Soil Test Nutrient Changes Induced by Poultry Litter under Conventional Tillage and No-Tillage

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Poultry litter (PL) can supply N, P, K, and other plant nutrients; however, excessive application may cause environmental problems, depending on management and crop nutrient demand. Changes in soil test (ST) nutrient content in a Cecil soil (a fine, kaolinitic, thermic Typic Kanhapludult) during a 10-yr period of PL use was evaluated at the USDA-ARS J. Phil Campbell, Sr., Natural Resource Conservation Center, Watkinsville, GA. During the cotton (*Gossypium hirsutum* L.) cropping phase (1995–2000), 4.4 Mg PL ha^{-1} yr^{-1} resulted in small changes in ST nutrient content in the surface 15 cm. Differences were observed between tillage treatments, with less accumulation of Ca, Mg, and Mn and greater accumulation of Zn for no-till (NT) than conventional tillage (CT). During the corn (*Zea mays* L.) cropping phase (2001–2005), average annual PL inputs (11.2 Mg ha^{-1}) increased P and Zn contents, with changes being similar for CT and NT. After 10 yr, ST nutrient contents in the surface 15 cm reflected 25, 4, 45, 26, 17, and 97% of the input from PL for P, K, Ca, Mg, Mn, and Zn, respectively. Changes in soil profile nutrient content (to a depth of 60 cm) from 1997 to 2005 were predominantly at 0 to 15 cm, where P and Zn increased >200%. Accumulation of Ca, K, P, and Zn at lower depths was also observed. Strategies for increasing nutrient removal following repeated long-term application of PL should be considered to avoid excessive levels of nutrients.

Abbreviations: CF, conventional fertilizer; CT, conventional tillage; FS, fertilizer source; NT, no-till; PL, poultry litter; ST, soil test.

The southern states of Alabama, Arkansas, Georgia, Mississippi, and North Carolina account for more than 60% of the 8.6 billion broilers raised in the United States (National Agricultural Statistics Service, 2007) and consequently produce nearly 9.3 million Mg of PL (a mixture of bedding material and manure) for use on agricultural lands. Poultry litter has been used on crops and pastures as a readily available source of N, P, and K and also contains other plant nutrients, such as Ca, Mg, S, Cu, Mn, and Zn (Stephenson et al., 1990; Tewolde et al., 2005; Mitchell and Tu, 2006; Adeli et al., 2007). Positive responses to the application of PL have been shown for forages (Sharpley et al., 1993; Kingery et al., 1994) and row crops (Wood et al., 1996; Endale et al., 2002; Tewolde et al., 2005; Mitchell and Tu, 2005). Mitchell and Tu (2005) found no difference in crop yield responses to PL for cotton and corn in conventional and conservation tillage systems in Alabama.

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Because long-distance transportation of PL is costly, repeated application to agricultural lands within short distances of growing facilities can lead to overapplication and negative environmental impacts on air, soil, and water quality. Increases in concentrations of P, K, Ca, Mg, Cu, and Zn have been found for soils receiving PL for an extended period of time (Kingery et al., 1993, 1994; Bagley and Burdine, 1996; Wood et al., 1996; Mitchell and Tu, 2006). Kingery et al. (1994) reported significant accumulation of NO_3^- at 1 to 3 m in a soil profile in Alabama following long-term PL application. Nutrients such as Ca, K, Mg, Mn, Cu, and Zn may also accumulate at the soil surface and potentially move in runoff from PL-amended fields.

In the past, application of PL has been based on crop N needs and often resulted in application of P in excess of crop requirements. Typically, PL is about 1.1 to 1.5% P on a dry weight basis, with N/P ratios reported as 2.3:1 by Barker et al. (1994) and 3:1 by Vest et al. (1994). Since crops typically require higher rates of N than P, repeated application of poultry litter commonly results in the accumulation of P. Accumulation of P in surface soils from PL applications has been reported for soils used for forage (Sharpley et al., 1993; Kingery et al., 1994; Wood et al., 1996; Franzluebbers et al., 2004) and row crops (Gascho and Hubbard, 2006). Phosphorus tends to accumulate in surface soils, where it is sorbed on Fe and Al oxides. Once the P adsorption capacity is exceeded, the potential for loss as dissolved P in runoff or leachate increases and will depend on soil mineralogy, the quantity of P added, and the potential for preferential flow. Changes in soil P chemistry and reaction products may also occur after long-term application of animal manures that alter the extractability and solubility of P (Sharpley et al., 2004). Inevitably, the accumulation of P in surface soils raises concerns about losses in runoff and eutrophication of surface water (Moore et al., 1995; Sharpley et al., 1994).

Accumulation of heavy metals is also a potential concern with repeated application of PL (Jackson et al., 2003, 2006). Several trace elements such as As, Co, Cu, Fe, Mn, Se, and Zn are added to poultry feed to minimize health disorders and avoid diseases (Sims and Wolf, 1994; Moore, 1998; Angel and Powers, 2006). Because only small portions of these trace metals are absorbed in the digestive tract of poultry (Kunkle et al., 1981), repeated application of PL may result in the accumulation of levels toxic to plants, animals, and humans (Mitchell and Browne, 1992; Jackson et al., 2003). Kpomblekou-A et al. (2002) reported that concentrations of elements varied widely in 33 PL samples from Alabama. Median concentrations of K, Ca, and Mg were 25.9, 27.3, and 6.1 g kg^{-1}, respectively, while the median concentrations of the trace nutrients Cu, Mn, and Zn were 410, 356, and 371 mg kg^{-1}, respectively. Application of 9 Mg ha^{-1} PL in Texas added 9.4, 6.5, and 5.8 kg ha^{-1} of Cu, Mn, and Zn, respectively (Evers, 2002), while similar applications in southeastern soils added 3.4, 3.2, and 2.7 kg ha^{-1} of Cu, Mn, and Zn, respectively (Jackson et al., 2003). Kingery et al. (1994) reported that topsoil Cu and Zn concentrations were greater in PL-treated soils (2.5 and 10 mg kg^{-1}) than in untreated soils (0.75 and 2.2 mg kg^{-1}, respectively) following long-term application of PL to tall fescue (*Festuca arundinacea* Schreb.) in several Ultisols in Alabama. Limited uptake of trace nutrients by crops contributes to accumulation following PL application (Brink et al., 2001; Evers, 2002; Tewolde et al., 2005). Long-term application of PL to soils may not only increase content but may also affect metal solubility due to the addition of organic compounds to form soluble organometallic complexes in soils (del Castilho et al., 1993).

