Residual impact of raw and composted poultry litter on soil carbon pools

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ABSTRACT

Application of animal manures or composts to soils increases soil carbon levels and improves soil physical properties. However, there is little information on the duration of these effects after manure or compost applications cease. We evaluated the four-year residual effects of applying poultry litter (PL) and composted poultry litter (CPL) at < 4 Mg ha^{-1} $application^{-1}$ on soil carbon fractions and other soil properties in low input crop rotations. We sampled soil in 2001, which was four years after PL and CPL were last applied in wheat-soybean-corn rotations fertilized with 1) NPK mineral fertilizers (MF) only, 2) PL supplemented with MF, and 3) CPL supplemented with MF. Soil bulk density was greater in MF than in PL and CPL systems compared to initial values ($P < 0.10$) four years after PL and CPL were last applied. There were no differences among systems in total soil C and N or in active and slow soil C pool sizes four years after PL and CPL were last applied. The size of the slow C pool, however, was positively related to C input levels during the years that PL and CPL were applied, indicating that there was a 4-year residual impact of C inputs on the slow C pool. Also, active and slow C pool rate constants were greater in PL than in MF systems ($P < 0.05$), averaging 0.2870 and 0.0053 d^{-1} compared to 0.1103 and 0.0037 d^{-1}, respectively. Rate constants were intermediate in CPL systems, averaging 0.2398 and 0.0045 d^{-1}. Since C mineralization rates are generally correlated with N mineralization rates, PL applications may have had a positive residual effect on soil N fertility relative to MF. We conclude that soil quality benefits of low rate applications of PL and CPL can last up to four years after PL is last applied and that these improvements should be considered when valuing PL and CPL as soil amendments and as sources of fertility. The results will be useful in the development of best management practices for PL and CPL applications.

Key words: active carbon pool, carbon pool mean residence time, carbon pool mineralization rate constant, composted poultry litter, poultry litter, slow carbon pool, soil productivity, soil quality

Abbreviations: Beltsville Agricultural Research Center (BARC); concentrated animal feeding operations (CAFOs); composted poultry litter (CPL); maximal flux density (flux $density_{max}$); mean residence time (MRT); mineral fertilizer (MF); poultry litter (PL); soil test phosphorus (STP)

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INTRODUCTION

Poultry litter is an important source of plant nutrients (Bouldin et al., 1984; Sims, 1987; Bitzer and Sims, 1988; Simpson, 1990; Eck and Stewart, 1995; Mitchell and Tu, 2005; Sistani et al., 2008) that also improves soil physical and biological properties. For example, poultry litter has been shown to decrease soil bulk density (Weil and Kroontje, 1979; Sharpley et al., 1993) and increase total soil C and N (Kingery et al., 1994; Clark et al., 1998; Nyakatawa et al., 2001b; Sistani et al., 2004; Roberson et al., 2008). Studies using manures other than PL have shown that applying animal manures increases biologically active forms of soil C and N (Wander et al., 1994; Wander and Traina, 1996; Ginting et al., 2003), fractions that are more sensitive indicators than are soil total C and N of changes in soil quality and in crop response (Eghball et al., 2004; Wander, 2004). While early research showed that PL applied at high rates for extended periods of time increases soil potentially mineralizable N (Griffin and Laine, 1983), there are few reports on the impacts of PL applied at agronomic rates on soil C and N fractions. The only study we found that investigated this effect is a long-term cropping systems study in California. Researchers there found that potentially mineralizable N and microbial biomass C were usually greater in treatments that included PL and CPL than in similar treatments receiving only MF (Scow et al., 1994; Clark et al., 1998; Gunapala and Scow, 1998).

Composting has been proposed as a possible manure management tool for reducing the cost of transporting PL to nutrient deficient lands (Sims and Wolf, 1994) since composting significantly reduces the volume of waste materials (DeLuca and DeLuca, 1997) and stabilizes nutrients (Tiquia and Tam, 2002), thereby reducing their release rates (Dao, 1999; Dao and Cavigelli, 2003). Thus, there is usually less synchrony between N release and crop N uptake for CPL than for PL (Sims et al., 1993; Evanylo et al., 2008). Composted PL has also been shown to increase soil C and P levels when applied every other year for 8 years at 4 to 7 Mg ha^{-1} (Clark et al., 1998). Much less research has been conducted on CPL than on PL and there seems to be no studies on the residual impact of CPL on soil C pools.

Poultry litter can also have some deleterious effects on soil and environmental quality. Since the ratio of P:N in PL and other animal manures is greater than that required by plants, applying animal manures at rates that meet crop N needs can lead to substantial increases in soil P (Kingery et al., 1994; Eck and Stewart, 1995; Sharpley, 1995; Sistani et al, 2004). In addition, PL and other animal manures have often been applied at greater than agronomically optimum rates and often during times of the year when plant uptake of manure nutrients is low. Such practices can result in nitrate leaching (Liebhardt et al., 1979; Cooper et al., 1984; Weil et al., 1990; Kingery et al., 1994), and in excessive soil P levels that can result in high P losses via erosion, runoff and subsurface transport in artificial drainage (Magette, 1988; Sharpley et al., 1993; Sims and Wolf, 1994; Sharpley, 1995). In addition, feed additives and naturally occurring substances in PL, including heavy metals (arsenic in the form of roxarsone, Cu, Zn, and Se) (Kingery et al., 1994; Sistani et al., 2008), antibiotics, and endocrine disrupting chemicals accumulate in soils where PL has been applied and may pose environmental risks (Jackson et al., 2003; Fisher et al., 2005). These issues suggest that long-term application and/or excessive PL application rates should be limited so that soil building benefits can be accrued while limiting potential adverse impacts of PL applications.

The development of agronomically and environmentally sound PL and CPL application practices requires that the residual impacts of PL and CPL applications be incorporated into application recommendations (Bitzer and Sims, 1988). Studies on the residual impacts of PL on crop performance generally show that PL has a greater residual impact on crop yield than MF. For example, Nyakatawa et al. (2001a) showed that PL applications (100 kg available N ha^{-1} for 2 years) increased corn grain yield by 13% compared to a MF control one year after PL applications ceased. Malik and Reddy (2002) showed that PL and CPL applications (40, 80, and 120 kg available N ha^{-1} for five years) increased corn grain yield by 9 to 81% and 24 to 202%, respectively, compared to a MF control one year after PL applications ceased. Sims (1987), however, showed inconsistent residual impacts of one or two years of PL applied at 84, 168, and 252 kg available N ha^{-1} relative to a MF control on corn grain yield one or two years after applications ceased. All three studies investigated residual impacts for only one year.

