ABSTRACT

MONTALVO GRIJALVA, DANIELA FERNANDA. Nitrogen and Phosphorus Availability and Liming Effect of Poultry Layer Manures in North Carolina Coastal Plain and Piedmont Soils. (Under the co-direction of Drs. T. Jot Smyth and Carl R. Crozier).

Nutrient availability from poultry manures can be affected by soil types and manure processing. Estimates of nutrient release from manures are important when recommending their use. Three separate laboratory experiments were conducted to evaluate N and P availability, and liming value of poultry layer manures (fresh, composted, and pelleted) with surfaces samples of three NC soils: Belhaven (loamy, mixed, dysic, thermic Terric Haplosaprists), Cecil (fine, kaolinitic, thermic Typic Kanhapludults), and Lynchburg (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults). The N incubation compared N mineralization from poultry manures and urea, applied at a rate of 133 µg N cm^{-3} soil (200 kg ha^{-1}) and incubated for 90 days. Net N mineralized from the manures was described by a single pool first order kinetic model. Potential available N, estimated as the proportion of applied N, was greater for the fresh and composted manures than for the pelleted source in the three soils investigated. Nitrogen availability in fresh, composted, and pelleted manures for the Belhaven soil was 57, 53, and 46 % of total N applied, respectively; 83, 73, and 61 % of total N applied in the Lynchburg soil; and 41, 33, and 25 % for the same order of manure sources in the Cecil soil. The 21 day lime incubation compared poultry manure rates of 1333 and 2667 µg cm^{-3} of soil (2 and 4 t ha^{-1}) with multiple rates of $CaCO_3$. Liming materials in all the manures were just as effective in neutralizing soil acidity as equivalent amounts of $CaCO_3$. Nitrification of manure N, however, can reduce the net liming effect by the release of H^+. The 21 day P incubation experiment compared available P from the manures applied at rates of 1333 and 2667 µg cm^{-3} of soil (2 and 4 t ha^{-1}) with multiple rates of $Ca(H_2PO_4)_2$. A linear relationship across all P sources and rates was the best estimator of the increase in Mehlich-3 extractable P per unit of P added. These results suggested that P from the manures behaved similar to inorganic P fertilizer. Treatments in a subsequent greenhouse experiment were designed to evaluate millet [*Urochloa ramosa* (L.) T. Q. Nguyen] response to N, P and lime supplied in manures. Plant available N from the manures, estimated from the urea-N fertilizer equivalence of plant N accumulation, followed the decreasing order of fresh > composted > pelleted. This ranking among manures is similar to that obtained in the N incubation study. Millet dry matter and nutrient accumulation at targeted levels of N supply and soil values of Mehlich-3 P and pH were similar between treatments of manure supplemented with P fertilizer and lime, and treatments receiving only inorganic fertilizers and lime. These results indicate that optimum plant growth in manure amended systems requires the appropriate identification and correction of soil N, P and/or acidity constraints. Type of manure processing affects total N availability, and soil properties such as texture and buffer capacity can influence N mineralization and soil available P.

Nitrogen and Phosphorus Availability and Liming Effect of Poultry Layer Manures in North Carolina Coastal Plain and Piedmont Soils

by
Daniela Fernanda Montalvo Grijalva

A thesis submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
Requirements for the degree of
Master of Science

Soil Science

Raleigh, North Carolina

2008

APPROVED BY:

Dr. T. Jot Smyth
Co-chair of Advisory Committee

Dr. Carl R. Crozier
Co-chair of Advisory Committee

Dr. David Hardy
Member of Advisory Committee

DEDICATION

This thesis is dedicated to my parents for their endless love and unconditional support.

BIOGRAPHY

Daniela Montalvo was born and raised in Quito, Ecuador. She received her school education from Cardinal Spellman High School. In 2005, Daniela obtained her undergraduate degree in Agriculture from the Army Polytechnic School (Quito, Ecuador). Following her graduation she worked as a technician in a cut flower farm, this experience helped her to affirm her great interest in soil nutrient management, and encouraged to continue further on with her education. In the fall of 2006, Daniela was admitted to North Carolina State University to pursue her Master’s degree in Soil Science, under the direction of Dr. Jot Smyth and Dr. Carl Crozier.

ACKNOWLEDGMENTS

I would like to express my deep and sincere gratitude to my advisors Dr. Jot Smyth and Dr. Carl Crozier for their continuous support, excellent advice, and personal guidance that has lead me to the successful completion of this program. I would like to also extend my gratitude to Dr. David Hardy, member of my Advisory Committee, for his expertise and detailed comments; they have been of great value to my research work. I warmly thank Kim Hutchison, Guillermo Ramirez, Peggy Longmire, Wesley Childres, and Chris Niewoehner for their counseling in laboratory chemical techniques and in the use of analytical instruments. I also thank Neil Hardison who made several long trips to assist me in my greenhouse experiment. My profound thanks to my friends Subathra Muruganandam, Sara Knies and Wesley Childres for their help in those long days and nights of soil extractions, their constant encouragement, and the happy moments we shared outside Williams Hall. Finally, I would like to extend my deep appreciation to Bertha Monar for her help during my first weeks in Raleigh, making my transition to a new country smooth.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Poultry is one of the largest livestock industries in North Carolina and plays an important role in the state's economy. In 2006, poultry accounted for $2.9 billion in cash receipts and represented 36% of the total farm income (NCDA & CS-Agricultural Statistics Division, 2007). Although broilers are the largest poultry enterprises economically, other poultry systems are important; egg production is the 7^{th} largest cash farm commodity in North Carolina. According to the National Agricultural Statistics Service (USDA-NASS, 2008), the average number of layer chicken in North Carolina increased from 10 million in 2003 to 12 million in 2007; hence, the state ranked ninth nationally in the number of chickens, representing 3.5% of the U.S. production. The predominant counties that produce chickens in North Carolina are: Alexander, Nash, Yadkin, Iredell, Union, Randolph, and Wilkes.

Great and rapid growth of the poultry industry in concentrated regions has caused environmental concerns due to generation of large amounts of manure with limited disposal methods. Land application of poultry manure is an acceptable practice to recycle nutrients and maintain soil fertility (Moore et al., 1995).

Poultry manure is well documented as a valuable source of macro and micro nutrients (N, P, K, S, Ca, Mg, B, Cu, Fe, Mn, and Zn) and as a soil amendment (Havlin et al., 2006; Mahimairaja et al., 1995; Sims and Wolf, 1994). However, the nutrient content and availability may vary depending on the bedding material, storage and processing methods to which it is exposed (Siddique and Robinson, 2003; Chadwick et al., 2000; Van Kessel et al., 2000; Sims and Wolf, 1994).

Siddique and Robinson (2003) indicated that the total N, P, and Ca on a dry weight basis are lower in poultry litter compared to poultry manure without the bedding material. Therefore, there is a dilution effect when mixing the manure with a material low in N and P, but high in C. Nitrogen loss by volatilization during storage under covered conditions is reported by Sims and Wolf (1994), to be 30 to 45% of the total N in the poultry manure (no storage time was given). Thomsen (2004) measured 7 to 10% of N loss in poultry litter that was stored for 10 days at 15˚C.

Poultry Manure Types

Two basic types of poultry manures are distinguished based on confinement systems. For broilers the most common is the floor/litter system. Here the birds are raised on a floor. The manure commonly known as litter results from a mixture of manure and the bedding material generally consisting of a carbonaceous source such as wood chips, sawdust or peanuts hulls. The other type of poultry waste comes from caged layer chickens. In this system the birds' feces are collected in a pit and the waste with a higher moisture content contains no litter material. Both types of waste can contain feathers and feed droppings. Chadwick et al. (2000) characterized broiler litter and poultry layer manures and indicated that the total N on a dry weight basis was similar for both sources 44 and 45 g kg^{-1}, respectively. However, the C:N ratio was larger in the broiler litter than in the layer manure due to the carbonaceous material in the litter. In addition to that, the inorganic N plus uric acid content was 28 and 46% of the total N in broiler litter and layer manure, respectively.

Agricultural application of manures should try to match their nutrient release with crop nutrient uptake and minimize potential nutrient losses. Poultry manure can be applied directly to the field as fresh material, a term used for manure collected by scraping the pit where the waste is accumulated, or it can be processed before its application. Processing methods like composting and pelletizing are used to transform fresh manure into value-added products that are easy to apply, transport and store.

Composting is the biological decomposition of organic wastes under aerobic conditions that produces a more stable product, free of pathogens and viable weed seeds. Other advantages of composted over fresh manure are a reduction in weight and volume that facilitates handling and decreases odor that retards fly-breeding potential (Amanullah et al., 2006; Havlin et al., 2006; Eghball, 2002; Hadas and Portnoy, 1994). Preusch et al. (2002) reported lower C:N ratios in fresh broiler litter (8-9:1) compared to composted sources (11-15:1). Compared with N, composting did not have a consistent effect on C:P ratios, being 9-12:1 for fresh litter and 6-25: 1 for the composted source. Similar results were described by Cooperband et al. (2002).

Pelletizing manure is a process that involves drying, extrusion, and cooling of the manure providing advantages of odor and pathogens reduction and easy transportation. Pellitization offers benefits, but can alter the manure chemical composition and influence nutrient availability. Gale et al. (1991) indicated that oven drying fresh manure at 66°C decreased the total N from 5.65 to 4.01%, but did not affect the concentration of P, K, Ca, Mg, or S.

Fresh poultry manure has higher N mineralization rates than composted manure when the materials are mixed with soils. Nitrogen in the latter source is present in more stable organic forms with higher C: N ratios that can result in N immobilization (Amanullah et al., 2006). Nitrogen mineralization for composted broiler litter (produced under covered conditions) with a C:N ratio of 10:1 was 3.6% when incubated in a loamy sand and 5.8% in a sandy loam soil. However, N mineralization of fresh broiler litter with C:N ratio of 5:1 was 28.2 and 39.8%, respectively, with the loamy sand and sandy loam soils (Tyson and Cabrera, 1993).

Nutrient Forms in Manures

Nitrogen

Nitrogen in poultry manure exists in both organic and inorganic forms. The complex organic forms are more slowly available to plants and include undigested proteins. The labile organic form is uric acid which can be rapidly hydrolyzed to urea and NH_3 if the environmental conditions (temperature, pH and moisture) are favourable for microbial activity. Undigested proteins and uric acid represent 70 and 30% respectively, of the total N present in poultry feces (Groot Koerkamp, 1994).

The inorganic NH_4-N and NO_3-N in manures are the final products from the processes of mineralization and nitrification (Sims and Wolf, 1994). Because the greatest percentages of the N in poultry manures are in the organic fractions, information on the rate of mineralization is necessary to predict N availability for crop uptake.

Nitrogen mineralization in soils incubated with manures can be determined under laboratory conditions (Moore et at., 2005; Gordillo and Cabrera, 1997; Bitzer and Sims, 1988; Sims, 1986; Castellanos and Pratt, 1981). The rate of N mineralization from manures is controlled by several factors such as temperature, moisture, chemical composition of the organic material and decomposer organisms (Chadwick et al., 2000; Westerman et al., 1988; Gale and Gilmour, 1986; Castellanos and Pratt, 1981). Due to these factors, several mineralization rates are reported. For instance, Castellanos and Pratt (1981) found that under laboratory conditions 48% of the organic N in fresh poultry manures and 30% of the N in composted manures mineralized within 10 weeks of incubation.

Nitrogen Mineralization Models

The mineralization process is frequently described by a first order kinetic equation (Talpaz et al., 1981):

$$N_t = N_o (1 - e^{-kt})$$

where N_t is the mineralized N, N_o is the potential mineralizable N at t = 0, *t* is time and *k* is the mineralization rate constant.

Hadas et al. (1983) and Gordillo and Cabrera (1997) used a two-pool first-order kinetics model that considered the rapid and slow mineralization phases, suggesting that two substrates are mineralized independently.

$$N_t = N_{of} (1 - e^{-kft}) + N_{os} (1 - e^{-kst})$$

where N_t is the inorganic N at any time, N_{of} is the potential mineralizable N from the rapid phase, N_{os} is the potential mineralizable N from the slow phase, *t* is time, *kf* and *ks* are the rates of mineralization constants for the fast and slow pools, respectively.

Gordillo and Cabrera (1997a) incubated broiler litter in different types of soils and reported that 39 to 43% of potential mineralizable N corresponded to the fast pool, with mineralization rates (*kf*) of 0.9 to 4.2 day^{-1}. The mineralization rates for the slow pool were smaller with values ranging from 0.018 to 0.069 day^{-1}.

Moore et al. (2005) described the potential organic N mineralization from swine sludge with a first order equation (adapted from Chescheir et al., 1986):

$$N_t = N_o\,(1 - e^{-kt}) + N_{ss}$$

where N_t is the inorganic N, N_o is the potential mineralizable organic N, *t* is the time, *k* is the rate of mineralization, and N_{ss} is the inorganic N concentration at time = 0.

Moore et al. (2005) reported, 57 and 43% of the total available N to correspond with the potential mineralizable N (N_o), and readily available N (N_{ss}), respectively, and the estimated mineralization rate was 0.32 week^{-1}.

<u>Phosphorus</u>

Phosphorus in manures are present in organic and inorganic fractions, but most of the P is in the inorganic form (84% of total P) as indicated by Sharpley and Moyer (2000). Several studies have used sequential extractions to evaluate the forms of inorganic and organic P present in the manures (Barnett, 1994).

The variation in the plant available P extracted from soils amended with poultry manures can be explained by differences in soil types and their initial soil P levels rather than the manure sources. Preusch et al. (2002) reported higher amounts of Mehlich-1 extractable P for poultry manure incubated in a sandy loam compared to extractable P measured in a silt loam amended with the same sources, due to greater P adsorption to the clay fraction in the latter soil.

Lime Effect

The liming value of manures is attributed to their calcium carbonate content associated with the birds' feed. Layer chickens require calcium to form their skeleton and, at productive ages, for eggshell formation. Most of the common calcium sources used in animal feed are: calcium carbonate and dibasic and monobasic calcium phosphate. Increase in soil pH may occur by displacement of Al^{3+} and H^+ from exchangeable sites by basic cations from the manures and precipitation of displaced exchangeable Al^{3+} as Al hydroxide. Materechera and Mkhabela (2002) reported that the application of 5 t ha^{-1} of poultry layer manure with 26% $CaCO_3$ equivalence in an acid Oxisol reduced the acid saturation from 72 to 28% and increased slightly the soil pH from 4.11 to 4.28.

Nutrient Management

Rates of poultry manure application are usually calculated to meet crop N requirements; the reason to support this approach is the manure's high N contents. Several studies reported that excessive application of manures have caused serious environmental problems like groundwater contamination by NO_3-N and eutrophication of surface waters by runoff from soils with large accumulations of P (Vervoort et al., 1998; Sims and Wolf, 1994). When fertilizing crops with poultry manures, factors like manure type, soil types and previous land use should be considered to ensure efficient nutrient use and avoid environmental concerns. Manure types determine the forms of nutrients (N, P) which are present. After the manures are applied to the soil, however, other factors interact and affect plant nutrient availability. For instance, plant availability of inorganic P from manures can be reduced by adsorption to the surfaces of Fe and Al oxides and clay minerals, or it can precipitate as Fe and Al phosphates in acid soils. Another aspect to be addressed is the soil's land use history. Manure-enriched soils contain more organic C, exchangeable Ca, total P and higher pH values relative to non-amended soils (Haynes and Naidu, 1998; Sharpley et al., 2004). Soil properties (pH, organic matter, texture) and previous land use are important to consider in addition to the manure types, when determining nutrient availability (N and P) and liming effect from the manure amended soils.

Poultry manures are a complete source of plant nutrients; however, few studies have evaluated their fertility value (N, P, and lime) and the potentially different responses associated with soil types and previous land use. The main objectives of this investigation were 1) to evaluate N and P availability, and liming value of three sources of poultry layer manures through laboratory incubations with surfaces samples of three North Carolina soils and 2) to assess manure N and P fertilizer value and liming effect through plant dry matter production and nutrient accumulation in a subsequent greenhouse experiment with the same manure sources and soils.

MATERIALS AND METHODS

Poultry Layer Manures

Three sources of poultry layer manures were evaluated in laboratory incubation studies and a greenhouse experiment: 1) fresh layer manure from Red Hill Farm, Nash County, NC, 2) composted layer manure from Rose Acre Farm, Hyde County, NC, and 3) commercially available pelletized manure from Rose Acre farms, Jackson County, IN. The fresh material was collected directly from the layer facilities; the composted manure was produced under covered conditions; and the pelleted manure production process involved the extrusion of fresh manure followed by drying for 10 minutes and cooling before packing.

The manure samples were mixed thoroughly and ground to pass through a 2-mm sieve. A subsample of each source was analyzed by the North Carolina Department of Agriculture and Consumer Service (NCDA & CS) waste analysis laboratory for total C and N using the method of oxygen combustion, NH_4-, NO_3-, and urea-N by sulfuric acid extraction (Campbell, 1992). Total P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na were analyzed in extracts from a nitric acid digestion by inductively coupled plasma emission spectroscopy (ICP) (Campbell and Planck, 1992; Donohue and Aho, 1992). Calcium carbonate equivalence (CCE %) was determined by titration and pH was measured in water (AOAC, 1990). The manure sources were stored in polyethylene plastic bags and refrigerated at 4^{o} C until used.

Soil Collection and Chemical-Physical Characterization

Three surface soil samples low in P were selected to represent each class (mineral, mineral-organic, and organic) defined by the NCDA & CS soil testing service (Hardy et al., 2008). The samples corresponded to three North Carolina soil series: Belhaven (organic class; loamy, mixed, dysic, thermic Terric Haplosaprists), Cecil (mineral class; fine, kaolinitic, thermic Typic Kanhapludults), and Lynchburg (mineral-organic class; fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults) (Soil Survey Staff, 2008).

The Belhaven soil was collected from an agricultural field under long-term corn-soybean cultivation in Carteret County. The Cecil soil was collected from Wake County and the land use of the site was pasture. The Lynchburg soil was collected in Pitt County from a field that was planted to the first crop of corn after timber harvest and forest clearing.

Bulk soil was collected from a 5 to 15-cm depth, air dried, and sieved to pass a 4-mm sieve, followed by thorough mixing. A subsample ground to pass through a 2-mm sieve was used for soil chemical and physical characterization and the subsequent laboratory incubation studies.

Soil pH (1:2.5 soil/deionized water ratio) was measured using a glass electrode after stirring for 10 minutes, allowing the mixture to stand for 30 minutes and stirring again for 2 minutes before measurement. Exchangeable acidity (H and Al), Ca and Mg were extracted using 1M KCl solution; P, K, Cu, Fe, Mn, and Zn were extracted with the Mehlich-3 solution (Mehlich, 1984). All the exchangeable cations were extracted with a 1:10 soil/solution ratio, (with 10 minutes shaking in the case of the 1M KCl solution and 5 minutes with the Mehlich-

3 extractant) and filtered through a medium flow 8-µm filter paper. Exchangeable acidity was determined by titration of an aliquot with 0.01 M NaOH to the phenolphthalein indicator endpoint. Calcium, Mg, K, Fe, Mn, Cu, and Zn were analyzed by atomic absorption spectrometry. Ammonium- and NO_3-N were also extracted with 1M KCl at a 1:10 soil/solution ratio, shaken for 30 minutes and filtered through prewashed filter paper. Ammonium-N, NO_3-N and P were measured using Lachat QuickChem Methods 10-107-06-2-A, 10-107-04-1-A and 10-115-01-1-B, respectively (Lachat Instruments, 1995). Total soil carbon was determined by oxygen combustion. Soil texture was determined using the pipette method (Gee and Bauder, 1986), after prior oxidation of the organic matter with hydrogen peroxide on the Lynchburg and Belhaven samples. Duplicate samples were analyzed for soil texture, triplicate samples for total carbon and quintuple samples for the chemical analyses.

Soil Water Container Capacity

Container water holding capacity was determined on duplicate samples of each soil using a stack of 10 rings, each with an inside diameter of 7.7 cm and 2.6 cm length (Cassel and Niesel, 1986). Air dried soil ground to pass a 2-mm sieve was added to the stacked rings and weighed. Deionized water estimated to approximate water holding capacity of five rings of soil was added to the top and allowed to redistribute within the column for 24 hours. Thereafter, a subsample of 20 g was taken from each of the ten rings and oven-dried at 105^{o}C for 24 hours to determine gravimetric soil water content. Container capacity was determined as the mean water content of the surface soil segments, once the excess of water had drained into the underlying layers. Due to the hydrophobic properties of the air-dried Belhaven sample, the soil was pre-moistened by spraying with water, mixing and equilibrating for 24 hours before adding the soil to the column rings. Additional water was added to the top and soil moisture determinations were made after 48 hours of gravitational draining.

Nitrogen Mineralization Study

This laboratory incubation study compared N mineralization from three poultry layer manures and reagent grade urea, each applied at the rate of 133 μg N cm^{-3} of soil (200 kg N ha^{-1}). A fifth N treatment for each soil was a control without added N. Therefore, the experiment consisted of a factorial arrangement of 3 soils, 5 N treatments and 3 replications. Soil samples (260 cm^3) were placed in sealable 0.045mm-thick plastic bags with dimensions of 17.8 x 20.3 cm. The manure sources were added in a solid form and urea as a solution, and thoroughly mixed with the soil. Soils were moistened to 80% container capacity, stored at room temperature and weighed bi-weekly to readjust water content whenever moisture loss was greater than 5% on a weight basis. All bags were opened to ensure adequate aeration at each bi-weekly weighing. On days 0, 3, 14, 30, 60, and 90 of incubation, a 10-cm^{-3} subsample of soil was taken from each bag for determination of KCl-extractable NH_4- and NO_3-N.