Nutrient accumulation, removal, and loss will depend on the source and rate of nutrient input, the crops being grown, and the soil management strategies used. Conservation tillage offers significant environmental and economic advantages for crop production (Bruce et al., 1995; Allmaras et al., 2000; Endale et al., 2002, 2008; Schomberg et al., 2003) and is an effective tool for reducing soil erosion caused by wind or water. Soil productivity increases with soil C in conservation tillage systems due to improved water availability (less runoff and more infiltration) and increased nutrient holding capacity (Bruce et al., 1995; Allmaras et al., 2000). Endale et al. (2002) showed that the response to PL was greater for cotton in a NT system than in a CT system during a period with adequate rainfall. During a drought period, there was little difference in response to nutrient source between the two tillage systems. Nutrient dynamics within cropping systems are the outcomes of both management and environmental influences. Because of contrasting physical, chemical, and biological soil properties, assessment of management practices often needs to be site or system specific (Tarkalson and Mikkelsen, 2004).

The objective of this research was to evaluate tillage and management influences on ST nutrient concentrations in a Cecil soil where PL was used as a source of fertilization for an extended (multiyear) period of cotton and corn production, with PL input based on the N needs of the crops. We were particularly interested in identifying how the accumulation of ST nutrients might change in relationship to PL inputs.

MATERIALS AND METHODS

Experimental Site and Soil

This research was conducted on the instrumented water quality facility at the USDA-ARS J. Phil Campbell, Sr., Natural Resource Conservation Center, Watkinsville, GA (83°24′ W, 33°54′ N) from 1995 to 2005. The facility consists of 12 large (10- by 30-m) tile-drained plots, located on nearly level (<2% slope) Cecil sandy loam soil. The facility was originally used to determine nutrient and chemical losses associated with cover crops and conservation tillage and for improving models of subsurface N losses (McCracken et al., 1993, 1995; Johnson et al., 1999). Each plot is underlain by five 30-m-long drain lines spaced 2.5 m apart. Drain lines consist of 10-cm-diameter, flexible, slotted polyvinyl chloride pipe installed on a 1% grade. At the lower plot edge, the depth of each drain line is 1 m from the soil surface. To exclude subsurface lateral flow, plot borders are enclosed with polyethylene sheeting that extends from the soil surface to the depth of the drain lines. Plots are equipped with refrigerated samplers to collect runoff and drainage associated with rainfall events. The facility has only three replications due to the logistics associated with establishing and maintaining the intensive runoff and drainage sample collection system.

The experimental design from 1991 to fall 1994, before applications of PL, was a randomized, complete block, split-plot design with three replications. The main plot was tillage (CT or NT), and the subplot was a winter cover crop (fallow or rye [*Secale cereale* L.]). In the fall of 1994, all plots were planted to a rye cover crop and the subplot treatments were changed from a comparison of fall-planted cover crops to a comparison of spring-applied conventional fertilizer (CF), either NH_4NO_3 or $(NH_4)_2SO_4$ for N, and PL (3.3% N, 1.5% P, 2.7% K). This arrangement results in a factorial combination of treatments: CT–CF, CT–PL, NT–CF, and NT–PL. Conventional tillage is conducted in the spring and fall and consists of a 30-cm-deep chisel plowing to break possible hard pans, followed by one to two diskings to 20-cm depth and a subsequent 8-cm-deep disking with a tandem disk to smooth the seed bed. Soil disturbance in NT is limited to that caused by a coulter and double-disk opener on the NT planter. No-till began in the fall of 1991 and PL application began in the spring of 1995.

Cecil soil has a sandy loam surface over a clayey argillic subsurface and is developed from residual saprolite weathered from felsic igneous and metamorphic rocks. This class of soils tends to have a low pH, low base saturation, and low cation exchange capacity, and has abundant Fe and Al oxides in the Bt horizon. The soil at the research site has a 20-cm-thick Ap horizon of brown sandy loam with 75% sand and 6% clay, and is underlain by a 5- to 10-cm-thick BA horizon of red sandy clay loam to clay loam texture (Bruce et al., 1983). The Bt horizon consists of about 100 cm of red clay followed by about a 30-cm-thick red loam to clay loam BC horizon. The C horizon is a loamy saprolite. Initial ST nutrient contents in the fall of 1991 before the study to evaluate cover crops and tillage effects on leaching of NO_3^- were 18.8, 1.8, 125, 33, 777, 111, 33, and 3.2 kg ha^{-1} for C, N, P, K, Ca, Mg, Mn, and Zn, respectively, and the pH was 6.0 (Johnson et al., 1999).

Average daily air temperature ranges from 6 to 8°C in winter and from 23 to 27°C in summer. Frost-free days in the growing season range from 200 to 250. Mean annual precipitation is 1240 mm, with fall seasonal rainfall typically less than the other seasons. Precipitation is typically the greatest in March and least in October. Mean potential evapotranspiration during the research was 1.6 mm in winter, 3.6 mm in spring, 4.8 mm in summer, and 2.6 mm in fall.

Cropping Systems

From fall 1994 to fall 2000 (the cotton phase), the cropping sequence was a cereal rye (cv. Hy Gainer) cover crop followed by cotton (cv. Stoneville 474) in the spring. Cotton was fertilized with 67 kg ha^{-1} as NH_4NO_3 in the CF treatment, while in the PL treatment an equivalent amount of N was added by applying 4.5 Mg PL ha^{-1} (fresh weight basis) on the assumption that mineralization of the N in the PL was 50% (Vest et al., 1994) during the main cropping season. The PL used throughout the study originated from the same poultry houses and was brought to the research site and kept under cover for no more than 2 wk before application. Variation in numbers of birds between clean outs, moisture content, and diet during the length of the study resulted in variability in nutrient concentrations in the PL. The PL consisted of manure and pine (*Pinus palustris* P. Miller and *Pinus elliottii* Englem.) wood shavings. Each batch was analyzed at the Soil, Plant and Water Analysis Laboratory at the University of Georgia, Athens. Total N was determined by the Dumas method (Bremner and Mulvaney, 1982). All other elements were determined by inductively coupled plasma analysis after digestion with HNO_3 and $HClO_4$ (Agricultural and Environmental Services Laboratories, 2002). The mass of nutrients and other elements applied annually was calculated from the rate of PL or CF application and actual source concentrations (Table 1). Based on the ST recommendations for cotton, CF plots received 25 kg P ha^{-1} and 47 kg K ha^{-1} from inorganic fertilizers, while the PL contained sufficient P and K (Table 1). The rye cover crop in both the PL and CF treatments received 56 and 37 kg K ha^{-1}, respectively, from inorganic fertilizer. Nutrients were applied 1 to 2 d before planting and incorporated in the CT treatment during the final disking operation. In both the CT and NT treatments, the cover crop was chemically killed by applying glyphosate [*N*-(phosphonomethyl) glycine, 2.3 L ha^{-1}] 2 to 3 wk before planting of cotton. Cotton stalks were shredded after harvest with a rotary mower. Crop residues were incorporated by tillage operations before planting in the CT treatment. Standard recommended practices were followed for controlling weeds and pests and in the application of cotton harvest aids.

Table 1. Average nutrient input from conventional fertilizer (CF) and poultry litter (PL) sources during the cotton and corn phases of the field experiment at Watkinsville, GA.

