Effects of Annual Turkey Litter Application on Surface Soil Quality of a Texas Blackland Vertisol

R. Daren Harmel, Rick L. Haney, and Doug R. Smith

Abstract: Proper application management is essential to minimize adverse environmental effects and maximize agronomic benefits of land applying poultry litter as a nutrient source and soil amendment. In this study, turkey (*Meleagris gallopavo*) litter was applied to five cultivated fields (target rates 4.5, 6.7, 9.0, 11.2, 13.4 Mg ha^{-1}) and to two pasture fields (target rates 6.7, 13.4 Mg ha^{-1}) to evaluate the effects on surface soil quality in the Vertisol-dominated Texas Blackland Prairie. A cultivated field that received only inorganic fertilizer and two pasture fields (one native prairie and one grazed pasture) served as "controls." Despite the annual variability in litter composition, actual application rates, and weather conditions, 7 years of litter application produced several significant differences in surface soil properties. Litter application produced significant increasing trends in soil organic C and extractable P for several cultivated and pasture fields. Similarly, after seven annual litter applications, litter rate was significantly related to total N, total P, extractable P, Zn, and Cu in the cultivated fields and to total P, extractable P, Zn, and Cu in the pasture fields. These observations coupled with previous findings indicate that annual litter application rates should be within 2.2 to 4.5 Mg ha^{-1} for cropland and 4.5 to 6.7 Mg ha^{-1} for pasture to limit the buildup of extractable P, Zn, and Cu in the soil. Although these target rates appear to be appropriate, the annual variability in litter composition (both nutrients and moisture) can, if not accounted for, make it difficult to determine proper application rates. Therefore, preapplication soil and litter testing and spreader calibration is strongly recommended so that litter application supplies only crop nutrient requirements (typically P) and balances agronomic and environmental concerns.

Key words: Waste utilization, poultry litter, soil quality, fertilizer.

(*Soil Sci* 2011;176: 227–236)

The poultry industry has expanded greatly in central Texas in the last decade, and this rapid increase has raised concerns about the environmental impact of using the poultry litter by-product. According to USDA-NASS (2009), seven counties in this region each produced more than 1 million birds in 2007. Current production has grown to more than 3 million birds annually in 10 counties, including an estimated 40 million birds per year for Leon and Robertson counties (based on Texas State Soil and Water Conservation Board estimates). As in many areas, land application is the most common, and usually most desirable, method of using the nutrient and organic matter resources in animal manure and litter (USDA-USEPA, 1999). Land application is a common practice both onsite at animal production facilities and offsite at conventional farm and ranch operations that import the manure or litter as a soil amendment and nutrient source.

Many studies have warned about adverse environmental impacts associated with mismanaged land application (Sharpley et al., 2003; Gascho and Hubbard, 2006; He et al., 2009; Endale et al., 2009). Typical issues of concern associated with mismanaged land application include excessive N and P concentrations in runoff, offensive odors, and rapid buildup of P and metals in soil. Much of the previous research on litter application impacts on soil quality has been conducted in the southeast United States. Kingery et al. (1994) reported that long-term high-rate broiler litter application increased concentrations of beneficial organic C in the soil but also increased total N, extractable P, Cu, and Zn levels, which can be beneficial or detrimental, depending on crop needs, soil properties, and watershed conditions. Shuman and McCracken (1999) observed dramatic increases in soil Zn and Cu after 2 years of litter application to cultivated fields in Georgia. Schomberg et al. (2009) and He et al. (2009) reported that 4.5 Mg ha^{-1} litter application did not increase soil total P, Zn, or Cu concentrations, but that these levels increased substantially when litter rates were doubled or quadrupled. Gascho and Hubbard (2006) found that extractable P, Cu, and Zn increased dramatically but that soil C also increased at litter rates from 9 to 27 Mg ha^{-1}.

The importance of proper litter application in terms of runoff water quality and offsite economics for central Texas has been noted (Harmel et al., 2004, 2008, 2009), but the soil quality impacts of repeated annual poultry litter application have not been studied in this region. Thus, the objective of this study was to evaluate how repeated annual litter application affects organic C, total N, total P, extractable P, Zn, and Cu levels in expansive clay soils of the Texas Blackland Prairie.

MATERIALS AND METHODS

Site Description

In August 2000, six cultivated and four pasture fields were selected as the experimental units for this study (Table 1). These homogeneous land-use areas are best described as field-scale watersheds. It was at that scale that treatments were assigned and evaluated. All of the study fields are located at the USDA-ARS Grassland, Soil and Water Research Laboratory near Riesel, Texas (Fig. 1). The research site is dominated by Houston Black clay soil (fine, smectitic, thermic, udic Haplustert), which is widely recognized as a classic Vertisol. These highly expansive clays, which shrink and swell with changes in moisture content, have a typical particle size distribution of 17% sand, 28% silt, and 55% clay. These soils are very slowly permeable when wet (saturated hydraulic conductivity ≈ 1.5 mm h^{-1}); however, preferential flow associated with soil cracks contributes to high infiltration rates when the soil is dry (Arnold et al., 2005; Allen et al., 2005).

Land Management

Six litter application rates and two land uses were evaluated in this 8-year study. Litter application rates from 0.0 to 13.4 Mg ha^{-1} were determined *a priori* and then randomly assigned to each of the six cultivated fields (Table 1). These rates

---

USDA-ARS, 808 E. Blackland Rd., Temple, TX 76502. Dr. R. Daren Harmel is corresponding author. E-mail: daren.harmel@ars.usda.gov
Received January 4, 2011.
Accepted for publication February 9, 2011.

ISSN: 0038-075X
DOI: 10.1097/SS.0b013e318214fab4

TABLE 1. Land Management and Watershed Characteristics of Cultivated and Pasture Watersheds

	Cultivated Watersheds						Pasture Watersheds			
	Y6	**Y13**	**Y10**	**W12**	**W13**	**Y8**	**SW12**	**SW17**	**W10**	**Y14**
Area, ha	6.6	4.6	7.5	4.0	4.6	8.4	1.2	1.2	8.0	2.3
Slope, %	3.2	2.3	1.9	2.0	1.1	2.2	3.8	1.8	2.5	1.6
Litter rate, Mg ha^{-1} year^{-1}	0.0	4.5	6.7	9.0	11.2	13.4	0.0	0.0	6.7	13.4
Average N rate, kg ha^{-1} year^{-1}	146	196	231	245	289	338	0.0	0.0	158	335
Average P rate, Mg ha^{-1} year^{-1}	15	87	130	149	200	254	0.0	0.0	124	257
Year	**Land Use/Crop**						**Land Use/Crop**			
2000–2001	Fallow	Fallow	Fallow	Fallow	Fallow	Fallow	Hayed	Grazed	Hayed	Hayed
2001–2002	Corn	Corn	Corn	Corn	Corn	Corn	Hayed	Grazed	Hayed	Hayed
2002–2003	Corn	Corn	Corn	Corn	Corn	Corn	Hayed	Grazed	Hayed	Hayed
2003–2004	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Hayed	Grazed	Hayed	Hayed
2004–2005	Corn	Corn	Corn	Corn	Corn	Corn	Hayed	Grazed	Hayed	Hayed
2005–2006	Corn	Corn	Corn	Corn	Corn	Corn	Hayed	Grazed	Hayed	Hayed
2006–2007	Wheat	Wheat	Wheat	Wheat	Wheat	Wheat	Hayed	Grazed	Hayed	Hayed
2007–2008	Corn	Corn	Corn	Corn	Corn	Corn	Hayed	Grazed	Hayed	Hayed