Belhaven samples were pre-moistened 48 hours before the N sources were added to start the incubation, due to the soil's hydrophobic properties. Seven days prior to adding the N sources to the Lynchburg samples, 4533 μg of reagent grade $CaCO_3$ cm^{-3} of soil (6.8 t ha^{-1})

were added to pre-moistened soil to raise the initial soil pH of 3.8 to 5.5. The appropriate amount of $CaCO_3$ was pre-determined in a 14-day incubation study, wherein 200 g of air dried soil sieved to pass a 2-mm screen were incubated at room temperature and 90% of container capacity in sealable plastic bags with $CaCO_3$ at rates of 0, 1333, 2667, and 5333 µg cm^{-3} of soil (0, 2, 4, and 8 t ha^{-1}).

Lime Incubation Study

The experiment evaluated the liming effect of the manures when compared to $CaCO_3$ in three North Carolina soils. The lime treatments consisted of two rates of chicken layer manures, 1333 and 2667 µg cm^{-3} of soil (2 and 4 t ha^{-1}), that were common for all the soils, and multiple rates of $CaCO_3$ that were specific to each soil: 0, 667, 1333, and 2667 µg cm^{-3} soil (0, 1, 2, and 4 t ha^{-1}) for Belhaven; 0, 333, 667, and 1333 µg cm^{-3} soil (0, 0.5, 1, and 2 t ha^{-1}) for Cecil; and 0, 1333, 4000 and 6667 µg cm^{-3} soil (0, 2, 6, and 10 t ha^{-1}) for Lynchburg. The experiment was a factorial combination of ten lime treatments with three replicates for each soil.

Soil samples (360 cm^3) were placed in sealable plastic bags (0.045mm thick) and lime sources were added and mixed thoroughly with the soil. Soils were moistened to 80% container capacity. The Belhaven samples were pre-moistened 48 hours prior to the addition of the lime sources. The bags were stored at room temperature throughout the incubation. Soil subsamples were taken from each bag at 0, 7, 14, and 21 days of incubation and analyzed for pH in water, KCl-extractable Ca, Mg and exchangeable acidity, and Mehlich 3-

extractable K as previously mentioned.

Phosphorus Incubation Study

The experiment compared available P from the manure sources with reagent grade monocalcium phosphate [$Ca(H_2PO_4)_2$] when applied to the unlimed soils. An additional soil treatment consisted of the Lynchburg limed to a pH of 5.5. The P treatments consisted of chicken layer manures rates of 1333 and 2667 $\mu g\ cm^{-3}$ of soil (2 and 4 t ha^{-1}) and various rates of $Ca(H_2PO_4)_2$. For Belhaven and Lynchburg soils, the rates of $Ca(H_2PO_4)_2$ were 0, 13, 27, and 40 $\mu g\ cm^{-3}$ of soil (0, 20, 40, and 60 kg ha^{-1}) and rates for the Cecil soil were 0, 33, 67, and 100 $\mu g\ cm^{-3}$ of soil (0, 50, 100, and 150 kg ha^{-1}). The experiment was a factorial combination of 10 P treatments with 3 replicates for each of the four soils.

Soil samples (258 cm^3) were placed in sealable plastic bags (0.045mm thick) and P sources were added and mixed with the soil. Soils were moistened to 80% container capacity. The Belhaven soil was moistened 48 hours prior to the addition of the P sources. The bags were stored at room temperature throughout the incubation period. On days 0, 7, 14, and 21 soil subsamples were taken from each bag and analyzed for Mehlich-3 extractable P and water soluble P (Kuo, 1996).

Greenhouse Experiment

A greenhouse experiment was conducted to evaluate aboveground plant biomass and nutrient accumulation as affected by the three layer manure sources, urea, and $Ca(H_2PO_4)_2$.

Soil fertility treatments shown in Tables 1 – 3 were established to characterize plant growth response to N, P and lime in the Belhaven, Cecil, and Lynchburg soils, respectively.

The fertilizer treatments included rates of 0, 25, 49, 74, and 99 μg N cm^{-3} of soil (0, 37, 74, 111, and 148 kg N ha^{-1}) applied as urea with the optimum level of P (NCDA & CS recommendation of 60 mg dm^{-3}) (Hardy et al., 2008) as $Ca(H_2PO_4)_2$. Phosphorus requirement was calculated considering each soil's P buffer capacity, being: 45 μg P cm^{-3} of soil (68 kg P ha^{-1}) for Belhaven, 119 μg P cm^{-3} soil (178 kg P ha^{-1}) for the Cecil, 29 μg P cm^{-3} soil (44 kg P ha^{-1}) for the limed Lynchburg, and 33 μg P cm^{-3} soil (49 kg P ha^{-1}) for the unlimed Lynchburg. For the manure treatments, each source was applied on a N-basis (111 kg N ha^{-1}) and complimentary P in the form of $Ca(H_2PO_4)_2$ was added to reach the optimal level that was not supplied by the manures. The complimentary rates of $Ca(H_2PO_4)_2$ used in the Belhaven soil were 29 μg P cm^{-3} of soil (44 kg P ha^{-1}) for fresh manure, 20 μg P cm^{-3} soil (30 kg P ha^{-1}) for composted manure, and 19 μg P cm^{-3} soil (28 kg P ha^{-1}) for pelleted manure. For the Cecil soil, complimentary P rates were 103 μg P cm^{-3} soil (154 kg P ha^{-1}) for fresh manure, 93 μg P cm^{-3} soil (140 kg P ha^{-1}) for composted manure, and 92 μg P cm^{-3} soil (138 kg P ha^{-1}) for pelleted manure. For the Lynchburg soil, complimentary P rates were 13 μg P cm^{-3} soil (20 kg P ha^{-1}) for fresh manure, 4 μg P cm^{-3} soil (6 kg P ha^{-1}) for composted manure, and 3 μg P cm^{-3} soil (4 kg P ha^{-1}) for pelleted manure. Plant response to P was evaluated on an additional treatment without added inorganic P, but with the optimum level of N (111 kg N ha^{-1}) applied as either urea or each of the three manure sources.

The Lynchburg soil was limed with $CaCO_3$ to reach a pH of 5.5 seven days prior to the addition of the fertility treatments. On the manure treatments, supplementary $CaCO_3$ was added to achieve the target pH. A treatment without lime, yet receiving optimum rates of urea-N and inorganic P, was also included.

Pots were placed on one greenhouse bench at the N.C. State University Method Road greenhouse facilities in a complete randomized block design with 12 treatments for the Belhaven and Cecil soils, 13 treatments for the Lynchburg soil and 3 replications. Treatments for each pot were applied and mixed thoroughly with 1200 cm^3 of soil sieved to pass a 4-mm screen. Soils were moistened to 90% container capacity. The Belhaven soil was pre-moistened 48 hours prior to the addition of the treatments.

Ten seeds of millet [*Urochloa ramosa* (L.) T. Q. Nguyen] cv. Browntop were planted in each pot and thinned to 5 plants per pot on day 14. Pots were watered 2-3 times each day with daily weighing to ensure maintenance of 90% water container capacity.

At day 30 of the experiment, plant tops were harvested, dried at 65^oC for 48 hours and weighed. The dry plant material was ground and analyzed for total N by the method of oxygen combustion, while total P, K, Ca, Mg, Mn, Cu, Fe, and Zn were extracted by acid digestion and determined with ICP. The soil from the pots was analyzed for Ca, Mg, and acidity using 1M KCl extraction method described previously. A complete routine nutrient analysis was also performed at the NCDA & CS soil testing laboratory, where: P, K, Ca, Mg, Mn, Zn, Cu, S, and Na were extracted with Mehlich-3 solution (Mehlich, 1984) and determined using ICP. Soil acidity was measured using Mehlich-buffer method (Mehlich et al., 1976).

Statistical Analysis

The analysis of variance was performed for each soil for the N, P, and lime incubation studies and the greenhouse experiment using the PROC ANOVA procedure of Version 9.1.3 of the Statistical Analysis System software (SAS Institute, 2003). Regression analyses were also performed using either the PROC REG or PROC NLIN procedures in SAS. Least significant differences (LSD) were calculated using the appropriate standard errors for effects which were significant in the analysis of variance at the 0.05 probability level.

RESULTS AND DISCUSSION

Soil Characterization

Soil chemical and physical properties are summarized in Tables 4 and 5. All soils were low in Mehlich-3 extractable P, meeting one of the selection criteria of soils for this study. Phosphorus concentrations corresponded to NCDA & CS P indices of 13, 8, and 30 (16.0, 9.3, and 35.6 μg P cm^{-3}), respectively for the Belhaven, Cecil, and Lynchburg soils. The NCDA & CS soil test laboratory uses a numerical index system to report the nutrient level on a soil. Indices in the range of 0 to 25 and 26 to 50 characterize low and medium nutrient content, hence the application of fertilizers is recommended to achieve high crop yield response. Values greater than 50 and greater than 100 indicate high and very high nutrient content on the soil, respectively; and fertilizer application is not recommended (Hardy et al., 2008).

The Lynchburg soil presented the highest level of exchangeable acidity, which correlated with the low pH value measured. Exchangeable Ca and Mg were higher in the Belhaven than in the other soils and the pH value of 4.8, along with only 1% acid saturation in this organic soil, indicated that a major proportion of the exchangeable acidity was in the form of H^+. The higher concentrations of NH_4- and NO_3-N in the Lynchburg soil were attributed to the application of inorganic N fertilizers to the initial corn crop before sampling this soil after clearing and harvesting timber. Due to the range of density values from 0.4 to 0.9 g cm^{-3} among the soils and to facilitate comparisons between soils, results will be presented on a volume basis.

Soil Water Container Capacity (2-mm Sieved Soil)

Soil water container capacity is the maximum amount of water the soil can hold after gravitational water has drained. In the Belhaven soil, the highest soil water content occurred in the four upper rings of the cylinder while for the Cecil and Lynchburg soils, this was observed in the upper five and two rings, respectively (Fig. 1). The average values from these top layers of each cylinder were used as the water container capacity for each soil and were expressed as a volume percentage (%V). Therefore, the volumetric water container capacity for the Belhaven soil (61%) was higher than for the Cecil (24%) and Lynchburg (30%) soils.

Poultry Layer Manure Characterization

Chemical properties of the three sources of poultry layer manures (fresh, composted, and pelleted) are summarized in Table 6. Total N concentrations were in the order of fresh > composted > pelleted with corresponding values of 65, 53, and 37 g kg^{-1}, respectively. Inorganic N content (NH_4-N + NO_3-N) for the fresh and composted sources were 2-fold that of the pelleted manure. The lower total N value for the pelleted source can be explained as N lost by volatilization during the drying process in its preparation. Gale et al. (1991) found that oven drying fresh poultry layer manure at 66^{o}C reduced the total N content from 5.65 to 4.01%. Phosphorus content of the manures was 13, 14, and 18 g kg^{-1} for pelleted, fresh, and composted manures, respectively. The pH values for the fresh and composted manures were greater than for the pelleted source. The acid neutralization potential of the manures expressed as weight percentage of $CaCO_3$ was 23, 30, and 36% for composted, fresh, and pelleted manures, respectively.

Nitrogen Mineralization Study

Lime Requirement for the Lynchburg Soil

Lime was applied to the acid Lynchburg soil 7 days prior to the N mineralization trial, to minimize potential inhibition of nitrification by the elevated acidity levels. The amount of lime to add was determined from a preliminary incubation of the Lynchburg soil with multiple quantities of $CaCO_3$ ranging from 0 to 5333 μg $CaCO_3$ cm^{-3} of soil (0 to 8 t ha^{-1}). A linear relationship between soil pH and added $CaCO_3$ was found (Fig. 2). Based on the linear regression equation, the target pH of 5.5 was achieved by the addition of 4533 μg $CaCO_3$ cm^{-3} soil (6.8 t ha^{-1}) to the Lynchburg soil.

Analysis of Variance

The analysis of variance by soil indicated significant effects for N-sources, sampling time and the interaction between N sources and sampling time on the levels of NH_4-N, NO_3-N and net inorganic N within each soil (Table 7). As explained below, the net inorganic N released to the soil from the various N sources is adjusted for the inorganic N mineralized from the control treatments without added urea or manure; therefore, the degrees of freedom for the net inorganic N are less than for soil levels of NH_4-N and NO_3-N.

Nitrogen Mineralization from Native Soil Organic Reserves

The control treatments, without added N, were included in the experiment to evaluate N availability and forms from existing reserves in each soil. The conversion of organic soil N to inorganic forms (NH_4-N and NO_3-N) involves biological processes mediated by enzymes produced by microorganisms; therefore, factors affecting microbial activity such as soil moisture, temperature, pH, and nutrient availability among others, can affect these processes (Stevenson, 1986). Figure 3 illustrates the patterns of N mineralization and nitrification observed in non-amended soils throughout the incubation period. For the initial 3 days, NH_4-N increased by 5 μg cm^{-3} in the Belhaven soil and 16 μg cm^{-3} in the Cecil soil. Thereafter, NH_4-N decreased to negligible concentrations due to nitrification resulting in higher levels of NO_3-N.

In the Lynchburg soil, N accumulated primarily in the form of NH_4-N, and NO_3-N concentrations remained constant up to day 60; at day 90 of the incubation significant nitrification was observed. The high initial concentrations of NH_4-N (98 μg cm^{-3} soil) and NO_3-N (51 μg cm^{-3} soil) in the soil suggest that a mixed NH_4 and NO_3 source of fertilizer N was applied to the corn crop before the soil was sampled for these investigations. Furthermore, for nitrification to occur nitrifier populations needed to be present and active in the soil. Nitrification can take place over a wide range of soil pH values; however, nitrifying bacteria grow better under neutral pH values and their activity is often limited under acidic conditions (Sylvia et al., 2005). Dancer et al. (1973) showed a linear relationship between NO_3-N accumulation and soil pH, where a 4-fold increase in nitrification occurred by raising the pH from 4.7 to 6.5. In the present study, at day 30 of the incubation soil pH was measured in all samples. The average pH in the control treatments of the Lynchburg soil was 5.6, indicating that good environmental conditions were achieved with liming and that nitrifier populations may require more time to reestablish and become active. This appeared to occur as noted by higher levels of NO_3-N at day 90.

Net NH_4- and NO_3-N Release Patterns from N Sources

Net NH_4- and NO_3-N was calculated by subtracting at each sampling time NH_4-N and NO_3-N measured in the non-amended control samples from its corresponding N form in the N-treated samples. This corrects for N mineralization of indigenous N in the soil and evaluates NH_4-N and NO_3-N release by the N sources.

Accumulation of N in the NH_4-N form during the three initial days of incubation in Belhaven and Cecil soils was attributed to the mineralization of readily degradable organic forms of N. Maximum net NH_4-N concentrations among N sources at day 3 of the incubation for the respective sources of fresh, composted, pelleted manures, and urea were 57, 60, 43, and 98 µg NH_4-N cm^{-3} in the Belhaven soil, and 46, 38, 27, and 100 µg NH_4-N cm^{-3} in the Cecil soil. Thereafter, a rapid decline in net NH_4-N was observed which coincided with net NO_3-N accumulation due to the nitrification process (Fig. 4).

In the Lynchburg soil, net inorganic N accumulated primarily as NH_4 and nitrification was not detected until day 90 (Fig. 5). At day 60 of the incubation, sample extracts were also analyzed for NO_2-N to determine whether delayed net NO_3-N accumulation was associated with limited activity of *Nitrobacter* which is involved in the oxidation of NO_2^- to NO_3^-. However, NO_2-N was not detected, suggesting that the conversion of NH_4^+ to NO_2^- by *Nitrosomonas* was also limited. The delay in nitrification, due to limited activity of nitrifying bacteria, is also supported by the initial high NH_4-N concentrations found in the control treatment without added N, as described in the previous section. The patterns of NH_4-N and NO_3-N accumulation among the N sources are similar to that described for the control treatments.

The patterns of N mineralization in the Belhaven and Cecil soils are similar to those reported in previous studies by several authors. Gordillo and Cabrera (1997), Tyson and Cabrera (1993), Gale and Gilmour (1986), and Hadas et al. (1983) found that the maximum net inorganic N released from poultry manure occurred during the seven initial days of incubation (rapid phase) followed by a period of slow N release (slow phase). This indicates that a fraction of organic N from the manures can rapidly mineralize and convert to plant available forms.

Nitrogen Mineralization Models

Potential N mineralization from each N source was estimated by regressing net inorganic N (N_t) as a function of time using a first order kinetic model that assumes a single organic N pool (N_o). Nonlinear regression was used to derive the equation parameters reported in Table 8. The equation values are these which gave the least sum of squares for the error term when the convergence criterion was met.

Figures 6 – 8 illustrate N release from manure sources and urea in all soils investigated. The potential mineralizable N (N_o) values for the fresh, composted, and pelleted manure treatments were 75.2, 70.7, and 61.4 μg N cm^{-3} soil for the Belhaven soil and 110.7, 97.0, and 80.9 μg N cm^{-3} soil for the Lynchburg soil (Table 8). These values are higher than those predicted for the Cecil soil, 53.9, 43.6, and 33.9 μg N cm^{-3} soil for fresh, composted, and pelleted manures, respectively. Gordillo and Cabrera (1997a) and Chescheir et al. (1986) reported small amounts of N mineralized from poultry manures when applied to soils with large clay contents. This was corroborated by Sorensen and Jensen (1996) who observed that N mineralization of sheep urine and urea was similar in a sandy soil, but diminished for urine applied in a sandy loam soil. The authors' explanation attributed immobilization of urine-N and protection of microbial biomass with increasing clay content. Due to the high total N content found in poultry manures, immobilization is less possible to occur. However, protection from decomposition of the organic compounds by binding on clay surfaces or entrapment of the material in sites that are inaccessible to microorganisms may be associated with this phenomenon.

The concentrations of readily available forms of N (NH_4-, NO_3-, and urea-N) in the poultry layer manures comprise about 12, 15, and 11 μg N cm^{-3} soil from the total N applied (133 μg cm^{-3}) for fresh, composted, and pelleted manures, respectively. The amount of N available in these N fractions is relatively small when compared to the estimated quantities of potentially mineralizable N.

At day 0 of the incubation the amount of applied N that was readily available for the fresh and composted sources averaged 23% in the Belhaven and 26% in the Lynchburg soil, while in the Cecil soil it was of 15%. From the pelleted manure about 9% of the applied N was readily available in Belhaven and Cecil soils and 16% on the Lynchburg soil (Fig. 6 – 8). The inorganic N measured at day 0 indicates that the manure sources contain readily available forms of N that can mineralize and be immediately available after soil incorporation.

Potentially available N, estimated as the proportion of total N applied in the N_o fraction, was greater for the fresh and composted manures than for the pelleted source, in the three soils investigated. The potentially available N for fresh, composted, and pelleted manures was 57, 53, and 46 %, respectively, in the Belhaven soil and 83, 73, and 61 % in the Lynchburg soil; N availability in the Cecil soil was 41, 33, and 25 % for the same order of manure sources.

Chescheir et al. (1986) reported N availabilities from poultry layer manures of 51% and 44% after 182 days of incubation with Norfolk and Cecil soils, respectively. Preusch et al. (2002) observed significantly greater N mineralization rates from fresh broiler litter (42 to 64%) than from composted broiler litter (1 to 9%). The current study agrees with previous reports that differences in soils affect N mineralization rates. Nitrogen release from fresh and composted manures were similar and superior to that from the pelleted manure source. These results suggest that differences in soils and manure processing are important when estimating potentially mineralizable N. Furthermore, the soluble urea N source released the highest amount of N (80 % average of three soils) independently of the soil type.

Manure N recommendations by NCDA & CS for the first crop year after application are based on the adjustment of the total N content of the manure by a coefficient factor. The factor value differs between manure incorporation or surface application (Shaffer and Cleveland, 2008). Considering the total N analysis reported in Table 6 and the incorporation of manures in the present study, NCDA & CS recommendation would predict that 58, 49, and 58% of the total N in fresh, composted, and pelleted manures would be available to the first crop. When compared to estimates of percent available N in Table 8, the NCDA & CS recommendations would underestimate the values of available N in the Lynchburg soil by a factor of 1.4 for the fresh manure and by 1.5-fold for the composted manure. Similar comparisons for the Cecil soil indicate that NCDA & CS recommendations would overestimate percent available N in the manures by 1.4 to 2.3-fold.

Lime Incubation Experiment

Analysis of Variance

The analysis of variance by soil indicated that treatment and time effects for soil pH, acid saturation (%), Ca, Mg, and ECEC were significant for all soils. The time by treatment interaction effects were significant for these variables in the Lynchburg soil; while in the Cecil soil, the interaction effects were significant for acid saturation (%) and Ca (Table 9). Nevertheless, results will be presented as average values across sampling dates to facilitate comparisons between soils.

Effects on Soil pH and Acid Saturation (%)

As shown in Table 6, the calcium carbonate equivalence (CCE %) of the poultry layer manures was 23, 30, and 36 % for composted, fresh, and pelleted manures, respectively. These values are similar to the 22% reported by Naramabuye and Haynes (2006) and the 26% reported by Materechera and Mkhabela (2002) who used fresh poultry manure collected from commercial layer facilities in their investigations.

