5	16.5
Average	89B	104A	69A	72A

For a particular row, means followed by the same letter are not significant at the 5% level (t - test).

Table 3.12. The main effects of nitrogen on apparent N recovery from a pot experiment with maize fertilized with broiler chicken manure and (Magusheni and Nikwe soil)

Soil	N rate (g N pot ⁻¹)				
	0.6 (M)	1.2 (M)	0.2 (F)	0.6 (F+M)	1.2 (F+M)
	ANR (%)				
Magusheni	88.5	67	153	91	84.5
LSD _{0.05}	22.0				
Nikwe	63	56.5	101	70	61
LSD _{0.05}	11.8				
	Orthogonal Contrast				
Magusheni	Lime rate	0.6 & 1.2 (M) vs. 0.6 & 1.2 (F+M)			
ANR (%)	No Lime	0.9725 (NS)			
	Lime	0.0716 (NS)			
Nikwe					
ANR (%)	No Lime	0.8132 (NS)			
	Lime	0.0274			



Fig. 3.1. The effect of lime and N fertilizer (applied at a rate of 1.2 g N pot^{-1} , as chicken manure only, M) on maize plant height (5 weeks after planting) in unlimed (left) and limed (right) soil as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 1999 and 2000 (Magusheni soil, top and Nikwe soil, bottom).

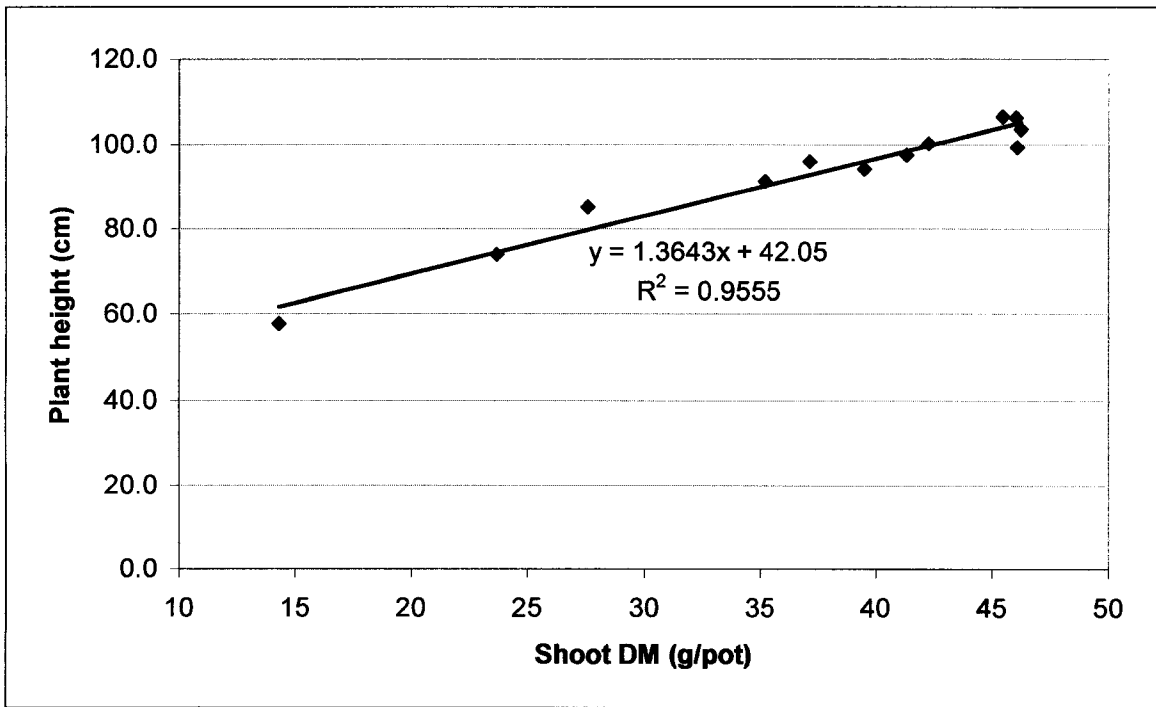
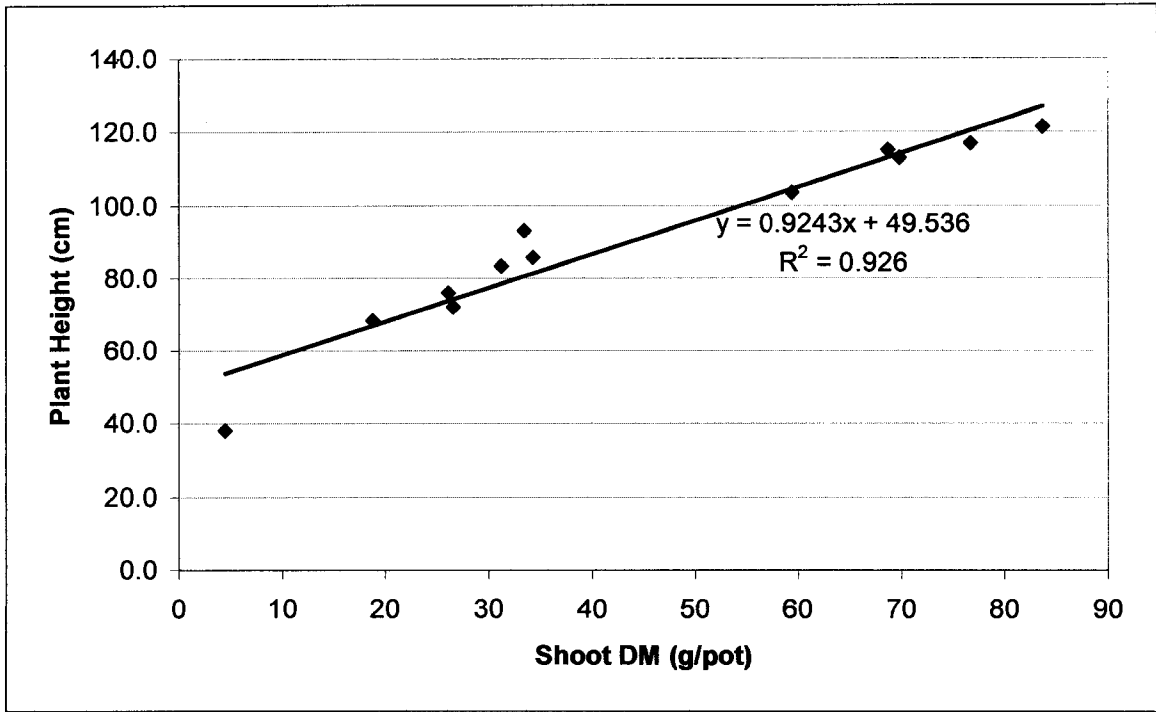