One of the few studies that includes information on the residual impact of PL on soil properties showed that soil total C and N in the 0-15 cm depth were about 13% greater in a system receiving PL (application rates not reported) than in a similar system receiving MF five years after PL applications ceased (Clark et al., 1998). There was no residual impact on soil test P or exchangeable K, Ca, or Mg. Sistani et al. (2008), however, found that Mehlich-3 soil extractable P, K, Ca, Mg, Cu, Fe, and Zn were all greater than a MF control four years after PL application ceased. The PL had been applied for four years at ~8 and ~16 Mg ha^{-1}. Since residual impacts of PL applications on crop yields may be due to a combination of improved soil fertility and soil physical factors (Mahimairaja et al., 1995; Nyakatawa et al., 2001a), there is a need to better understand the residual effects of PL applications on various soil properties. The residual impacts of PL applications on soil C fractions and physical properties, for example, have not been fully evaluated.

Since PL is an organic fertilizer source, understanding C dynamics of PL applied to soil provides a first step in understanding PL fate in soils. The size and mineralization rates of two biologically active soil C pools—the active and slow carbon pools—can be determined using long-term soil incubations (Paul et al., 1999). The active pool, which has field mean residence times (MRT) of less than one year (Paul et al., 1999), represents that portion of soil C most readily mineralized and is strongly correlated with N mineralization and P release rates (Castellanos and Pratt, 1981; Gilmour et al., 1985; Hadas and Portnoy, 1994; Dao and Cavigelli, 2003). The slow pool has field MRTs of 10 years or more and its size reflects the degree of stabilization of soil C. These two C pools are the fractions that must be managed when using organic materials to supply soil fertility (Paul et al., 1999), so it is essential that we understand the effects of organic materials on these fractions to evaluate how best to use organic materials such as PL and CPL on agricultural lands. These two pools also serve as early indicators of changes in soil organic C and soil quality in response to management long before changes in total C can be detected (Paul et al., 1999).

In 1996, we initiated a long-term study at the USDA-ARS Henry A. Wallace Beltsville Agricultural Research Center (BARC) in Beltsville, MD that included an assessment of the impacts of PL and CPL on soil quality and productivity. Because PL and CPL were only applied during the first two years of the project, we were able to assess the residual effects of PL and CPL on soil properties four years after application. Our objectives were to quantify the residual effects of PL and CPL four years after last application on soil carbon fractions using long-term incubations, and on soil bulk density and soil chemical properties.

MATERIALS AND METHODS

Study site

The study site is at the western edge of the Atlantic Coastal Plain at the USDA-ARS Beltsville Agricultural Research Center (BARC). The dominant soil types, all silt loam Ultisols, are Christiana (fine, kaolinitic, mesic Typic Paleudults), Matapeake (fine-silty, mixed, semiactive, mesic Typic Hapludults), Keyport (fine, mixed, semiactive, mesic, Aquic Hapludults), Mattapex (fine-silty, mixed, active, mesic Aquic Hapludults), and a Keyport variant (fine, mixed, semiactive, mesic Aeric Ochraquults). Slopes across the site vary from 0 to 8%. Prior to 1996, the entire 16 ha site on which the project is

Table 1. Crop rotations for plots receiving fertilizer inputs as mineral fertilizer (MF) only, poultry litter (PL) plus MF, composted poultry litter (CPL) plus MF. Wheat is winter wheat sown the previous fall.

	Year				
	1996	1997	1998	1999	2000
Crops harvested or killed	Hairy vetch Oats Soybean	Corn	Wheat Soybean	Corn	Wheat† Soybean‡

† Wheat was not planted in the CPL system plots in the fall of 1999 in preparation for transitioning CPL system plots to other systems within the larger long-term project.

‡ Soybeans were not planted in the PL and CPL system plots in preparation for transitioning these plots to other systems within the larger long-term project. PL system plots were fallow and CPL system plots were planted to a sudangrass cover crop during the summer of 2000. PL and CPL system plots were planted to alfalfa, wheat or hairy vetch in the fall of 2000, depending on the specific system to which the plot was being transitioned.

located had been managed as one field and had been under no-tillage management for at least 11 years. From 1985 to 1992 the field was planted to alfalfa (*Medicago sativa* L.) and dairy manure was applied regularly. From 1993 to 1995 the field was planted to corn (*Zea mays* L.) under no-tillage management.

Cropping systems

In 1996, seven cropping systems, arranged in four randomized complete blocks, were established as a long-term cropping systems research project at the site. So that each phase of each rotation would be present each year, each cropping system was split into the appropriate number of plots (17 plots per block). Each plot is 9.1 m x 111 m (0.10 ha) in size. We report on data collected on one phase of the rotation for three of the original seven cropping systems, which were established as two-year wheat-soybean-corn rotations that differed only in crop nutrient source. One system relied solely on mineral fertilizers (MF) and the other two systems relied on MF supplemented with PL at < 4 Mg ha^{-1} y^{-1} or CPL at < 4 to ~8 Mg ha^{-1} y^{-1} (all on a dry wt. basis). We refer to these three systems as the MF, PL, and CPL systems, respectively. Plots in the three treatments were conventionally tilled and weeds were controlled using herbicides and cultivation. Commercial-scale farming equipment was used for all operations including applying PL and CPL.

Broiler litter for direct application to soil and for making compost was collected from chicken (*Gallus gallus domesticus*) houses on a working farm on the Maryland eastern shore. The litter was composed of broiler manure mixed with sawdust (and feathers and dead chickens) in the production house. The compost was made at the BARC compost facility by combining PL with appropriate ratios of ground hay to provide moisture and wood chips to provide additional C. The 100 m windrows were aerated twice per week for 8 weeks.

Poultry litter and CPL were applied in 1996 and 1997 only. Applications planned for 1998 to 2000 were not made for various reasons. This change in management allowed us to evaluate the residual effects of PL and CPL applications on soil quality up to four years after PL and CPL applications ceased since the MF, PL and CPL systems were managed similarly for the following four years (1998 to 2001).

The crops present in the plots we sampled are listed by year in Table 1. The entire site had been planted to a hairy vetch (*Vicia villosa* Roth) cover crop in the fall of 1995. In the spring of 1996 the vetch was killed using herbicides, and oats (*Avena sativa* L.) were sown to mimic the winter wheat that was part of the planned rotation. Poultry litter and CPL were applied and incorporated into the soil in the appropriate plots prior to sowing oats. Oats were harvested for silage in July and soybean (*Glycine max* Merr.) was planted immediately following oat harvest. The wheat-soybean-corn rotation was continued into 2001 except for changes made in the CPL system in fall 1999 and in spring 2000 in the PL system (Table 1).

Corn in all three management systems received starter fertilizer (19-19-19) at 112 kg ha^{-1}. Corn in the MF system received an additional 138 kg N ha^{-1} as a sidedress application of a 30% UAN solution. Poultry litter and CPL were incorporated into the soil in the PL and CPL systems, respectively, prior to corn planting in 1997. The amount of N fertilizer added as a sidedress application was adjusted to account for the calculated N availabilities of these materials (Table 2). The wheat in the MF and PL systems received 28 kg ha^{-1} N at planting and, on average, 70 kg ha^{-1} N topdressed as UAN in early spring. Composted PL was added to wheat in the CPL systems in the fall of 1997. Total nutrient inputs to soil, in the forms of MF, PL and CPL, from 1996 to 2000 are listed in Table 3.