The addition of $CaCO_3$ and poultry layer manures altered the pH value of all soils, and was particularly evident across the broad range of applied $CaCO_3$ (Fig. 9). When treatment pH values were related to the $CaCO_3$ equivalents, added as either reagent grade $CaCO_3$ or manures, all data for each soil were described by a single linear regression function. These results suggest that the liming materials in the manures are just as effective in neutralizing soil acidity as an equivalent amount of lime.

Reductions in the % acid saturation of the soil's ECEC for each $CaCO_3$ and manure treatment were also related to added $CaCO_3$ equivalents through exponential regression functions (Fig. 10). Whereas a single function described the relation between % acid saturation and added $CaCO_3$ from all sources in the Lynchburg soil, differences were noted between the organic and inorganic lime sources in the Belhaven and Cecil soils. In these two soils the application of poultry layer manures was less effective in reducing % acid saturation than equivalent amounts of $CaCO_3$. The observed difference between soils could be due, in part, to the amount of acid saturation (%) of the unlimed treatments between the Lynchburg soil (almost 60%) and the Belhaven and Cecil soils (less than 2%).

Another reason for the reduced lime efficiency of the manures could be associated to the H^+ released during nitrification of NH_4^+ as shown in the following reaction (Haynes and Mokolobate, 2001):

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

Therefore, poultry manures provide an additional source of acidity to be neutralized by the added $CaCO_3$.

The N mineralization experiment indicated that nitrification did not occur in the Lynchburg soil within the timeframe of this lime incubation experiment. Consequently inorganic N accumulated as NH_4^+ and there would be release of OH^- by the following mineralization reaction of organic N:

$$\text{Organic N} \rightarrow NH_4^+ + OH^-$$

This would lead to greater efficiency in the reduction of soil acidity by the lime equivalents added in the manures. These results suggest that the potential liming value of poultry layer manures is dependent on their $CaCO_3$ equivalence and the extent to whether N mineralization proceeds through ammonification and nitrification.

Effects on Exchangeable Cations and Effective Cation Exchange Capacity (ECEC)

The application of poultry layer manures increased the concentration of Ca, Mg, K, and the ECEC of the Cecil and Lynchburg soils when compared to the control treatment (Table 10). Levels of Ca and Mg were considerably greater in the Belhaven soil and the application of manures increased the soil K levels.

Phosphorus Incubation Study

Analysis of Variance

The analysis of variance for each of the four soil treatments indicated significant effects for treatments (P source and rates) on measured values of Mehlich-3 extractable P and water soluble P (Table 11). There was a significant effect of sampling date (time) during the incubation on both measured P variables in the Cecil and the unlimed Lynchburg soils, whereas only water soluble P changed with sampling date in the limed Lynchburg soil. Treatment by time interactions were significant only for the variable of water soluble P in the Cecil and the limed Lynchburg soils. Therefore, results are presented as either, P sources and rates averaged across time or sampling dates averaged across P sources and rates.

Mehlich-3 Extractable P

The Mehlich-3 extractant (Mehlich, 1984) is a common soil test used to quantify plant available P in neutral and acid soils. As illustrated in Fig. 11, Mehlich-3 extractable P levels in all soils were related to the amount of applied P regardless of the P source. The increase in Mehlich-3 P per unit of added P in soil samples receiving P as poultry layer manures was similar to treatments receiving P as $Ca(H_2PO_4)_2$. Therefore, a linear regression across all P sources and rates was used to estimate the increase in Mehlich-3 extractable P per unit of P added. Sharpley and Moyer (2000) indicated that 84 % of total P found in poultry manure was in the inorganic form. The absence of a difference in Mehlich-3 values for similar amounts of added P from either manures or inorganic P fertilizer supports this observation. Preusch et al. (2002) reported similar Mehlich-1 extractable P concentrations for soils amended with either fresh or composted broiler litter.

Although the source of applied P did not affect changes in Mehlich-3 P, the slopes of the regression equations (Fig. 11) indicate that the increase in Mehlich-3 P per unit of added P differed among the four soil treatments. The smallest slope value was calculated for the Cecil soil (0.46) followed by the Belhaven and unlimed Lynchburg soils (0.87). A slope value greater than 1.0 for the limed Lynchburg soil is associated with the highest mean square error term in this soil treatment.

The most pronounced reduction in Mehlich-3 extractable P with incubation time was observed with the Cecil soil, decreasing from 28.8 µg P cm^{-3} soil after P treatments were added on day 0 to 20.5 µg P cm^{-3} soil on day 21 (Fig. 12). The Cecil soil contained the highest amount of clay (12 %) and the mineral commonly found in the clay fraction of this soil series is kaolinite (Soil Survey Staff, 2008a). Therefore, the reduction in Mehlich-3 soil P can be explained by P adsorption to surface hydroxyl (OH) and aluminol (AlOH) groups that occur on the broken edges of kaolinite clay minerals, and to Fe and Al oxide and hydroxide minerals that are normally found in highly weathered soils (Havlin et al., 2006 and Sparks, 2003).

Liming the acid Lynchburg soil neutralized exchangeable Al present in this soil by precipitating it as $Al(OH)_3$, thus increasing soil P availability. This was evident in the limed Lynchburg soil treatment where at day 21 of the incubation Mehlich-3 extractable P was 62.2 µg P cm^{-3} soil, whereas in the unlimed Lynchburg soil it was of 54.0 µg P cm^{-3} soil (Fig. 12).

Water Soluble P

Water soluble P or environmental P test is a good indicator of the potential loss of P by runoff (Kleinman et al., 2002). Figure 13 indicates that water soluble P for all P treatments within each soil increases as a linear function of the quantity of added P. In the Cecil and limed Lynchburg soils, the intercepts of the equations were not significant and the negative value of the Cecil soil can be explained by adsorption of P in the clay fraction.

Differences in soil P extracted by the Mehlich-3 and water soluble methods reflect measurement of different soil P fractions. The Mehlich-3 soil test extracts both the soluble P and the labile soil P (the capacity of the soil to sustain available P), whereas the water soluble P extracts the soil solution P (intensity factor). Therefore, the latter method measures a smaller pool of soil P.

The linear regression slopes relating water soluble P to added P for the Cecil and Lynchburg soils (limed and unlimed) were considerably less than for the Belhaven soil (Fig. 13). The lowest value was observed in the Cecil soil, which can be related to a higher buffer capacity of this soil. Water soluble P also decreased with time in the Cecil and Lynchburg soils (Fig.12).

Calculation of Soil P Buffer Capacities

Soil P buffering capacity was determined for each soil treatment by subtracting the average across four sampling dates of Mehlich-3 extractable P of the control samples (no P added) from the extractable P of the amended samples. When related to quantities of applied

P, linear regression slope values provide an estimate of the increment in Mehlich-3 extractable soil P per unit of applied P. Since the Mehlich-3 increment is zero without applied P the linear regression forced the intercept parameter to pass through the origin (Fig. 14). The slope values for each soil treatment were 0.45, 0.90, 1.00, and 1.21 µg P increment cm^{-3} soil/ µg P added cm^{-3} soil, for the Cecil, Belhaven, unlimed Lynchburg, and limed Lynchburg soils, respectively. The lower P buffer capacity value for the Cecil is consistent with its greater clay content and P sorption capacity. These P buffer capacity values were used to determine quantities of applied P needed to achieve specific Mehlich-3 soil P levels in the following greenhouse experiment.

Greenhouse Experiment

<u>Soil Water Container Capacity (4-mm Sieved Soil)</u>

The volumetric water container capacity for the Belhaven (54%), Cecil (27%), and Lynchburg (28%) soils were calculated by the mean water content values of the four upper rings of the cylinders for the Belhaven and Cecil soils and the average of two upper rings of the cylinder for the Lynchburg soil after excess water added to the surface had drained into the underlying cylinders of dry soil (Fig. 15). The water container capacity of the 2-mm sieved Belhaven and Lynchburg soils were slightly greater than the calculated for the same soils but sieved to pass a 4-mm sieve. The opposite was observed in the Cecil soil, where the mean water content in the 4-mm sieved soil was greater than the corresponding 2-mm sieved soil.

Lime Requirement for the Lynchburg Soil

Calcium carbonate was applied to the limed Lynchburg soil treatments 7 days before starting the experiment. The amount of lime applied was calculated using the regression equation developed from the data of the previous lime incubation trial in the laboratory (Fig. 9). Therefore, 4104 µg $CaCO_3$ cm^{-3} soil (6.2 t ha^{-1}) were added in order to reach the target soil pH of 5.5.

Analysis of Variance of Soil Chemical Properties

As shown in Table 12, the analysis of variance by soil indicated significant treatment effects on pH, buffer acidity, cation exchange capacity (CEC) and Mehlich-3 extractable Ca, Mg, P, S, Mn, Cu, and Zn in post-harvest analysis of the Belhaven soil. In the Cecil soil treatment effects were significant for all measured variables except Mehlich-3 extractable Cu and Zn, and KCl-extractable acidity. Only the Mehlich-3 extractable K was not significantly different among the treatments in the Lynchburg soil. There were more degrees of freedom in the analysis of variance for the Lynchburg soil, because additional treatments were included to evaluate a response to lime.

Effects of Fertility Treatments on Mehlich-3 Extractable Soil P

Post-harvest soil P data corroborate the results reported for the previous laboratory incubation experiment with P additions, wherein Mehlich-3 extractable P in each soil increased with the quantity of applied P regardless of the sources evaluated (Tables 13 – 15).

Mehlich-3 soil P values for treatments targeting a specific P index value, with P added as $Ca(H_2PO_4)_2$ or as poultry layer manures supplemented with $Ca(H_2PO_4)_2$, were similar within each soil.

For the Cecil soil, the average P supplied by treatments (22, 23 and 24) receiving only manures was 19% of the total amount needed to achieve a soil P index of 50, because this soil has more clay and a greater soil P buffer capacity value. Consequently, the average Mehlich-3 soil P value of 15.7 µg P cm^{-3} for the manure-only treatments was less than for the two other soils.

Effects of Fertility Treatments on Soil pH and Acidity

A lime treatment was not evaluated in the Belhaven and Cecil soils, because the initial pH of these soils approximated the target values based on the soil classification recommended by NCDA & CS (Hardy et al., 2008). Post-harvest soil analyses data indicated that there were no major differences between treatments for soil pH, buffer acidity and KCl-exchangeable acidity in the Belhaven and Cecil soils (Tables 13 and 14). In the Lynchburg soil, however, the values of pH 4.2, 66% acid saturation and buffer acidity of 6.3 $cmol_c$ L^{-1} for the unlimed treatment (T31) are significantly different from the other treatments receiving lime (Table 15). Values of acidity by the Mehlich buffer method were greater than those of exchangeable acidity determined by KCl extraction, because the former method contains both exchangeable and non-exchangeable acidity and the latter measures primarily the exchangeable acidity (Ngachie and Smyth, 1989).

Effect of Fertility Treatments on Basic Cations, CEC and ECEC

There were minor differences in Ca, Mg, K, CEC and ECEC between the treatments in all three soils. For the unlimed Lynchburg soil (T31) the level of KCl-extractable Ca (1.15 $cmol_c$ L^{-1}) was considerable less than the average value 6.00 $cmol_c$ L^{-1} for all the limed treatments. Calcium and Mg extracted with the Mehlich-3 solution were generally higher than those extracted with the KCl solution. Likewise, CEC values calculated using the measurements of buffer acidity were greater than ECEC which use the KCl-exchangeable acidity (Tables 13 – 15).

Effect of Fertility Treatments on Micronutrients

The concentrations of Mn, Cu, and Zn tended to be greater in treatments receiving manures than those receiving inorganic sources of fertilizers. Poultry manures contain micronutrients as they are added to the animals feed as growth promoters and biocides (Jackson et al., 2003).

Analysis of Variance of Plant Growth and Nutrient Concentrations

The analysis of variance by soil indicated significant treatment effects in all three soils for plant dry weight, number of tillers, and tissue concentrations of N, P, K, Ca, and Zn (Table 16). There were also significant treatment effects on plant tissue concentrations of Mg and Mn in Belhaven and Cecil soils. There was a significant difference among treatments in the concentrations of Cu and Fe for plants grown in the Belhaven and Lynchburg soils.

Effects of Fertility Treatments on Plant Nutrient Concentration

In all three soils, tissue % N increased with applied inorganic N (Tables 17 – 19). The lowest N concentrations (2.20, 1.01, and 2.64 % for Belhaven, Cecil, and Lynchburg soils, respectively) were observed in treatments without applied N, wherein plants depended on the native soil N reserves. The % N values for the zero-N treatments among soils agreed with the laboratory soil N incubation results in Table 4, where the largest amounts of native soil inorganic N were measured in the Lynchburg, followed by the Belhaven and Cecil soils.

Increased tissue % P with P applications relative to the treatment in each soil without applied P, corroborates the initial characterization of all soils as P deficient. Phosphorus deficiency was most evident in the zero-P treatment of the Cecil soil, where the lowest plant dry weight (2.03 g pot^{-1}) and number of tillers (8) were observed. Reductions in plant dry weight and number of tillers upon the exclusion of applied P in the other soils were not as pronounced as with the Cecil soil. Average tissue % P for treatments receiving only $Ca(H_2PO_4)_2$ in each soil (1.2, 0.26, and 0.23 % for Belhaven, Cecil, and Lynchburg soils, respectively) were not significantly different from the average values for treatments where added P in manures was supplemented with inorganic P fertilizer to achieve identical rates of total applied P (0.72, 0.26, and 0.20%). This lack of difference corroborates the previous laboratory soil incubation results that P from poultry layer manures is readily available and behaves similar to inorganic P fertilizers.

The lowest dry weight (3.61g pot^{-1}) and tiller number (13) in the Lynchburg soil occurred with the unlimed treatment (Table 19). These results support the previous soil data interpretation that a 66 % acid saturation of the ECEC places acidity as a major constraint to plant growth in this soil. Plant dry weight and number of tillers were similar in the limed-no-P treatment and the limed-P treatments, corroborating that acidity was more limiting to plant growth than P deficiency in this soil.

Analysis of Variance of Plant Nutrient Accumulation

The analysis of variance by soil indicated significant treatment effects in all three soils on P, K, Ca, Mg, Mn, and Zn accumulated in the plants (Table 20). Nitrogen uptake was significant on Belhaven and Cecil soils, while Cu and Fe accumulation were significant in the plants of the Belhaven and Lynchburg soils.

Plant N Accumulation and Fertilizer N Equivalency of Poultry Layer Manures

Nitrogen accumulation from urea and poultry layer manures was calculated as the product of plant dry weight and plant tissue N concentration. Regressions were fit to the relation between N accumulation and applied N for treatments receiving only urea-N in each soil. A quadratic equation described the data for the Belhaven soil, while linear equations were used for data in the Cecil and Lynchburg soils (Fig. 16). In all cases plant N accumulation increased with increasing rates of applied N. Urea-N equivalency for the treatments receiving N from manures and supplemented with inorganic P (and lime for the Lynchburg soil) were estimated from the regression equations by solving for the applied urea-N level that corresponded to plant N accumulation values in each soil. Therefore, the fertilizer N equivalencies for 89 mg N pot^{-1} (74 μg N cm^{-3} of soil) applied as fresh, composted, and pelleted manures to the Belhaven soil were 31, 16, and 4 mg N pot^{-1}, respectively. For the same amounts of N supplied as manure to the Cecil soil, the respective fertilizer N equivalency values for fresh, composted, and pelleted manures were 56, 50, and 34 mg N pot^{-1}. In the Lynchburg soil, plant N accumulation with the fresh and pelleted manures exceeded that of the urea-N treatments, whereas the fertilizer N equivalency for the composted manure was of 86 mg N pot^{-1}. The urea-N equivalency values derived from plant N accumulation for the organic manures in the Belhaven and Cecil soils are in the decreasing order of fresh > composted > pelleted. This ranking is similar to the one obtained during the laboratory soil N incubation experiment, where the proportion of total applied N that was potentially available followed the same ranking order among the manure sources (Table 8).

Phosphorus Accumulation

Phosphorus accumulation in millet was greater in the Belhaven soil than in the Lynchburg and Cecil soils (Tables 21 – 23). Comparisons between P sources were made with average values of P accumulation in each soil for treatments that only received $Ca(H_2PO_4)_2$, treatments receiving P from both manures and inorganic fertilizer P, treatments receiving only P from manure, and treatments without applied P (Fig. 17). These comparisons indicate similar amounts of accumulated P in treatments amended with either inorganic P fertilizer or the mixture of inorganic and manure P in all three soils. In the Lynchburg soil, P accumulation was not affected by treatment. This is attributed to the higher initial Mehlich-3 soil P level of 41 µg cm^{-3} in this soil (Table 15) relative to values of 4 µg cm^{-3} in the Belhaven and Cecil soils.

CONCLUSIONS

Differences in soil properties and manure processing are factors that need to be considered when estimating plant available N from the manures. Potential available N calculated from the 90-day laboratory incubation with Belhaven soil was 57, 53, and 46 % of the total N applied as fresh, composted, and pelleted manures, respectively; 83, 73, and 61 % of the total N applied in the Lynchburg soil; and 41, 33, and 25 % for the same order of manure sources in the Cecil soil. Nitrogen released from the fresh and composted manures was greater than the pelleted source in all three soils. Total N content of the pelleted manure was less than for the two other sources and may be associated with volatilization N loss when manures are dried during the pelletizing process. A lower proportion of manure N mineralized in the Cecil soil may be related to greater clay content relative to the other soils and more physical protection to decomposition through binding with clay surfaces. Independently of the soil type, urea released the highest amount of N (80% average of three soils).

A fraction of the organic N in poultry manures can rapidly mineralized and be in forms immediately available for plants (NH_4^+ and NO_3^-). The average available N for fresh and composted sources was 23, 26 and 15% for the Belhaven, Lynchburg, and Cecil soils respectively, while from the pelleted manure about 9% was immediately available in the Belhaven and Cecil soils and 16% in the Lynchburg soil. These values are higher than the concentrations of inorganic forms of N and urea measured in the manure analyses.

Poultry layer manures have a liming value, and their effectiveness in neutralizing soil acidity is similar to the application of equivalent amounts of $CaCO_3$. However, the net liming effect of manures can be partially reduced by the release of H^+ ions during nitrification of manure N.

Phosphorus in poultry layer manures is readily available for plants uptake and behaves similar to inorganic P fertilizer. Soil properties such as the buffer capacity, rather than the source of P, needed to be considered when estimating the amount of applied P required to achieve a target soil test P level.

The preliminary results from laboratory soil incubations on N mineralization, P availability and lime effect of poultry manures were corroborated in a subsequent greenhouse experiment, indicating that valuable information can be obtained from laboratory incubations that will enhance our understanding of the behaviour of nutrient release from poultry manure sources. Maximum plant growth was achieved whenever the N, P and/or acidity constraints of each soil were corrected. When manures are applied on the basis of their N supply, their P content and lime equivalence should also be considered and, if needed, supplemented with inorganic fertilizers and lime. Greenhouse millet dry matter and nutrient accumulation in treatments with manures and supplementary P fertilizer and lime were similar to that of treatments receiving only inorganic fertilizers and lime.

Both soil properties and manure nutrient content should be considered when making recommendations on poultry manure applications. Additional field research is needed to validate the availability coefficients from these laboratory and greenhouse experiments, because environmental conditions that may affect nutrient availability will not be as constant as under our controlled conditions.

REFERENCES

Amanullah, M.M., M.M. Yassin, E. Somasundaram, K. Vaiyapuri, K. Sathyamoorthi, and S. Pazhanivelan. 2006. N availability in fresh and composted poultry manure. Research Journal of Agriculture and Biological Sciences 2(6):406-409.

AOAC. 1990. 955.01. Neutralizing value for liming materials. p.1. Official methods of analysis of official analytical chemists. 15th ed. Vol.1. Washington, D.C.

Barnett, G.M. 1994. Manure P fractionation. Bioresour. Technol. 49:149-155.

Bitzer, C.C., and J.T. Sims. 1988. Estimating the availability of nitrogen in poultry manure through laboratory and field studies. J. Environ. Qual. 17:47-54.

Campbell, C.R. 1992. Determination of total nitrogen in plant tissue by combustion. p. 21-23. *In* C.O. Plank (ed.) Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Cooperative Series Bulletin 368.

Campbell, C.R. and C.O. Plank. 1992. Sample preparation. p. 8-9. *In* C.O. Plank (ed.) Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Cooperative Series Bulletin 368.

Cassel, D.K., and D.R. Nielsen. 1986. Field capacity and available water capacity. p. 901–926. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Castellanos, J.Z., and P.F. Pratt. 1981. Mineralization of manure nitrogen-correlation with laboratory indexes. Soil Sci. Soc. Am. J. 45:354-357.

Chadwick, D.R., F. John, B.F. Pain, B.J. Chambers, and J. Williams. 2000. Plant uptake of nitrogen from the organic nitrogen fraction of animal manures: A laboratory experiment. J. Agric. Sci. (Cambridge) 134:159-168.

Chescheir, G.M., P.W. Westerman, and L.M. Safley, Jr. 1986. Laboratory methods for estimating available nitrogen in manures and sludges. Agricultural Wastes. 18:175-195.

Cooperband, L., G. Bollero, and F. Coale. 2002. Effect of poultry litter and composts on soil nitrogen and phosphorus availability and corn production. Nutrient Cycling in Agroecosystems. 62:185-194.