Fig. 3.2. Correlations between aboveground plant biomass (shoot DM) and plant height as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 1999 and 2000 (Magusheni soil, top and Nikwe soil, bottom).

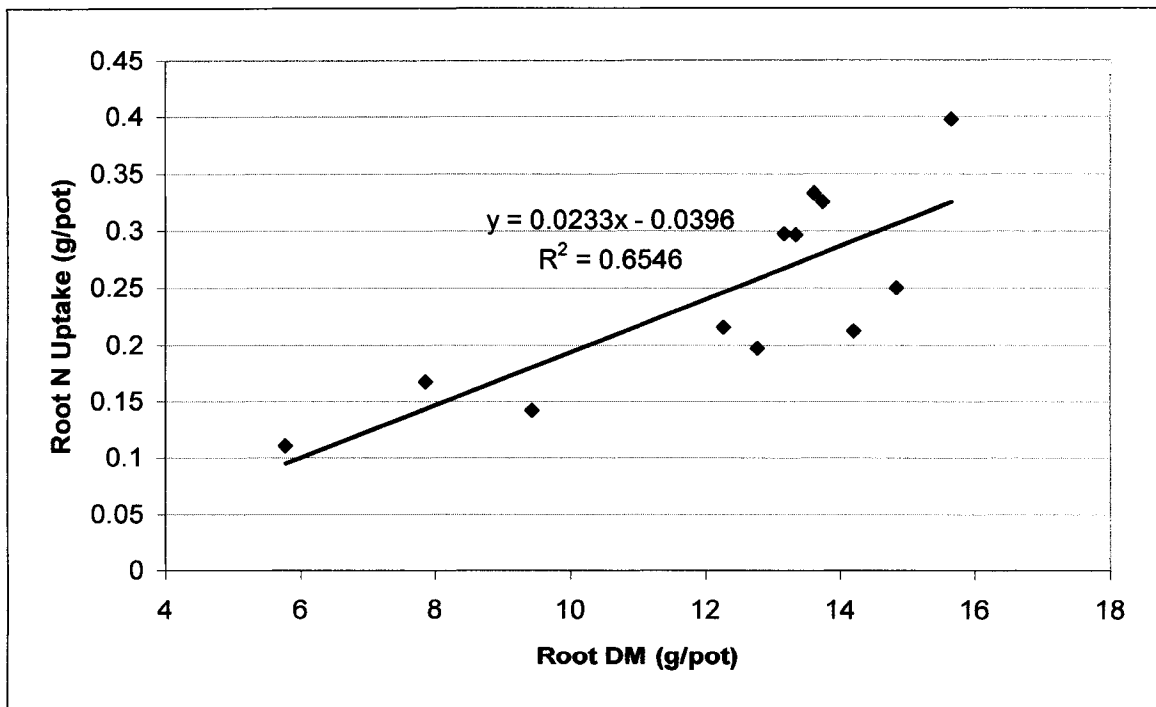
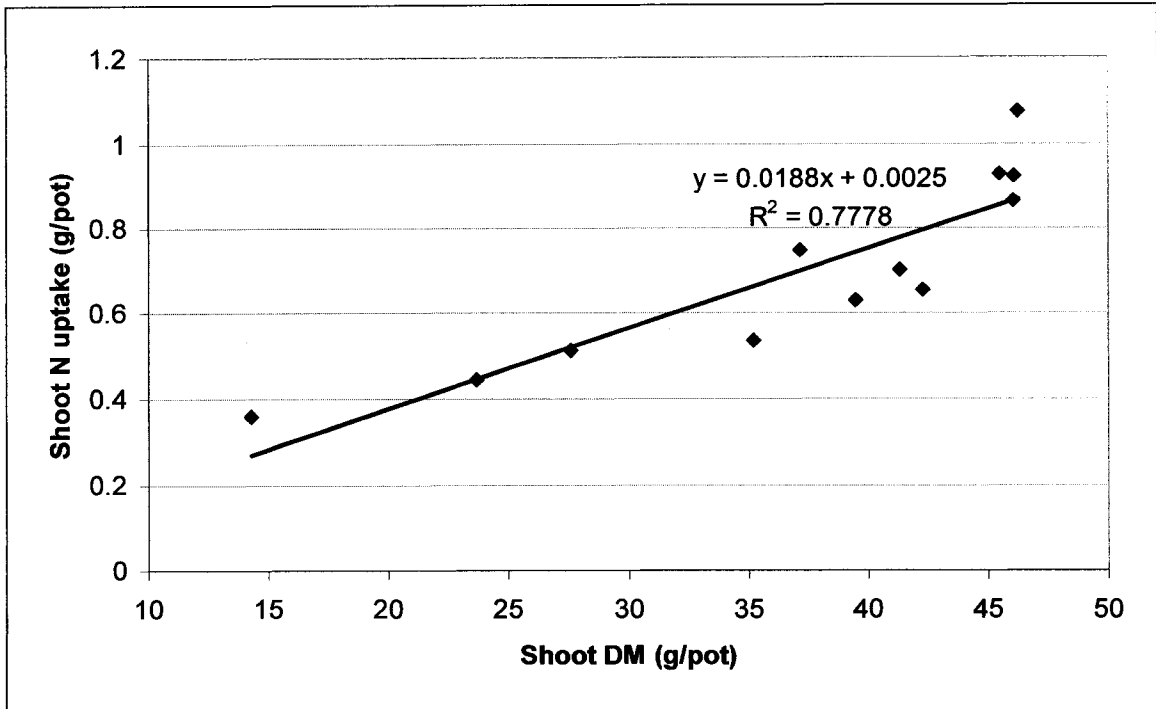


Fig. 3.3. Correlations between aboveground biomass plant dry matter (top) or belowground biomass plant dry matter (bottom) and N uptake as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 2000 (Nikwe soil).