are best termed "target rates" because litter was bought and applied with the practices used in real-world agronomic settings. In other words, the litter was not carefully weighed as might be conducted in a small-plot research setting to ensure the "exact" desired rate was applied. Instead, litter was applied based on application truck speed, gear, and rear gate settings for the desired litter rate. The implications of using real-world application techniques and suggested improvements are discussed in the Results and Discussion section. The range of litter rates was chosen to encompass and exceed the typical range of application rates used in the region. The litter was obtained in the vicinity of the study site from the cleanout (either complete cleanout for multiple flocks or "cake out" from a single flock) of turkey houses. The bedding material in litter was either wood shavings or rice hulls. Within each study year, all litter came from the same source.

Field Y6 served as the control for the cultivated fields and, as such, received only inorganic fertilizer. Two pasture fields received no litter and served as controls because of their

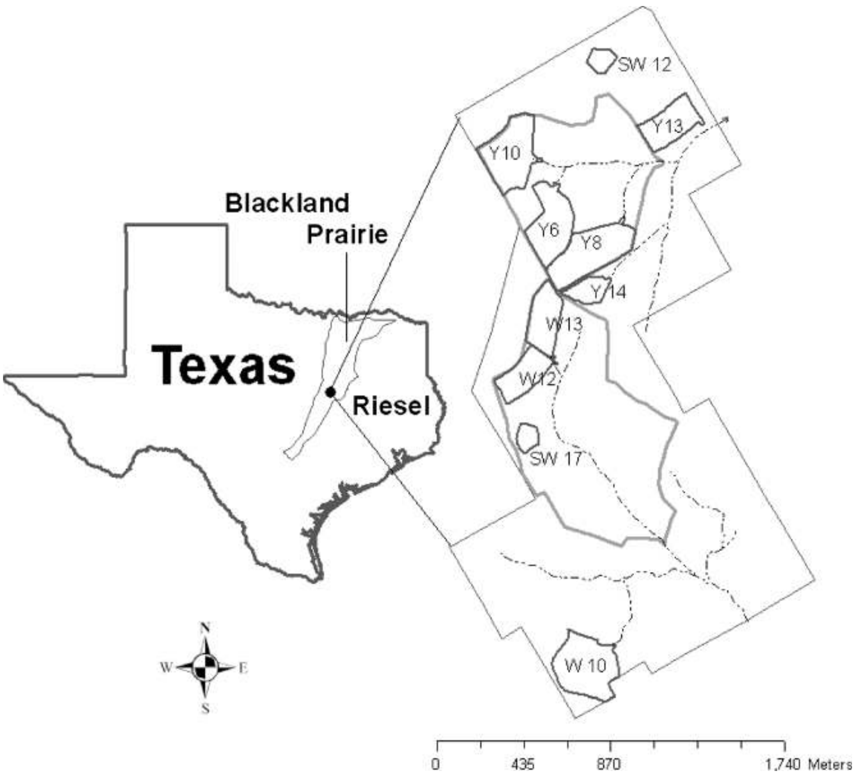

FIG. 1. Field-scale watersheds (experimental units) for this study at the USDA-ARS Grassland, Soil and Water Research Laboratory, Riesel, Texas.

management as native prairie (SW12) and grazed pasture (SW17). Litter rates for the other two pasture fields were determined *a priori* and then randomly assigned (Table 1). Management within land-use type (cultivated or pasture) was consistent to minimize confounding differences caused by differing management; only fertilization varied among treatments.

Each cultivated field had broad-base terraces on the contour and grassed waterways at the terrace outlets. Management consisted of tillage, planting, harvest, and application and incorporation of litter, supplemental N, and pesticides. In 2000–2001, the cultivated fields were kept fallow and no fertilizer was applied. In 2001–2002, a 3-year crop rotation of corn (*Zea mays* L.)-corn-wheat (*Triticum aestivum*) was initiated, with fallow periods between these crops. Each field received a constant annual litter rate beginning in 2001–2002. In the corn years, target available N rates were set at approximately 170 kg ha^{-1} based on production recommendations by Gass (1987). It was assumed that the litter N available in the first year after application increased from 40% initially to 50% in 2004–2007 as soil microbial communities were enhanced (Acosta-Martinez and Harmel, 2006). It was also assumed that 5% to 10% of litter N was available in the second year after application. Supplemental inorganic N was applied before planting to reach the 170-kg ha^{-1} N target. In the wheat years, no supplemental N was applied because litter supplied adequate N for wheat production (>67 kg available N ha^{-1}). The cultivated control field (Y6) received only inorganic N and P at rates of 170 kg N ha^{-1} and 14 kg P ha^{-1} in corn years and at 80 kg N ha^{-1} and 17 kg P ha^{-1} in wheat years.

Management for the four pasture fields consisted of annual litter application, hay harvest (or grazing), and herbicide application. No fertilizer was applied to any of the pasture fields in 2000–2001, but a consistent litter application rate was applied to Y14 and W10 each year from 2001 to 2007. For the pasture fields, no supplemental N or P was applied. The grazed pasture field (SW17) was opened for selective grazing for about 8 months per year.

Data Collection and Analysis

No crops were planted, and no fertilizer was applied in the first study year (August 2000–July 2001) to establish baseline conditions. Then, 7 years of soil quality data were collected after litter application (August 2001–July 2008). Detailed supplemental data (e.g., hydrology and water quality data for each runoff event and every management activity on each field) are available on request. Related data and analyses are also available on water quality impacts (Harmel et al., 2004, 2009), on-farm agronomic and economic effects (Harmel et al., 2008), and soil microbial communities and enzyme activities (Acosta-Martinez and Harmel, 2006).

Litter Properties

Litter samples were collected for analysis each year immediately before application. Moisture content was determined by drying at 116°C for 24 h. Water-extractable $NO_3 + NO_2$-N, NH_4-N, and PO_4-P concentrations were determined with extraction methodology described in Self-Davis and Moore (2000) and subsequent colorimetric analysis. Total N and total P were determined by the Kjeldahl digestion and colorimetric analysis. Organic C was determined using a total C analyzer, with the temperature of the primary sample ignition furnace reduced to 650°C (McGeehan and Naylor, 1988; Schulte and Hopkins, 1996). Concentrations of Zn and Cu were determined by inductively coupled plasma (ICP) analysis after nitric acid digest (Havlin and Soltanpour, 1989).