Dancer, W.S., L.A. Peterson, and G. Chesters. 1973. Ammonification and nitrification of N as influenced by soil pH and previous N treatments. Soil Sci. Soc. Am. Proc. 37:67-69.

Donohue, S.J. and D.W. Aho. 1992. Determination of P, K, Ca, Mg, Mn, Fe, Al, B, Cu, and Zn in plant tissue by inductively coupled plasma (ICP) emission spectroscopy. p. 37-40. *In* C.O. Plank (ed.) Plant analysis reference procedures for the southern region of the United States. Georgia Agric. Expt. Sta., Southern Cooperative Series Bulletin 368.

Eghball, B. 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. Agron. J. 94:128-135.

Gale, P.M., and J.T. Gilmour. 1986. Carbon and nitrogen mineralization kinetics for poultry litter. J. Environ. Qual. 15:423-426.

Gale, P.M., J.M. Phillips, M.L. May, and D.C. Wolf. 1991. Effect of drying on the plant nutrient content of hen manure. J. Prod. Agric. 4:246-250.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383-411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Gordillo, R.M., and M.L. Cabrera. 1997. Mineralizable nitrogen in broiler litter: I. Effect of selected litter chemical characteristics. J. Environ. Qual. 26:1672-1679.

Gordillo, R.M., and M.L. Cabrera. 1997a. Mineralizable nitrogen in broiler litter: II. Effect of selected soil characteristics. J. Environ. Qual. 26:1679-1686.

Groot Koerkamp, P.W.G. 1994. Review on emissions of ammonia from housing systems for laying hens in relation to sources, processes, building design and manure handling. J. Agric. Engng. Res. 59:73-87.

Hadas, A., B. Bar-Yosef, S. Davidov, and M. Sofer. 1983. Effect of pelleting, temperature, and soil type on mineral nitrogen release from poultry and dairy manures. Soil Sci. Am. J. 47:1129-1133.

Hadas, A., and R. Portnoy. 1994. Nitrogen and carbon mineralization rates of composted manures incubated in soil. J. Environ. Qual. 23:1184-1189.

Hardy, D., M.R. Tucker, and C.E. Stokes. 2008. Crop fertilization based on North Carolina soil tests. Available at http://www.ncagr.gov/agronomi/pdffiles/obook.pdf (accessed 20 Aug. 2008; verified 4 Sep. 2008). NCDA & CS-Agronomic Division, Raleigh, NC.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2006. Soil fertility and fertilizers: An introduction to nutrient management. 7th ed. Prentice-Hall of India, New Delhi.

Haynes, R.J., and R. Naidu. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. Nutrient Cycling in Agroecosystems. 51:123-137.

Haynes, R.J., and M.S. Mokolobate. 2001. Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: A critical review of the phenomenon and the mechanisms involved. Nutrient Cycling in Agroecosystems. 59:47-63.

Jackson, B.P., P. M. Bertsch, M.L. Cabrera, J.J. Camberato, J.C. Seaman, and C.W. Wood. 2003. Trace element speciation in poultry litter. J. Environ. Qual. 32:535-540.

Kleinman, P.J.A., A.N. Sharpley, A.M. Wolf, D.B. Beegle, and P.A. Moore, Jr. 2002. Measuring water-extractable phosphorus in manure as an indicator of phosphorus in runoff. Soil Sci. Soc. Am. J. 66:2009-2015.

Kuo, S. 1996. Phosphorus. p. 869-919. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. ASA and SSSA, Madison, WI.

Lachat Instruments. 1995. Lachat QuickChem Method. Milwaukee, WI.

Mahimairaja, S., N.S. Bolan, and M.J. Hedley. 1995. Agronomic effectiveness of poultry manure composts. Commun. Soil Sci. Plant Anal. 26(11&12):1843-1861.

Materechera, S.A. and T.S. Mkhabela. 2002. The effectiveness of lime, chicken manure and leaf litter ash in ameliorating acidity in a soil previously under black wattle (*Acacia mearnsii*) plantation. Bioresour. Technol. 85:9-16.

Mehlich, A., S.S. Bowling, A.L Hatfield. 1976. Buffer pH acidity in relation to nature of soil acidity and expression of lime requirement. Commun. Soil Sci. Plant Anal. 7(3):253-263.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15(12):1409-1416.

Moore, P.A., T.C. Daniel, A.N. Sharpley, and C.W. Wood. 1995. Poultry manure management: Environmentally sound options. J. Soil Water Conserv. 50(3):321-327.

Moore, A.D., D.W. Israel, and R.L. Mikkelsen. 2005. Nitrogen availability of anaerobic swine lagoon sludge: Sludge source effects. Bioresour. Technol. 96:323-329.

Naramabuye, F.X., and R.J. Haynes. 2006. Short-term effects of three animal manures on soil pH and Al solubility. Aust. J. Soil Res. 44:515-521.

NCDA & CS-Agricultural Statistics Division. 2007. Cash receipts from farming by commodity. Annual statistics book. Available at http://www.agr.state.nc.us/stats/2007AgStat/CashReceiptsfromFarming.pdf (accessed 15 May 2008; verified Sep 3 2008). NCDA & CS. Raleigh, NC.

Ngachie, V., and T. J. Smyth. 1989. Relationships between buffer acidity and exchangeable acidity in lime trials with ultisols and histosols. Commun. Soil. Sci. Plant Anal. 20(13 & 14):1427-1438.

Preusch, P.L., P.R. Adler, L.J. Sikora, and T.J. Tworkoski. 2002. Nitrogen and phosphorus availability in composted and uncomposted poultry litter. J. Environ. Qual. 31:2051-2057.

SAS Institute. 2003. The SAS system for Windows. V.9.1.3. SAS Inst., Cary, NC.

Shaffer, K.A., and B. Cleveland. 2008. Livestock manure production rates and nutrient content. 2008 North Carolina agricultural chemicals manual. Available at http://ipm.ncsu.edu/agchem/agchem.html (accessed 22 Aug. 2008; verified 5 Sep. 2008). College of Agriculture and Life Sciences, NC State University. Raleigh, NC.

Sharpley, A., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 29:1462-1469.

Sharpley, A.N., R.W. McDowell, and P.J.A. Kleinman. 2004. Amounts, forms and solubility of phosphorus in soils receiving manure. Soil Sci. Soc. Am. J. 68:2048-2057.

Siddique, M.T., and J.S. Robinson. 2003. Phosphorus sorption and availability in soils amended with animal manures and sewage sludge. J. Environ. Qual. 32:1114-1121.

Sims, J.T. 1986. Nitrogen transformations in a poultry manure amended soil: Temperature and moisture effects. J. Environ. Qual. 15:59-63.

Sims, J.T. and D.C. Wolf. 1994. Poultry waste management: Agricultural and environmental issues. p. 2-83. *In* D.L. Sparks (ed) Adv. Agronomy. 52. Academic Press, San Diego, CA.

Soil Survey Staff. 2008. Soil Series Classification Database. Available at http://soils.usda.gov/technical/classification/scfile/index.html, (accessed on 10 Feb. 2008; verified 20 Sep. 2008). USDA-NRCS. Lincoln, NE.

Soil Survey Staff. 2008a. National Soil Survey Characterization Data. Soil Survey Laboratory. National Soil Survey Center. Available at http://ssldata.nrcs.usda.gov/rptExecute.asp?p=25862&r=1&submit1=Get+Report, (accessed on 13 Aug. 2008; verified 5 Sep. 2008). USDA-NRCS. Lincoln, NE.

Sorensen, P., and E.S. Jensen. 1996. The fate of fresh and stored ^{15}N-labelled sheep urine and urea applied to a sandy and a sandy loam soil using different application strategies. Plant and Soil. 183:213-220.

Sparks, D. L. 2003. Environmental soil chemistry. 2nd ed. Academic Press, San Diego, CA.

Stevenson, F.J. 1986. Cycles of soil. John Wiley & Sons, Inc. New York.

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel, and D.A. Zuberer. 2005. Principles and applications of soil microbiology. 2nd ed. Prentice-Hall, New Jersey.

Talpaz, H., P. Fine, and B. Bar-Yosef. 1981. On the estimation of N-mineralization parameters from incubation experiments. Soil Sci. Soc. Am. J. 45:993-996.

Thomsen, I.K. 2004. Nitrogen use efficiency of ^{15}N-labeled poultry manure. Soil Sci. Soc. Am. J. 68:538-544.

Tyson, S.C., and M.L. Cabrera. 1993. Nitrogen mineralization in soils amended with composted and uncomposted poultry litter. Commun. Soil Sci. Plant Anal. 24(17&18):2361-2374.

USDA-National Agricultural Statistics Service. 2008. Chickens and eggs 2007 summary [Online]. Available at http://www.usda.gov/nass/PUBS/TODAYRPT/lyegan08.pdf (accessed 21 Jun. 2008; verified 3 Sep. 2008). USDA-NASS. Washington, DC.

Van Kessel, J.S., J.B. Reeves III, and J.J. Meisinger. 2000. Nitrogen and carbon mineralization of potential manure components. J. Environ. Qual. 29:1669-1677.

Vervoort, R.W., D.E. Radcliffe, M.L. Cabrera, and M. Latimore, Jr. 1998. Nutrient losses in surface and subsurface flow from pasture applied poultry litter and composted poultry litter. Nutrient Cycling in Agroecosystems. 50:287-290.

Westerman, P.W., L.M. Safley, Jr, and J.C. Barker. 1988. Available nitrogen in broiler and turkey litter. Trans. ASAE. 31(4):1070-1075.

Table 1. Fertility treatments used in the greenhouse experiment for the Belhaven soil.

Treatment	N	P	Source of N and P‡	Treatment purpose
	—— $\mu g\ cm^{-3}$ ——			
T1	0	45	CP	Fertilizer N rates to characterize plant
T2	25	45	U, CP	response to N (T1 – T5)
T3	49	45	U, CP	
T4	74	45	U, CP	Plant growth with optimum N and P
T5	99	45	U, CP	
T6	74	0	U	Plant growth without P
T7	74	45 (29, 16)†	FM, CP	Fertilizer N equivalency of the manures (T7 –
T8	74	45 (20, 25)†	CM, CP	T9)
T9	74	45 (19, 26)†	PM, CP	
T10	74	16	FM	Plant growth with N and P supplied from the
T11	74	25	CM	manures (T10 – T12)
T12	74	26	PM	

† First value in parenthesis indicates the rate applied as $Ca(H_2PO_4)_2$; the second value is the corresponding amount of P supplied by the manure.
‡ U: urea; CP: $Ca(H_2PO_4)_2$; FM: fresh manure; CM: composted manure; PM: pelleted manure.

Table 2. Fertility treatments used in the greenhouse experiment for the Cecil soil.

Treatment	N	P	Source of N and P‡	Treatment purpose
	—— $\mu g\ cm^{-3}$ ——			
13	0	119	CP	Fertilizer N rates to characterize plant
14	25	119	U, CP	response to N (T13 – T17)
15	49	119	U, CP	
16	74	119	U, CP	Plant growth with optimum N, P
17	99	119	U, CP	
18	74	0	U	Plant growth without P
19	74	119 (103, 16)†	FM, CP	Fertilizer N equivalency of the manures (T19 -
20	74	119 (94, 25)†	CM, CP	T21)
21	74	119 (93, 26)†	PM, CP	
22	74	16	FM	Plant growth with N and P supplied from the
23	74	25	CM	manures (T22 – T24)
24	74	26	PM	

† First value in parenthesis indicates the rate applied as $Ca(H_2PO_4)_2$; the second value is the corresponding amount of P supplied by the manure.
‡ U: urea; CP: $Ca(H_2PO_4)_2$; FM: fresh manure; CM: composted manure; PM: pelleted manure.

Table 3. Fertility treatments used in the greenhouse experiment for the Lynchburg soil.

Treatment	N	P	Lime	Source of N, P, and lime‡	Treatment purpose
	—— $\mu g\ cm^{-3}$ ——		$mg\ cm^{-3}$		
25	0	29	4.1	CP, CC	Fertilizer N rates to characterize
26	25	29	4.1	U, CP, CC	plant response to N (T25 – T29)
27	49	29	4.1	U, CP, CC	
28	74	29	4.1	U, CP, CC	Plant growth with optimum N, P and no acidity constraint
29	99	29	4.1	U, CP, CC	
30	74	0	4.1	U, CC	Plant growth without P
31	74	33	0	U, CP	Plant growth without lime
32	74	29 (13, 16)†	3.8	FM, CP, CC	Fertilizer N equivalency of
33	74	29 (4, 25)†	3.8	CM, CP, CC	the manures (T32 – T34)
34	74	29 (3, 26)†	3.4	PM, CP, CC	
35	74	16	3.8	FM, CC	Plant growth with N and P
36	74	25	3.8	CM, CC	supplied from the manures
37	74	26	3.4	PM, CC	and lime (T35 – T37)

† First value in parenthesis indicates the rate applied as $Ca(H_2PO_4)_2$; the second value is the corresponding amount of P supplied by the manure.
‡ U: urea; CP: $Ca(H_2PO_4)_2$; CC: $CaCO_3$; FM: fresh manure; CM: composted manure; PM: pelleted manure.

Table 4. Chemical properties of soil samples used in the experiments.

Soil	Exchangeable cations				ECEC†	Acid sat.‡	KCl-extractable		Mehlich 3-extractable				pH	C	NCDA &CS§ Classification
	Ca	Mg	K	Acidity			NH_4-N	NO_3-N	P	Cu	Fe	Mn			
	$cmol_c\ L^{-1}$					%	µg cm^{-3}							%	
Belhaven	20.19	7.97	0.10	0.19	28.45	1	11.3	8.6	16.0	1.5	114.7	3.6	4.8	42.7	Organic
Cecil	3.78	1.16	0.33	0.10	5.37	2	4.8	1.3	9.3	1.6	170.0	72.8	5.8	1.3	Mineral
Lynchburg	1.05	0.53	0.23	2.94	4.74	62	105.0	56.5	35.6	0.6	260.2	0.8	3.8	4.7	Mineral-organic

†ECEC: Effective cation exchange capacity = (Exchangeable Ca + Mg + K + Acidity).
‡Acid sat.: Acid saturation = 100 x (Exchangeable Acidity / ECEC).
§NCDA & CS Classification: Soil class used by North Carolina Department of Agriculture and Consumer Services.

Table 5. Physical properties of soil samples used in the experiments.

Soil	Sample density	Water container capacity	Sand	Silt	Clay
	g cm^{-3}	cm^3 cm^{-3}	———	%	———
Belhaven	0.4	0.61	22	69	9
Cecil	0.9	0.24	47	41	12
Lynchburg	0.8	0.30	60	38	2

Table 6. Characteristics of fresh, composted, and pelleted poultry layer manures used in the experiments.†

Manure sources	TN‡	NH_4-N	NO_3-N	Urea-N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Na	C	pH	DM§	CCE¶
	g kg^{-1}																	%	
Fresh	65.3	5.6	0.04	0.04	14.3	28.1	113.7	7.8	6.0	0.26	0.43	0.75	0.10	0.04	0.5	293.4	6.5	75.9	29.5
Composted	52.9	5.6	0.01	0.01	18.0	36.1	98.4	9.0	5.4	0.67	0.45	0.50	0.14	0.06	6.7	273.6	6.6	76.7	23.0
Pelleted	37.4	2.8	0.03	0.07	13.3	28.3	148.8	8.2	7.2	1.16	0.36	0.43	0.07	0.04	6.6	247.5	6.2	91.0	36.3

† Waste analysis report by NCDA & CS; all values expressed on a dry weight basis.
‡TN: Total nitrogen.
§DM: Dry matter.
¶CCE: Calcium carbonate equivalence.

Table 7. F-test values and probabilities of significance from the analysis of variance by soil for NH_4-N, NO_3-N and net inorganic N accumulation among N treatments and sampling dates during the 90-day incubation.

Source	NH_4-N			NO_3-N			Net inorganic N		
	df	*F* value	*Pr* > *F*	df	*F* value	*Pr* > *F*	df	*F* value	*Pr* > *F*
					Belhaven				
Replicates	2	3.73	0.03	2	0.40	0.67	2	0.99	0.38
N source	4	568.17	< 0.0001	4	1123.83	< 0.0001	3	479.13	< 0.0001
Time	5	3084.73	< 0.0001	5	10566.10	< 0.0001	5	459.76	< 0.0001
Manure x time	20	131.15	< 0.0001	20	186.03	< 0.0001	15	12.82	< 0.0001
					Cecil				
Replicates	2	1.08	0.35	2	1.79	0.18	2	2.14	0.13
N source	4	806.72	< 0.0001	4	551.62	< 0.0001	3	650.37	< 0.0001
Time	5	2479.84	< 0.0001	5	2582.11	< 0.0001	5	194.63	< 0.0001
Manure x time	20	192.42	< 0.0001	20	82.45	< 0.0001	15	29.61	< 0.0001
					Lynchburg				
Replicates	2	0.50	0.61	2	2.14	0.13	2	10.39	0.0002
N source	4	72.37	< 0.0001	4	2.20	0.08	3	13.07	< 0.0001
Time	5	70.89	< 0.0001	5	59.12	< 0.0001	5	95.89	< 0.0001
Manure x time	20	4.59	< 0.0001	20	3.53	< 0.0001	15	3.31	0.0009

Table 8. Prediction equations for net inorganic N mineralized, estimates of potential mineralizable N (N_o), and available N for N-sources during a 90-day incubation period.

Soil	N source	Model parameters†	R^2	N_o	Available N‡
				μg N cm^{-3}	% applied N
Belhaven	Fresh	$N_t = 75.21 (1 - e^{-0.49t})$	0.96	75.2	57
	Composted	$N_t = 70.68 (1 - e^{-0.64t})$	0.95	70.7	53
	Pelleted	$N_t = 61.42 (1 - e^{-0.41t})$	0.98	61.4	46
	Urea	$N_t = 106.1 (1 - e^{-0.91t})$	0.98	106.1	80
Cecil	Fresh	$N_t = 53.98 (1 - e^{-0.70t})$	0.98	53.9	41
	Composted	$N_t = 43.64 (1 - e^{-0.65t})$	0.95	43.6	33
	Pelleted	$N_t = 33.88 (1 - e^{-0.53t})$	0.97	33.9	25
	Urea	$N_t = 101.3 (1 - e^{-145.5t})$	0.99	101.3	76
Lynchburg	Fresh	$N_t = 110.7 (1 - e^{-0.43t})$	0.95	110.7	83
	Composted	$N_t = 97.02 (1 - e^{-0.50t})$	0.95	97.0	73
	Pelleted	$N_t = 80.89 (1 - e^{-0.43t})$	0.97	80.9	61
	Urea	$N_t = 111.3 (1 - e^{-0.27t})$	0.99	111.3	84

†N_t: Net inorganic N mineralized (μg N cm^{-3} soil); t: time (day).
‡Available N = (N_o / Applied N) x 100

Table 9. F-test values and probabilities of significance from the analysis of variance by soil for pH, acid saturation, Ca, Mg, K, and effective cation exchange capacity (ECEC) during a 21-day incubation period.

		pH		Acid saturation		Ca		Mg		K		ECEC	
Source	df	*F* value	*Pr* > *F*	*F* value	*Pr* > *F*	*F* value	*Pr* > *F*	*F* value	*Pr* > *F*	*F* value	*Pr* > *F*	*F* value	*Pr* > *F*
							Belhaven						
Replicates	2	7.38	0.0012	8.58	0.0004	1.50	0.23	2.17	0.12	0.94	0.40	2.57	0.08
Treatment	9	11.62	<0.0001	14.29	<0.0001	14.09	<0.0001	3.81	0.0005	39.79	<0.0001	7.18	<0.0001
Time	3	9.49	<0.0001	17.17	<0.0001	6.74	0.0004	9.80	<0.0001	3.20	0.03	7.90	0.0001
Trt.† x time	27	0.70	0.85	0.56	0.96	1.25	0.22	0.89	0.62	1.81	0.02	1.05	0.41
							Cecil						
Replicates	2	2.77	0.07	2.37	0.1	1.83	0.17	0.35	0.71	5.79	0.005	0.13	0.88
Treatment	9	56.25	<0.0001	8.23	<0.0001	318.98	<0.0001	21.68	<0.0001	38.85	<0.0001	104.85	<0.0001
Time	3	108.03	<0.0001	24.65	<0.0001	15.30	<0.0001	4.52	0.006	4.37	0.007	5.37	0.0021
Trt. x time	27	0.93	0.57	1.69	0.04	2.44	0.0012	0.72	0.83	0.64	0.90	1.20	0.27
							Lynchburg						
Replicates	2	14.71	<0.0001	15.38	<0.0001	0.71	0.49	20.00	<0.0001	1.37	0.26	6.62	0.0022
Treatment	9	338.66	<0.0001	431.34	<0.0001	2680.21	<0.0001	190.07	<0.0001	18.31	<0.0001	398.22	<0.0001
Time	3	12.13	<0.0001	38.10	<0.0001	3.21	0.03	113.92	<0.0001	2.56	0.06	23.25	<0.0001
Trt. x time	27	2.17	0.0043	2.85	0.0002	11.32	<0.0001	3.63	<0.0001	0.76	0.78	3.83	<0.0001

†Trt.: Treatment.