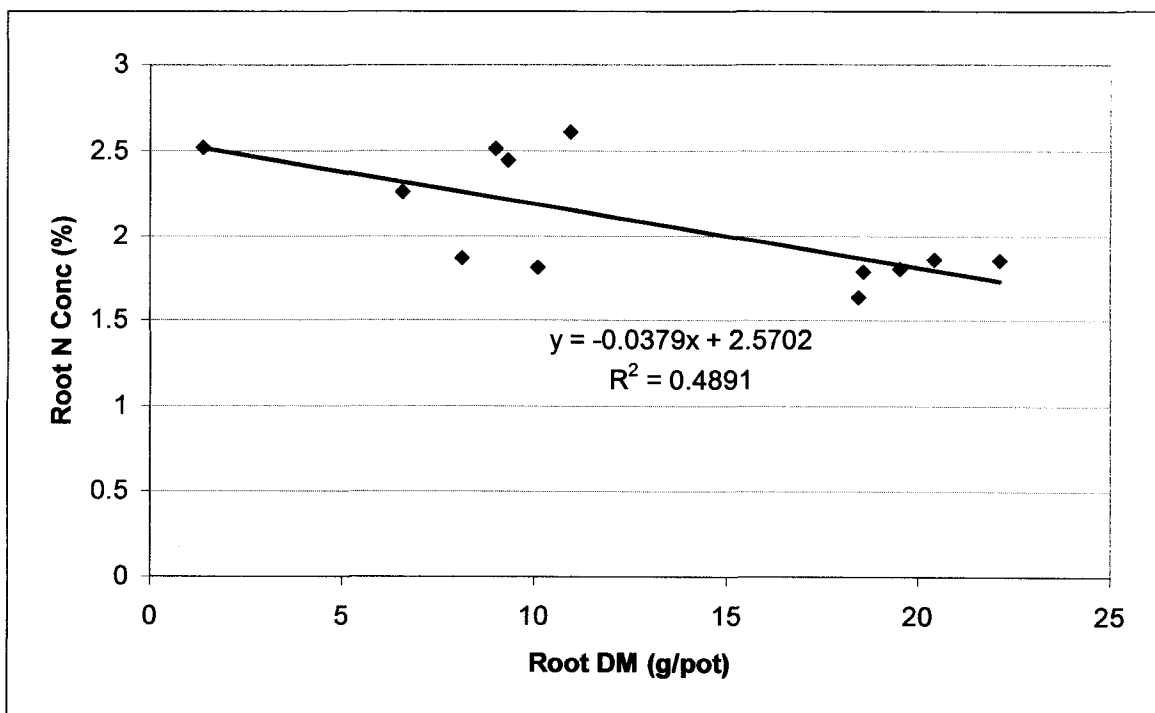
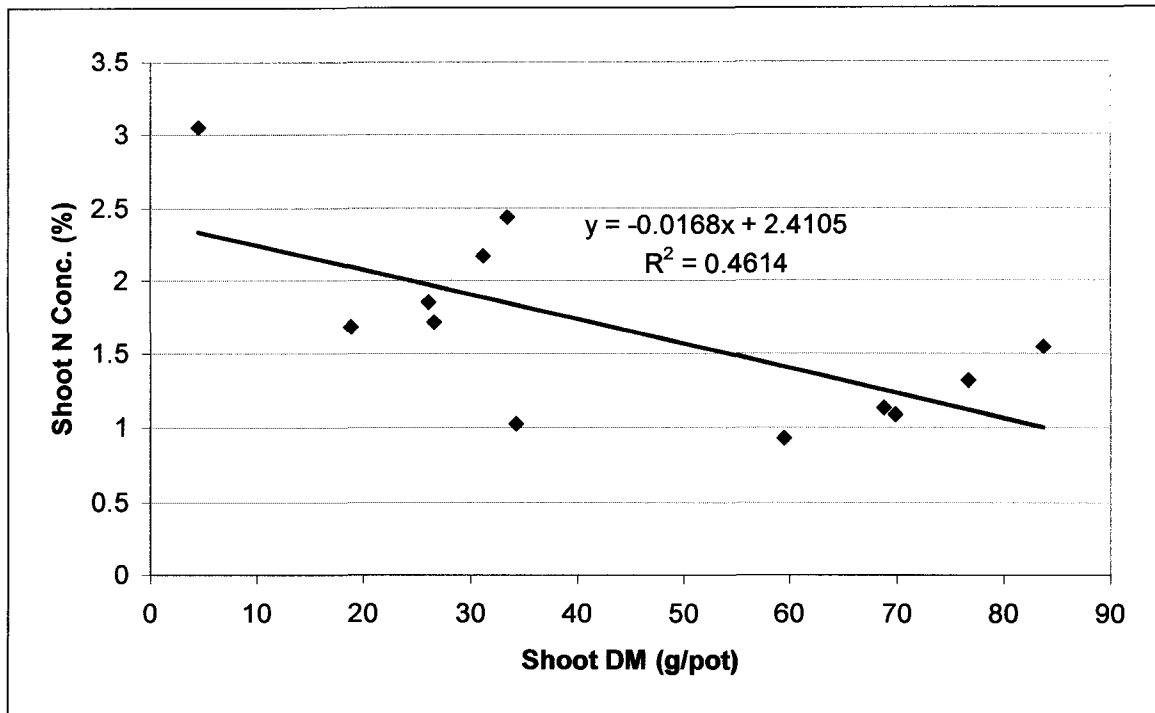


Fig. 3.4. Correlations between aboveground biomass plant dry matter (top) or belowground biomass plant dry matter (bottom) and N concentration as measured in a pot experiment, with soil obtained from field experimental plots that were initiated in 1999 (Magusheni soil).