Crop and nutrient source	N	P	K	Ca	Mg	Mn	Zn
	kg ha^{-1}						
	Cotton phase						
Cotton							
CF	65	25	47	0	0	0	0
PL	152	71	92	72	16	1.9	1.3
Rye							
CF	56	0	37	0	0	0	0
PL†	56	0	37	0	0	0	0
	Corn phase						
Corn							
CF	201	20	45	197	49	0.0	0.0
PL	433	215	364	322	66	6.1	5.1
Rye‡							
CF	95	0	10	0	0	0	0
PL	173	67	144	111	21	1.8	1.7

† Rye in the cotton-phase PL treatment was fertilized with CF.

‡ Rye in the corn phase received PL in 2001, 2002, and 2003 and CF N in 2004. Data for PL are the 3-yr average applications.

Beginning in spring 2001 (the corn phase), corn (cv. Pioneer 3223) was planted as the summer crop while rye continued to be used as the winter cover crop (Endale et al., 2008). Nitrogen fertilization was increased to 168 kg ha^{-1} based on recommendations for corn and was applied as $(NH_4)_2SO_4$ in the CF treatment. The PL treatment received 11.2 Mg PL ha^{-1}, providing an equivalent amount of plant-available N. The N application rate to corn was doubled (to 336 kg N ha^{-1} in CF and 22.4 Mg PL ha^{-1} in PL) in the spring of 2003 to test for loss of estradiol and testosterone from the PL. Corn N fertilization was reduced to 168 kg ha^{-1} in 2004 and 2005. The rye cover crop (4.5 Mg ha^{-1}) in the PL treatment was fertilized with PL during 2001, 2002, and 2003 and with CF in 2004 and 2005 of the corn cropping phase, in contrast to the use of CF during the entire cotton phase. Corn and rye residues were shredded with a rotary mower in both the CT and NT treatments but were only incorporated in the CT treatment.

Soil Sampling and Analysis

Surface soil samples (0–15 cm) were collected from each plot 1 to 2 wk before planting and before fertilization of the summer and fall crops. Samples were composited from three to four cores taken with a 1.25-cm-diameter probe from three to four random locations in the plots. In the fall of 1997, 2000, and 2005, soil profile samples (0–60 cm) were collected from three locations in each plot using a tractor-mounted hydraulic soil coring device. Soil cores (2.5-cm diameter) were partitioned into 0- to 15-, 15- to 30-, and 30- to 60-cm depth increments and composited. All samples (surface and profile) were dried at 55 to 60°C for 3 to 5 d and sent to the Soil, Plant and Water Analysis Laboratory at the University of Georgia, Athens, for analysis of extractable ST nutrients (Ca, K, Mg, Mn, P, and Zn) using the double acid (0.05 mol L^{-1} HCl + 0.025 mol L^{-1} H_2SO_4) extraction method (Mehlich-1) and an inductively coupled plasma emission spectrometer (Agricultural and Environmental Services Laboratories, 2002). Soil test nutrient concentration was converted to kilograms per hectare using bulk density estimates for the different soil layers in the NT and CT plots (Bruce et al., 1983; Sangsupan et al., 2006).

Statistical Analysis

Statistical analysis of changes in ST nutrient contents was conducted using the PROC MIXED procedure of SAS (Littell et al., 2000; SAS Institute, 2003). Replication, replication × tillage, and replication × tillage × fertilizer source (FS) were treated as random effects in all analyses. Initially, differences between cropping phases were evaluated, with tillage, FS, phase, and their interactions treated as fixed effects. In the subsequent by-phase analyses, tillage, FS, year (time), and their interactions were fixed effects, with year being treated as a quantitative (regression) variable. The sums of squares for the quantitative variables were partitioned into linear and lack-of-fit components. Treatment effects were tested and regression coefficients were estimated within the MIXED procedure. The approach described for evaluating year as a regression variable was also used in the evaluation of changes in ST nutrient contents in relation to cumulative PL nutrient inputs. Where regressions were different between tillage systems or nutrient sources, two lines and equations are presented in the figures.

If no difference was determined between treatments, one regression line is presented to represent the average of both treatments.

Changes in soil profile nutrient contents between 1997, 2000, and 2005 were evaluated with PROC MIXED using the random effects noted above. Tillage, FS, year, and their interactions were fixed effects, with year treated as a qualitative variable in this case since these were simply the initial, post-corn, and post-cotton ST nutrient contents. Treatment differences in ST nutrient content among the three sampling dates were identified using the DIFF option of the LSMEANS statement at $\alpha = 0.05$, and 95% confidence limits were used to indicate minimum significant differences.

RESULTS AND DISCUSSION

Annual nutrient inputs in the PL treatment were greater than in the CF treatment during both the cotton and corn phases of the experiment (Table 1). Additions of PL were targeted to provide the equivalent amount of plant-available N as in the CF treatment, based on the assumption that 50% of the N in the PL would be available to the crop during the growing season (Vest et al., 1994). Using the N-based application of PL resulted in 2.8 and 2 times more applied P and K, respectively, during the cotton cropping phase and 14.1 and 9.2 times more applied P and K, respectively, during the corn cropping phase compared with CF. Because of differences in nutrient inputs between PL and CF and between cropping phases, we expected that temporal changes in ST nutrient content and soil pH with time would be greater in the PL treatment than in the CF treatment and greater during the corn phase than the cotton phase. Preliminary statistical analysis for differences between cropping phases confirmed significant phase effects or phase interactions with the FS for all ST nutrient contents. We therefore further explored tillage and FS effects on changes in ST nutrient contents and pH with time separately for each phase.

Within each cropping phase, changes in ST nutrient contents and pH were a function of time (year) either as a main effect or in an interaction with a treatment variable (Table 2). For most ST nutrients, there were significant interactions between year and tillage during the cotton phase and between year and FS during both phases. The significant linear trends with time (Table 2) are presented as linear regression lines in Fig. 1 and 2 to illustrate long-term tillage and FS effects. In these figures, two lines are present where significant differences were found between slopes for treatments (either FS or tillage). If only one line is present, then treatments were not different.

During the cotton phase, the temporal changes in Ca, K, Mg, and Mn were significantly different between CT and NT, while the temporal changes for Ca, K, P, and Zn were different between fertilizer sources (Table 2). The tillage × FS interaction and linear trends for tillage × FS with time were not significant for any of the ST nutrients. During the cotton phase, Ca, Mg, and Mn losses were greater and accumulation of K was less for NT than CT (Table 3, Fig. 1). The slope of the regression lines indicate that for Ca, the decline was nearly two times greater with NT than with CT (–80 vs. –36.7 kg ha^{-1} yr^{-1}), while for K, increases were an order of magnitude greater in CT than NT (13.5 vs. 1.35 kg ha^{-1} yr^{-1}). The observed rate of increase in Zn was greater for CT than for NT (0.34 vs. 0.20 kg ha^{-1} yr^{-1}), although the difference is small. This probably resulted from greater water infiltration and drainage through the profile in the NT treatment. Endale et al. (2002) reported that drainage was nearly two times greater for the NT treatment than the CT treatment during the cotton cropping phase of this experiment. The responses for P and pH during the cotton phase were not influenced by tillage (Fig. 1).