Table 2. Dry matter (DM) applied, elemental composition (on dry weight basis), and moisture content of raw and composted poultry litter (PL and CPL, respectively) applied to wheat-soybean-corn rotations.

Year, season and source	DM applied	Total N	Total P	Total K	Total Ca	Total Mg	NH_4-N	Moisture	N availability†
	Mg ha^{-1}	g kg^{-1}							kg ha^{-1}
1996, spring									
PL	3.0	63.7	15.5	24.4	14.8	9.1	17.1	339	121
CPL	3.1	10.8	8.8	7.3	11.0	4.5	0.3	417	6
1997, spring									
PL	3.8	53.5	21.0	35.1	23.0	8.9	18.3	447	136
CPL	3.8	18.9	14.7	21.3	38.6	12.6	2.7	264	19
1997, fall									
CPL‡	3.9	18.9	14.7	21.3	38.6	12.6	2.7	264	20

† N availability as kg N available per ha = [(Total N – NH_4-N) x A + NH_4-N] x Dry matter applied, where A, the N mineralization factor, is 0.5 for PL and 0.15 for CPL (Shipley, personal communication).
‡ Compost applied in fall 1997 was the same batch as that applied in spring 1997. Analyses were conducted in the spring.

Estimating C inputs to soil

We determined aboveground plant biomass at physiological maturity or just prior to incorporating plant material into the soil by clipping shoots at ground level in 2 to 8 quadrats per plot for all crops and cover crops except corn. For corn, we cut 40 plants per plot and multiplied biomass per plant by plant population density, which we determined by counting plants in 100 m of row. All plant samples were dried to 65^{o}C and weighed. The amount of crop residues returned to the soil for crops harvested for grain and straw was determined by subtracting grain and straw yields from biomass values. Grain yields were determined by harvesting the middle rows from the full length of each plot using a combine and weighing the grain in weigh wagons. In corn and soybean plots, the four middle rows (3.0 m) were harvested. In wheat plots, the middle 3.8 m were harvested. Straw yields were determined by weighing straw bales harvested from full plots. Grain yield data were converted to oven-dry equivalents for residue calculations. In cases of missing biomass data (some biomass data were not collected in 1998 and 1999), we estimated values based on grain yields and literature values for harvest index (Bolinder et al., 1997; Weilenmann and Luquez, 2000), on data collected from other plots in the same study, or on data collected from similar experiments located nearby (unpublished data).

Root biomass for corn, soybeans and wheat was estimated from aboveground biomass using shoot to root ratios of 1.99, 2.08, and 1.79, respectively (Buyanovsky and Wagner, 1986). Since soil was mixed by tillage to a depth of about 20 cm and since we took soil samples to a depth of 10 cm for soil C fraction measurements, we included only roots growing in the top 20 cm of soil as inputs for the purposes of these calculations. For oats, we estimated root biomass using a shoot to root ratio of 2.50 (Bolinder et al., 1997). Vetch root biomass was estimated from aboveground biomass using a shoot to root ratio of 2.55 (Cavigelli, 1990). Weed root biomass was estimated using vetch shoot to root ratios for weeds sampled in the spring and soybean shoot to root ratio for weeds sampled in the summer. Summer weed communities were dominated by *Amaranthus hybridus* L. and *Chenopodium album* L. Weeds were sampled in 2000 only; since weeds accounted for only 2% of total C inputs we assume that not including weed measurements in other years is

Table 3. Estimated total C and nutrient inputs to soil from spring 1996 to fall 2000 in wheat-soybean-corn rotations receiving fertilizer inputs as mineral fertilizer (MF) only, poultry litter (PL) plus MF, and composted poultry litter (CPL) plus MF. Total C inputs include those from plant residues, PL and CPL. Nutrient inputs include those from MF, PL, and CPL.

System	Total inputs C	N†	P	K	Ca	Mg
	Mg ha^{-1}	kg ha^{-1}				
MF	15.3	283	51	43	0	0
PL	16.6	624	73	240	109	52
CPL	18.9	355	159	230	331	112

† Does not include N_2-fixation or atmospheric deposition.

inconsequential to total C input estimates. All plant materials were assumed to contain 400 g C kg^{-1} dry weight (Gregorich et al., 2001).

Raw and composted PL C inputs were calculated by multiplying the weight (corrected for moisture) of applied materials by estimated C contents. The C contents of PL and CPL (378 and 313 g C kg^{-1} dry weight, respectively) were estimated from measurements made on PL and CPL samples collected from the same farm in 1998.

Soil sampling and analysis

Initial soil properties (Table 4) were measured on soil samples collected in 1994 and 1995 as part of a site uniformity assessment, or in spring 1996. Bulk density was measured on samples collected to a depth of 0.076 m in 1994. Total C and N were determined on samples collected to a depth of 0.30 m in 1995. Soil pH, P, exchangeable K, Ca, Mg and effective CEC (CEC_e) were determined on soil samples collected to the depth of the Ap horizon (0.23-0.26 m) in April 1996.

The effects of PL and CPL on soil chemical properties were measured on samples collected in fall 1999. Soil pH, P, exchangeable K, Ca, Mg and CEC_e were determined on soil samples collected to a depth of 0.16m.

Table 4. Initial soil properties for long-term research plots at Beltsville, MD.

Soil properties†	Mean	Range
Bulk density, g cm^{-3}	1.34	1.29-1.41
pH	6.99	6.63-7.30
Total C, g kg^{-1}	15.0	13.5-16.2
Total N, g kg^{-1}	1.25	1.13-1.35
Mehlich I P, kg ha^{-1}	183	114-228
Exchangeable K, cmol kg^{-1}	0.22	0.13-0.34
Exchangeable Ca, cmol kg^{-1}	6.37	5.98-6.79
Exchangeable Mg, cmol kg^{-1}	1.29	0.95-1.60
CEC_e, cmol kg^{-1}	8.47	7.06-9.64

† Soil bulk density was measured in 1994; total soil C and N were measured in 1995; all other soil properties were measured in 1996.

The effects of PL and CPL on soil C and N were measured on samples collected in April 2001. Total C and N, bulk density and CO_2 flux density (to determine C pool sizes and mineralization rate constants) were measured on samples collected to a depth of 0.10 m. Since initial soil properties were measured on soils sampled to different depths than soils sampled in 1999 and 2001, we present results as ratios of soil properties in 1999 or 2001 vs. initial soil properties. These ratios are not intended to indicate absolute changes in any particular property within a cropping system but they do allow us to compare relative changes in soil properties among the three systems.

Soil bulk density was measured by dividing the weight of soil samples (corrected for soil moisture) by the volume of soil sampled (Blake and Hartge, 1986). Soil pH was measured in a 1:1 soil:water slurry (McLean, 1982). Soil P was measured in Mehlich I extracts using the colorimetric method (Olsen and Sommers, 1982). Exchangeable soil K, Ca, Mg and CEC were extracted using NH_4OAc and measured using atomic absorption spectrophotometry (Lanyon and Heald, 1982; Thomas, 1982). Total soil C and N were measured by dry combustion (Sollins et al., 1999). Poultry litter and CPL samples were analyzed by the University of Maryland soil testing lab as part of their nutrient management support program.

