Bermudagrass Management in the Southern Piedmont, USA: IX. Trace Elements in Soil with Broiler Litter Application

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ABSTRACT

An understanding of the long-term cycling of trace elements in soil with broiler litter fertilization under various forage utilization strategies is needed to develop sustainable agricultural production systems. We evaluated differences in Cu, Mn, Zn, and six other trace elements in response to 5 yr of bermudagrass [*Cynodon dactylon* (L.) Pers.] management varying in fertilization and harvest strategies on a Typic Kanhapludult in Georgia. Chicken (*Gallus gallus*) broiler litter was a significant source of trace elements that led to 3.4 ± 0.5 times higher Cu, 2.0 ± 0.3 times higher Mn, and 2.1 ± 0.2 times higher Zn in the surface 3 cm of soil than when forage was fertilized inorganically. There were variable effects of broiler litter fertilization on other trace elements, depending upon element, depth of sampling, and forage utilization strategy. Concentrations of all trace elements in soil were below levels considered toxic to plants. Soil at a depth of 0 to 3 cm under grazed paddocks had 33 ± 5% greater Cd, 18 ± 1% greater Cr, 53 ± 24% greater Cu, and 24 ± 7% greater Zn compared with unharvested and hayed management. Trace elements in soil were unaffected whether forage was unharvested or removed as hay. These results suggest that broiler litter is a significant source of several trace elements and that ruminant processing of forage and subsequent deposition of excreta on the paddock allow these trace elements to accumulate more at the soil surface where they might interact with the high concentration of organic matter.

Contemporary chicken broiler production in the southeastern USA confines birds within a house shortly following hatching until processing, generally within 6 to 10 wk. Large quantities of litter (i.e., manure mixed with bedding material, feathers, wasted feed, and soil) are removed from the house periodically, from as often as after each flock to once every three years (Moore, 1998). Land application of broiler litter is the most common method of disposal (Moore et al., 1995) and also considered the best utilization of this resource if applied according to a best management plan (Hatfield and Stewart, 1998). Broiler litter contains significant concentrations of N, P, and K, as well as secondary and trace elements (Edwards and Daniel, 1992). The value of animal manures as a fertilizer source is well recognized (Wilkinson, 1979).

One concern with repeated animal manure application is the accumulation of trace elements that might become toxic to plants, animals, and humans (Pierzynski et al., 2000). Repeated application of broiler litter with significant concentrations of trace elements may therefore pose an environmental threat with time, although sufficient long-term evaluations under various management conditions are currently not available. Kingery et al. (1994) observed more than threefold increases in surface-soil (0–15 cm) concentrations of Cu and Zn following 21 ± 4 yr of heavy application of poultry litter (1.1 ± 0.5 kg m^{-2} yr^{-1}) to variably managed tall fescue (*Festuca arundinacea* Schreb.) stands. This study was from a survey of 12 sites managed in a variety of manners without experimental control.

Various elements are added to poultry rations, such as As, Co, Cu, Fe, Mn, Se, and Zn (Moore, 1998). Copper sulfate is often added to the diet of broilers to increase weight gain and avoid diseases (Johnson et al., 1985). Other elements are added to feed so that young birds can tolerate various stresses under high-population conditions in the house (Tufft and Nockels, 1991). It is generally assumed that concentrations of these elements applied to soil do not reach toxic levels, although various trace elements have been detected in surface runoff from pastures fertilized with broiler litter (Moore, 1998). Accumulation of Cu in soil may have adverse effects on plant growth, as well as the activity of aquatic organisms should excessive runoff occur following broiler litter application (Pierzynski et al., 2000). Detectable levels of As were found in cattle hair samples when cattle grazed pastures fertilized with broiler litter, suggesting potential animal health impacts (Isaac et al., 1978).