Significant year × FS interactions during the cotton cropping phase reflected the differences in nutrient inputs between the PL and CF treatments (Table 2, Fig. 2). The contents of P and Zn declined in the CF treatment and increased in the PL treatment during the cotton phase (Table 4, Fig. 2). The regression equations (Table 4) indicate that P accumulated at the rate of 3.1 kg ha^{-1} yr^{-1} in the PL treatment but decreased at the rate of 0.67 kg ha^{-1} yr^{-1} in the CF treatment. Increases in soil K content occurred with both nutrient sources, but were greater for the PL. Declines in Mg and Ca contents were greater in the CF than the PL treatment. The Mn content did not change during the cotton cropping phase. Soil pH declined slightly in the CF treatment but changed very little in the PL treatment during the cotton cropping phase and the difference between the two treatments was not significant. Changes in ST nutrient contents during the cotton cropping phase were significant for some nutrients (Ca, Mg, and K). These changes were a product of both different rates of application for some nutrients between the PL and CF treatments and the amounts being removed by the crop or moving deeper in the soil profile.

During the corn cropping phase, tillage and temporal changes associated with tillage (tillage × year interaction) did not influence ST nutrient contents or pH (Table 2). The regressions developed for tillage in the corn phase indicate average rates of change combining tillage treatments (Table 3). The greatest rate of increase was seen for Ca and P (65 and 34 kg ha^{-1} yr^{-1}, respectively). In contrast, FS and the temporal changes (inter-

Table 2. Analysis of variance for evaluating tillage, fertilizer source (FS), and year influences on changes in soil test nutrient contents and pH for the cotton and corn cropping phases.

Effect	*P > F*						
	Ca	K	Mg	Mn	P	Zn	pH
				Cotton phase			
Tillage	0.139	0.062	0.147	0.153	0.368	0.340	0.849
FS	0.037	0.036	0.196	0.908	0.059	0.007	0.148
Tillage × FS	0.989	0.793	0.463	0.517	0.886	0.650	0.676
Year†	0.000	0.000	0.000	0.148	0.094	0.000	0.000
Year × tillage	0.019	0.000	0.023	0.027	0.254	0.218	0.832
Year × FS	0.003	0.002	0.123	0.903	0.010	0.000	0.076
Year × tillage × FS	0.989	0.780	0.420	0.821	0.877	0.625	0.653
LOF‡ year × tillage	0.155	0.164	0.033	0.825	0.442	0.054	0.781
LOF year × FS	0.702	0.836	0.739	0.942	0.066	0.093	0.871
				Corn phase			
Tillage	0.340	0.597	0.305	0.531	0.956	0.322	0.928
FS	0.001	0.010	0.001	0.659	0.000	0.000	0.010
Tillage × FS	0.570	0.686	0.954	0.644	0.346	0.443	0.622
Year	0.000	0.428	0.000	0.025	0.000	0.000	0.000
Year × tillage	0.216	0.538	0.175	0.452	0.948	0.193	0.918
Year × FS	0.000	0.000	0.000	0.635	0.000	0.000	0.000
Year × tillage × FS	0.538	0.665	0.952	0.619	0.739	0.817	0.595
LOF year × tillage	0.097	0.943	0.327	0.565	0.909	0.617	0.168
LOF year × FS	0.060	0.085	0.000	0.666	0.034	0.152	0.013

† For year and year interactions, the F test indicates the significance of linear trends in the data.

‡ LOF is the test for lack of fit for the linear component. Where significant, it indicates that significant quadratic or cubic effects may also be present.

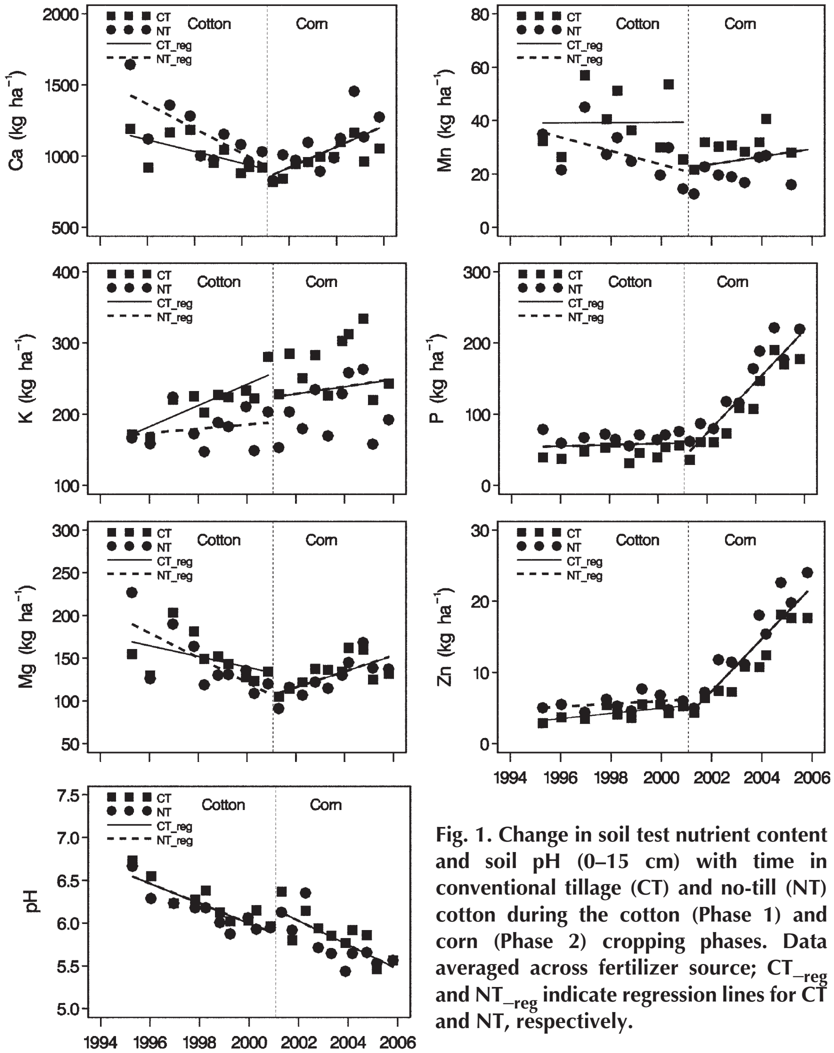

Fig. 1. Change in soil test nutrient content and soil pH (0–15 cm) with time in conventional tillage (CT) and no-till (NT) cotton during the cotton (Phase 1) and corn (Phase 2) cropping phases. Data averaged across fertilizer source; CT_{-reg} and NT_{-reg} indicate regression lines for CT and NT, respectively.

Table 3. Linear regression equations indicating changes in soil test nutrient contents with time for conventional and no-till management during the cotton phase. In the corn phase, there were no significant tillage or tillage × year effects.