Soil C pool sizes and mineralization rate constants were determined using soil incubations (Paul et al., 2001; Dao and Cavigelli, 2003). We first removed roots and other undecomposed organic matter by hand from fresh soil samples. We then placed 80 g sub samples into 946 mL glass canning jars and wet them to 70% water-filled pore space (WFPS) according to the method of Paul et al. (2001). Canning jars were sealed with lids fitted with septa to allow headspace sampling and incubated for 406 d in a 25^{o}C constant temperature room in the dark. Headspace samples were taken periodically and were analyzed for CO_2 using an infrared gas analyzer (California Analytical Instruments, Model 3300, Orange, CA). When CO_2 concentrations in the headspace approached 6%, we removed lids, flushed the vessels with ambient air, resealed the jars, and sampled and analyzed headspace gas again to reestablish baseline CO_2 concentrations.

Data analyses

Crop yield data were subjected to analysis of variance using the PROC GLM procedure of the Statistical Analysis System and means were separated using LSMEANS (SAS Institute, 2001). Ratios of soil properties were analyzed using the same procedures after the data were subjected to an arcsine transformation (Ott, 1984).

The incubation data were analyzed two different ways. First, CO_2 flux densities were calculated and quantitatively described using a log-normal probability function as detailed in Dao and Cavigelli (2003). We then used these equations to predict cumulative CO_2 production, from which we determined the size, mineralization rates, and field mean residence times of the active and slow soil C pools (Robertson et al., 1999; Paul et al., 1999; Paul et al., 2001). We compared the sizes, mineralization rate constants and MRTs of these two pools using analysis of variance and separated means using the Duncan's multiple range test (SAS Institute, 2001).

RESULTS

Poultry litter had consistently greater N, P, and K content than CPL, but there were no consistent differences in Ca and Mg composition between PL and CPL (Table 2). Cumulative P, Ca, and Mg additions were greater and cumulative N additions were lesser in CPL than in PL systems from 1996 to 2000 (Table 3). Potassium inputs were similar for the two treatments. Considerably more total nutrients were applied in PL and CPL systems than in the MF system (Table 3). Estimated C inputs to the soil were greatest in the CPL and least in the MF system. Differences in C inputs among systems were due mostly to the PL and CPL additions: the MF, PL, and CPL systems received 15.3, 14.4, and 15.9 Mg C ha^{-1} in plant residue C additions, respectively, as there were few differences in crop yields during the experiment. The only recorded differences in crop yields during this time were in 1998. Wheat (P = 0.07) and soybean (P = 0.02) yields were greater in the PL (5832 and 865 kg ha^{-1}, respectively) than in the MF (5054 and 545 kg ha^{-1}, respectively) system while wheat and soybean yields in the CPL system (5487 and 689 kg ha^{-1}, respectively) were not statistically different than in either the MF or PL systems.

Initial soil test P (STP) and exchangeable Ca and Mg were very high (Table 4), likely due, in part, to a history of repeated dairy manure applications at this site. Soil K levels were in the medium (0.09-0.17 cmol kg^{-1}) to optimum (0.17-0.34 cmol kg^{-1}) ranges as defined by the University of Maryland (Coale, 1996).

Soil bulk density in the MF system increased relative to that in the PL and CPL systems between 1994 and 2001 (Table 5). While there was a trend for increased soil nutrient levels in PL and CPL systems relative to the MF system, none of these changes were statistically significant. There were also no statistically significant differences in soil total C or N among systems (Table 5).

Maximum carbon flux density (Fig. 1) was greater in the PL and CPL systems than in the MF system about four years after PL and CPL were last applied. We fitted log-normal probability density functions to these data and the goodness-of-fit had r^2 values $\geq$ 0.910 (Fig. 1). Cumulative CO_2-C fluxes as a function of time, predicted from curves presented in Fig. 1, are shown in Fig. 2, along with observed values. Predicted cumulative CO_2-C flux densities also fit the observed values well (r^2 $\geq$ 0.991). The curves shown in Fig. 2 (left-hand column) are comprised of two independent first-order reactions, $y = a(1-e^{-bx}) + c(1-e^{-dx})$, where a is the active C pool, c is the slow C pool, and b and d are the mineralization rate constants for the active and slow C pools, respectively. The values for these two pools, rate constants and field MRTs are shown in Table 6. Active and slow C pool sizes did not differ among systems but active and slow C mineralization rate constants were greater in the PL than in the MF system and MRTs—the inverse of rate constants, corrected for mean annual temperature—of these pools were greater in the MF than the PL system. Rate constants in the CPL system were not significantly different than rate constants in either MF or PL systems.

Table 5. Changes in soil properties in wheat-soybean-corn rotations receiving fertilizer inputs as mineral fertilizer (MF) only, poultry litter (PL) plus MF, and composted poultry litter (CPL) plus MF two or four years after PL and CPL applications. Changes are expressed as ratios of soil properties measured in 1999 or 2001 vs. initial soil properties since different soil sampling methods were used for initial and later measurements.

Ratio of soil properties† measured in 1999 or 2001 vs. initial soil properties	MF		PL		CPL‡		ANOVA P
Bulk density §	1.06	a	1.03	b	1.01	b	0.07
pH	0.96	a	0.94	a	0.96	a	0.19
Total C	1.10	a	1.10	a	1.16	a	0.37
Total N	1.06	a	1.12	a	1.14	a	0.69
Mehlich I P	0.98	a	1.35	a	1.19	a	0.19
Exchangeable K	0.93	a	1.17	a	1.20	a	0.11
Exchangeable Ca	0.96	a	1.01	a	1.05	a	0.44
CEC_e	0.96	a	1.02	a	1.04	a	0.55

† Soil bulk density was measured in 1994 and 2001; total soil C and N were measured in 1995 and 2001; all other soil properties were measured in 1996 and 1999. Ratios for exchangeable Mg could not be calculated since Mg levels in all plots were reported as > 0.13 meq (100 g soil)$^{-1}$ in 1999.

‡ In the fall of 1996 an extra application of CPL was mistakenly made to one of the CPL system plots. This plot was not included in the statistical analyses of soil productivity and bulk density.

§ Values followed by the same letter within a row are not significantly different at P < 0.10.