Although the quantity of trace elements supplied with broiler litter may not be high enough to cause acute toxicity in plants, animals, or humans (Moore et al., 1995), there is growing concern for the possibility of subclinical effects due to long-term exposure to slightly elevated quantities of various trace elements (Pierzynski et al., 2000). Long-term grazing management studies are needed to document the levels of various trace elements that might accumulate in soil, which could ultimately affect soil microorganisms, plants, animals, and humans through various interactions in the food chain (McLaughlin et al., 1999). The Environmental Protection Division of the Georgia Department of Natural Resources has established critical soil concentrations of various trace elements that would trigger notification requirements (Environmental Protection Division, 1994).

Grazing of a forage crop compared with haying returns much of the manure directly to the land, which should affect trace element distribution in soil (Follett and Wilkinson, 1995). To better understand trace element cycling in forage management systems receiving broiler litter, comparisons are needed along a gradient in forage utilization from unharvested (no utilization) to grazing (forage consumption with excreta returned to soil) to hay harvest (full utilization with aboveground forage removed). Harvest management would be expected to alter the distribution of trace elements among soil depths, because of the effects of animal traffic, rumi-

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nant processing of forage (i.e., biological transformation of nutrients), and nutrient removal with hay.

The extent of trace element accumulation within the immediate surface soil layers under repeated broiler litter application has not been adequately investigated. Our objective was to characterize the concentration and depth distribution of various trace elements in response to broiler litter fertilization under different forage utilization strategies. We hypothesized that with equivalent amounts of total N applied, fertilization with broiler litter versus inorganic or a combination of inorganic plus biological N fixation would affect the quantity and depth distribution of trace elements in soil.

MATERIALS AND METHODS

Site Characteristics

A 15-ha upland field (33°22′ N, 83°24′ W) in the Greenbrier Creek subwatershed of the Oconee River watershed near Farmington, GA, had previously been conventionally cultivated with wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], and cotton (*Gossypium hirsutum* L.) for several decades before sprigging of 'Coastal' bermudagrass in 1991. Bermudagrass was sprigged again in 1992 to fill in bare areas and allowed to fully establish until the experiment began in 1994 by applying recommended inorganic fertilizer and mowing periodically. Before 1994 when fencing was installed, the entire field was managed uniformly. Mean annual temperature is 16.5°C, rainfall is 1250 mm, and potential evaporation is 1560 mm. Sampled on a 30-m grid, the frequency of soil series was 46% Madison, 22% Cecil, 13% Pacolet, 5% Appling, 2% Wedowee (all of the above are fine, kaolinitic, thermic Typic Kanhapludults), 11% Grover (fine-loamy, micaceous, thermic Typic Hapludults), and 1% Louisa (loamy, micaceous, thermic, shallow Ruptic-Ultic Dystrudepts). Soil textural frequency of the Ap horizon (21 ± 12 cm) was 75% sandy loam, 12% sandy clay loam, 8% loamy sand, and 4% loam.

Experimental Design

The experimental design (3 × 4 factorial arrangement) was a split-plot with three replications. Individual paddocks were 0.69 ± 0.03 ha. Spatial design of paddocks minimized runoff contamination and handling of animals through a central roadway. Each paddock contained a 3- × 4-m shade, mineral feeder, and water trough placed in a line 15 m long near the top of the landscape. Unharvested and hayed exclosures within a paddock were 100 m^2. Whole plots were fertilization strategy (n = 3) and split-plots were harvest strategy (i.e., forage utilization) (n = 4) for a total of 36 experimental units.