Soil nutrient	Conventional tillage	No-till	SE intercept	SE slope
	kg ha^{-1}			
		Cotton phase		
Ca	$y = 74285 - 36.7$yr	$y = 162208 - 80.6$yr	26842	13.44
K	$y = -26828 + 13.5$yr	$y = -2517 + 1.35$yr	4641	2.32
Mg	$y = 12968 - 6.42$yr	$y = 27687 - 13.8$yr	4520	2.26
Mn	$y = -913 + 0.48$yr	$y = 4470 - 2.22$yr	1683	0.84
P†	$y = -2188 + 1.12$yr		2049	1.03
Zn	$y = -679 + 0.34$yr	$y = -387 + 0.20$yr	183	0.09
pH‡	$y = 6.25$ (0.04)	$y = 6.14$ (0.05)		
		Corn phase§		
Ca	$y = -130882 + 65.9$yr		31793	15.87
K	$y = -4924 + 2.6$yr		7024	3.51
Mg	$y = -17293 + 8.7$yr		3856	1.93
Mn	$y = -2055 + 1.04$yr		900	0.45
P	$y = -68171 + 34.1$yr		7486	3.74
Zn	$y = -6908 + 3.46$yr		713	0.36
pH	$y = 261 - 0.13$yr		44	0.02

† For the cotton phase, a common slope model is presented for P because slopes were similar for the two tillage systems.

‡ Means and standard errors are presented for pH in the cotton phase because the slopes are not different from zero and are not different between the two tillage systems.

§ Common slope models are presented for all measurements in the corn phase because there were no significant differences between tillage systems.

action between FS and year) significantly influenced pH and all ST nutrient contents except Mn (Table 2). As expected, significant increases in ST nutrient contents were observed in the PL treatment (Table 4, Fig. 2). Annual rates of increase (slopes in Table 4) ranged from 6.2 kg ha^{-1} yr^{-1} for Zn to 182 kg ha^{-1} yr^{-1} for Ca in the PL treatment. Soil test nutrient contents tended to decline or change only slightly in the CF treatment. Comparing annual rates of PL nutrient inputs (Table 1) with the rates of increase in ST nutrient contents in the top 15 cm (Table 4 slopes for PL) for P, K, Ca, Mg, Mn, and Zn demonstrates that the ST nutrient contents account for 25, 4, 45, 26, 17, and 97%, respectively, of the input amounts. Transformations to less extractable forms and leaching of nutrients below the sample zone are the most likely causes of the differences.

Changes in Soil Test Nutrient Content Relative to Poultry Litter Input

Changes in ST nutrient content with time relative to the cumulative nutrient input from PL were evaluated using cumulative nutrient input as a quantitative variable. As in the previous analysis, responses to PL nutrient inputs were different between the cotton and corn cropping phases ($P < 0.05$). In the cotton phase, a significant interaction between tillage and nutrient input was present only for K and Mg (Table 5). During the cotton phase, Ca, Mg, and Mn contents declined with time, while K, P, and Zn contents increased (Fig. 3) but were often not different between the tillage systems (Tables 5 and 6). The rate of increase in K was more than two times greater under CT than under NT (0.17 vs. 0.07 kg kg^{-1} K input) (Table 6). This difference may have been related to greater crop uptake of K in the NT treatment than in CT as reflected in significantly greater yields for cotton reported by Endale et al. (2002) in this study. The differential response for Mg appears to result from a difference in initial soil Mg content (in 1995), which may have been related to different lime inputs between NT and CT plots in the fall of 1994. Average Ca, Mn, and P contents were different between the two tillage systems, with amounts of 1030, 39, and 57 kg ha^{-1} in CT and 1151, 29, and 82 kg ha^{-1} in NT, respectively.

During the corn phase, there was a significant response for all ST nutrient contents due to increased rates of PL application (Table 5). Consistent differences in the content of K and Mn were found between CT and NT during the corn growing phase (Table 5, no significant interactions between tillage and cumulative PL nutrient input). Soil K and Mn contents averaged 341 and 31 kg ha^{-1}, respectively, under CT and 272 and 22 kg ha^{-1}, respectively, under NT. During the corn cropping phase, all ST nutrient contents increased because the rate of nutrient input exceeded the crop nutrient demand and losses due to leaching (Fig. 3, Table 6). The greatest rate of increase for ST nutrient content was for Zn, where the increase was 0.9 kg kg^{-1} Zn input (Table 6). Other ST nutrient contents had much smaller increases, with the smallest being K; this is probably due to the mobility of K in the low cation exchange capacity Cecil soil and crop demand for K. Annual nutrient inputs from PL during the corn cropping phase were about three times greater than in the cotton cropping phase, but were variable among nutrients. Comparing ST nutrient contents from fall 2005 to those in fall 1996 indicates that Ca, K, Mg, Mn, P, and Zn increased by 1.6, 1.6, 1.4, 1.0, 5.3, and 6.4 times, respectively. The large increases for P and Zn may be of concern due to the agronomic and environmental implications of excess accumulation of these two elements (Sharpley et al., 1994; Jackson et al., 2003).

Changes in Soil Profile Nutrient Contents

Changes in soil profile nutrient contents (0–45 cm) in relation to PL inputs were evaluated with soil samples collected in the fall of 1997, 2000, and 2005. The 1997 samples were the earliest available for depths below 15 cm and were collected after three applications of PL (totaling 13.4 Mg ha^{-1}). The samples collected in 2000 were at the end of the cotton cropping phase after six applications of PL (totaling 26.8 Mg ha^{-1}), while the samples collected in 2005 were at the end of the corn cropping phase after a total application of >110 Mg PL ha^{-1}. Differences in nutrient contents among sampling dates were present primarily for the 0- to 15-cm depth, but differences were also observed for some nutrients at lower depths (Tables 7 and 8). For the 0- to 15-cm depth, ST nutrient contents were greater in 2005 than in 2000 but were often not different from those in 1997. The greatest changes in nutrient contents were observed for P and Zn, as discussed above. Tillage × year interactions were present for Mn and Zn, where contents were much greater in 2005 for NT and CT (Table 7). The decline and increase in Mn may have been due to changes in Mn solubility during storage before sample analysis (Bartlett and James, 1980; Ross et al., 2001). The samples from 1997 were analyzed at the same time as the samples from 2005 after a long period of storage, whereas the 2000 and 2005 samples were analyzed within 1 to 2 wk of collection. The Zn content was greater in the NT soil than in the CT soil in 2005 due to the greater PL input during the corn cropping phase compared with the cotton cropping phase.