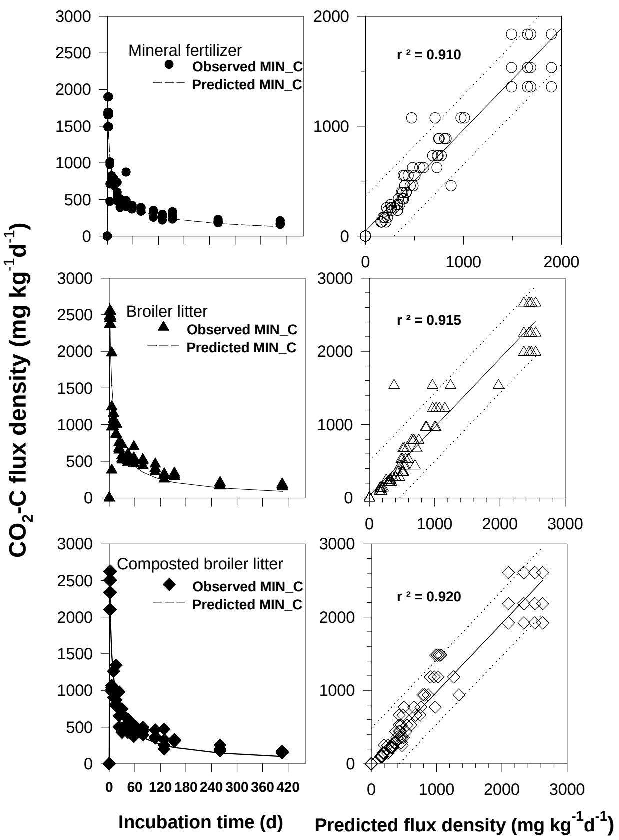

Fig. 1. Observed CO_2-C flux densities and flux densities predicted by the lognormal density function (left), and relationship between observed and predicted CO_2-C flux densities (right) for soils incubated at 25^{o}C from wheat-soybean-corn rotations receiving fertilizer inputs as mineral fertilizer (MF) only, poultry litter (PL) plus MF, and composted poultry litter (CPL) plus MF.

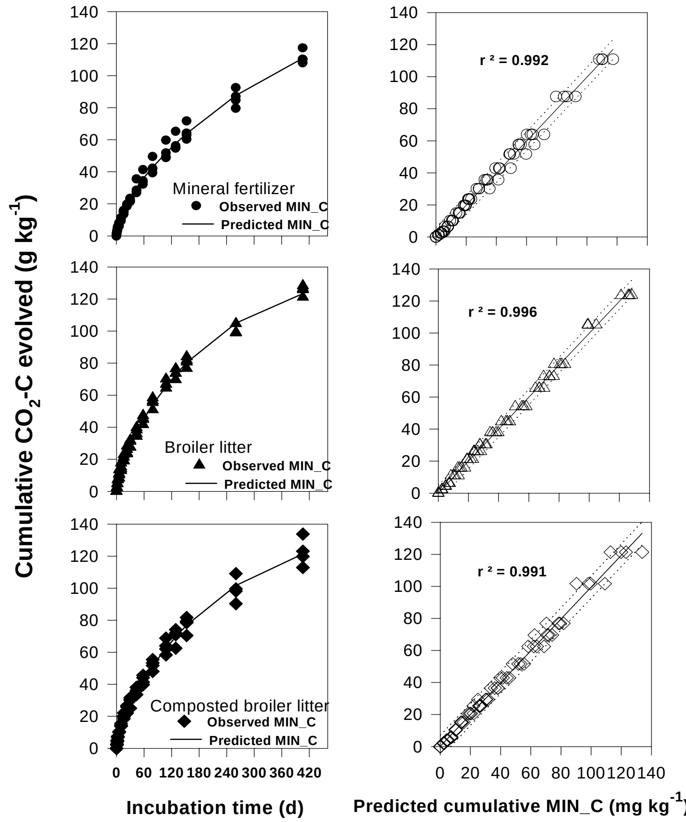

Fig. 2. Observed and predicted cumulative CO_2-C flux as a function of time, for soils incubated at 25^{o}C (left), and relationship between observed and predicted cumulative CO_2-C flux as a function of time (right) from wheat-soybean-corn rotations receiving fertilizer inputs as mineral fertilizer (MF) only, poultry litter (PL) plus MF, and composted poultry litter (CPL) plus MF.

Total C inputs for 1996 to 2000 and for 2000 were not correlated with the size, mineralization rate constants, or the MRTs of either C pool (data not shown). However, C inputs for 1996, 1997, and 1996 to 1997 were each positively correlated with the size of the slow C pool (respectively: r = 0.59, P = 0.04; r = 0.64, P = 0.02; r = 0.73, P = 0.007). The relationship between C inputs for 1996 to 1997 and slow C pool size is illustrated in Fig. 3.

DISCUSSION

The PL we applied was generally greater in total N and NH_4-N concentrations than PL values reported in the literature (Table 2; Sims, 1987; Sims and Wolf, 1994; Nyakatawa et al., 2001b; Mitchell and Tu, 2005; Sistani et al., 2008; but see Bitzer and Sims, 1988). As a result, a PL application rate of ~4 Mg ha^{-1} was adequate to meet the N needs of corn, whereas others have usually applied two (or more) times as much PL of lower N content to meet crop N needs (e.g. Sims, 1987; Clark et al., 1998; Nyakatawa et al., 2001b; Mitchell and Tu, 2005; Sistani et al., 2008). Nutrient concentrations of the CPL were generally lower than those of the starting material, which is consistent with values reported by Evanylo et al. (2008) but not by Tiquia and Tam (2002). Adding wood chips to raise the C-to-N ratio and conserve N during composting decreased nutrient concentrations in the CPL used in our study. These results illustrate the importance of testing individual batches of PL and CPL to assure appropriate nutrient application rates.

Long-term PL applications and/or heavy PL application rates have been shown to decrease soil bulk density (Weil and Kroontje, 1979; Sharpley et al., 1993); our study seems to be the first report of low and short-term PL or CPL application rates having a similar effect. Long-term PL applications and/or heavy PL application rates have also been shown to increase soil C and N levels (Kingery et al., 1994; Clark et al., 1998). The lack of change in total soil C and N between 1996 and 2001 in

Table 6. Mineralizable C pool sizes, mineralization rate constants, and field mean residence times (MRT), based on 406 d soil incubations, for wheat-soybean-corn rotations receiving fertilizer inputs as mineral fertilizer (MF) only, MF plus poultry litter (PL), and MF plus composted poultry litter (CPL) about four years after the last applications of PL and CPL.

	Pool size†		Mineralization rate constant		MRT	
System	Active C	Slow C	Active C	Slow C	Active C	Slow C
	---- μg C (g C)$^{-1}$ ----		------------- d^{-1} -------------		---------- d ----------	
MF‡	13 455 a	122 519 a	0.1103 b	0.0037 b	32.9	680
PL	12 212 a	125 509 a	0.2870 a	0.0053 a	15.4	441
CPL	14 437 a	126 444 a	0.2398 ab	0.0045 ab	16.1	515

† Cumulative mineralizable C was fitted to a model comprised of two independent first-order reactions, $y=a(1-e^{-bx}) + c(1-e^{-dx})$, where a = active C pool, b = active C pool mineralization rate constant, c = slow C pool, d = slow C pool mineralization rate constant.