Fertilization was targeted to supply 20 g total N m^{-2} yr^{-1} using one of the following strategies: (i) inorganic fertilizer as NH_4NO_3 broadcast in split applications in May and July, (ii) inorganic fertilizer with half of the N as NH_4NO_3 broadcast in July and the other half assumed fixed and released by crimson clover (*Trifolium incarnatium* L.) cover crop during the previous winter and spring, and (iii) by broiler litter broadcast in split applications in May and July (Table 1). Broiler litter was supplied by the same chicken producer, who spread the manure with wood-shaving bedding (houses cleaned every 8 wk) with a commercial truck. We assumed that crimson clover would provide the equivalence of 11 g N m^{-2} yr^{-1} based on the results of a 3-yr study at a nearby site, where equivalent 'Coastal' bermudagrass hay yield (1.3 kg m^{-2} yr^{-1}) was obtained with half the inorganic N when overseeded with crimson clover as with bermudagrass alone supplied with 22 g total N m^{-2} yr^{-1} (Carreker et al., 1977). Phosphorus and K applications varied among treatments, because excess P and K were applied with broiler litter to meet N requirements, while triple super phosphate and muriate of potash were applied based on soil testing recommendations with inorganic only and clover + inorganic fertilization. Dolomitic limestone (224 g m^{-2} $event^{-1}$) was applied based on soil testing to inorganic only and clover + inorganic treatments in February 1995 and only to the inorganic treatment in November 1996. Crimson clover was direct-drilled in clover treatments at approximately 1 g m^{-2} in October each year. All paddocks were mowed in late April following soil sampling and residue was allowed to decompose [i.e., clover biomass in the clover + inorganic treat-

Table 1. Characteristics and rates of trace elements applied with broiler litter.†

Variable	1994 May	1994 July	1995 May	1995 July	1996 May	1996 July	1997 May	1997 July	1998 May	1998 July	5-yr mean application Mass	5-yr mean application Concentration‡
	mg m^{-2}										mg m^{-2} yr^{-1}	mg kg^{-1} yr^{-1}
	Trace element application rate											
Mn	149	241	224	271	173	191	122	133	131	155	358	4.37
Cu	111	194	70	183	91	63	91	93	155	144	239	2.92
Zn	84	144	174	150	124	147	75	103	74	92	233	2.84
Sr	11	22	22	22	21	17	ND§	ND	ND	ND	38.1	0.46
B	11	19	22	19	17	19	7	9	7	9	27.8	0.34
Ba	5	11	8	11	8	6	ND	ND	ND	ND	16.2	0.20
Cr	4	9	10	11	8	7	1	1	1	1	10.3	0.13
Pb	2	10	6	16	7	5	1	1	1	1	10.0	0.12
Ni	2	5	5	6	5	7	1	1	1	2	7.2	0.09
Co	1	2	2	2	2	1	ND	ND	ND	ND	3.2	0.04
Cd	1	1	1	1	1	1	<1	<1	<1	<1	1.3	0.02
	g m^{-2}										g m^{-2} yr^{-1}	g kg^{-1} yr^{-1}
	Broiler litter characteristics											
Dry mass	228	294	273	378	272	247	249	254	240	264	539	6.6
C	88	96	93	112	94	75	101	92	82	84	183	2.2
N	9.6	9.9	8.5	13.1	10.1	6.4	12.4	9.9	7.9	9.3	19.4	0.24

† Broiler litter contained 0.26 ± 0.04 g water g^{-1} dry mass during application.
‡ Equivalent addition to 0- to 6-cm depth of soil assuming 82 kg m^{-2} soil.
§ Not determined. The 5-yr-mean application rate for those elements that were not analyzed in 1997 and 1998 assumes that the mean application rate from previous years was the same as in later years.

ment and winter annual weeds (primarily *Lolium annuum* L. and *Bromus catharticus* Vahl.) in the other treatments].

Harvest strategy mimicked a gradient in forage utilization consisting of the following treatments: (i) unharvested (biomass cut and left in place at the end of the growing season), (ii) low grazing pressure (put-and-take system for a target of 300 g m^{-2} of available aboveground forage mass), (iii) high grazing pressure (put-and-take system for a target of 150 g m^{-2} of available aboveground forage mass), and (iv) hayed monthly at a 4-cm height to remove aboveground biomass. Yearling Angus steers (*Bos taurus*) grazed low- and high-grazing pressure treatments during a 140-d period from mid-May until early October each year, except during the first year of treatment implementation (1994) when grazing began in July due to repairs to infrastructure following a tornado. Average stocking density was 7 and 9 head ha^{-1} under low and high grazing pressure, respectively. No grazing occurred in the winter. Animals were weighed, available aboveground forage mass determined, and paddocks restocked on a monthly basis.