Soil Properties

Soil samples for each field were taken annually in the winter with a manual soil probe (2.54 cm diameter) and a depth of 15 cm. Samples were collected at a frequency of at least one core per 0.4 ha, with a random sampling scheme stratified to ensure that samples were collected from the top, middle, and bottom portions of each field. Then the cores were composited to create one sample for each field. To focus land-use comparisons on agronomic impacts, the same sampling depth was chosen for cultivated and pasture fields. In contrast, different sampling depths (0–15 cm cultivated, 0–5 cm pasture) may be more appropriate for comparisons of "environmental risk" (Torbert et al., 2002; Vadas et al., 2007), although Hart and Cornish (2011) recently suggested that a 0- to 10-cm sampling depth was sufficient for estimating P runoff potential in pasture soils.

Soil samples were analyzed for organic C by the method of McGeehan and Naylor (1988) and Schulte and Hopkins (1996). Extractable P was determined with the Mehlich 3 extractant (Mehlich, 1984) and ICP analysis. In many south-central U.S. states, Mehlich 3 has become the required extractant to judge regulatory compliance in terms of waste application (e.g., Texas and Arkansas, Mehlich 3 with ICP analysis; Oklahoma, Mehlich 3 with colorimetric analysis), although its design intent for acid soils and important differences in colorimetric and ICP results are too often ignored (Pittman et al., 2005; Haney et al., 2006; Somenahally et al., 2009). Total N and total P levels were determined by a salicylic acid modification of a semimicro-Kjeldahl digestion procedure (Technicon Industrial Systems, 1976). The Cu and Zn concentrations were determined by extraction with a 0.005 *M* DTPA solution (Lindsay and Norvell, 1978) and ICP analysis.

Experimental Design and Statistical Analyses

Ten fields (watersheds) were the experimental units, each with a land-use (cultivated and pasture) and litter rate (0.0–13.4 Mg ha^{-1}) component. In addition to graphical comparisons, one-way analysis of variance followed by Tukey pairwise mean comparison (family error rate, $\alpha = 0.05$) was used to examine whether differing litter application rates created differences in mean soil properties between experimental units within land-use categories. Linear regression analyses with an *a priori* $\alpha = 0.05$ probability level was used to compare litter rate treatment effects and to examine possible temporal trends in the effects of repeated litter application. All statistical tests were conducted with Minitab software (Minitab, 2000) according to procedures described in Helsel and Hirsch (1993) or Haan (2002).

RESULTS AND DISCUSSION

Litter Properties

Litter properties in this study (Table 2) were at times similar and at times very different than reported in other studies. The moisture content was extremely variable, ranging from 9.8% to 49.5% compared with a range of 22% to 29% reviewed and reported by Edwards and Daniel (1992), although mean values were 25% in both cases. The litter Zn and Cu concentrations were similar to those reported by Shuman and McCracken (1999) but were substantially larger than reported by Edwards and Daniel (1992) or Stephenson et al. (1990). The litter organic C, total N, and NH_4-N were consistently within the ranges reported by Edwards and Daniel (1992), but NO_3-N and total P occasionally exceeded the reported ranges.

For every litter property, the within-year variability (heterogeneity) in litter stock piles before application was less than

TABLE 2. Mean Annual Litter Properties Presented on a Dry-Weight Basis

							Water-Extractable Nutrients		
	Moisture	**Organic C**	**Zn**	**Cu**	**Total N**	**Total P**	**NO$_3$-N**	**NH$_4$-N**	**SRP**
Applied	**%**	**%**	**mg kg^{-1}**	**mg kg^{-1}**	**%**	**%**	**- - - - - - - - - - mg kg^{-1}**	**- - - - - - - - - -**	
July 2001	49.5	58.4	na	na	4.87	4.56	345	2,424	1,795
September 2002	9.8	34.6	433	355	3.38	3.86	933	4,104	1,369
September 2003	32.1	39.8	711	579	4.82	2.45	381	6,946	1,132
August 2004	28.0	38.9	804	753	3.17	2.78	685	4,122	1,131
August 2005	20.6	40.1	731	640	3.26	2.47	28	2,220	500
August 2006	14.8	36.9	451	323	3.19	1.65	8	3,287	3,392
October 2007	21.1	39.5	648	517	2.61	1.81	577	4,081	512
Mean	25.1	41.2	630	528	3.62	2.80	423	3,883	1,404
Cv[†]	0.52	0.19	0.24	0.31	0.24	0.38	0.80	0.40	0.70
S.D.[†]	13.1	7.8	154	166	0.88	1.06	339	1,569	989

[†] The coefficients of variation (Cv) and S.D. for annual means are also presented.

SRP: soluble reactive P.

the year-to-year variability caused by differing litter ages, bedding materials, and sources (based on the S.D. for a dry-weight basis). The moisture content, water-extractable nutrient concentrations, and total P concentrations were all extremely variable (Cv $\geq$ 0.38) on an annual basis (Table 2). The Zn, Cu, organic C, and total N concentrations were less variable (Cv $\leq$ 0.31).

Soil Organic C

Soil C dynamics have received recent attention related to C sequestration in various agricultural land management systems. On average, litter application added 303 kg of organic C per Mg of litter ("as is" basis) per year; however, estimated organic C inputs ranged from 227 to 514 kg Mg^{-1} of litter because of the variability of litter composition and actual application rates.

Five of the six cultivated fields experienced significant increases in soil organic C during the study period; however, these changes did not produce differences in treatment means (Table 3; Fig. 2). Only Y10 did not show an increasing trend, although the slope *P* value of 0.059 was very near the null hypothesis rejection criterion of 0.05. The mean annual rate of soil organic C accumulation increased from 0.07% for the 0.0 Mg ha^{-1} litter rate (Y6) to 0.16% for the 13.4 Mg ha^{-1} litter rate (Y8).

The effects of litter application on soil organic C were much less pronounced on the pasture fields (Table 3). Although the mean soil organic C level for the native prairie field (SW12) was significantly larger than that of the other pasture fields (Fig. 2), this difference is attributed to larger initial soil organic C levels not to litter rate influences. None of the pasture fields experienced significant increases in soil organic C during the study period (although the slope *P* value for Y14 was 0.067, which does cast doubt on the null hypothesis of no significant trend). In fact, soil organic C levels at W10 exhibited a decreasing trend. The mean annual change of +0.13% from 2.52% to 3.37% for Y14 is much greater than that reported for pasture