In the 15- to 30-cm depth, Ca and K contents were greater and P contents were smaller in the CT treatment than the NT treatment. There were differences among years for K, P, and Zn contents, with amounts being greater in 2005 following long-term PL application. Similar changes were noted in the 30- to 45-cm depth, indicating differences among sample dates. Increases were observed in 2005 for K, P, Ca, and Mg (P = 0.07) compared with earlier sample dates. Differences in pH were detected at the lowest depth for both tillage systems, with pH being less in 2000 than 1997 and 2005, but there is

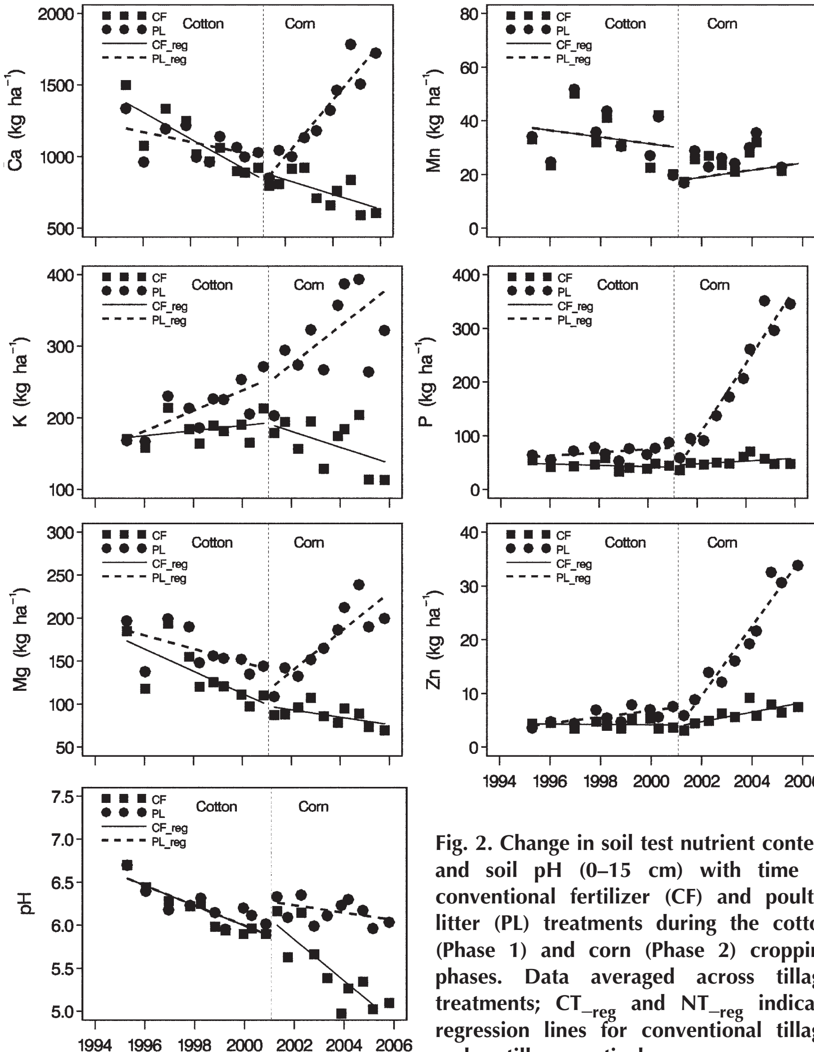

Fig. 2. Change in soil test nutrient content and soil pH (0–15 cm) with time in conventional fertilizer (CF) and poultry litter (PL) treatments during the cotton (Phase 1) and corn (Phase 2) cropping phases. Data averaged across tillage treatments; CT_{-reg} and NT_{-reg} indicate regression lines for conventional tillage and no-till, respectively.

Table 4. Linear regression equations indicating fertilizer source (conventional fertilizer [CF] vs. poultry litter [PL]) influences on changes in soil test nutrient contents and pH with time.

Soil nutrient	CF	PL	SE intercept	SE slope
	kg ha^{-1}			
		Cotton phase		
Ca	y = 174867 − 87.4yr	y = 61625 − 30.3yr	26388	13.2
K	y = −4808 + 2.5yr	y = −24537 + 12.4yr	4742	2.4
Mg	y = 25264 − 12.6yr	y = 15391 − 7.6yr	4581	2.3
Mn†	y = 32.8 (1.7)	y = 32.0 (1.6)		
P	y = 1380 − 0.67yr	y = −6057 + 3.1yr	1997	1.0
Zn	y = 61 − 0.03yr	y = −1127 + 0.56yr	165	0.08
pH‡	y = 223 − 0.11yr		24	0.01
		Corn phase		
Ca	y = 102684 − 50.9yr	y = −364448 + 182.6yr	31766	15.9
K	y = 24795 − 12.3yr	y = −34642 + 17.4yr	9103	4.5
Mg	y = 8178 − 4.0yr	y = −42763 + 21.4yr	4212	2.1
Mn	y = 25.0 (1.0)	y = 26.4 (1.0)		
P	y = −4904 + 2.5yr	y = −131438 + 65.7yr	6120	3.1
Zn	y = −1481 + 0.7yr	y = −12335 + 6.2yr	685	0.3
pH	y = 445 − 0.2yr	y = 77 − 0.04yr	56	0.02

† Means and standard errors are presented for Mn because the slopes are not different from zero and are not different between CF and PL.

‡ A common slope model is presented for pH in the cotton phase because slopes and intercepts were not different (P > 0.05) for CF and PL.

Table 5. Analysis of response of soil test nutrient contents to cumulative nutrient inputs from poultry litter during the cotton and corn cropping phases.

Parameter	P > F					
	Ca	K	Mg	Mn	P	Zn
			Cotton phase			
Tillage	0.024	0.005	0.026	0.010	0.017	0.119
Cumulative nutrient†	0.020	0.000	0.003	0.100	0.010	0.000
Cumulative nutrient × tillage	0.100	0.023	0.021	0.1240	0.577	0.694
			Corn phase			
Tillage	0.070	0.013	0.054	0.021	0.125	0.872
Cumulative nutrient	0.000	0.000	0.000	0.005	0.000	0.000
Cumulative nutrient × tillage	0.063	0.963	0.179	0.505	0.472	0.105

† Cumulative nutrient represents the cumulative input of nutrients applied in the poultry litter.

Table 6. Linear regression equations† indicating changes in soil test nutrient contents with time relative to cumulative nutrient inputs from the poultry litter (PL).

Soil nutrient	Conventional tillage	No-till	SE intercept	SE slope
	kg kg^{-1} PL input			
	Cotton phase			
Ca	$y = 1200 - 0.44$Ca		142.0	0.19
K	$y = 170 + 0.17$K	$y = 170 + 0.07$K	11.7	0.03
Mg	$y = 164 - 0.11$Mg	$y = 211 - 0.83$Mg	24.6	0.21
Mn	$y = 39 - 0.72$Mn		3.1	0.44
P	$y = 61 + 0.04$P		6.4	0.01
Zn	$y = 3.7 + 0.49$Zn		1.2	0.07
	Corn phase			
Ca	$y = 677 + 0.44$Ca		129.7	0.04
K	$y = 220 + 0.04$K		18.9	0.01
Mg	$y = 98 + 0.26$Mg		17.0	0.02
Mn	$y = 20 + 0.24$Mn		2.3	0.08
P	$y = -51 + 0.23$P		13.2	0.01
Zn	$y = -0.89 + 0.89$Zn		1.6	0.06

† Common slope models are presented for soil test nutrient contents where differences were not significant between tillage systems. All slopes are significantly different from zero.

no apparent reason for this difference. In general, movement of K, P, Ca, Mn, and Zn were limited to the top 30 cm and indicates a limited potential for movement to greater depths following long-term PL application in Piedmont soils. Although concerns about losses of crop nutrients are often raised for the use of PL, reducing runoff losses appears to be the most effective area to target for protecting the environment (Jackson et al., 2003; USEPA, 2004).