Sampling and Analyses

Broiler litter was sampled by compositing approximately 1 kg of material from three to four different areas of each truckload just before application to the pasture. Three or four samples of litter (one from each truckload) per application period were digested (1 g of litter in a mixture of 10 mL concentrated nitric acid + 5 mL concentrated perchloric acid) with heating on a hot plate (for 5 min beyond the time when white, dense perchloric acid fumes appeared). The cooled digest was diluted with 10 mL of 25% HCl and brought to 100 mL volume with deionized water and subsequently analyzed for total element concentrations with inductively coupled plasma spectroscopy by the University of Georgia Agricultural and Environmental Services Laboratory (2003).

Soil was sampled in February 1999 at the end of 5 yr of management from a composite of eight 4.1-cm-diameter soil cores collected at depths of 0 to 3 and 3 to 6 cm. Surface residue from randomly selected areas (0.04 m^2 each) within each of three zones within paddocks (i.e., 0- to 30-, 30- to 70-, and 70- to 120-m distances from shades) and within each exclosure was removed before soil coring. Soil was oven-dried (55°C, 72 h) and gently crushed to pass a 4.75-mm screen. The three subsamples within a paddock were composited before laboratory analyses.

Soil bulk density was calculated from the oven-dried soil weight and coring device volume and was reported along with soil organic C in Franzluebbers et al. (2001). Trace elements in soil were analyzed with inductively coupled plasma spectroscopy following the same digestion procedure previously described for broiler litter by the University of Georgia Agricultural and Environmental Services Laboratory. The effects of management on soil organic C and bulk density (Franzluebbers et al., 2001), particulate and biologically active soil C (Franzluebbers and Stuedemann, 2003), soil N (Franzluebbers and Stuedemann, 2001), soil P (Franzluebbers et al., 2002), and soil pH and nutrient cations (A.J. Franzluebbers, unpublished data, 2003) during this same evaluation period were reported elsewhere.

Trace element concentrations for the 0- to 6-cm depth were weighted based on bulk density differences among soil depth increments. Analysis of variance was conducted for each depth separately according to the split-plot design with three replications using SAS (SAS Institute, 1990). Effects were considered significant at $p \leq 0.05$. The fertilizer comparison was between broiler litter and the average of inorganic only and clover + inorganic regimes. In a preliminary analysis, there were few differences in soil trace element concentrations between inorganic only and clover + inorganic fertilization regimes. Correlations among soil variables at a depth of 0 to 6 cm were evaluated from a total of 36 observations.

RESULTS AND DISCUSSION

Plant-Essential Trace Elements

Of the nine trace elements analyzed in this study, five were considered essential for plant growth, and therefore would be expected to cycle in soil differently than non-essential trace elements, because of the significant transfer of elements through various plant parts and debris. Manganese, Cu, and Zn were applied in the greatest quantity with broiler litter, averaging 0.2 to 0.4 g m^{-2} yr^{-1} (Table 1). At the end of 5 yr, Mn concentration in soil was significantly greater with broiler litter than with inorganic fertilization regimes (i.e., inorganic only and clover + inorganic) at both 0- to 3- and 3- to 6-cm depths (Table 2). This effect was significant under most harvest strategies, with 2.0 ± 0.4 times greater soil Mn concentration (an absolute difference of 147 ± 46 mg kg^{-1}) following broiler litter fertilization (mean ± standard deviation among harvest strategies and depths). Based on broiler litter sampling, the Mn applied in litter itself would have contributed a total of 22 mg kg^{-1} within the surface 6 cm of soil during these 5 yr of management. An additional source of Mn that would have contributed to all grazed management systems, irrespective of fertilization regime, was from mineral salt supplement provided to cattle on the pastures, estimated as 10 and 15 mg m^{-2} yr^{-1} under low and high grazing pressure, respectively. However, the effect of forage utilization on soil Mn concentration was not significant. The larger concentration difference in soil Mn than from applied sources is not easily explained, but may be due to a series of random discrepancies associated with the natural variability in broiler litter composition and application, as well as in soil sampling and analysis.