TABLE 3. Soil Organic C Levels

	Cultivated Watersheds						Pasture Watersheds			
Litter Rate,	**Y6**	**Y13**	**Y10**	**W12**	**W13**	**Y8**	**SW12**	**SW17**	**W10**	**Y14**
Mg ha^{-1}Year^{-1}	**0.0**	**4.5**	**6.7**	**9.0**	**11.2**	**13.4**	**0.0**	**0.0**	**6.7**	**13.4**
Year	**- Organic C, %- -**									
2000–2001	1.53	1.32	1.45	1.24	1.36	1.46	3.82	2.51	3.31	2.52
2001–2002	1.54	1.64	1.40	1.32	1.41	1.60	3.41	2.09	2.88	2.29
2002–2003	1.46	1.52	1.47	1.39	1.46	1.65	3.96	2.38	2.96	2.38
2003–2004	1.69	1.62	1.47	1.28	1.42	1.88	3.08	1.72	2.41	1.87
2004–2005	2.12	2.03	1.67	2.11	2.02	2.30	3.76	2.59	3.12	2.99
2005–2006	1.86	1.81	1.87	1.97	1.73	2.08	3.69	2.57	3.01	2.92
2006–2007	1.72	1.90	1.48	1.88	1.83	2.07	3.72	2.25	2.82	2.72
2007–2008	1.99	2.15	1.79	2.20	2.19	2.74	3.78	2.78	3.04	3.37
Mean[†]	1.74a	1.75a	1.58a	1.67a	1.68a	1.97a	3.65a	2.36b	2.94c	2.63bc
Average annual change	+0.07[‡]	+0.10[‡]	+0.05	+0.14[‡]	+0.11[‡]	+0.16[‡]	+0.01	+0.05	−0.02	+0.13

[†] Within land-use categories, mean values with the same letter are not significantly different.

[‡] Annual trend at that site is significant at $\alpha = 0.05$.

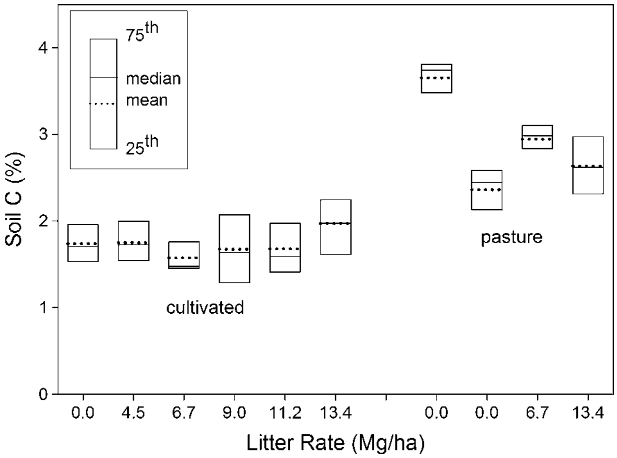

FIG. 2. Box plots of soil C for various litter rates on cultivated and pasture fields.

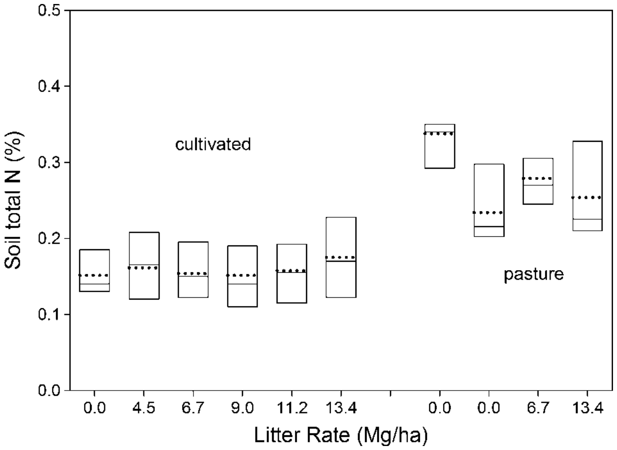

FIG. 3. Box plots of soil total N for various litter rates on cultivated and pasture fields.

fields in Alabama, with a high rate broiler litter application for 15 to 28 years (Kingery et al., 1994), which may be partly caused by the coarser texture of the Sand Mountain soils. Kingery et al. (1994) also speculated that mineralization may occur year round in Alabama because of warm temperatures and a uniform precipitation distribution, which would cause the soils with low initial organic C levels (~1.1%) to experience lower annual increases in soil organic C (0.01%–0.02%).

Soil Total N and Total P

Similar to soil C, litter application did not produce significant differences in treatment means for soil total N, and any apparent difference is likely caused by inherent land-use effects (Table 4; Fig. 3). Some effects appear to be occurring for soil total P (Fig. 4), although the effect was not sufficient to produce significant differences in means (Table 5). None of the fields experienced significant linear trends in total soil N or P during 8 years (Tables 4 and 5). However, at the end of the study (2007–2008), after seven annual litter applications, litter rate was significantly related to total soil N ($r^2 = 0.86$, $P = 0.008$) and total soil P ($r^2 = 0.80$, $P = 0.016$) in the cultivated fields and to total soil P in the pasture fields ($r^2 = 0.96$, $P = 0.022$). Schomberg et al. (2009) reported average annual increases of 0.0001% at the 4.5 Mg ha^{-1} litter rate (compared with +0.003% for the same rate at Riesel) and annual increases of 0.003% at litter rates of 11.2 then 22.3 Mg ha^{-1} (compared with +0.009% at Riesel). The coarser textured Cecil soils in that study, which had much lower initial soil P levels, experienced slower total P accumulation probably caused by higher rainfall rates and increased P leaching and runoff.

The lack of clear treatment effects on soil total N and P can be attributed to two main factors. One factor was the annual variability in litter composition and actual application rates, which produced dramatic differences in N and P rates applied as litter (Fig. 5). This observation of dramatic differences in applied nutrients even with the same organic amendment (turkey litter) and the same target application rate was shocking and

TABLE 4. Soil Total N Levels

	Cultivated Watersheds						Pasture Watersheds			
Litter Rate,	Y6	Y13	Y10	W12	W13	Y8	SW12	SW17	W10	Y14
Mg ha^{-1}Year^{-1}	0.0	4.5	6.7	9.0	11.2	13.4	0.0	0.0	6.7	13.4
Year	Total N, %									
2000–2001	0.13	0.12	0.13	0.11	0.11	0.12	0.33	0.23	0.31	0.22
2001–2002	0.13	0.14	0.12	0.11	0.13	0.14	0.30	0.20	0.26	0.21
2002–2003	0.22	0.21	0.21	0.20	0.20	0.23	0.53	0.35	0.42	0.35
2003–2004	0.17	0.20	0.18	0.15	0.17	0.22	0.35	0.21	0.26	0.21
2004–2005	0.09	0.10	0.09	0.11	0.10	0.10	0.20	0.13	0.17	0.15
2005–2006	0.13	0.12	0.14	0.13	0.14	0.13	0.29	0.22	0.24	0.23
2006–2007	0.15	0.19	0.16	0.16	0.17	0.20	0.35	0.21	0.28	0.26
2007–2008	0.19	0.21	0.20	0.24	0.24	0.26	0.35	0.32	0.29	0.40
Mean[†]	0.15a	0.16a	0.15a	0.15a	0.16a	0.18a	0.34a	0.23a	0.28a	0.25a
Average annual change[‡]	0.00	+0.01	0.00	+0.01	+0.01	+0.01	−0.01	0.00	−0.01	+0.01

[†] Within land-use categories, mean values with the same letter are not significantly different.

[‡] Annual trend at that site is significant at $\alpha = 0.05$.