‡ Parameters followed by the same letter within a column are not significantly different at the 0.05 level of probability according to Duncan's multiple range test.

our study is probably due to the total amount of C added to the PL and CPL systems being only slightly greater than that added to the MF system (Table 3). Overall residue returns to soil were relatively low since aboveground oat and wheat biomass were harvested, soybean produces relatively low levels of residue, and corn was grown during two drought years, resulting in relatively low yields and residue production (data not shown). Evanylo et al. (2008) also showed no increase in soil C and N after a total of 31 Mg ha^{-1} CPL was applied to soil during a 3-year period. In addition, small changes in soil C and N are always difficult to detect and biologically meaningful changes in soil C are more appropriately studied by examining specific C fractions (Paul et al., 1999).

The strong relationships between observed and predicted CO_2-C flux densities and cumulative CO_2-C fluxes as a function of time show that the log-normal approach to analyzing CO_2 flux density data developed by Dao and Cavigelli (2003) is robust for this data set and can predict the behavior of soil C under diverse management regimes. The active and slow C pool mineralization rate constants derived from these incubations show that PL applied only 2 times at < 4 Mg ha^{-1} had a residual effect on soil C quality and biological activity four years after PL was last applied. These differences were not due to the management differences among systems in 2000 since there were no significant correlations between plant C inputs in 2000 and any C fraction parameters. In addition, the change in the crop rotation in the PL system in 2000 (fallow instead of a soybean crop) would have the effect of decreasing the C pool mineralization rate constant in the PL system relative to that in the MF system, the opposite of the pattern described here.

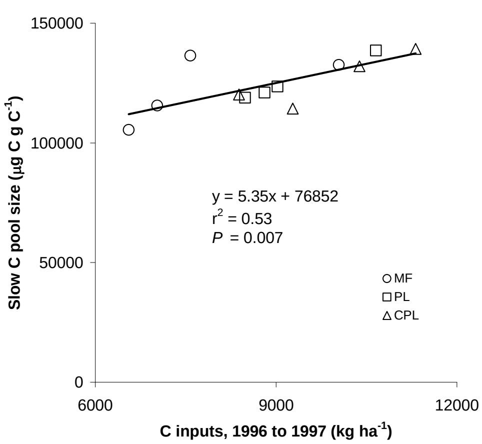

Fig. 3. Relationship between C inputs from 1996 to 1997 and slow soil C pool size for wheat-soybean-corn rotations receiving fertilizer inputs as mineral fertilizer (MF) only, poultry litter (PL) plus MF, and composted poultry litter (CPL) plus MF.

Greater mineralization rate constants in the PL than in the MF system indicate that C pools in the PL system are composed of C forms that decompose more readily (Paul et al., 2001) and that microbial activity is greater than in the MF system. Others have shown that N mineralization from raw manure-amended soil (Hadas et al., 1983; Bitzer and Sims, 1988) and composted manure-amended soil (Hadas and Portnoy, 1994) follows a similar two-step or three-step (Gale and Gilmour, 1986) process and that C mineralization rates are correlated with N mineralization and P release rates for these two organic matter pools (Castellanos and Pratt, 1981; Gilmour et al., 1985; Hadas and Portnoy, 1994; Dao and Cavigelli, 2003). Thus, we are likely to have greater N and P release rates in the PL than in the MF system four years after PL was last applied. Although more CPL than PL was applied in this experiment, soil C fractions were not significantly different in CPL than in MF or PL systems. Thus, while both PL and CPL improved soil physical properties (bulk density), only PL showed a clear benefit to soil C pools four years after the last application.

The positive correlations between slow C pool size and estimated C inputs in 1996, 1997, and 1996 to

1997 reflect the fact that the size of the slow C pool is related to the level of C inputs during preceding years (Paul et al., 1999, 2001). Manures contain more recalcitrant forms of C than do plant residues (Paustian et al., 1997) and recalcitrant forms of PL and CPL C likely contributed to the size of the slow C pool four years after PL and CPL were applied. That there were relationships between slow C pool size and C inputs in 1996 and 1997 but no treatment effect on slow C pool size was due to high within treatment variability in C pool sizes and C input levels, especially for the MF system (Fig. 3). Conducting correlation analyses between C inputs and C pool sizes allowed us to detect the expected effect of C input levels on the slow C pool size.

It is not surprising that we found no relationship between C inputs and the active C pool size since active pool MRTs are less than one year (Paul et al., 1999). A lack of significant relationship between C inputs for 2000 and the size and mineralization rate of the active C pool could have been due to removing undecomposed organic matter from the soil samples prior to conducting the incubations.

The lack of significant correlations between estimated C inputs and C pool mineralization rate constants (and MRTs) is not surprising. The rate constants and MRTs indicate how readily mineralizable the two C pools are. Mineralization rate constants and MRTs should be more closely related to the quality than to the quantity of C inputs to the soil. We did not measure C input quality, but our treatments, which did affect C pool mineralization rate constants, reflect differences in the quality of C inputs. Thus, finding a difference in the rate constants for soils from the PL and the MF systems but not between the CPL and MF systems reflects differences in the C quality of the PL and CPL materials and is consistent with the general finding that composted manures release nutrients (and carbon) slower than raw manures (Hadas and Portnoy, 1994; Dao, 1999; Dao and Cavigelli, 2003; Evanylo et al., 2008).

Changes in soil pH following PL applications can be of some concern due to the effect of soil pH on micronutrient availability (Sims and Wolf, 1994). Sims (1986) found that soil pH increased from 6.5 to 7.5 immediately after PL application but after 20 weeks pH was reduced due to the acidifying effect of nitrification. Hileman (1967) reported decreased pH after applying more than 9 Mg PL ha^{-1} for three years. Kingery et al. (1994), on the other hand, found that soil pH increased by 0.5 units to a depth of 60 cm after 15-28 yr of PL application and Sistani et al. (2008) found that pH was greater by 0.3 units four years after PL had been applied for four years at ~16 Mg ha^{-1} dry weight, but saw no difference when PL application rate was ~8 Mg ha^{-1} dry weight. We found no change in soil pH two years after PL and CPL had been applied and suspect, based on Sistani et al. (2008), that rates of application in our study were not sufficient to have a residual impact on soil pH.

When PL is applied at rates intended to meet crop N needs, as in this study, STP levels and P loss potential generally increase since the plant-available N:P ratios of PL (2.5 to 4.1) and CPL (1.2) (Table 2) are lower than that required by plants (Eck and Stewart, 1995; Sharpley, 1995). Although we did not detect a statistically significant increase in STP in the PL and CPL systems relative to the MF system in the short term ($P > 0.10$), the data suggest that further low application rates of PL and CPL might increase STP levels above those in MF system plots as others have shown. Mean STP increases of 19 and 35% in the CPL and PL systems, respectively, should be cause for future concern. However, the magnitude of these increases may be higher than normally expected at these PL and CPL application rates since plant uptake and subsequent removal of P in grain and straw was relatively low from 1997 to 1999 since these were significant drought years (rainfall levels ~60% of normal levels between May and Sept; Cavigelli et al., 2008). Also, the concentration of P in PL is likely to decrease in the near future as producers adopt high available P corn, phytase additions to feed, and alum additions to PL (Smith et al., 2004**;** Alliance for the Chesapeake Bay, 2008). However, the impact of other feed additives (trace metals—Cu, Se, Zn, As (roxarsone), antibiotics, endocrine disrupting chemicals including natural hormones) on soils to which PL and CPL are applied and to the environment in general also must be kept in mind (Jackson et al., 2003; Fisher et al., 2005).