Soil Cu concentration was significantly greater with broiler litter than with inorganic fertilization regimes at 0- to 3- and 3- to 6-cm depths (Table 2). The fertilization effect was significant under all harvest strategies, with 3.5 ± 0.6 times greater soil Cu concentration with broiler litter than with inorganic fertilizer at a depth of 0 to 3 cm and 1.7 ± 0.2 times greater soil Cu at a depth of 3 to 6 cm. Soil Cu concentration became more stratified with time under broiler litter fertilization, reflecting the accumulation of Cu at the soil surface without mechanical disturbance. This accumulation of Cu at the soil surface could pose an environmental threat to adjacent ecosystems should significant runoff events occur, but the concomitant increase in soil organic matter at the soil surface especially with grazing in this study (Franzluebbers et al., 2001) would have probably facilitated Cu sorption to soil (Düring et al., 2002), thus preventing significant Cu movement across the landscape. In addition, the accumulation of soil organic matter in these forage management systems has led to few significant water runoff events following installation of edge-of-

Table 2. Soil Mn, Cu, and Zn concentration in perchloric acid digest as affected by fertilization regime, forage utilization, and soil depth at the end of 5 yr of 'Coastal' bermudagrass management.†

		Mn		Cu		Zn	
Fertilization	Forage utilization	0 to 3 cm	3 to 6 cm	0 to 3 cm	3 to 6 cm	0 to 3 cm	3 to 6 cm
		mg kg^{-1}					
Inorganic	unharvested	162	163	7	8	19	17
	low pressure	126	132	8	8	20	17
	high pressure	178	150	9	10	22	20
	hayed	168	208	6	7	16	15
	mean	158	163	8	8	19	17
Broiler litter	unharvested	308	352	21	14	37	34
	low pressure	304	349	28	15	38	23
	high pressure	321	253	39	15	51	29
	hayed	284	289	19	12	32	23
	mean	304	311	26	14	40	27
Mean	unharvested	235	258	14	11	28	26
	low pressure	215	241	18	12	29	20
	high pressure	249	202	24	12	37	25
	hayed	226	249	12	9	24	19
LSD (p = 0.05) between fertilization means		137*‡	143*	3*	3*	12*	12
LSD (p = 0.05) among utilization means		82	102	4*	3	5*	7
LSD (p = 0.05) among fertilization × utilization values		116*	145*	5*	5*	7*	9*

† Critical soil concentrations that would trigger notification requirements by the Georgia Environmental Protection Division (1994) are 100 mg kg^{-1} for Cu and Zn; Mn is not regulated.
‡ The * denotes significance among treatment means.

field runoff collectors in low-grazing-pressure paddocks in 1998 (Franklin et al., 2002).

Forage utilization led to significant differences in Cu concentration at a depth of 0 to 3 cm (Table 2). Soil under grazed treatments had higher Cu concentration than under ungrazed treatments with broiler litter fertilization, but not with inorganic fertilization, although there was a similar tendency. At a depth of 0 to 3 cm, soil Cu concentration was 1.7 times greater under grazed than under ungrazed management with broiler litter and 1.3 times greater under grazed than under ungrazed management with inorganic fertilization. These changes in Cu concentration with respect to forage utilization coincided with similar changes in soil organic C concentration (Franzluebbers et al., 2001), although the association was rather weak (p = 0.07; Table 3). Apart from other trace element concentrations, soil microbial biomass C concentration was the most highly related property to soil Cu concentration (p = 0.004; Table 3), suggesting that Cu was associated with biological transformations of soil organic matter. Although extreme contamination of soil with various trace elements can inhibit soil microbial activity (Brookes, 1995), lower levels of trace element additions can stimulate microbial activity (Stuczynski et al., 2003). Soil Cu concentrations were within the range considered normal in soil (i.e., 2–60 mg kg^{-1}; Bowie and Thornton, 1985), but greater than the levels of 1 to 4 mg kg^{-1} from Typic and Plinthic Kandiudults from the Coastal Plain region in Georgia (Gaskin et al., 2003).