Table 10. Exchangeable cations and effective cation exchange capacity (ECEC) for manure and $CaCO_3$ treatments in each soil.†

Treatments	$CaCO_3$	Exchangeable cations			ECEC
		Ca	Mg	K	
		cmol$_c$ L^{-1}			
		Belhaven			
Fresh manure	0.6	18.02	6.17	0.19	24.62
	1.2	17.92	6.22	0.25	24.73
Composted manure	0.48	17.86	6.21	0.20	24.52
	0.94	17.96	6.23	0.36	24.92
Pelleted manure	0.88	17.93	6.20	0.21	24.64
	1.76	18.05	6.20	0.29	24.84
$CaCO_3$	0	17.98	6.26	0.10	24.52
	1.34	18.54	6.06	0.10	24.87
	2.66	18.73	6.09	0.10	25.04
	5.32	19.91	5.99	0.11	26.10
LSD‡		0.48	0.13	0.04	0.48
		Cecil			
Fresh manure	0.6	3.42	0.98	0.35	4.84
	1.2	3.51	1.00	0.46	5.07
Composted manure	0.48	3.27	1.02	0.40	4.76
	0.94	3.30	1.03	0.48	4.90
Pelleted manure	0.88	3.35	0.96	0.37	4.77
	1.76	3.52	1.00	0.44	5.05
$CaCO_3$	0	3.29	0.91	0.27	4.56
	0.66	3.69	0.94	0.31	4.98
	1.34	4.14	0.89	0.27	5.32

Table 10 (continued).

Treatments	$CaCO_3$	Exchangeable cations			ECEC
		Ca	Mg	K	
		cmol$_c$ L^{-1}			
	2.66	5.01	0.83	0.27	6.12
LSD		0.09	0.04	0.04	0.12
		Lynchburg			
Fresh manure	0.6	1.82	0.57	0.31	4.70
	1.2	2.19	0.63	0.38	4.72
Composted manure	0.48	1.73	0.60	0.36	4.65
	0.94	1.99	0.64	0.43	4.96
Pelleted manure	0.88	1.87	0.55	0.32	5.19
	1.76	2.21	0.60	0.44	5.26
$CaCO_3$	0	1.33	0.47	0.22	4.94
	2.66	3.59	0.47	0.23	5.44
	8.00	7.52	0.45	0.21	8.42
	13.32	9.84	0.42	0.25	10.70
LSD		0.16	0.02	0.06	0.28

†Values shown are treatment average across sampling dates.
‡LSD: Least significant difference at the 0.05 probability level.

Table 11. F-test values and probabilities of significance from the analysis of variance by soil for treatment effects on Mehlich-3 extractable P and water soluble P during a 21-day incubation period.

	Mehlich-3 extractable P			Water soluble P		
Source	df	*F* value	*Pr* > *F*	df	*F* value	*Pr* > *F*
			Belhaven			
Replicates	2	1.29	0.28	2	1.26	0.29
Treatment	9	30.52	< 0.0001	9	49.61	< 0.0001
Time	3	1.18	0.32	3	2.01	0.12
Treat. x Time	27	1.24	0.23	27	0.53	0.97
			Cecil			
Replicates	2	0.32	0.73	2	1.61	0.21
Treatment	9	74.39	< 0.0001	9	83.28	< 0.0001
Time	3	18.94	< 0.0001	3	64.56	< 0.0001
Treat. x Time	27	1.17	0.29	27	16.40	< 0.0001
			Lynchburg unlimed			
Replicates	2	0.20	0.82	2	0.38	0.69
Treatment	9	35.65	< 0.0001	9	14.01	< 0.0001
Time	3	2.91	0.04	3	9.32	< 0.0001
Treat. x Time	27	0.85	0.67	27	1.13	0.33
			Lynchburg limed			
Replicates	2	1.49	0.23	2	3.22	0.05
Treatment	9	18.09	< 0.0001	9	32.81	< 0.0001
Time	3	2.18	0.10	3	5.96	0.001
Treat. x Time	27	1.21	0.25	27	2.58	0.0006

Table 12. F-test values and probability of significance from the analysis of variance by soil for soil pH, buffer acidity (BA), cation exchange capacity (CEC), effective cation exchange capacity (ECEC), Mehlich-3 extractable Ca, Mg, K, P, S, Mn, Cu, and Zn and KCl-extractable Ca, Mg, and acidity measured at harvest of millet in the greenhouse experiment.

		pH	BA	CEC	ECEC	Mehlich-3 extractable								KCl- extractable		
						Ca	Mg	K	P	S	Mn	Cu	Zn	Ca	Mg	Acidity
Source	df	*F*-value														
Belhaven																
Replicates	2	0.73NS	13.00***	6.02**	4.78*	2.36NS	4.31*	0.38NS	0.20NS	0.13NS	5.44*	0.25NS	1.59NS	4.24*	6.33**	1.50NS
Treatment	11	3.27**	8.16***	4.43**	1.42NS	5.16***	2.55*	2.16NS	7.43***	6.45***	6.64***	3.52**	13.39***	1.40NS	1.54NS	1.95NS
Cecil																
Replicates	2	1.67NS	1.18NS	1.36NS	1.71NS	0.54NS	0.74NS	0.25NS	0.57NS	2.49NS	0.56NS	0.28NS	0.50NS	2.66NS	4.19*	1.30NS
Treatment	11	8.34***	21.18***	9.24***	9.45***	17.19***	19.64***	15.85***	50.98***	5.73***	7.41***	1.37NS	1.56NS	15.57***	27.10***	1.89NS
Lynchburg																
Replicates	2	0.26NS	1.90NS	8.44**	0.65NS	5.00*	0.41NS	0.94NS	2.00NS	1.79NS	1.14NS	2.64NS	2.30NS	0.21NS	1.68NS	1.82NS
Treatment	12	70.94***	45.53***	63.53***	15.03***	258.33***	4.51***	0.82NS	34.88***	15.12***	12.91***	2.51*	10.22***	150.54***	7.08***	256.43***

*** Significant at the 0.001 probability level.
** Significant at the 0.01 probability level.
* Significant at the 0.05 probability level.
NS: Not significant at the 0.05 probability level.

Table 13. Chemical properties of the Belhaven soil for treatments used in the greenhouse experiment.

Treatment†	Mehlich-3 exchangeable			Buffer acidity	KCl-exchangeable			CEC‡	ECEC§	Mehlich-3 extractable						Acid sat.¶	pH
	Ca	Mg	K		Ca	Mg	Acidity			P	S	Mn	Cu	Zn	Na		
	cmol$_c$ L^{-1}									μg cm^{-3}						%	
T1	17.31	6.74	0.02	5.37	17.69	5.56	0.08	29.33	23.56	13.0	3.20	5.65	0.60	4.33	0.20	0.4	5.3
T2	17.23	6.58	0.02	5.23	16.85	5.22	0.06	29.03	22.34	12.3	4.80	5.60	0.58	4.33	0.20	0.3	5.3
T3	16.84	6.55	0.01	5.43	17.01	5.42	0.07	28.87	22.71	10.3	4.00	5.07	0.55	4.03	0.20	0.3	5.2
T4	16.15	6.29	0.01	5.67	16.75	5.42	0.08	28.17	22.46	11.3	4.96	4.80	0.86	3.79	0.20	0.3	5.2
T5	17.62	6.66	0.02	5.10	16.92	5.28	0.09	29.37	22.50	11.3	4.32	5.71	0.59	4.35	0.20	0.4	5.3
T6	17.36	6.69	0.02	5.10	16.94	5.37	0.06	29.10	22.59	5.3	3.52	5.65	0.63	4.31	0.20	0.3	5.3
T7	17.68	6.82	0.02	5.23	17.52	5.47	0.08	29.63	23.29	17.7	4.80	5.76	0.62	5.07	0.20	0.3	5.3
T8	17.82	6.89	0.02	5.60	17.88	5.67	0.09	30.37	23.86	18.7	4.96	5.76	0.96	4.93	0.20	0.4	5.2
T9	18.30	6.78	0.03	5.20	17.94	5.60	0.08	30.33	23.84	13.7	5.28	6.35	0.63	5.19	0.20	0.3	5.3
T10	18.37	6.98	0.02	5.33	17.68	5.58	0.09	30.80	23.57	9.3	4.32	6.19	0.68	5.28	0.20	0.4	5.3
T11	17.42	6.75	0.02	5.27	17.19	5.49	0.09	29.37	23.00	14.7	4.96	5.97	0.66	4.79	0.20	0.4	5.3
T12	18.38	7.31	0.02	5.63	18.00	5.76	0.10	31.33	24.08	14.0	7.04	6.29	0.99	5.12	0.20	0.4	5.3
LSD $_{0.05}$	0.83	0.45	NS	0.20	NS	NS	NS	1.23	NS	3.8	1.10	0.51	0.23	0.39	NS	NS	0.1
CV%	2.84	4.02	29.98	2.25	3.95	4.01	21.24	2.50	3.92	18.06	14.20	5.36	20.15	5.08	0.00	21.18	0.64

†Treatment descriptions are specified in Table 1.
‡CEC: Cation exchange capacity = (Mehlich-3 exchangeable Ca + Mg + K + Buffer acidity).
§ECEC: Effective cation exchange capacity = (KCl-exchangeable Ca + Mg + Acidity + Mehlich-3 exchangeable K + Na).
¶Acid sat.: Acid saturation = 100 x (Exchangeable Acidity / ECEC).
LSD: Least significant difference at 0.05 probability level; NS: Not significant at 0.05 probability level.

Table 14. Chemical properties of the Cecil soil for treatments used in the greenhouse experiment.

Treatment†	Mehlich-3 exchangeable			Buffer acidity	KCl-exchangeable			CEC‡	ECEC§	Mehlich-3 extractable						Acid sat.¶	pH
	Ca	Mg	K		Ca	Mg	Acidity			P	S	Mn	Cu	Zn	Na		
	cmol$_c$ L^{-1}									µg cm^{-3}						%	
T13	5.20	1.25	0.11	1.77	3.72	0.79	0.03	8.33	4.66	50.4	13.12	64.16	1.85	3.81	0.00	0.7	5.8
T14	5.27	1.26	0.11	1.80	3.69	0.77	0.06	8.40	4.63	53.2	15.04	69.49	1.71	3.49	0.00	1.3	5.8
T15	5.38	1.25	0.10	1.83	3.71	0.74	0.05	8.50	4.64	58.8	15.04	70.08	1.97	3.64	0.03	1.1	5.8
T16	5.15	1.13	0.10	1.90	3.63	0.71	0.05	8.30	4.49	46.8	11.36	73.12	1.62	3.61	0.00	1.1	5.8
T17	5.30	1.19	0.11	1.90	3.61	0.70	0.05	8.47	4.48	50.8	12.16	71.57	1.71	4.51	0.00	1.1	5.8
T18	4.93	1.33	0.15	1.73	3.42	0.82	0.04	8.13	4.45	4.0	14.56	73.97	1.86	4.05	0.03	0.8	5.7
T19	5.74	1.29	0.13	1.80	3.84	0.77	0.02	8.97	4.87	48.8	14.72	76.69	1.80	4.52	0.10	0.4	6.0
T20	5.55	1.27	0.12	1.70	3.62	0.79	0.04	8.63	4.67	57.6	16.32	75.15	1.78	4.29	0.10	0.9	5.9
T21	5.83	1.34	0.14	1.57	3.70	0.82	0.05	8.93	4.81	61.2	23.36	75.84	1.69	4.33	0.10	1.0	5.9
T22	5.29	1.29	0.14	1.57	3.48	0.81	0.03	8.27	4.56	10.4	15.20	75.25	1.78	4.61	0.10	0.7	6.0
T23	5.87	1.52	0.14	1.40	3.44	0.83	0.02	8.93	4.53	16.8	19.20	75.68	1.77	4.60	0.10	0.4	5.9
T24	5.93	1.52	0.16	1.33	3.44	0.85	0.04	8.93	4.60	20.0	23.52	71.41	1.77	4.57	0.10	0.9	5.9
LSD $_{0.05}$	0.22	0.08	0.01	0.12	0.10	0.03	NS	0.29	0.12	8.4	4.74	3.79	NS	NS	0.04	NS	0.1
CV%	2.47	3.47	6.91	4.15	1.66	1.98	40.87	2.02	1.57	12.63	17.71	3.14	7.51	14.20	40.45	40.75	0.96

† Treatment descriptions are specified in Table 2.
‡CEC: Cation exchange capacity = (Mehlich-3 exchangeable Ca + Mg + K + Buffer acidity).
§ECEC: Effective cation exchange capacity = (KCl-exchangeable Ca + Mg + Acidity + Mehlich-3 exchangeable K + Na).
¶Acid sat.: Acid saturation = 100 x (Exchangeable Acidity / ECEC).
LSD: Least significant difference at 0.05 probability level; NS: Not significant at 0.05 probability level.

Table 15. Chemical properties of the Lynchburg soil for treatments used in the greenhouse experiment.

Treatment†	Mehlich-3 exchangeable			Buffer acidity	KCl-exchangeable			CEC‡	ECEC§	Mehlich-3 extractable						Acid sat.¶	pH
	Ca	Mg	K		Ca	Mg	Acidity			P	S	Mn	Cu	Zn	Na		
	——— cmol$_c$ L^{-1} ———									——— µg cm^{-3} ———						%	
T25	9.02	0.77	0.07	3.77	6.36	0.42	0.22	13.60	7.10	63.6	13.60	1.92	0.55	3.16	0.03	3.1	5.1
T26	8.91	0.67	0.07	3.77	6.34	0.42	0.21	13.43	7.05	62.4	13.60	1.92	0.49	3.07	0.00	3.0	5.1
T27	8.62	0.69	0.07	3.53	6.15	0.43	0.23	12.93	6.87	60.8	14.40	1.92	0.57	3.33	0.00	3.3	5.2
T28	8.60	0.70	0.08	3.80	6.02	0.42	0.24	13.17	6.77	61.6	13.28	1.92	0.51	3.09	0.00	3.6	5.1
T29	8.60	0.77	0.07	3.33	6.04	0.43	0.22	12.77	6.76	59.6	13.76	1.92	0.54	2.85	0.00	3.2	5.2
T30	8.63	0.78	0.08	3.53	5.90	0.43	0.22	13.00	6.62	41.2	13.44	1.97	0.51	3.00	0.00	3.3	5.2
T31	2.33	0.90	0.06	6.30	1.15	0.54	3.39	9.57	5.14	73.6	11.36	2.03	0.55	3.45	0.00	65.9	4.2
T32	8.42	0.79	0.07	4.00	6.08	0.46	0.23	13.23	6.93	67.2	15.04	2.24	0.54	3.67	0.10	3.3	5.1
T33	8.39	0.78	0.07	3.77	6.02	0.45	0.16	12.97	6.79	64.8	14.40	2.13	0.56	3.39	0.10	2.4	5.2
T34	7.98	0.76	0.08	3.87	5.51	0.46	0.23	12.67	6.38	57.2	18.40	2.13	0.56	3.23	0.10	3.7	5.1
T35	8.53	0.80	0.07	3.87	6.19	0.48	0.18	13.27	7.01	53.6	14.40	2.24	0.60	3.72	0.10	2.5	5.2
T36	8.54	0.76	0.08	4.10	5.80	0.45	0.14	13.50	6.57	62.0	16.00	2.24	0.57	3.48	0.10	2.2	5.3
T37	7.81	0.80	0.08	4.63	5.60	0.48	0.16	13.30	6.42	56.0	19.36	2.29	0.47	3.36	0.10	2.5	5.1
LSD $_{0.05}$	0.31	0.08	NS	0.32	0.32	0.04	0.16	0.37	0.37	3.7	1.58	0.12	0.07	0.23	0.03	1.1	0.1
CV%	2.34	6.02	18.64	4.81	3.43	4.82	21.34	1.74	3.40	3.72	6.52	3.49	7.43	4.22	32.87	8.29	1.07

† Treatment descriptions are specified in Table 3.
‡CEC: Cation exchange capacity = (Mehlich-3 exchangeable Ca + Mg + K + Buffer acidity).
§ECEC: Effective cation exchange capacity = (KCl-exchangeable Ca + Mg + Acidity + Mehlich-3 exchangeable K + Na).

Table 15. (continued).

¶Acid sat.: Acid saturation = 100 x (Exchangeable Acidity / ECEC).
LSD: Least significant difference at 0.05 probability level.
NS: Not significant at 0.05 probability level.

Table 16. F-test values and probability of significance from the analysis of variance by soil for plant dry matter, number of plant tillers and plant tissue concentrations of N, P, K, Ca, Mg, Cu, Fe, Mn, and Zn.

		Dry weight	# of tillers	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
Source	df	*F*-values										
						Belhaven						
Replicates	2	1.85NS	5.33*	1.03NS	2.19NS	1.66NS	1.41NS	0.63NS	0.43NS	3.99*	0.08NS	5.35*
Treatment	11	22.64***	2.35*	91.84***	142.01***	3.14**	16.41***	32.11***	2.91*	26.83***	2.50*	46.21***
						Cecil						
Replicates	2	0.21NS	1.75NS	0.72	0.29NS	1.57NS	0.40NS	2.00NS	0.45NS	1.36NS	7.81**	5.77**
Treatment	11	5.17***	7.59***	24.11***	51.16***	15.07***	19.41***	16.28***	1.95NS	0.73NS	12.84***	4.51**
						Lynchburg						
Replicates	2	7.57**	0.70NS	5.63**	0.53NS	0.71NS	9.47***	11.11***	3.23NS	4.61*	1.18NS	5.91**
Treatment	12	5.56***	14.55***	23.16***	3.17**	22.38***	8.71***	1.14NS	5.04***	2.92*	1.81NS	2.67*

*** Significant at the 0.001 probability level.
** Significant at the 0.01 probability level.
* Significant at the 0.05 probability level.
NS Not significant at the 0.05 probability level.

Table 17. Effect of treatments on number of tillers, dry matter yield and nutrient concentration of millet plants grown on the Belhaven soil.

Treatment†	Tiller number	Dry weight	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	# pot^{-1}	g	%					μg g^{-1}			
T1	20	4.52	2.20	1.19	0.67	0.49	1.56	7.44	80.68	323.27	76.57
T2	22	5.87	2.23	1.11	0.55	0.47	1.52	5.80	74.94	430.53	79.35
T3	24	5.85	2.63	1.09	0.52	0.43	1.50	6.31	78.60	364.10	78.06
T4	25	5.10	3.13	1.19	0.56	0.45	1.53	6.27	78.55	349.47	87.85
T5	22	4.75	3.46	1.23	0.57	0.49	1.60	7.53	84.95	398.13	91.36
T6	22	5.20	2.95	0.48	0.52	0.45	1.42	4.80	75.42	396.20	75.75
T7	23	8.21	1.61	0.78	0.64	0.40	1.25	4.91	56.28	307.90	50.03
T8	24	9.07	1.28	0.70	0.64	0.33	1.12	4.49	46.64	272.23	47.45
T9	25	8.38	1.24	0.67	0.66	0.39	0.14	4.46	48.71	295.37	48.46
T10	23	7.84	1.58	0.48	0.49	0.38	1.19	4.43	53.93	300.17	46.03
T11	24	8.59	1.31	0.54	0.63	0.35	1.07	4.52	42.52	292.00	45.35
T12	22	8.99	1.27	0.49	0.66	0.35	1.00	5.78	51.14	294.37	45.51
$LSD_{0.05}$	3	1.08	0.24	0.07	0.10	0.04	0.11	1.92	8.71	93.17	7.82
CV%	7	9.50	7.04	5.42	10.57	5.54	5.01	20.83	8.16	16.76	7.33

†Treatment descriptions are specified in Table 1.
LSD: Least significant difference at 0.05 probability level.

Table 18. Effect of treatments on number of tillers, dry matter yield and nutrient concentration of millet plants grown on the Cecil soil.

Treatment†	Tiller number	Dry weight	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	# pot^{-1}	g	——	——	%	——	——	——	——	µg g^{-1}	——
T13	16	5.07	1.01	0.27	2.51	0.27	0.42	8.16	73.16	106.05	42.42
T14	17	5.05	1.32	0.27	2.46	0.29	0.50	8.44	89.40	96.20	44.21
T15	16	5.50	1.43	0.23	2.14	0.30	0.53	9.37	81.20	88.10	48.63
T16	19	6.47	1.62	0.25	1.94	0.30	0.55	8.57	73.61	89.10	46.45
T17	18	5.26	2.07	0.26	2.04	0.31	0.61	9.59	78.33	83.21	57.92
T18	8	2.03	3.34	0.10	3.89	0.55	0.50	13.42	80.99	63.16	69.16
T19	19	6.20	1.29	0.25	2.37	0.27	0.49	12.89	129.39	75.41	44.66
T20	19	6.42	1.20	0.28	2.88	0.27	0.46	8.20	58.55	73.71	43.77
T21	19	5.20	1.33	0.26	2.95	0.29	0.46	7.22	66.75	78.80	44.31
T22	14	4.64	1.55	0.10	2.99	0.30	0.42	7.35	64.63	59.46	69.95
T23	16	5.95	1.34	0.11	2.71	0.27	0.40	6.79	57.63	59.05	49.11
T24	15	4.89	1.48	0.11	3.21	0.30	0.39	8.74	63.75	59.24	58.92
$LSD_{0.05}$	3	1.49	0.36	0.03	0.41	0.05	0.05	NS	NS	12.49	13.41
CV%	12	17.15	13.66	9.10	9.24	9.81	5.99	28.53	51.41	9.70	15.67

† Treatment descriptions are specified in Table 2.
LSD: Least significant difference at 0.05 probability level.
NS: Not significant at 0.05 probability level.