Long-term repeated application of poultry litter on crop and grazing lands could be a significant environmental liability in areas with concentrated poultry production. As with the application of any nutrient source, prudent management of inputs requires that additions be made to meet the needs of crops without excessive application. Our results and those of many other recent studies (Franzluebbers et al., 2004; Tewolde et al., 2005; Gascho and Hubbard, 2006; Mitchell and Tu, 2006; Adeli et al., 2007, 2008) and older research (Sharpley et al., 1993; Kingery et al., 1994; Wood et al., 1996) indicate a potential problem following application of PL in agronomic systems where crop demand is exceeded. Phosphorus accumulated at the soil surface may be transported to surface water bodies via erosion or runoff, resulting in eutrophication (Moore et al., 1995; Novak et al., 2002). Adeli et al. (2008) reported that Mehlich-3 P concentrations in the top 15 cm of a silt loam soil in Mississippi after 3 yr of PL at the rate of 7.8 Mg ha^{-1} were 17.8 and 14.6 mg kg^{-1} greater for incorporated and unincorporated treatments, respectively, than for an unfertilized control. Loss of P was inferred from the lower P concentration for the unincorporated treatment. The PL treatment had added approximately 300 kg P ha^{-1} during the 3-yr period, which would be eight to 10 times more than removed by seed cotton (Mullins and Burmester, 1997; Mitchell and Tu 2005). In Georgia,

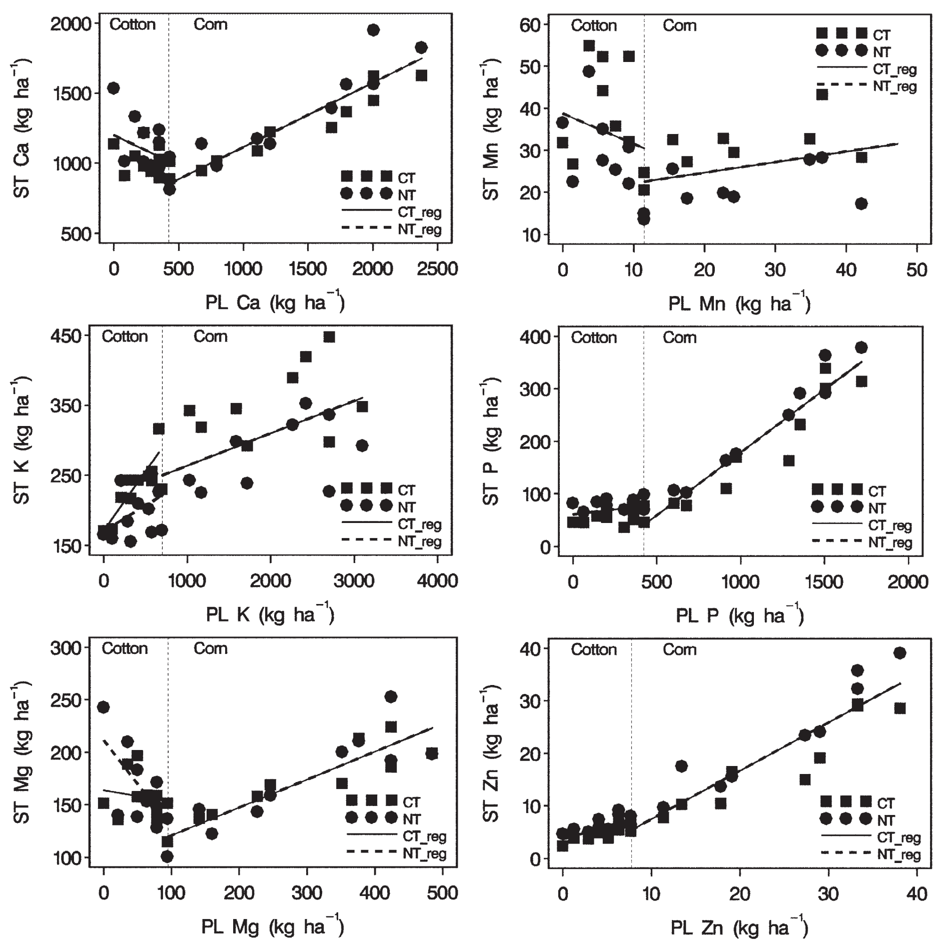

Fig. 3. Comparison of changes in soil test nutrient contents (*y* axis) in the 0- to 15-cm depth relative to poultry litter nutrient inputs (*x* axis) between tillage treatments during the cotton (Phase 1) and corn (Phase 2) cropping phases; CT_{-reg} and NT_{-reg} indicate regression lines for conventional tillage and no-till, respectively.

Table 7. Analysis of variance comparing tillage and time (1997 initial, 2001 end of cotton phase, and 2005 end of corn phase) influences on changes in soil profile soil test nutrient contents due to poultry litter inputs.

Factor	*P* > *F*						
	Ca	K	Mg	Mn	P	Zn	pH
				0–15 cm			
Tillage	0.682	0.021	0.550	0.064	0.065	0.044	0.238
Year	0.000	0.003	0.008	0.000	0.000	0.000	0.874
Tillage × year	0.154	0.421	0.650	0.004	0.386	0.000	0.939
				15–30 cm			
Tillage	0.002	0.024	0.053	0.087	0.041	0.490	0.329
Year	0.134	0.000	0.315	0.019	0.000	0.005	0.010
Tillage × year	0.337	0.051	0.179	0.858	0.001	0.436	0.952
				30–45 cm			
Tillage	0.930	0.451	0.791	0.320	0.096	0.613	0.683
Year	0.023	0.000	0.067	0.139	0.052	0.109	0.000
Tillage × year	0.455	0.188	0.244	0.616	0.049	0.931	0.754

soils are considered to be excessive (for P) when Mehlich-1 P exceeds 500 kg ha^{-1} because this is the point where runoff P concentrations can exceed 1 mg L^{-1} and the risk of impairment of water bodies is increased (Cabrera et al., 2002). Research has demonstrated movement of P through the soil profile and the potential for losses to groundwater (Kingery et al., 1994), although this path is considered to be limited (Sharpley et al., 1993) and will depend on the forms of P present in the soil.