Soil Zn concentration was significantly greater with broiler litter than with inorganic fertilization regimes at a depth of 0 to 3 cm (Table 2). The fertilization effect was significant under all harvest strategies, with 2.0 ± 0.2 times greater soil Zn concentration with broiler litter than with inorganic fertilizer (mean ± standard deviation among harvest strategies at a depth of 0–3 cm). In addition, significantly greater soil Zn concentration occurred under high grazing pressure than under all other forage utilization strategies at a depth of 0 to 3 cm. Haying tended to have the lowest Zn concentration at both soil depths, suggesting that plant uptake and subsequent removal from the site in harvested forage was an output mechanism of importance. Soil Zn concentration was positively related to soil organic and

Table 3. Correlation matrix among trace element concentrations and other properties of soil at a depth of 0 to 6 cm (n = 36).†

	B	Cd	Cr	Cu	Mn	Ni	Pb	Zn	SOC	POC	SMBC	CMIN
B	–	−0.36	−0.36	−0.31	−0.20	−0.23	−0.38	−0.23	−0.17	−0.13	−0.29	−0.24
Cd	*	–	0.63	0.36	−0.28	0.33	0.57	0.26	0.40	0.47	0.45	0.38
Cr	*	***	–	0.65	0.12	0.60	0.63	0.45	0.36	0.38	0.36	0.34
Cu	‡	*	***	–	0.37	0.44	0.48	0.82	0.31	0.28	0.46	0.42
Mn	NS	‡	NS	*	–	0.54	0.38	0.55	−0.04	−0.20	−0.01	−0.09
Ni	NS	*	***	**	***	–	0.60	0.44	−0.02	−0.12	0.16	0.03
Pb	*	***	***	**	*	***	–	0.67	0.30	0.16	0.27	0.15
Zn	NS	NS	**	***	***	**	***	–	0.29	0.18	0.33	0.28
SOC	NS	*	*	‡	NS	NS	‡	‡	–	0.93	0.72	0.85
POC	NS	**	*	‡	NS	NS	NS	NS	***	–	0.71	0.83
SMBC	‡	**	*	**	NS	NS	NS	*	***	***	–	0.81
CMIN	NS	*	*	**	NS	NS	NS	‡	***	***	***	–

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† CMIN, mineralizable carbon in 24 d; POC, particulate organic carbon; SMBC, soil microbial biomass carbon; SOC, soil organic carbon. Data from Franzluebbers et al. (2001) and Franzluebbers and Stuedemann (2003).
‡ Significant at the 0.1 probability level.

microbial biomass C pools (Table 3). Concentrations of soil Zn were slightly below the range considered normal (i.e., 25–200 mg kg^{-1}; Bowie and Thornton, 1985) with inorganic fertilization regimes, but within the normal range with broiler litter fertilization. Broiler litter fertilization, therefore, was supplying Zn to raise concentrations to more acceptable levels in these eroded, nutrient-poor Ultisols.

Soil B and Mo concentrations were unaffected by the application of broiler litter compared with inorganic fertilization (data not shown). The quantity of B applied with broiler litter was minor (Table 1) and well below the natural variability that occurred among soil samples. Soil B (generally <0.6 mg kg^{-1}, which was the analytical detection limit) and soil Mo (<0.5 mg kg^{-1}, which was the analytical detection limit) concentrations were below the range considered normal for many soils (2–100 mg B kg^{-1} and 0.2–5 mg Mo kg^{-1}; Brady, 1990). Even the minor amounts of these trace elements supplied with broiler litter would probably be beneficial to these eroded Ultisols.