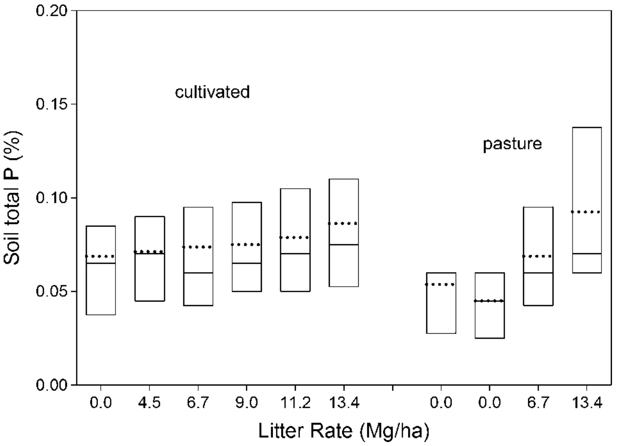

FIG. 4. Box plots of soil total P for various litter rates on cultivated and pasture fields.

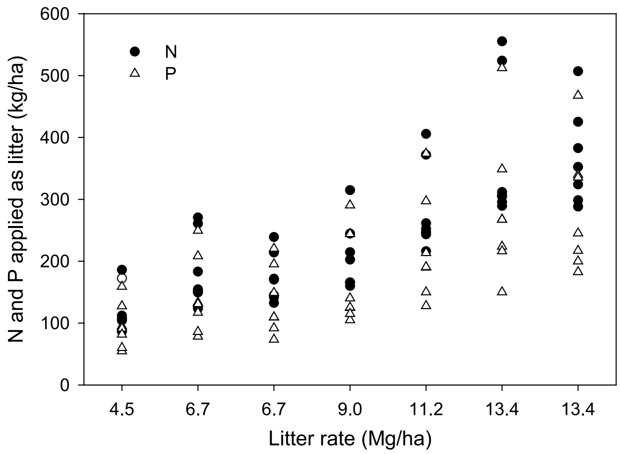

FIG. 5. Annual variability in N and P applied as turkey litter.

emphasizes the importance of accounting for this variability because of its agronomic and environmental implications. Additional discussion of the practical implications of this variability appears in the Litter Application Recommendations section.

Another factor is the magnitude of the total soil N and P pools. Because organic-dominated pools are much larger than the readily plant-available (inorganic) N and P pools, changes in total N and P can sometimes be difficult to detect (Stockdale et al., 2002; Haney et al., 2006). The largest soil N values were observed in the native prairie field, which has never received organic or inorganic fertilizer. The grazed pasture (converted to pasture about 1947) receives periodic manure deposition, and the other pasture fields (converted to pasture 30–45 years ago) are fertilized for hay production. The observation that all of these pastures regardless of fertilization history have greater total soil N levels than the cultivated fields indicates that pastures retain more N than cultivated fields. This is especially true for organic N, as water-extractable organic N was 62% of the total water-extractable N pool in the pastures as opposed to 44% in the cultivated fields (data not shown). In contrast, total P levels were similar between the cultivated and pasture land uses.

Soil-Extractable P

The buildup of extractable P caused by manure and litter application is often the subject of regulatory attention related to water quality. According to Mehlich 3 ICP analyses in this study, litter application has certainty affected soil-extractable P levels (Fig. 6), which is a common result with organic fertilizer application (Edmeades, 2003; Nelson and Janke, 2007). Several of the fields with applied litter exhibited significant increases in extractable P during 8 years (Table 6), and significant relationships were evident between extractable P and litter rate at the end of the study (2007–2008) for cultivated fields ($r^2 = 0.95$, $P = 0.001$) and pasture fields ($r^2 = 1.00$, $P = 0.001$). The average annual increases in soil test P were relatively small on Y13 and W10 (+4.7 mg kg^{-1} soil), which received litter at the upper limits of the agronomic P rate. Much larger annual

TABLE 5. Soil Total P Levels

	Cultivated Watersheds						Pasture Watersheds			
Litter Rate,	Y6	Y13	Y10	W12	W13	Y8	SW12	SW17	W10	Y14
Mg ha^{-1} Year^{-1}	0.0	4.5	6.7	9.0	11.2	13.4	0.0	0.0	6.7	13.4
Year	Total P, %									
2000–2001	0.06	0.07	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06
2001–2002	0.07	0.07	0.06	0.07	0.07	0.07	0.06	0.04	0.06	0.08
2002–2003	0.14	0.09	0.10	0.10	0.09	0.11	0.10	0.06	0.13	0.13
2003–2004	0.06	0.06	0.06	0.06	0.07	0.08	0.06	0.04	0.05	0.06
2004–2005	0.03	0.04	0.04	0.05	0.05	0.05	0.02	0.02	0.04	0.06
2005–2006	0.03	0.03	0.04	0.04	0.04	0.04	0.02	0.02	0.03	0.04
2006–2007	0.07	0.09	0.08	0.09	0.11	0.11	0.06	0.05	0.08	0.14
2007–2008	0.09	0.12	0.16	0.14	0.15	0.17	0.05	0.07	0.10	0.17
Mean[†]	0.07a	0.07a	0.07a	0.08a	0.08a	0.09a	0.05ab	0.05a	0.07ab	0.09b
Average annual change[‡]	0.00	0.00	+0.01	+0.01	+0.01	+0.01	0.00	0.00	0.00	+0.01

[†] Within land-use categories, mean values with the same letter are not significantly different.

[‡] Annual trend at that site is significant at $\alpha = 0.05$.

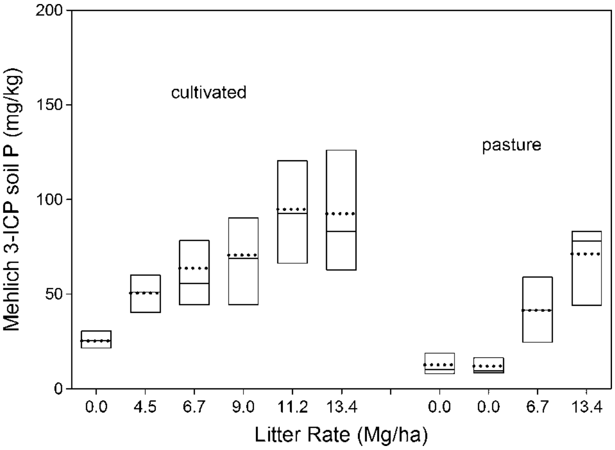

FIG. 6. Box plots of Mehlich 3 ICP soil P for various litter rates on cultivated and pasture fields.