Table 19. Effect of treatments on number of tillers, dry matter yield and nutrient concentration of millet plants grown on the Lynchburg soil.

Treatment†	Tiller number	Dry weight	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	# pot^{-1}	g	———	———	%	———	———	———	———	μg g^{-1}	———
T25	20	6.23	2.64	0.23	0.96	0.42	0.47	5.44	77.67	51.42	89.30
T26	21	6.55	2.61	0.21	0.84	0.37	0.46	5.59	75.27	47.67	87.27
T27	22	5.72	2.98	0.23	0.87	0.41	0.46	5.75	83.78	48.88	88.51
T28	20	5.98	3.21	0.21	0.83	0.39	0.43	7.17	85.98	44.86	91.89
T29	19	6.18	3.06	0.22	0.88	0.34	0.44	6.89	85.62	46.45	88.05
T30	17	5.57	3.39	0.15	1.00	0.36	0.44	8.27	89.82	43.65	106.10
T31	13	3.61	4.95	0.25	1.91	0.17	0.44	5.11	92.08	43.82	77.38
T32	21	6.82	2.98	0.20	1.30	0.36	0.43	6.46	82.32	48.22	84.36
T33	25	7.52	2.42	0.21	1.19	0.33	0.46	6.64	78.59	53.70	74.53
T34	23	7.62	2.52	0.18	1.41	0.32	0.44	6.01	78.91	49.01	78.74
T35	22	7.18	2.76	0.18	1.23	0.33	0.44	6.07	79.13	48.47	90.00
T36	21	7.67	2.82	0.20	1.39	0.34	0.43	6.17	80.02	48.56	85.32
T37	23	7.39	2.74	0.19	1.50	0.34	0.46	7.23	83.31	52.78	93.09
$LSD_{0.05}$	2	1.37	0.39	0.04	0.20	0.06	NS	1.11	8.25	NS	14.03
CV%	6.46	12.83	7.74	12.41	10.04	10.65	5.21	10.52	6.05	8.33	9.73

† Treatment descriptions are specified in Table 3.
LSD: Least significant difference at 0.05 probability level.
NS: Not significant at 0.05 probability level.

Table 20. F-test values and probability of significance from the analysis of variance by soil for nutrient accumulation in millet plants.

		N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
Source	df	*F*-values								
						Belhaven				
Replicates	2	0.56NS	0.38NS	4.86*	0.74NS	1.52NS	0.31NS	0.96NS	0.13NS	0.76NS
Treatment	11	17.79***	22.49***	25.42***	7.25***	3.97**	0.99NS	1.03NS	2.48*	2.65*
						Cecil				
Replicates	2	0.87NS	1.84NS	0.33NS	0.09NS	0.45NS	0.36NS	1.22NS	1.94NS	3.43NS
Treatment	11	5.18***	30.54***	6.38***	1.82NS	8.71***	1.86NS	1.22NS	6.67***	3.61*
						Lynchburg				
Replicates	2	2.46NS	1.95NS	2.71NS	0.73NS	3.56*	1.01NS	3.44*	2.15NS	1.56NS
Treatment	12	1.36NS	2.65*	9.60***	24.97***	8.77***	4.03**	4.27**	5.95***	6.84***

*** Significant at the 0.001 probability level.
** Significant at the 0.01 probability level.
* Significant at the 0.05 probability level.
NS Not significant at the 0.05 probability level.

Table 21. Effect of treatments applied to the Belhaven soil on nutrient accumulation of millet.

Treatment†	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	mg pot^{-1}					µg pot^{-1}			
T1	97	53	30	22	71	34	362	1503	342
T2	131	65	32	27	89	34	440	2522	466
T3	154	64	30	25	88	37	458	2132	455
T4	160	60	29	23	78	32	400	1777	447
T5	164	58	27	23	76	36	404	1879	434
T6	152	25	27	23	74	25	391	2114	392
T7	132	63	52	33	103	40	460	2510	408
T8	116	64	58	30	102	41	422	2470	429
T9	103	56	55	33	95	38	406	2450	404
T10	123	38	38	30	93	35	423	2350	360
T11	112	47	54	30	91	39	364	2499	388
T12	114	44	59	32	90	53	465	2635	410
$LSD_{0.05}$	15	8	8	4	15	NS	NS	650	66
CV%	7	9	11	10	11	32	14	18	10

†Treatment descriptions are specified in Table 1.
LSD: Least significant difference at 0.05 probability level.
NS: Not significant at 0.05 probability level.

Table 22. Effect of treatments applied to the Cecil soil on nutrient accumulation of millet.

Treatment†	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	mg pot^{-1}					µg pot^{-1}			
T13	51	14	127	14	21	42	369	538	216
T14	66	14	123	15	25	42	436	489	222
T15	78	13	117	16	29	52	441	490	267
T16	102	16	124	19	36	55	456	580	295
T17	108	14	106	16	32	50	409	436	302
T18	67	2	77	11	10	27	166	135	146
T19	80	15	147	17	30	80	802	468	276
T20	77	18	185	18	29	53	375	470	279
T21	69	14	154	15	24	38	344	413	229
T22	72	5	139	14	20	34	300	276	322
T23	79	6	161	16	24	40	343	351	289
T24	69	5	151	14	18	41	303	290	275
LSD $_{0.05}$	20	3	32	7	7	NS	NS	141	73
CV%	15	15	14	18	16	37	60	21	17

†Treatment descriptions are specified in Table 2.
LSD: Least significant difference at 0.05 probability level.
NS: Not significant at 0.05 probability level.

Table 23. Effect of treatments applied to the Lynchburg soil on nutrient accumulation of millet.

Treatment†	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	mg pot^{-1}					µg pot^{-1}			
T25	163	15	60	26	29	34	482	321	554
T26	170	13	55	24	30	36	490	311	567
T27	169	13	50	23	26	33	478	279	503
T28	188	13	49	23	26	42	505	268	541
T29	187	14	55	20	27	42	529	283	536
T30	189	8	56	20	25	46	500	244	591
T31	179	9	68	6	16	18	333	159	280
T32	202	14	88	24	29	44	559	327	571
T33	182	15	89	25	35	50	590	403	558
T34	192	14	108	24	34	46	601	373	599
T35	197	13	88	23	31	43	565	346	640
T36	212	16	106	25	32	47	606	369	632
T37	202	14	111	25	34	54	615	393	687
LSD $_{0.05}$	NS	4	22	3	5	13	106	80	106
CV%	11	18	17	8	10	19	12	15	11

†Treatment descriptions are specified in Table 3.
LSD: Least significant difference at 0.05 probability level.
NS: Not significant at 0.05 probability level.

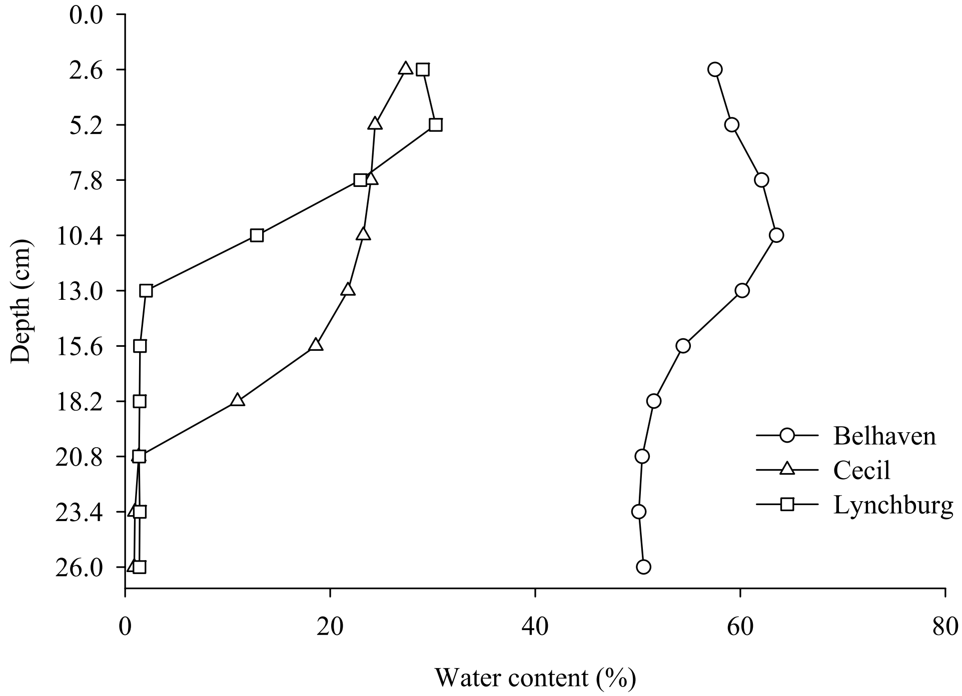

Fig. 1. Volumetric soil water content as a function of cylinder depth for Belhaven, Cecil, and Lynchburg soil samples (sieved to pass 2-mm).

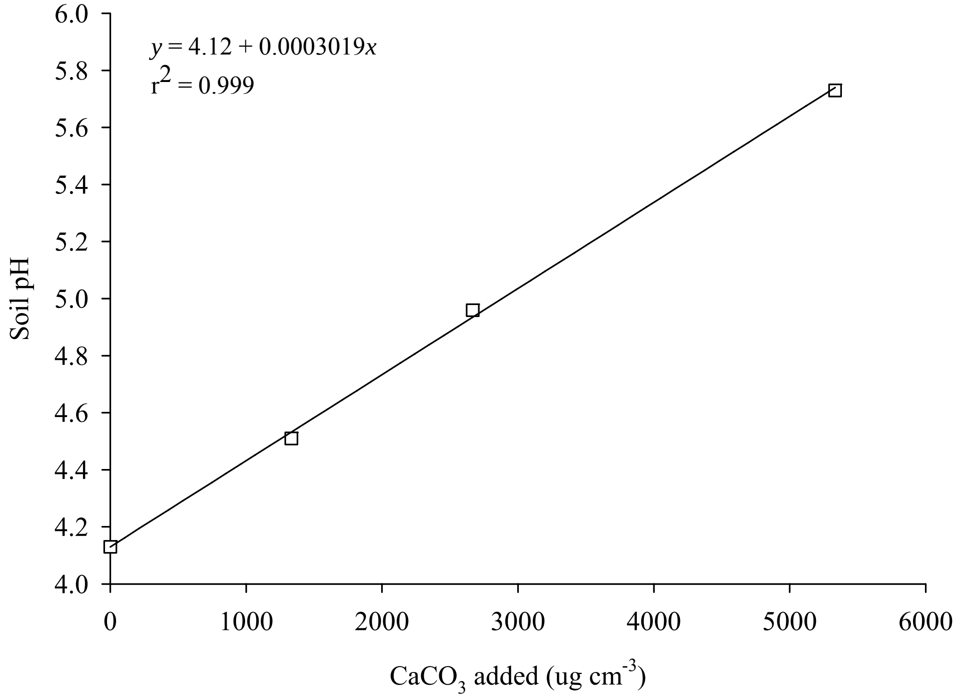

Fig. 2. Observed (symbols) and predicted (line) values of pH in the Lynchburg soil as a function of added $CaCO_3$.

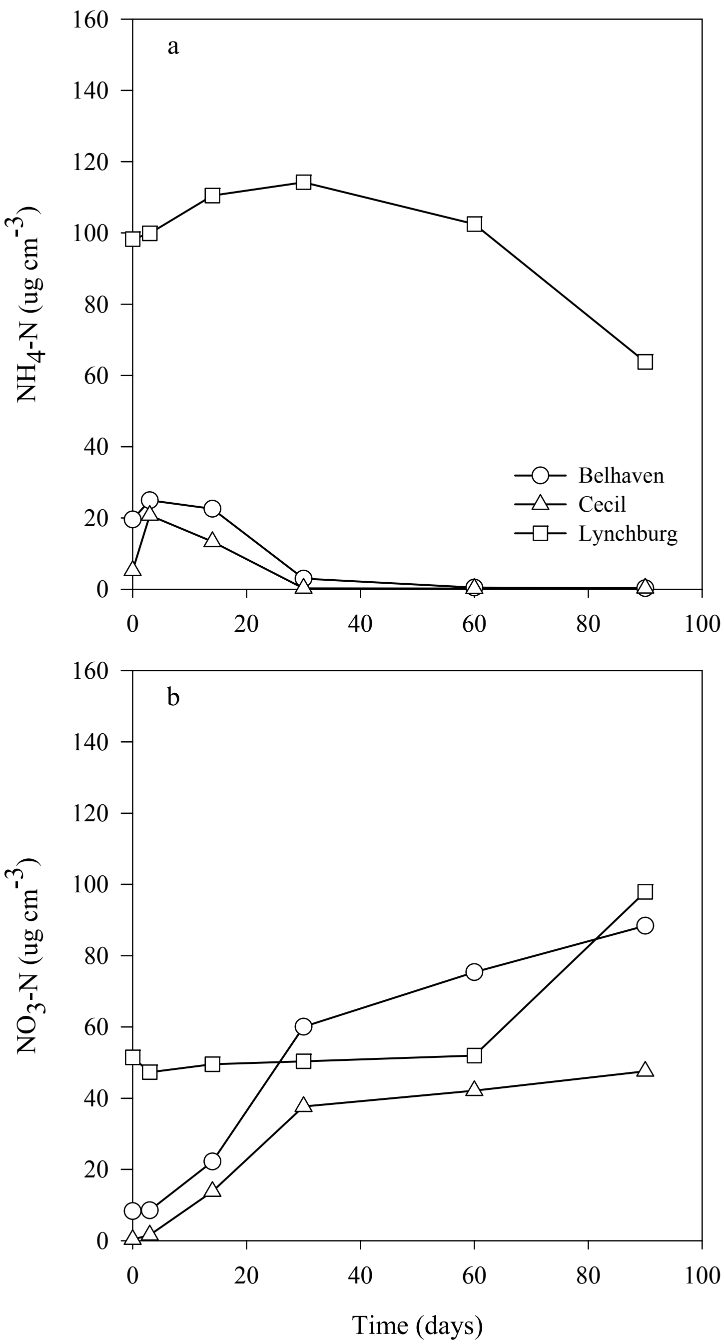

Fig. 3. (a) Ammonium-N and (b) NO_3-N accumulated in soils without added N (control treatments) during a 90-day incubation period.

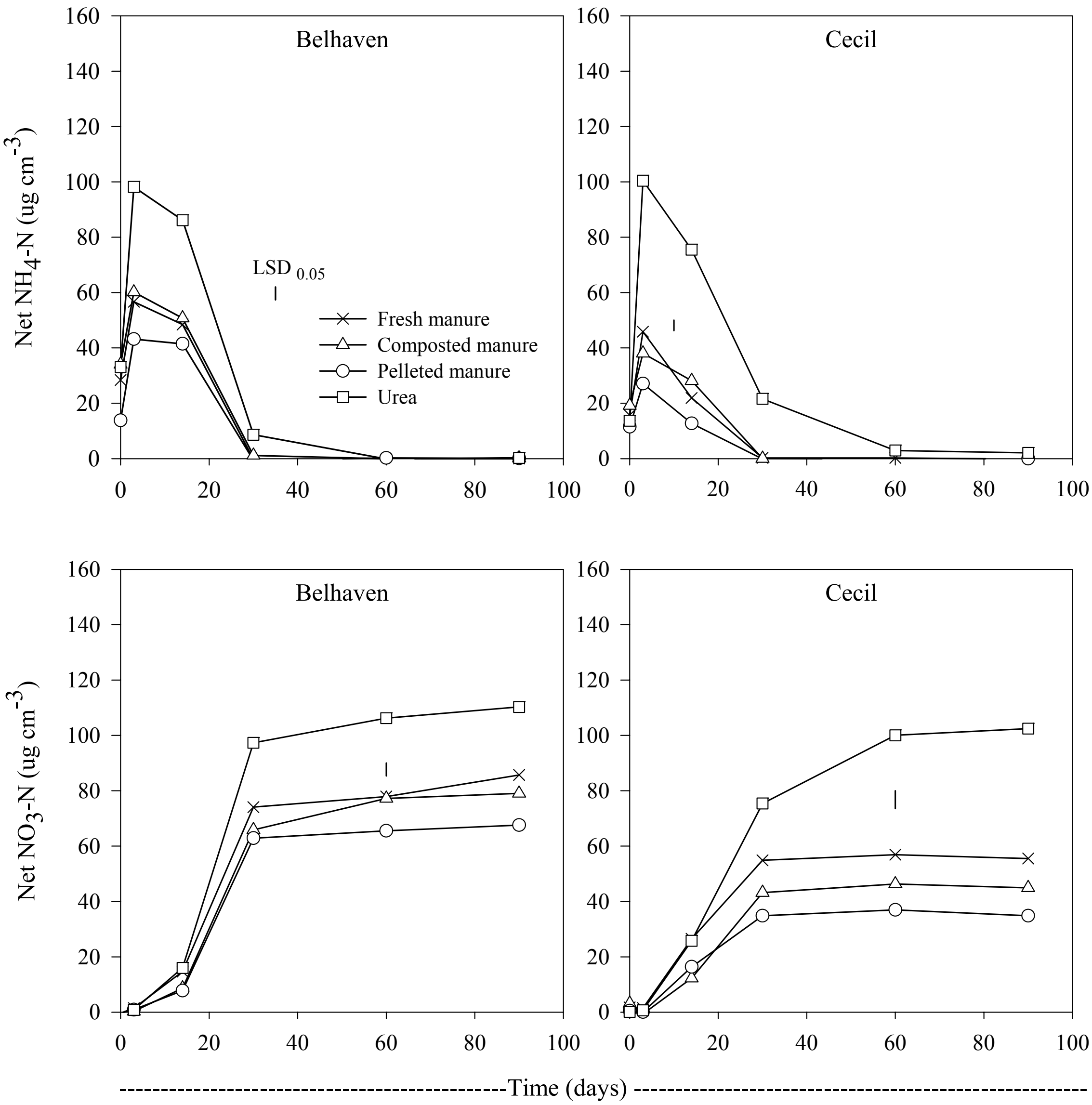

Fig. 4. Net NH_4-N and NO_3-N released from poultry layer manures and urea incubated in Belhaven and Cecil soils for a 90-day period. Vertical bars represent least significant difference (LSD) between the N-sources by time interaction at the 0.05 probability level.

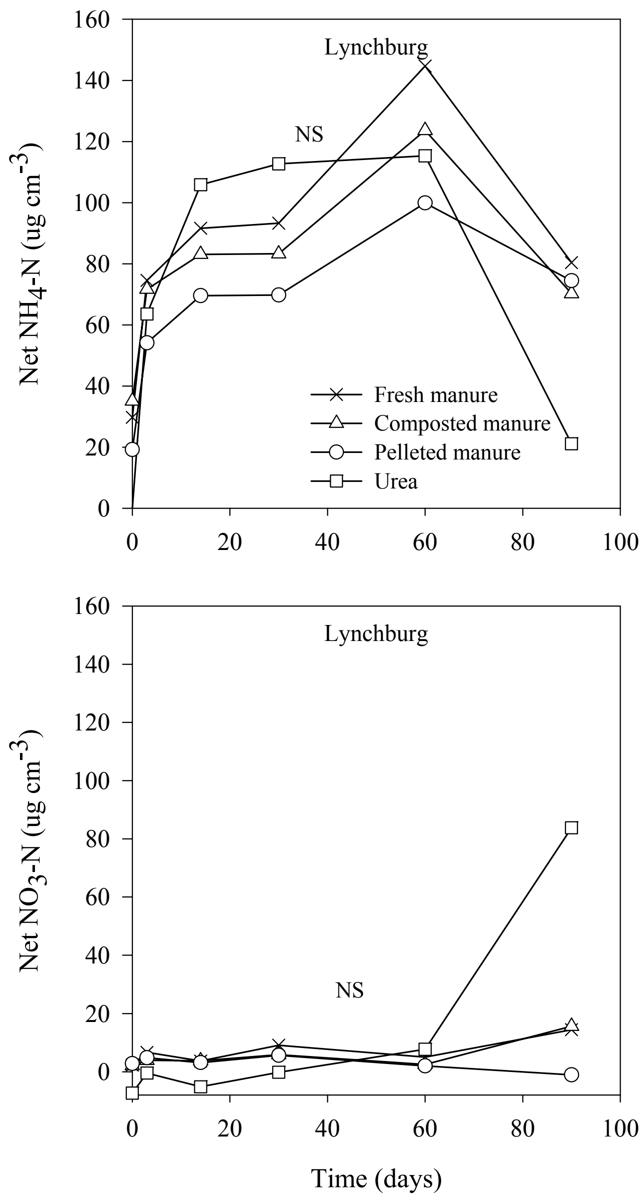

Fig. 5. Net NH_4-N and NO_3-N released from poultry layer manures and urea incubated in the Lynchburg soil for a 90-day period. NS represent nonsignificant difference between N-sources by time interaction.