Non-Essential Trace Elements

Soil Cd concentration was not affected by fertilization regime at either soil depth (Table 4). At both 0- to 3- and 3- to 6-cm depths, soil Cd concentration was greater under high grazing pressure than under unharvested and hayed management when averaged across fertilization regimes. There was also a tendency for Cd concentration to be higher under low grazing pressure than under ungrazed systems. Soil Cd concentration was highly related to particulate organic and microbial biomass C pools ($p < 0.01$; Table 3). These organic pools of C were higher with grazed than with ungrazed management (Franzluebbers and Stuedemann, 2003) and probably contributed to stronger sorption of Cd within various organic components during the cycling of Cd (Düring et al., 2002; Kaschl et al., 2002). The quantity of Cd supplied with broiler litter was minor (1.3 mg m^{-2} yr^{-1}; Table 1) and about the same as what might have been applied with inorganic and clover + inorganic fertilization regimes (average of 1.5 mg m^{-2} yr^{-1}) according to assumed Cd contaminant levels in P, K, and lime amendments (Pierzynski et al., 2000). Soil Cd concentrations were at the upper end of the range considered normal in soils (<1 to 2 mg kg^{-1}; Bowie and Thornton, 1985; Holmgren et al., 1993), but these levels were not due to recent management inputs since values were high under all systems. On Typic and Plinthic Kandiudults from the Coastal Plain region in Georgia, soil Cd concentrations were <0.2 mg kg^{-1} and unaffected by long-term sewage sludge application (Gaskin et al., 2003).

Soil Cr concentration was unaffected by fertilization regime (Table 4). The effect of grazed (low and high grazing pressure) versus ungrazed (unharvested and hayed) systems on soil Cr concentration averaged across fertilization regimes was nearly significant at a depth of 0 to 6 cm ($p = 0.07$; 20 vs. 17 mg kg^{-1}, respectively). Similar to other trace elements, this may have been due to greater sorption capacity with enhanced soil organic matter content. Soil Cr concentration was positively related to various soil C pools, as well as with soil Cd, Cu, Ni, Pb, and Zn concentrations (Table 3). Soil Cr concentrations were lower than those (46–61 mg kg^{-1}) reported for a loamy sand in England (Keller et al., 2002).

Soil Ni concentration was unaffected by fertilization regime (Table 4). Nickel supplied with broiler litter was minor, but varied considerably from year to year (Table 1). Soil Ni concentration was unrelated to soil organic matter pools, but highly related to the concentration of soil Cr, Cu, Mn, Pb, and Zn ($p < 0.01$; Table 3), as well as to soil Al, K, and Na (data not shown). It appears likely that inherent soil characteristics, which were differentially exposed at the soil surface by previous land use and erosion, were responsible for variations

Table 4. Soil Cd, Cr, Ni, and Pb concentration in perchloric acid digest as affected by fertilization regime, forage utilization, and soil depth at the end of 5 yr of 'Coastal' bermudagrass management.†

		Cd		Cr		Ni		Pb	
Fertilization	Forage utilization	0 to 3 cm	3 to 6 cm	0 to 3 cm	3 to 6 cm	0 to 3 cm	3 to 6 cm	0 to 3 cm	3 to 6 cm
		mg kg^{-1}							
Inorganic	unharvested	2.1	2.2	16	18	3.0	2.8	19	21
	low pressure	2.6	2.8	19	17	2.3	2.7	19	22
	high pressure	3.0	3.6	17	24	3.2	3.4	22	24
	hayed	2.0	2.2	15	15	3.0	3.0	19	22
	mean	2.4	2.7	16	18	2.9	3.0	20	22
Broiler litter	unharvested	2.0	2.5	16	26	3.0	3.7	21	28
	low pressure	2.4	2.6	20	23	2.9	3.5	19	24
	high pressure	2.8	3.0	19	26	3.8	3.4	23	24
	hayed	2.0	2.2	17	19	3.1	3.4	20	23
	mean	2.3	2.5	18	24	3.2	3.5	21	25
Mean	unharvested	2.0	2.4	16	22	3.0	3.3	20	25
	low pressure	2.5	2.7	20	20	2.6	3.1	19	23
	high pressure	2.9	3.3	18	25	3.5	3.4	23	24
	hayed	2.0	2.2	16	17	3.0	3.2	20	22
LSD ($p = 0.05$) between fertilization means		0.8	0.6	5	8	0.7	1.0	5	6
LSD ($p = 0.05$) among utilization means		0.6*‡	0.8*	4	7*	0.7*	0.8	4	4
LSD ($p = 0.05$) among fertilization × utilization values		0.9*	1.1*	6	10*	1.0*	1.1	6	6*