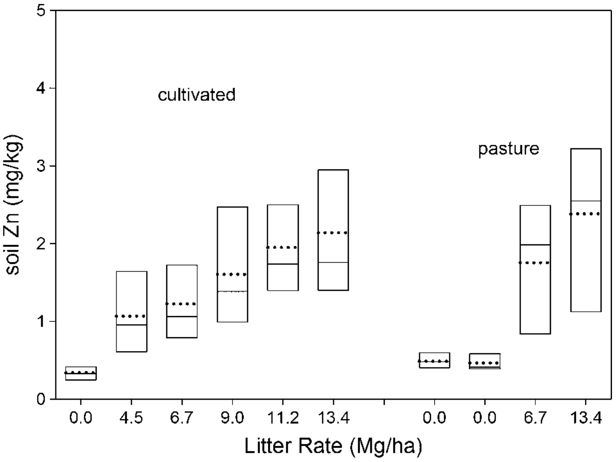

FIG. 7. Box plots of soil Zn for various litter rates on cultivated and pasture fields.

increases (+9.7–+14.9 mg kg^{-1} soil) occurred on fields with larger litter rates.

Based on these accumulation rates, annual litter application at 4.5 Mg ha^{-1} would not be expected to increase extractable P levels to the Texas regulatory limit of 200 mg kg^{-1} soil for 38 years on cultivated fields. Thus, the economically and environmentally optimal litter application rate for the cultivated cropping system evaluated in this region (2.2–3.4 Mg ha^{-1} based on Harmel et al., 2008, 2009) should allow at least 50 years of annual application before extractable P reaches the current regulatory threshold in Texas at which P application would be restricted.

Soil Zn and Cu

Repeated annual application of litter also clearly affected soil Zn and Cu levels (Figs. 7 and 8), and several significant differences in mean soil Zn and Cu values resulted (Tables 7 and 8). After 8 years, regression indicated strong linear relationships between litter rate and soil Zn and Cu concentrations for each land use and with land uses grouped (Zn, $r^2 = 0.98$, $P < 0.001$; Cu, $r^2 = 0.98$, $P < 0.001$). Litter application produced much larger mean annual accumulation rates than for the control fields with no litter, but only Y14 exhibited significant temporal trends in soil Zn and Cu levels because of substantial annual variability in soil test results.

Based on the regression relationships for cultivated fields with applied litter, annual accumulation rates ranged from 0.23 to 0.38 mg kg^{-1} soil for Zn and from 0.23 to 0.49 mg kg^{-1} soil for Cu (Tables 7 and 8). On pasture fields, annual accumulation rates ranged from 0.37 to 0.61 mg kg^{-1} soil for Zn and from 0.30 to 0.62 mg kg^{-1} soil for Cu. On pasture fields in Alabama with annual litter application rates of 6 to 22 Mg ha^{-1}, Kingery et al. (1994) reported similar Zn accumulation rates (0.3–0.5 mg kg^{-1} year^{-1}) but lower annual rates for Cu (~0.1 mg kg^{-1} year^{-1}). The soils in that study had similar background Cu levels (~0.7 mg kg^{-1}) but higher background Zn levels (~2.2 mg kg^{-1}) than the Houston Black clay soil (Tables 7 and 8). In contrast, Franzluebbers et al. (2004) reported

TABLE 6. Soil Test P Levels Determined With the Mehlich 3 Extractant and ICP Analysis

Litter Rate, Mg ha^{-1} Year^{-1}	Cultivated Watersheds						Pasture Watersheds			
	Y6	Y13	Y10	W12	W13	Y8	SW12	SW17	W10	Y14
	0.0	4.5	6.7	9.0	11.2	13.4	0.0	0.0	6.7	13.4
Year	Mehlich 3 ICP, mg kg^{-1}									
2000–2001	25	24	25	27	25	20	23	21	21	15
2001–2002	26	50	48	63	77	59	20	17	44	75
2002–2003	23	52	73	71	124	102	8	9	43	81
2003–2004	31	44	43	38	76	82	10	9	20	37
2004–2005	16	60	80	92	108	134	10	8	40	83
2005–2006	21	39	53	67	63	74	15	14	35	65
2006–2007	31	60	58	85	110	84	8	8	64	83
2007–2008	29	76	129	122	175	185	7	10	64	131
Mean[†]	25a	51ab	64ab	71ab	95b	93b	13a	12a	41b	71c
Average annual change	+0.4	+4.7[‡]	+9.0	+9.7[‡]	+12.7	+14.9[‡]	−1.8[‡]	−1.3	+4.7	+10.1[‡]

[†] Within land-use categories, mean values with the same letter are not significantly different.

[‡] Annual trend at that site is significant at $\alpha = 0.05$.

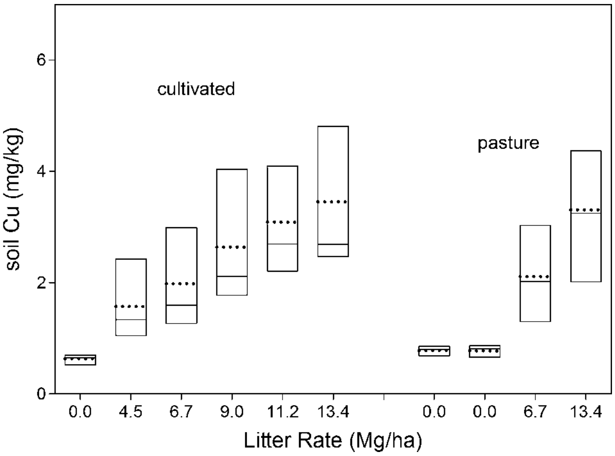

FIG. 8. Box plots of soil Cu for various litter rates on cultivated and pasture fields.

much greater initial soil Cu (7 mg kg^{-1}) and Zn (18 mg kg^{-1}) concentrations, presumably because of previous litter applications. That study also reported much greater accumulation rates after 5 years of litter application at 20 Mg ha^{-1} for both Cu (2.0 mg kg^{-1} $year^{-1}$) and Zn (3.5 mg kg^{-1} $year^{-1}$). The much more rapid Zn and Cu accumulation in the Franzluebbers et al. (2004) study can be partly, but not entirely, attributed to shallower soil sampling (0–6 cm).

Litter Application Recommendations

The potential variability in litter-applied macronutrients and micronutrients has important agroeconomic and environmental implications. Litter is typically bought and sold on a weight basis ($/ton); however, delivery trucks and spreaders are rarely weighed to confirm the actual litter amount. Instead, trucks and spreaders are loaded to a certain volume, and litter weight is assumed based on "typical" moisture content. In addition, results from this study show that N, P, C, micronutrient, and moisture contents can vary greatly from year to year, depending on the age, bedding material composition, and source of the litter.

In environmentally sensitive areas, the variability in actual application rates and in litter composition must be adequately detected and considered so that macronutrient or micronutrient application rates can be carefully managed. The following steps are suggested to determine and apply the proper litter rate. First, litter properties should be reported on a dry-weight basis and on an "as is" or wet basis, with moisture content clearly shown to improve litter comparisons. Second, a moisture and nutrient analysis should be conducted for each batch of litter (with "batch" defined as an amount of litter that has been treated the same and can reasonably be assumed somewhat homogeneous). Litter samples can be collected when house cleanout begins and processed within 7 to 10 days, so that the nutrient and moisture contents are known before land application. Third, the litter should be weighed before application. This can be accomplished by weighing a few delivery truck or spreader loads or smaller amounts with a known volume. When the litter composition is known and the crop nutrient needs are established from soil tests and reasonable yield goals, the required amount of litter can be delivered to the application site. Lastly, the spreader should be calibrated to ensure the target litter rate is actually applied. The resulting cost of analysis is negligible, especially considering the cost of fertilizer, and any time delay in application caused by weighing the litter and calibrating the spreader should be minimal.