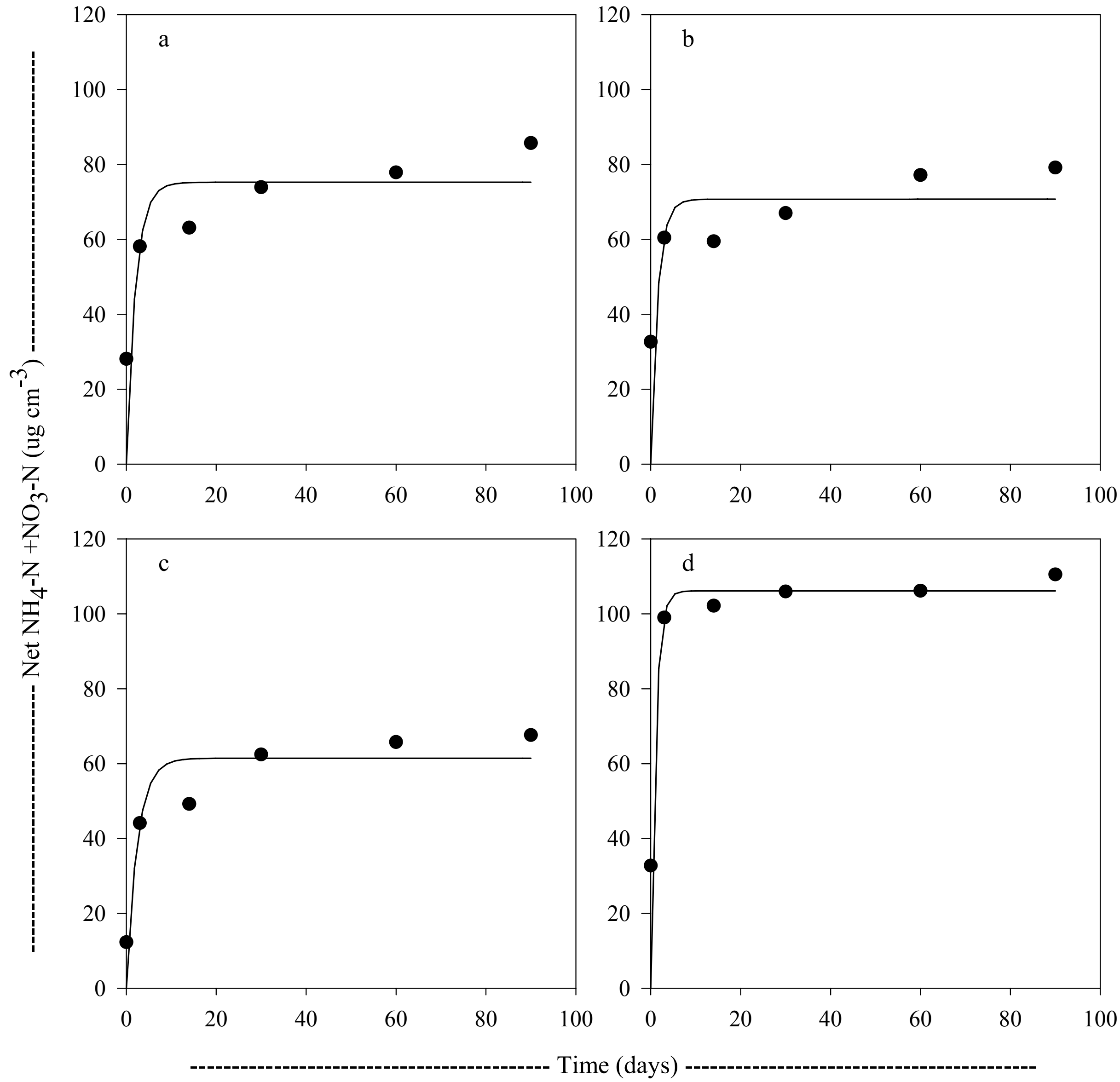

Fig. 6. Observed (symbols) and predicted (lines) for net NH_4-N + NO_3-N accumulation in the Belhaven soil during 90 days of incubation with equal amounts of N supplied as (a) fresh manure, (b) composted manure, (c) pelleted manure, and (d) urea.

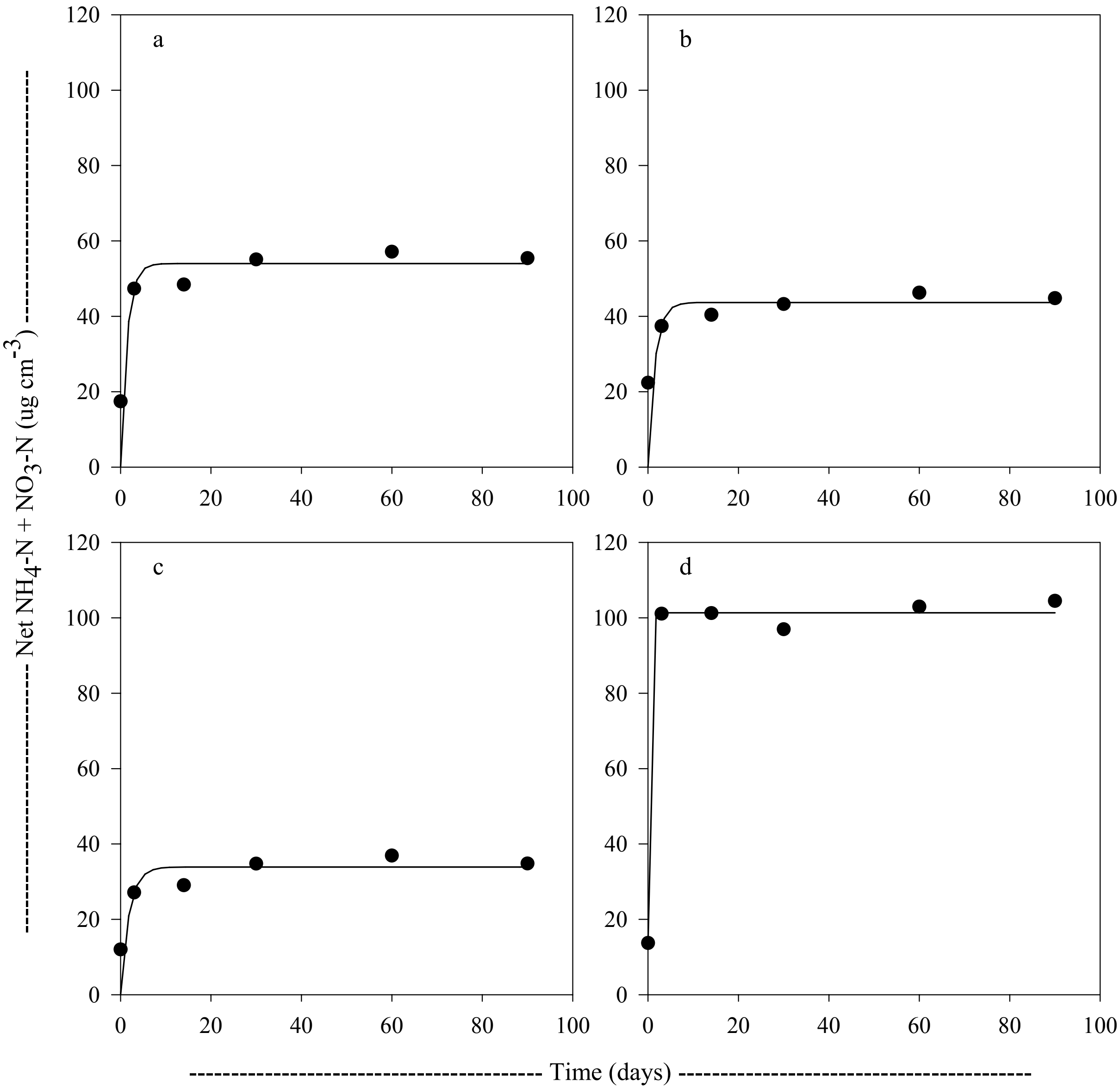

Fig. 7. Observed (symbols) and predicted (lines) for net NH_4-N + NO_3-N accumulation in the Cecil soil during 90 days of incubation with equal amounts of N supplied as (a) fresh manure, (b) composted manure, (c) pelleted manure, and (d) urea.

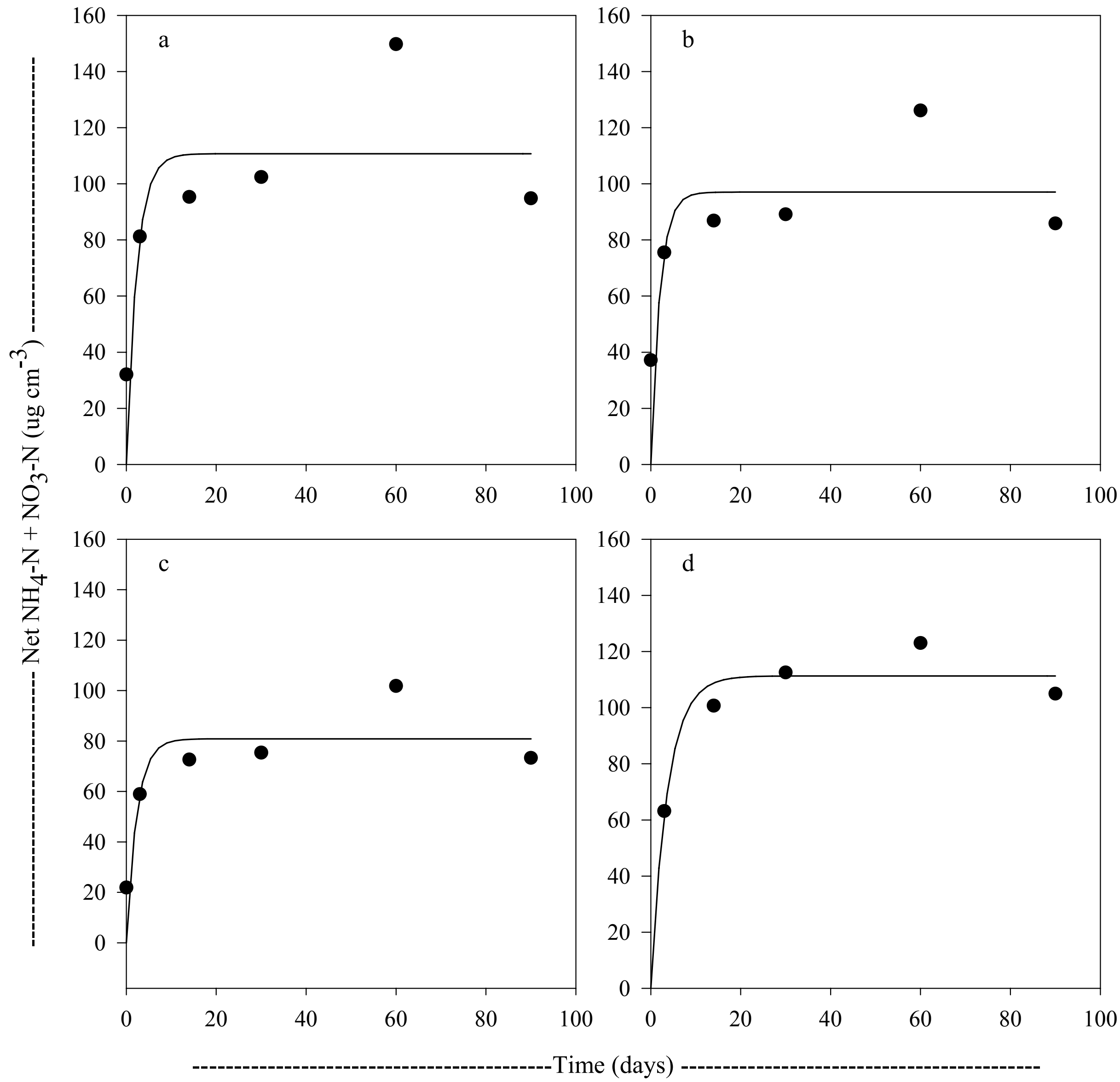

Fig. 8. Observed (symbols) and predicted (lines) for net NH_4-N + NO_3-N accumulation in the Lynchburg soil during 90 days of incubation with equal amounts of N supplied as (a) fresh manure, (b) composted manure, (c) pelleted manure, and (d) urea.

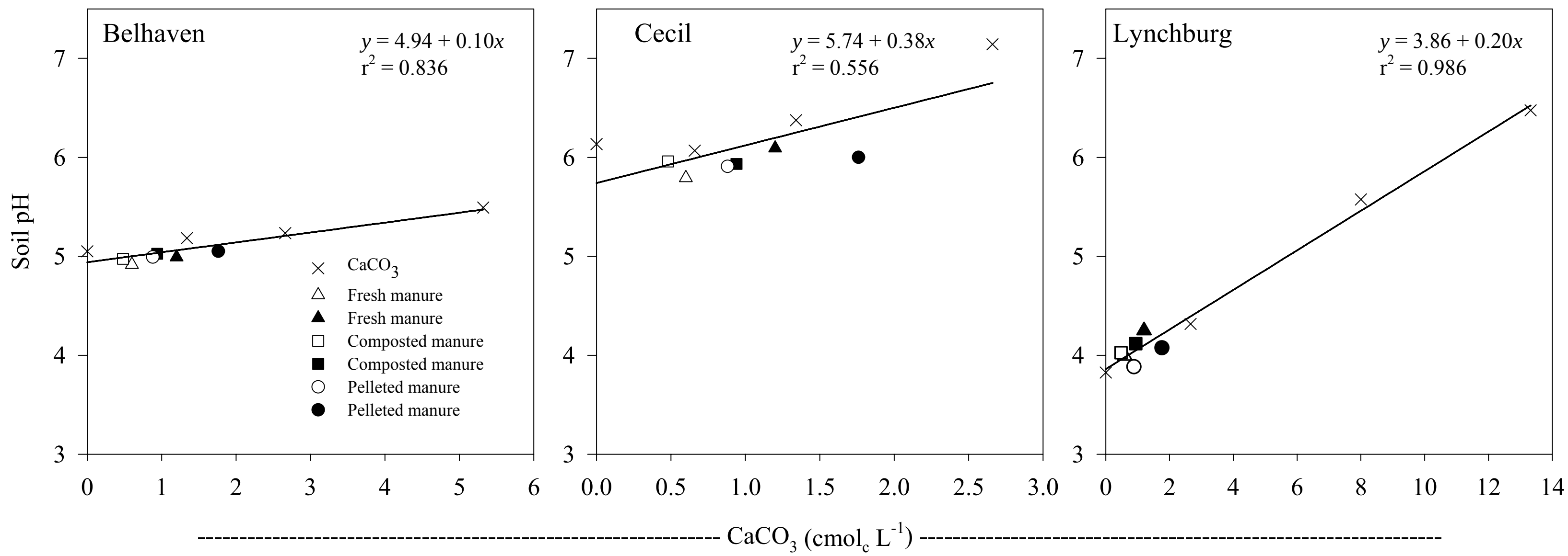

Fig. 9. Soil pH as a function of $CaCO_3$ equivalents applied to each soil as either reagent grade $CaCO_3$ or poultry layer manures. Open symbols are for manure rates (dry matter basis) of 1333 µg cm^{-3} and close symbols are for manure rates of 2667 µg cm^{-3}. Line for the regression equation.

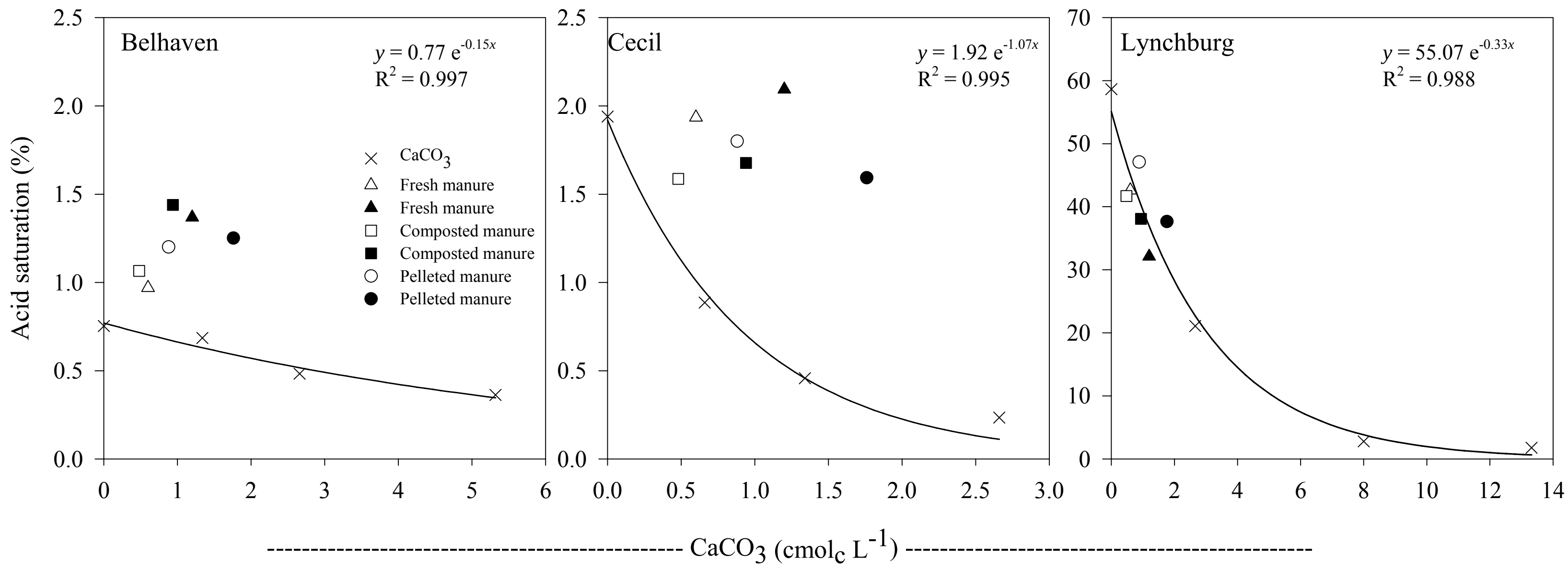

Fig. 10. Soil % acid saturation of the ECEC as a function of $CaCO_3$ equivalents applied to each soil as either reagent grade $CaCO_3$ or poultry layer manures. Open symbols are for manure rates (dry matter basis) of 1333 µg cm^{-3} and close symbols are for manure rates of 2667 µg cm^{-3}. The exponential equations were developed with data points for the treatments with reagent grade $CaCO_3$.

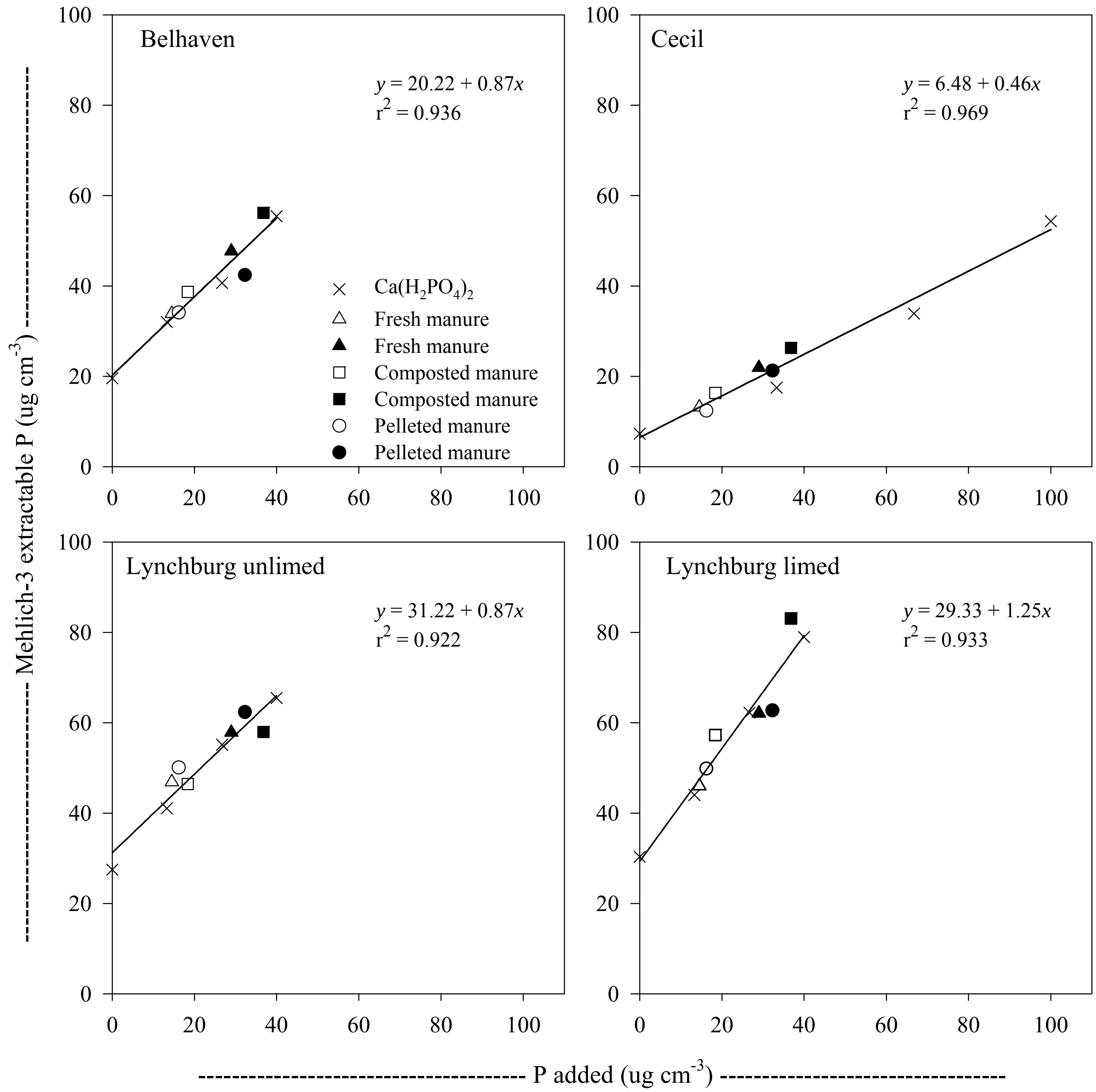

Fig. 11. Mehlich-3 extractable soil P, averaged across four sampling dates, as a function of added P as either $Ca(H_2PO_4)_2$ or poultry layer manures. Open symbols indicate the addition of 1333 µg manure cm^{-3} soil and close symbols indicate the addition of 2667 µg manure cm^{-3} soil (dry matter basis).