CONCLUSIONS

We conclude that applying PL and CPL at < 4 Mg ha^{-1} application^{-1} can be of long-term benefit to some components of soil quality and productivity. Soil bulk density in plots receiving only two applications of PL and three applications of CPL at < 4.0 Mg ha^{-1} was lower than in similarly managed plots that did not receive these organic amendments. While these low PL and CPL application rates were not sufficient to increase total soil C and total soil N, C mineralization rate constants for the active and slow C pools were greater in plots that received PL than in those that received MF four years after PL was last applied. In addition, the size of the slow C pool in spring 2001 was related to total C inputs in 1996 and 1997, the years that PL and CPL were applied. These results indicate that PL and CPL have residual effects on soil physical and biochemical properties and that PL has a stronger residual effect on soil C fractions than does CPL four years after last applied on these Coastal Plain soils. Further research on the residual impacts of PL and CPL on soil properties is warranted to better understand the relationship between C fractions and N fertility and to quantify how long such effects last, including in soils from other regions.

While we found some evidence for increased benefits to soil in PL- and CPL-amended soils it is also imperative to be sensitive to soil P levels when applying animal manures. These are especially significant concerns in the Chesapeake Bay watershed since high nutrient concentrations in the Bay have contributed to enhanced eutrophication and anoxia. Thus, the value of manure nutrients and the soil quality-building characteristics of PL and CPL applied at agronomically reasonable rates that we have demonstrated here, must be balanced against the risk of saturating the soil's capacity for nutrients, which can result in off-site discharge to surface waters.

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REFERENCES

Alliance for the Chesapeake Bay. 2008. VA poultry industry to increase use of phytase. Bay Journal [Online]. Available at http://www.bayjournal.com/article.cfm?article=3218 (accessed 22 May 2008; verified 22 May 2008).

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.

Blake, G.R., and K.H. Hartge. 1986. Bulk density. p. 363-376. *In* A. Klute (ed.) Methods of soil analysis: Physical and mineralogical methods, 2nd ed. ASA, Madison, WI.

Bolinder, M.A., D.A. Angers, and J.P. Dubuc. 1997. Estimating shoot to root ratios and annual carbon inputs in soils for cereal crops. Agric. Ecosyst. Environ. 63:61-66.

Bouldin, D.R., S.D. Klausner, and W.S. Reid. 1984. Use of nitrogen from manure. p. 221-245. *In* Hauck, R.D. (ed). Nitrogen in Crop Production. Am. Soc. Agron., Madison, WI.

Buyanovsky, G.A. and G.H. Wagner. 1986. Post-harvest residue input to cropland. Plant Soil 93:57-65.

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

Cavigelli, M.A. 1990. Phosphorus contributions of green manures to succeeding crops. M.S. Thesis, Kansas State University, 134 pp.

Cavigelli, M.A., J.R. Teasdale, and A.E. Conklin. 2008. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. Agron. J. 100:785-794.

Clark, M.S., W.R. Horwath, C. Shennan, and K.M. Scow. 1998. Changes in soil chemical properties resulting from organic and low-input farming practices. Agron J. 90:662-671.

Coale, F.J. 1996. Soil Fertility Management: Descriptions of the soil test interpretive categories used by the University of Maryland soil testing laboratory. Maryland Cooperative Extension Information Bulletin SFM-3.

Cooper, J.R., R.B. Reneau, Jr., W. Krrontje, and G.D. Jones. 1984. Distribution of nitrogeneous compounds in a rhodic Paleudult following heavy manure applications. J. Environ. Qual. 13:189-193.

Dao, T.H. 1999. Co-amendments to modify P extractability and N:P ratio in feedlot manure and composted manure. J. Environ. Qual. 28:1114-1121.

Dao, T.H. and M.A. Cavigelli. 2003. Mineralizable carbon, nitrogen and water-extractable phosphorus release from stockpiled and composted manure and manure-amended soils. Agron. J. 95:405-413.

DeLuca, T.H., and D.K. DeLuca. 1997. Composting for feedlot manure management and soil quality. J. Production Agric. 10:235-241.

Eck, H.V., and B.A. Stewart. 1995. Manure. p. 169-198. *In* J.E. Rechcigl (ed.) Soil amendments and environmental quality. Lewis Publ., Boca Raton, FL.

Eghball, B., D. Ginting, and J.E. Gilley. 2004. Residual effects of manure and compost applications on corn production and soil properties. Agron. J. 96:442-447.

Evanylo, G., C. Sherony, J. Spargo, D. Starner, M. Brosius, and K. Haering. 2008. Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. Agric. Ecosyst. Environ. doi:10.1016/j.agee.2008.02.014.

Fisher, D.J., K.W. Staver, L.T. Yonkos, M.A. Ottinger, and S. Pollack. 2005. Final report: Poultry litter-associated contaminants: Environmental fate and effects on fish. Maryland Center for Agro-Ecology, Inc., Queenstown, MD.

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

Gilmour, J.T., M.D. Clark, and G.C. Sigua. 1985. Estimating net N mineralization from carbon dioxide evolution. Soil Sci. Soc. Am. J. 49:1398-1402.

Ginting, D., A. Kessavalou, B. Eghball, and J.W. Doran. 2003. Greenhouse gas emissions and soil indicators four years after manure and compost applications. J. Environ. Qual. 32:23-32.

Gregorich, E.G., C.F. Drury, and J.A. Baldock. 2001. Changes in soil carbon under long-term maize in monoculture and legume-based rotation. Can. J. Soil Sci. 81:21-31.

Griffin, G.F., and A.F. Laine. 1983. Nitrogen mineralization in soils previously amended with organic wastes. Agron. J. 75:124-129.

Gunapala, N., and K.M. Scow. 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. Soil Biol. Biochem. 30:805-816.

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

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. Soc. Am. J. 47:1129-1133.

Hileman, L.H. 1967. The effect of broiler litter on soil under orchardgrass sod. Arkansas Farm Res. 16:6.

Jackson et al., 2003. Trace element speciation in poultry litter. J. Environ. Qual. 32:535-540.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23:139-147.

Lanyon, L.E. and W.R. Heald. 1982. Magnesium, calcium, strontium, and barium. p. 247-262. *In* A.L. Page et al. (ed.) Methods of soil analysis: Chemical and microbiological properties, 2nd ed. ASA, Madison, WI.

Liebhardt, W.C., C. Golt, and J. Tupin. 1979. Nitrate and ammonium concentrations of groundwater resulting from poultry manure applications. J. Environ. Qual. 8:211-215.