Although the variability in litter-applied nutrients was presented previously, the agroeconomic and environmental importance of detecting and considering this variability is further highlighted in the following example of P application rates on cultivated field Y13 (4.5 Mg ha^{-1} target litter rate). The estimated P application rate, which is commonly the recommended determinant of litter application rates, varied from 55 to 159 kg ha^{-1} (Fig. 5). The observation that P application rate could vary almost three times with a consistent target litter rate clearly demonstrates the importance of accounting for variability in litter composition and application in its use as an agronomic nutrient source. Although this variability directly

TABLE 7. Soil Zn Levels

	Cultivated Watersheds						Pasture Watersheds			
	Y6	**Y13**	**Y10**	**W12**	**W13**	**Y8**	**SW12**	**SW17**	**W10**	**Y14**
Litter Rate, Mg $ha^{-1}$$Year^{-1}$	**0.0**	**4.5**	**6.7**	**9.0**	**11.2**	**13.4**	**0.0**	**0.0**	**6.7**	**13.4**
Year	Zn, mg kg^{-1}									
2000–2001	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2001–2002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002–2003	0.24	0.36	0.66	1.03	1.45	1.46	0.59	0.57	0.65	0.93
2003–2004	0.32	0.69	0.83	0.87	1.40	1.49	0.43	0.41	0.90	1.19
2004–2005	0.38	1.57	1.58	2.48	2.27	2.56	0.61	0.39	2.52	2.56
2005–2006	0.25	0.74	0.91	1.03	1.38	1.21	0.33	0.39	1.52	2.53
2006–2007	0.34	1.17	1.21	1.74	2.02	2.02	0.47	0.41	2.45	2.90
2007–2008	0.51	1.86	2.15	2.47	3.18	4.10	0.49	0.61	2.48	4.18
Mean[†]	0.34a	1.07ab	1.22ab	1.60b	1.95b	2.14b	0.49a	0.46a	1.75b	2.38b
Average annual change	+0.04	+0.23	+0.22	+0.24	+0.28	+0.38	−0.02	+0.01	+0.37	+0.61[‡]

[†] Within land-use categories, mean values with the same letter are not significantly different.

[‡] Annual trend at that site is significant at $\alpha = 0.05$.

NA: not available.

TABLE 8. Soil Cu Levels

	Cultivated Watersheds						Pasture Watersheds			
Litter Rate,	**Y6**	**Y13**	**Y10**	**W12**	**W13**	**Y8**	**SW12**	**SW17**	**W10**	**Y14**
Mg ha^{-1}Year^{-1}	**0.0**	**4.5**	**6.7**	**9.0**	**11.2**	**13.4**	**0.0**	**0.0**	**6.7**	**13.4**
Year	**Cu, mg kg^{-1}**									
2000–2001	NA[c]	NA	NA	NA	NA	NA	NA	NA	NA	NA
2001–2002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002–2003	0.65	0.75	0.95	1.79	2.28	2.59	0.85	0.87	1.11	1.69
2003–2004	0.64	1.14	1.37	1.71	2.50	2.64	0.88	0.81	1.36	2.12
2004–2005	0.66	2.42	2.79	4.07	3.75	4.28	0.79	0.82	3.15	3.97
2005–2006	0.52	1.29	1.48	1.92	1.98	2.10	0.67	0.68	1.88	3.37
2006–2007	0.52	1.38	1.70	2.31	2.88	2.73	0.69	0.59	2.16	3.12
2007–2008	0.80	2.45	3.58	4.02	5.12	6.38	0.81	0.86	2.98	5.56
Mean[†]	0.63a	1.57ab	1.98ac	2.64bc	3.09bc	3.45c	0.78a	0.77a	2.11b	3.31b
Average annual change	+0.01	+0.23	+0.37	+0.31	+0.39	+0.49	−0.03	−0.02	+0.30	+0.62[‡]

[†] Within land-use categories, mean values with the same letter are not significantly different.

[‡] Annual trend at that site is significant at $\alpha = 0.05$.

NA: not available.

affects cost-effectiveness in agronomic settings with thin margins, environmental quality and offsite effects can also be important (Turnell et al., 2007); therefore, litter composition should be quantified and litter rate should be carefully managed, especially in environmentally sensitive areas.

SUMMARY AND CONCLUSIONS

Results of the present study on a Texas Blackland Vertisol are consistent with previous research findings that have demonstrated the importance of proper litter application management to minimize adverse environmental effects and maximum agronomic benefits. Results did indicate that larger litter rates build organic C more rapidly; however, this benefit was offset by undesirable buildup of extractable soil P, Zn, and Cu, which can adversely affect crop productivity and water quality. After seven annual applications, significant relationships occurred between litter rate and total N, total P, extractable P, Zn, and Cu in the cultivated fields. For the pasture fields, significant relationships were observed between litter rate and total P, extractable P, Zn, and Cu at the end of the study.

Thus, for cultivated land in the Texas Blackland Prairie, annual litter application at 4.5 Mg ha^{-1} seems to be acceptable in terms of soil quality, although reduced rates of 2.2 to 3.4 Mg ha^{-1} are recommended based on runoff water quality (Harmel et al., 2009) and economic returns (Harmel et al., 2008). For pasture land, the lowest litter rate evaluated in this study (6.7 Mg ha^{-1}) produced noticeable increases in extractable P, Zn, and Cu accumulation rates relative to the control fields, which indicates a lower litter rate (such as 4.5 Mg ha^{-1}) and is likely preferable to limit detrimental soil quality impacts on Texas Vertisols.

ACKNOWLEDGMENTS

Funding for this project was provided by the Texas State Soil and Water Conservation Board, the U.S. Environmental Protection Agency through a Clean Water Act 319 grant, and the USDA-ARS. The authors thank Shalamar Armstrong and Mark Cochran for their review and comments that improved this manuscript.Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

REFERENCES

Acosta-Martinez, V., and R. D. Harmel. 2006. Soil microbial communities and enzyme activities under various poultry litter application rates. J. Environ. Qual. 35(4):1309–1318.

Allen, P. M., R. D. Harmel, J. Arnold, B. Plant, J. Yeldermann, and K. King. 2005. Field data and flow system response in clay (Vertisol) shale terrain, north central Texas, U.S.A. Hydrol. Processes 19:2719–2736.

Arnold, J. G., K. N. Potter, K. W. King, and P. M. Allen. 2005. Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. Hydrol. Processes 19:589–603.

Edmeades, D. C. 2003. The long-term effects of manures and fertilisers on soil productivity and quality: A review. Nutr. Cycl. Agroecosyst. 66: 165–180.