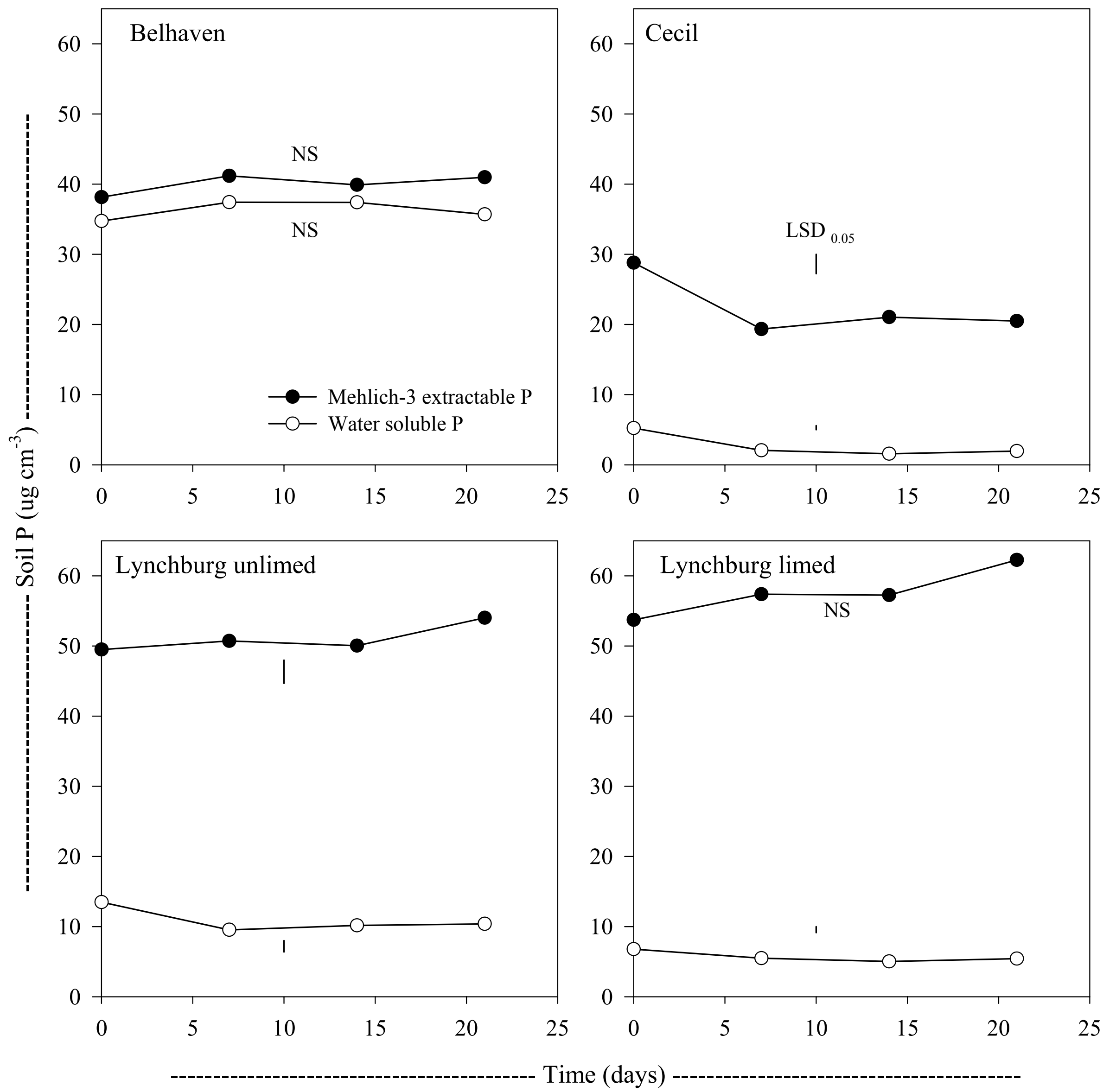

Fig. 12. Mehlich-3 extractable P and water soluble P averaged across P treatments, as a function of time during the 21-day incubation period. Vertical bars represent least significance difference (LSD) among sampling dates at a probability level of 0.05. NS represents nonsignificant difference.

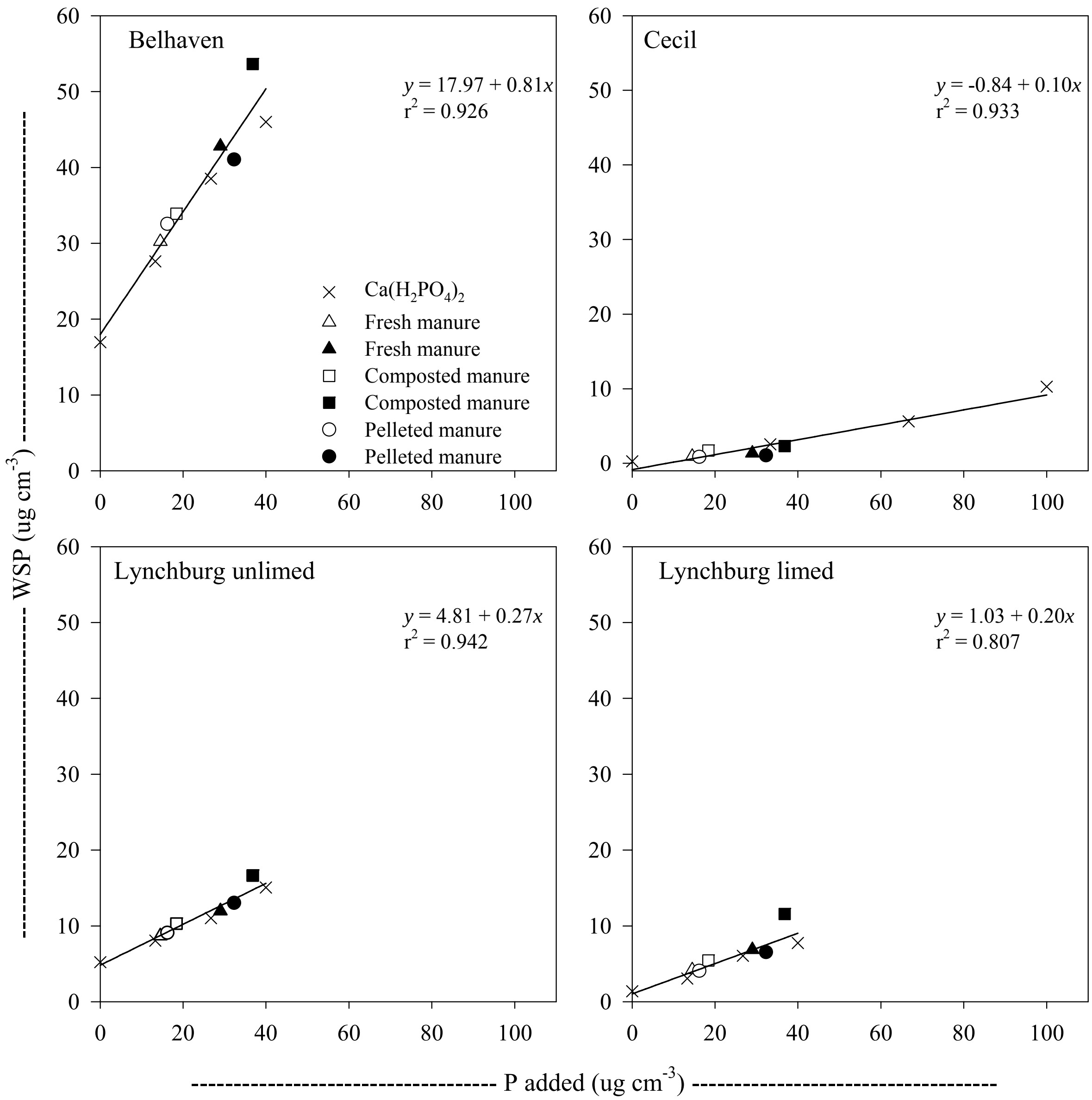

Fig. 13. Water soluble P (WSP), averaged across four sampling dates, as a function of added P as either $Ca(H_2PO_4)_2$ or poultry layer manures. Open symbols indicate the addition of 1333 µg manure cm^{-3} soil and close symbols indicate the addition of 2667 µg manure cm^{-3} soil (dry matter basis).

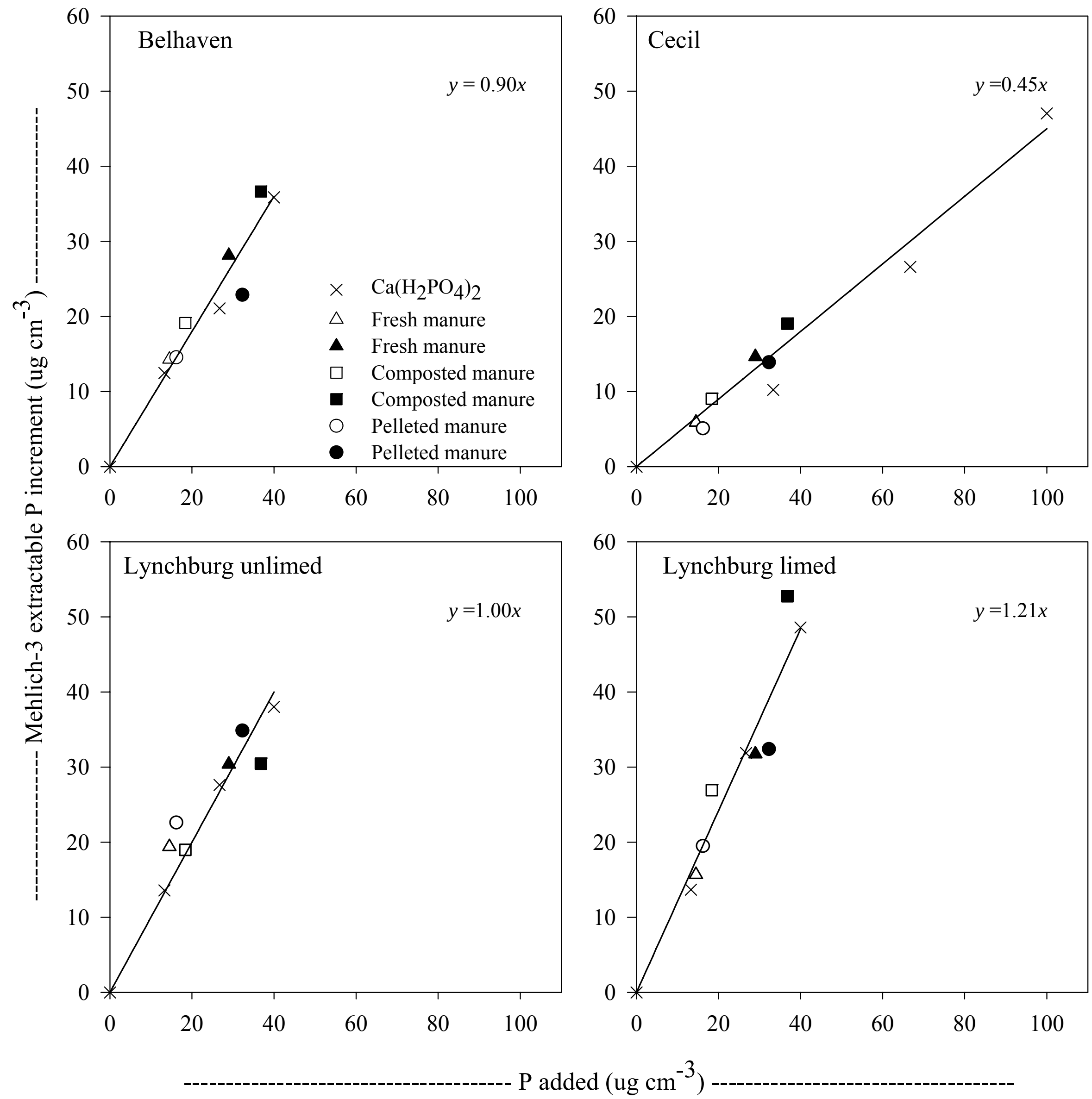

Fig. 14. Mehlich-3 extractable soil P increment as a function of P added as either $Ca(H_2PO_4)_2$ or poultry layer manures. Values used are the mean of treatments across sampling dates. Open symbols indicate the addition of 1333 µg manure cm^{-3} soil and close symbols indicate the addition of 2667 µg manure cm^{-3} soil (dry matter basis).

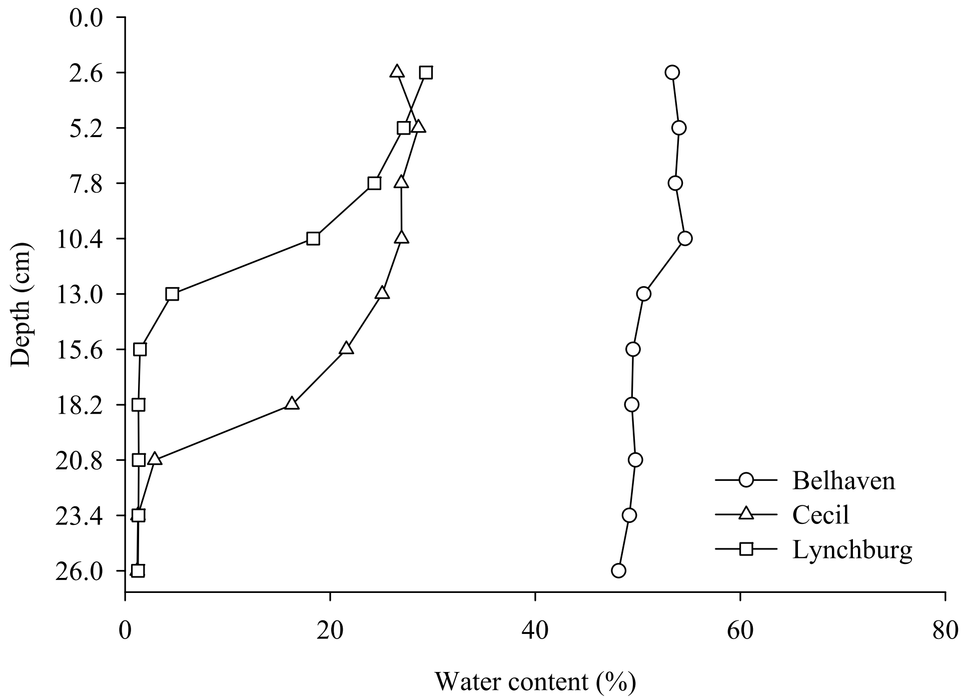

Fig. 15. Volumetric soil water content as a function of cylinder depth for Belhaven, Cecil, and Lynchburg soil samples (sieved to pass 4-mm) used in the greenhouse experiment.

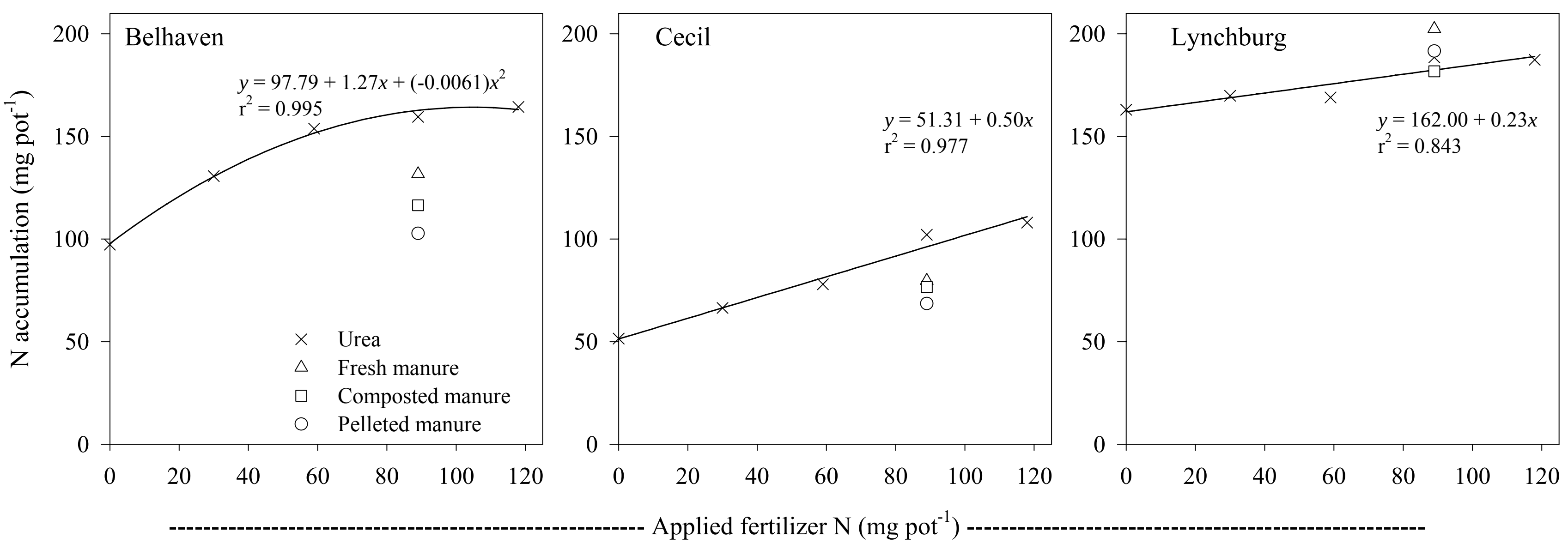

Fig. 16. Nitrogen accumulation in millet plants as a function of applied urea-N fertilizer and urea-N equivalency values of N supplied by poultry layer manures. Regression equations are for N accumulation in urea-N treatments.

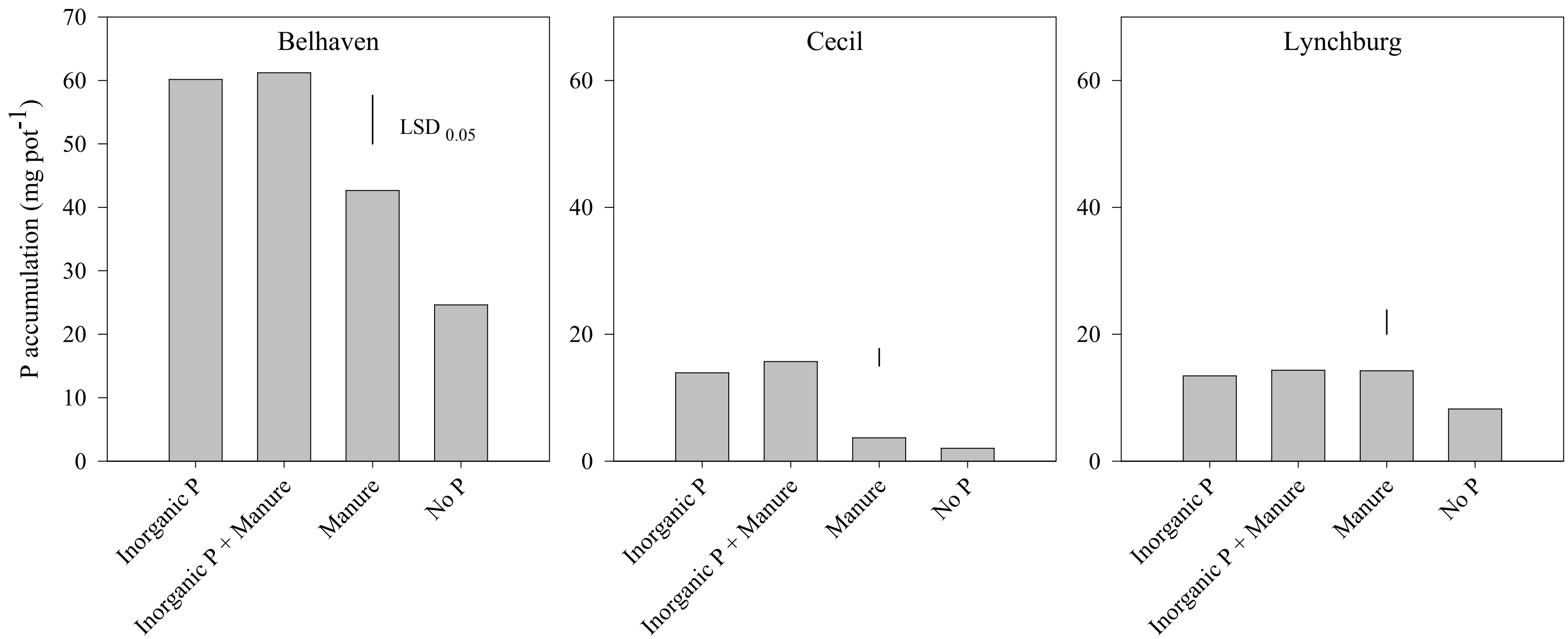

Fig. 17. Mean values of P accumulation in millet for treatments in each soil receiving P from inorganic fertilizer, inorganic fertilizer and manures, manures only and no P added. Vertical bars indicated least significant difference (LSD) for a 0.05 probability level.