Our results also indicate the potential for overapplication of Zn, which we found to increase significantly in the top 15 cm during the corn cropping phase. Sensitivity to Zn is crop specific. In North Carolina, critical soil concentrations for crops considered nonsensitive are generally >265 kg ha^{-1}, while sensitive crops (like peanut [*Arachis hypogaea* L.]) have critical levels of 44 kg ha^{-1} (Tucker et al., 2005). The ST nutrient content of Zn in 2005 averaged 30.4 kg ha^{-1} in the PL treatment averaged across NT and CT. Maintaining the same rate of PL input as in the corn cropping phase would result in phytotoxic levels of Zn in relation to peanut after only two additional years while phytotoxicity to nonsensitive plants would occur after 106 yr. Although the levels were not great enough to be a problem with crop production at this point, continued accumulation could eventually cause a problem for more sensitive crops. We would not expect losses of Zn in runoff to be great because Jackson et al. (2003) reported that the solubility of Zn from PL leachate was small, particularly compared with Cu and As, for a Cecil soil. Edwards et al. (1997) found that Zn from PL was an order of magnitude less mobile than Cu in an evaluation of vegetative filter strips.

Poultry production in the southeastern United States generates large quantities of PL each year and its safe use is a major concern. Applying PL for crop and hay production is the best management option that poultry producers have at this time. Our results, like those of Gascho and Hubbard (2006), support the use of P-based management of PL for soils considered "high" in P (Mehlich-3 P > 150 mg kg^{-1} soil). Rising fertilizer costs are increasing the demand for PL but increasing transportation costs continue to negatively affect the distances PL can be transported economically. More prudent management of areas receiving PL might include intensive cover crop production (with addition of N) to scavenge residual P during the winter or harvesting cover crop biomass for use as animal feed or for bioenergy production (McCracken et al., 1993, 1995). Increasing crop P removal would allow a greater environmental safeguard and extend the sustainability of using PL as a source of nutrients on crop and forage lands (Toor et al., 2005). Continued monitoring and caution is obviously needed when using high rates of PL on crops. It appears prudent to

Table 8. Poultry litter influences on soil test nutrient contents at three soil depths on three sampling dates (1997 initial, 2001 end of cotton phase, and 2005 end of corn phase) for the conventional tillage (CT) and no-till (NT) treatments.

Tillage	Year	Ca	K	Mg	Mn	P	Zn	pH
				kg ha^{-1}				
				0–15 cm				
CT		1265.6	289.9	178.9	122.0	143.2	13.6	6.1
NT		1319.6	226.6	168.5	79.6	180.1	17.7	6.0
P > *F*†		NS	0.02	NS	NS	0.07	0.04	NS
	1997	1240.2	208.5	189.6	117.3	75.3	7.5	6.0
	2000	1029.9	271.6	144.4	19.9	88.2	7.6	6.0
	2005	1607.7	294.7	187.1	165.2	321.5	31.7	6.1
MSD‡		193.8	49.3	33.5	17.3	40.9	2.1	0.2
CT	1997	1281.4	236.6	199.3	142.9	61.6	6.8	6.1
CT	2000	1013.7	316.6	151.4	24.7	77.0	7.1	6.1
CT	2005	1501.8	316.6	186.0	198.5	290.9	26.8	6.1
NT	1997	1199.0	180.4	179.9	91.7	89.0	8.1	6.0
NT	2000	1046.1	226.6	137.3	15.1	99.4	8.2	5.9
NT	2005	1713.5	272.8	188.2	132.0	352.0	36.7	6.0
MSD		349.7	89.1	60.8	30.7	74.0	3.7	0.3
				15–30 cm				
CT		834.9	234.7	156.3	106.0	16.6	3.8	6.0
NT		657.1	213.4	117.3	80.0	32.6	4.1	5.8
P > *F*		0.002	0.02	NS	NS	0.04	NS	NS
	1997	815.5	169.4	142.0	97.3	10.1	3.4	6.0
	2000	694.7	191.0	129.5	73.7	10.5	3.2	5.7
	2005	727.7	311.7	138.8	108.1	53.0	5.3	6.0
MSD		157.0	42.6	22.8	27.3	12.4	1.4	0.3
CT	1997	952.8	174.4	170.9	113.0	10.1	3.3	6.1
CT	2000	769.9	182.9	145.1	84.0	9.2	3.3	5.8
CT	2005	781.9	346.8	152.8	121.0	30.4	4.8	6.1
NT	1997	678.2	164.5	113.1	81.6	10.2	3.5	5.9
NT	2000	619.6	199.1	114.0	63.3	11.7	3.0	5.6
NT	2005	673.5	276.6	124.8	95.2	75.7	5.9	5.9
MSD		276.2	76.2	41.1	49.5	22.3	2.6	0.5
				30–45 cm				
CT		630.1	155.3	128.5	20.1	4.6	2.1	6.2
NT		622.6	165.7	122.6	17.0	6.1	2.3	6.2
P > *F*		NS	NS	NS	NS	NS	NS	NS
	1997	744.6	109.5	138.8	22.7	5.1	2.2	6.4
	2000	551.3	99.2	109.0	13.8	4.5	1.9	5.9
	2005	583.0	272.7	128.9	19.2	6.6	2.5	6.4
MSD		167.8	32.8	31.4	11.3	2.1	0.7	0.1
CT	1997	792.3	117.8	153.4	22.5	5.2	2.2	6.4
CT	2000	526.7	88.3	106.9	14.9	4.1	1.9	5.9
CT	2005	571.1	259.8	125.4	23.0	4.6	2.4	6.4
NT	1997	696.9	101.3	124.3	22.9	4.9	2.3	6.3
NT	2000	575.9	110.1	111.2	12.7	4.8	1.9	5.9
NT	2005	594.9	285.7	132.3	15.5	8.5	2.6	6.4
MSD		301.0	59.2	55.8	20.3	3.8	1.2	0.3

† *P* > *F* is the probability for a greater *F* value; NS is not significant. Values are from Table 7.

‡ MSD, minimum significant difference based on 95% confidence limits.

also monitor the accumulation of other trace nutrients to avoid contamination or accumulation of toxic levels of nutrients.

SUMMARY AND CONCLUSIONS

Concentrations of extractable soil nutrients from PL application remained below the levels of environmental concern after 10 yr on a Piedmont Cecil soil. At higher rates of PL application, the potential for problems exists with longer term applications due to buildup of P and Zn. Mehlich-1 P increased to >300 kg ha^{-1} in the surface 15 cm during the corn cropping phase of PL application. This level of P increases the risk of losses to water bodies unless precautions, such as riparian zones to trap and take up P or biomass harvesting from winter cover crops, are implemented (Novak et al., 2002). Concentrations of Zn in the surface soil increased more than fivefold and was greater in NT than CT. For some crops, continued PL application at high rates will probably lead to phytotoxicity. During the cotton cropping phase when PL was applied at 4.5 Mg ha^{-1}, the levels of P and Zn never reached excessive concentrations. Although this implies that the application of PL at a modest rate of 4.5 Mg ha^{-1} should present minimal environmental risk in the very long term, periodic evaluation to provide input for management of cropping practices would be needed to avoid excessive nutrient accumulation.

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