Magette, W.L. 1988. Runoff potential from poultry manure applications. p. 102-106. *In* E.C. Naber (ed.) Proc. Natl. Poultry Waste Manage. Symp., Columbus, OH. 18-19 Apr. 1988. Ohio State Univ. Press, Columbus.

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

Malik, R.K., and K.C. Reddy. 2002. Effects of long-term poultry litter application to cotton on succeeding corn crop production. J. Sust. Agric. 19:47-59.

McLean, E.O. 1982. Soil pH and lime requirement. p. 199-224. *In* A.L. Page et al. (ed.) Methods of soil analysis: Chemical and microbiological properties, 2nd ed. ASA, Madison, WI.

Mitchell, C.C., and S. Tu. 2005. Long-term evaluation of poultry litter as a source of nitrogen for cotton and corn. Agron. J. 97:399-407.

Nyakatawa, E.Z., K.C. Reddy, and G.F. Brown. 2001a. Residual effect of poultry litter applied to cotton in conservation tillage systems on succeeding rye and corn. Field Crops Res. 71:159-171.

Nyakatawa, E.Z., K.C. Reddy, and K.R. Sistani. 2001b. Tillage, cover cropping, and poultry litter effects on selected soil chemical properties. Soil & Tillage Res. 58:69-79.

Olsen, S.R. and L.E. Sommers. 1982. Soil pH and lime requirement. p. 403-422 *In* A.L. Page et al. (ed.) Methods of soil analysis: Chemical and microbiological properties, 2nd ed. ASA, Madison, WI.

Ott, L. 1984. An Introduction to Statistical Methods and Data Analysis, 2nd Ed. Duxbury Press, Boston.

Paul, E.A., D. Harris, H.P. Collins, U. Schultess, and G.P. Robertson. 1999. Evolution of CO_2 and soil carbon dynamics in biologically managed, row-crop agroecosystems. Appl. Soil Ecol. 11:53-65.

Paul, E.A., S.J. Morris, and S. Bohm. 2001. The determination of soil carbon pool sizes and turnover rates: Biophysical fractionation and tracers. p. 193-206. *In*: Lal et al., (eds.) Assessment methods for soil carbon. Lewis Publ., Boca Raton, FL.

Paustian, K., H.P. Collins, and E.A. Paul. 1997. Management controls on soil carbon. p. 15-49. *In*: Paul et al., (eds), Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Roberson, T., K.C. Reddy, S.S. Reddy, E.Z. Nyakatawa, R.L. Raper, D.W. Reeves, and J. Lemunyon. 2008. Carbon dioxide efflux from soil with poultry litter applications in conventional and conservation tillage systems in northern Alabama. J. Environ. Qual. 37:535-541.

Robertson, G.P., D. Wedin, P.M. Groffman, J.M. Blair, E.A. Holland, K.J. Nadelhoffer, and D. Harris. 1999. Soil carbon and nitrogen availability. N mineralization, nitrification, and soil respiration potentials. p. 258-271. *In*: Robertson et al., (eds.), Standard soil methods for long-term ecological research. Oxford Univ. Press, New York, NY.

SAS Institute, 2001. SAS user's guide. Statistics. Vers. 8. SAS Institute, Inc., Cary, NC.

Scow, K.M., O. Somasco, N. Gunapala, S. Lau, R. Venette, H. Ferris, R. Miller, and C. Shennan. 1994. Transition from conventional to low-input agriculture changes soil fertility and biology. Calif. Agric. 48:20-26.

Sharpley, A.N. 1995. Dependence of runoff to phosphorus loss in agricultural runoff. J. Environ. Qual. 24:920-926.

Sharpley, A.N., S.J. Smith, and W.R Bain. 1993. Nitrogen and phosphorus fate from long-term poultry litter applications to Oklahoma soils. Soil Sci. Soc. Amer. J. 57:1131-1137.

Simpson, T.W. 1990. Agronomic use of poultry industry waste. Poultry Sci. 70:1126-1131.

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. 1987. Agronomic evaluation of poultry manure as a nitrogen source for conventional and no-tillage corn. Agron. J. 79:563-570.

Sims, J.T., D.W. Murphy, and T.S. Handwerker. 1993. Composting of poultry wastes: Implications for dead poultry disposal and manure management. J. Sust. Agric. 12:67-82.

Sims, J.T. and D.C. Wolf. 1994. Poultry waste management: agricultural and environmental issues. Adv. Agron. 52: 1-83.

Sistani, K.R., G.E. Brink, A. Adeli, H. Tewolde, and D.E. Rowe. 2004. Year-round soil nutrient dynamics from broiler litter application to three bermudagrass cultivars. Agron J. 96:525-530.

Sistani, K.R., F.J. Sikora, and M. Rasnake. 2008. Poultry litter and tillage influences on corn production and soil nutrients in a Kentucky silt loam soil. Soil & Tillage Res. 98:130-139.

Smith, D.R., P.A. Moore, Jr., D.M. Miles, B.E. Haggard, and T.C. Daniel. 2004. Decreasing phosphorus runoff losses from land-applied poultry litter with dietary modifications and alum addition. J. Environ. Qual. 33:2210-2216.

Sollins, P., C. Glassman, E.A. Paul, C. Swanston, K. Lajtha, J.W. Heil, and E.T. Elliott. 1999. Soil carbon and nitrogen: pools and fractions. p. 89-105. *In* G.P. Robertson et al. (ed.) Standard soil methods for long-term ecological research. Oxford Univ. Press, New York, NY.

Thomas, G.W. 1982. Exchangeable cations. p. 159-165. *In* A.L. Page et al. (ed.) Methods of soil analysis: Chemical and microbiological properties, 2nd ed. ASA, Madison, WI.

Tiquia, S.M., and N. F.Y. Tam. 2002. Characterization and composting of poultry litter in forced-aeration piles. Process Biochem. 37:869-880.

Wander, M.M. 2004. Soil organic matter fractions and their relevance to soil function. p. 67–102. *In* F. Magdoff and R. Weil (ed.) Advances in agroecology. CRC Press, Boca Raton, FL.

Wander, M.M., and S.J. Traina. 1996. Organic matter fractions from organically and conventionally managed soils: II. Characterization of composition. Soil Sci. Soc. Am. J. 60:1087-1094.

Wander, M.M., S.J. Traina, B.R. Stinner, and S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 58:1130-1139.

Weil, R.R. and W. Kroontje. 1979. Physical condition of a Davidson clay loam after five years of heavy poultry manure applications. J. Environ. Qual. 8:387-392.

Weil, R.R., R.A. Weismiller, and R.S. Turner. 1990. Nitrate contamination of groundwater under irrigated coastal plain soils. J. Environ. Qual. 19:441-448.

Weilenmann de Tau, M.E. and J. Luquez. 2000. Variations for biomass, economic yield and harvest index among soybean cultivars of maturity groups III and IV in Argentina. Soybean Genetics Newsletter 27. [Online journal]. URL http://www.soygenetics.org/articles/sgn2000-007.htm (posted 11 May 2000) (verified 12/28/02).