Edwards, D. R., and T. C. Daniel. 1992. Environmental impacts of on-farm poultry waste disposal: A review. Bioresour. Technol. 41:9–33.

Endale, D. M., H. H. Schomberg, M. B. Jenkins, D. H. Franklin, and D. S. Fisher. 2009. Management implications of conservation tillage and poultry litter use for Southern Piedmont USA cropping systems. Nutr. Cycling Agroecosyst. 88:299–313.

Franzluebbers, A. J., S. R Wilkinson, and J. A. Stuedemann. 2004. Bermudagrass management in the southern Piedmont, U.S.A.: IX. Trace elements in soil with broiler litter application. J. Environ. Qual. 33: 778–784.

Gascho, G. J., and R. K. Hubbard. 2006. Long-term impact of broiler litter on chemical properties of a Coastal Plain soil. J. Soil Water Conserv. 61(2):65–74.

Gass, W. B. 1987. Plant Soil and Water Testing Laboratory Recommendations. Texas Agricultural Extension Service, College Station, TX.

Haan, C. T. 2002. Statistical Methods in Hydrology, 2nd Ed. The Iowa State Press, Ames, IA.

Haney, R. L., E. B. Haney, L. R. Hossner, and J. G. Arnold. 2006. Development of a new soil extractant for simultaneous phosphorus, ammonium, and nitrate analysis. Commun. Soil Sci. Plant Anal. 37:1511–1523.

Harmel, R. D., D. R. Smith, R. L. Haney, and M. Dozier. 2009. Nitrogen and phosphorus runoff from cropland and pasture fields fertilized with poultry litter. J. Soil Water Conserv. 64(6):400–412.

Harmel, R. D., B. Harmel, and M. C. Patterson. 2008. On-farm agro-economic effects of fertilizing cropland with poultry litter. J. Appl. Poultry Res. 17:545–555.

Harmel, R. D., H. A. Torbert, B. E. Haggard, R. Haney, and M. Dozier. 2004. Water quality impacts of converting to a poultry litter fertilization strategy. J. Environ. Qual. 33(6):2229–2242.

Hart, M. R., and P. S. Cornish. 2011. Soil sample depth in pasture soils for environmental soil phosphorus testing. Commun. Soil Sci. Plant Anal. 42(1):100–110.

Havlin, J. L., and P. N. Soltanpour. 1989. A nitric acid and plant digest method for use with inductively coupled plasma spectrometry. Commun. Soil Sci. Plant Anal. 14:969–980.

He, Z., D. M. Endale, H. H. Schomberg, and M. B. Jenkins. 2009. Total phosphorus, zinc, copper, and manganese concentrations in Cecil soil through 10 years of poultry litter application. Soil Sci. 174(12):687–695.

Helsel, D. R., and R. M. Hirsch. 1993. Statistical Methods in Water Resources. Elsevier, New York, NY.

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

Lindsay, W. L., and W. A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421–428.

McGeehan, S. L., and D. V. Naylor. 1988. Automated instrumental analysis of carbon and nitrogen in plant and soil samples. Commun. Soil Sci. Plant Anal. 19:493–505.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

Minitab. 2000. MINITAB 12. Minitab Inc., State College, PA.

Nelson, N. O., and R. R. Janke. 2007. Phosphorus sources and management in organic production systems. Hortic. Tech. 17(4):442–454.

Pittman, J. J., H. Zhang, J. L. Schroder, and M. E. Payton. 2005. Differences of phosphorus in Mehlich 3 extracts determined by colorimetric and spectroscopic methods. Commun. Soil Sci. Plant Anal. 36:1641–1659.

Schomberg, H. H., D. M. Endale, M. B. Jenkins, R. R. Sharpe, D. S. Fisher, M. L. Cabrera, and D. V. McCracken. 2009. Soil test nutrient changes induced by poultry litter under conventional tillage and no-tillage. Soil Sci. Soc. Am. J. 73:154–163.

Schulte, E. E., and B. G. Hopkins. 1996. Estimation of soil organic matter by weight by weight loss-on-ignition. *In* Soil Organic Matter: Analysis and Interpretation Special Publication No. 46. F. R. Magdoff, M. A. Tabatabai and E. A. Hanlon Jr (eds.). SSSA, Madison, WI, pp. 21–32.

Self-Davis, M. L., and P. A. Moore Jr. 2000. Determining water soluble phosphorus in animal manure. *In* Methods of Phosphorus Analysis in Soils, Sediments, Residuals and Waters. Southern Cooperative Series Bulletin No. 396. G. M. Pierzynski (ed.). North Carolina State University, Raleigh, NC.

Sharpley, A. N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 2003. Agricultural phosphorus and eutrophication, 2nd Ed. USDA-ARS Publication ARS–149. Washington, DC.

Shuman, L. M., and D. V. McCracken. 1999. Tillage, lime, and poultry litter effects on soil zinc, manganese, and copper. Commun. Soil Sci. Plant Anal. 30:1267–1277.

Somenahally, A., D. C. Weindorf, L. Darilek, J. P. Muir, R. Wittie, C. Thompson, and C. L. S. Morgan. 2009. Spatial variability of soil test phosphorus in manure-amended soils on three dairy farms in north central Texas. J. Soil Water Conserv. 64(2):89–97.

Stephenson, A. H., T. A. McCaskey, and G. G. Ruffin. 1990. A survey of broiler litter composition and potential value as a nutrient resource. Biol. Wastes 34:1–9.

Stockdale, E. A., M. A. Shepherd, S. Fortune, and S. P. Cuttle. 2002. Soil fertility in organic farming systems: Fundamentally different? Soil Use Manag. 18:301–308.

Technicon Industrial Systems. 1976. Individual/Simultaneous Determination of Nitrogen and/or Phosphorus in BD Acid Digest. Industrial Method No. 344-74a. Bran-Luebbe, Roselle, IL.

Torbert, H. A., T. C. Daniel, J. L. Lemunyon, and R. M. Jones. 2002. Relationship of soil test phosphorus and sampling depth to runoff phosphorus in calcareous and noncalcareous soils. J. Environ. Qual. 31(4): 1380–1387.

Turnell, J. R., R. D. Faulkner, and G. N. Hinch. 2007. Recent advances in Australian broiler litter utilisation. World's Poultry Sci. J. 63:223–231.

U.S. Department of Agriculture National Agricultural Statistics Service. 2009. 2007 Census of Agriculture. Volume 1, Chapter 2: County Level Data, Texas. U.S. Department of Agriculture National Agricultural Statistics Service, Washington, DC.

U.S. Department of Agriculture and U.S. Environmental Protection Agency. 1999. Unified National Strategy for Animal Feeding Operations, March 9, 1999. U.S. Department of Agriculture and U.S. Environmental Protection Agency, Washington, DC.

Vadas, P. A., R. D. Harmel, and P. J. A. Kleinman. 2007. Transformations of soil and manure phosphorus after surface application of manure to field plots. Nutr. Cycl. Agroecosyst. 77:83–99.