† Critical soil concentrations that would trigger notification requirements by the Georgia Environmental Protection Division (1994) are 2 mg kg^{-1} for Cd, 50 mg kg^{-1} for Ni, 75 mg kg^{-1} for Pb, and 100 mg kg^{-1} for Cr.
‡ The * denotes significance among treatment means.

in soil Ni and several other trace elements. Soil Ni concentrations were within the range considered normal (2–100 mg kg^{-1}; Bowie and Thornton, 1985) and similar to levels (1–2 mg kg^{-1}) for Typic and Plinthic Kandiulults from the Coastal Plain region in Georgia (Gaskin et al., 2003).

Soil Pb concentration was generally unaffected by fertilization regime, except for significantly higher soil Pb concentration with broiler litter than inorganic fertilization regimes under unharvested management at a depth of 3 to 6 cm (Table 4). It is unclear why this difference occurred at a depth of 3 to 6 cm and not at 0 to 3 cm. Forage utilization had no effect on soil Pb concentration. The quantity of Pb supplied with broiler litter was minor (10 mg m^{-2} yr^{-1}; Table 1), but still larger than what might have been applied with inorganic and clover + inorganic fertilization regimes (average of 2.3 mg m^{-2} yr^{-1}) according to assumed Pb contaminant levels in P, K, and lime amendments (Pierzynski et al., 2000). Soil Pb concentration was within the range considered normal (10–150 mg kg^{-1}; Bowie and Thornton, 1985) and similar to those (5–22 mg kg^{-1}) reported for a loamy sand in England (Keller et al., 2002).

CONCLUSIONS

Broiler litter fertilization (0.54 kg dry matter m^{-2} yr^{-1}) of 'Coastal' bermudagrass during the first 5 yr of management following establishment on eroded Ultisols supplied a diversity of trace elements, many of which were plant essential. Significantly greater soil concentrations of Cu, Mn, and Zn were observed with broiler litter fertilization than with inorganic fertilization regimes (i.e., inorganic only and clover + inorganic) at the end of 5 yr, especially at a depth of 0 to 3 cm. However, none of the soil trace elements had approached levels considered toxic to plants or animals grazing these plants. How bermudagrass was utilized had an important effect on soil concentrations of Cu, Zn, Cd, Cr, and Ni at the end of 5 yr, especially at a depth of 0 to 3 cm. These five trace elements in soil at a depth of 0 to 6 cm were 20 ± 15% more concentrated under cattle grazing than under unharvested or hayed management. In addition, soil at a depth of 0 to 6 cm under high grazing pressure had 21 ± 5% greater concentration of these same five elements than soil under low grazing pressure. At the end of 5 yr, there were no differences in concentration of any trace elements between unharvested and hayed management. Levels of soil microbial biomass C were positively associated with soil concentrations of Cd and Cu ($p \leq 0.01$) and Cr and Zn ($p \leq 0.1$), and negatively associated with concentration of B. It appears that the distribution of trace elements in soil was significantly modified by the dynamics of soil organic matter, which allowed greater sorption of many trace elements at the soil surface, especially with the generally greater application of trace elements with broiler litter fertilization. The risk of trace element contamination to receiving bodies of water following broiler litter application to grazed bermudagrass pastures might not be as great as perceived, despite elevated concentrations at the soil surface, because interactions of trace elements with high organic matter at the soil surface may limit transfer of these elements across the landscape. Further studies are needed to assess the bioavailability, in addition to total concentration, of both plant-essential and non-essential trace elements supplied to differently managed pastures with broiler litter application.

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