PASTURE MANAGEMENT AND FORAGE UTILIZATION

Bermudagrass Management in the Southern Piedmont USA: VIII. Soil pH and Nutrient Cations

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ABSTRACT

Forage utilization could affect soil nutrient dynamics and depth distribution, potentially changing long-term productivity and environmental quality. The effect of forage utilization on nutrient cycling might also be altered depending upon the source and quantity of nutrients applied. We evaluated changes in soil pH and extractable-soil nutrient cations during the first 5 yr of bermudagrass [*Cynodon dactylon* (L.) Pers.] management varying in fertilization (three different sources targeted to supply 200 kg N ha^{-1} yr^{-1}) and forage utilization (four levels). Chicken (*Gallus gallus*) broiler litter (5.4 Mg ha^{-1} yr^{-1}) was a significant source of nutrient cations in addition to N and P and therefore, at the end of 5 yr, resulted in extractable-soil concentrations (0- to 15-cm depth) that were 1.5 $\pm$ 0.1 times greater for K, 1.6 $\pm$ 0.2 times greater for Mn, 4.3 $\pm$ 2.2 times greater for Zn, and 7.5 $\pm$ 0.8 times greater for Cu than under inorganic and clover (*Trifolium incarnatum* L.) + inorganic fertilization regimes. The increases in extractable-soil K, Zn, Mn, and Cu concentrations with broiler litter, however, were only 13 $\pm$ 42% of nutrients applied. Removal of forage as hay resulted in significant declines in extractable-soil K and Mg under all fertilization regimes and in extractable-soil Ca and Mn with inorganic and clover + inorganic fertilization. Cattle (*Bos taurus*) grazing resulted in greater nutrient cycling within the paddock domain, and the more diverse and higher quantity of several nutrient cations applied with broiler litter either prevented a decline or contributed to an increase in concentrations with time.

Fertilization and forage utilization vary widely in the southeastern USA due to differences in soil types, marketing opportunities and strategies, types of livestock operations, cost of inputs, types of forages available, etc. (Ball et al., 2002). Although application of plant nutrients is recommended based on periodic soil testing, the most common fertilization practice for forages is prescribed based on meeting the heavy demand for N. Application of other nutrients depends more on soil type, forage type, cost of inputs, and availability of local manure resources.

Poultry production in the Appalachian Piedmont is extensive (Census of Agriculture, 1992). Poultry manure is often mixed with bedding material at the end of the production cycle, cleared from confinement housing, and applied as litter (manure plus bedding) to nearby land as a source of valuable nutrients for crop and pasture production. Depending upon management, however, repeated application of poultry litter to the same land could become a source of excessive nutrients threatening water quality and creating an imbalance in soil fertility (Sharpley et al., 1998). Compared with the recent concern for excessive P application with poultry litter, significantly less research has focused on the long-term changes in other soil properties with poultry litter application (Moore, 1998). Long-term (21 $\pm$ 4 yr), heavy application of poultry litter (11 $\pm$ 5 Mg ha^{-1} yr^{-1}) to variably managed tall fescue (*Festuca arundinacea* Schreb). stands has been shown to increase soil (0- to 15-cm depth) pH by 8%, extractable-soil Mg by nearly twofold, extractable-soil K and Ca by nearly threefold, and extractable-soil Cu and Zn more than threefold (Kingery et al., 1994). However, the effects of moderate poultry litter application on soil pH and nutrient cations during early pasture development under controlled management scenarios has not been thoroughly addressed. In a 2-yr study on 'Coastal' bermudagrass in eastern Texas, poultry litter application (9 Mg ha^{-1} yr^{-1}) raised extractable-soil nutrient levels (0- to 15-cm depth) 43% for K, 32% for Ca, and 73% for Mg compared with inorganic fertilization (Evers, 1998). However, it is likely that changes in soil nutrient cations with poultry litter application will depend on climate and soil.

Grazing of a forage crop compared with haying returns much of the nutrients with manure directly to the land, which should affect nutrient distribution in soil (Follett and Wilkinson, 1995). Bermudagrass cut for hay removed 30 $\pm$ 8% of the N, 12 $\pm$ 6% of the P, and 54 $\pm$ 11% of the K applied in poultry litter (9 Mg ha^{-1} yr^{-1}) (Evers, 1998). The quantity of Cu and Zn harvested from 16 plant species at maturity and fertilized with 9 Mg ha^{-1} of poultry litter averaged 41 and 213 g ha^{-1} in aboveground biomass and 10 and 24 g ha^{-1} in belowground biomass, respectively (Pederson et al., 2002). As a percentage of total Cu and Zn applied, aboveground harvested portions only represented 5 to 6%, suggesting that a low percentage of secondary plant nutrients may be removed even with harvested biomass.

The impact of whether forage is mechanically harvested or not on soil nutrients deserves attention, based on the extent of land currently managed under the Conservation Reserve Program offered by the government of the USA. How forage is utilized would be expected to alter the distribution of nutrients among soil depths because of the presence or absence of animal traffic, ruminant processing of forage (i.e., biological transformation of nutrients), and nutrient removal in hay. There are very few investigations that have reported comparisons of grazed vs. ungrazed forages on soil nutrient levels with time, despite the large economic impact of cattle

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production and extensive land area devoted to grazing lands (Phillips, 1998). At the end of 10 yr of differential stocking densities of sheep (*Ovis aries*), soil inorganic components were relatively unchanged in New Zealand (Scott, 2000).

We hypothesized that with equivalent amounts of total N applied, fertilization strategy (i.e., inorganic vs. organic) might affect the availability of nutrients to forage and thereby lead to an alteration in form and depth distribution in soil. We wanted to characterize soil nutrient dynamics and depth distribution in response to typical fertilization regimes based on equivalent N supply, which inherently have differences in diversity and quantity of secondary elements applied since fertilizer rates in most forage systems are still based on N requirements. Within those fertilization regimes, we wanted to ascertain the impact of forage utilization (i.e., grazed vs. ungrazed) on soil pH and extractable- and total-soil nutrient cations during the first 5 yr of grass management following conversion from long-term cultivated cropland.

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 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 pan 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 (fine, kaolinitic, thermic Typic Kanhapludults), 11% Grover (fine-loamy, micaceous, thermic Typic Hapludults), and 1% Louisa (loamy, micaceous, thermic, shallow Ruptic-Ultic Dystrudepts). Slope varied from 0 to 10%. Soil textural frequency of the Ap horizon (21 ± 12 cm) was 75% sandy loam, 12% sandy clay loam, 8% loamy sand, and 4% loam. Soil organic C and N concentrations in the surface 15 cm in 1994 were 14 and 0.9 g kg^{-1}, respectively, and changes thereafter were reported in Franzluebbers et al. (2001) and Franzluebbers and Stuedemann (2001). Extractable-soil P with time was reported in Franzluebbers et al. (2002).

Experimental Design

The experimental design was a randomized complete block with treatments in a split-plot arrangement in each of three blocks, which were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). Main plots were fertilization regime ($n = 3$), and split plots were forage utilization regime ($n = 4$) for a total of 36 experimental units. 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- by 4-m shade, mineral feeder, and water trough placed in a line 15 m long at the highest elevation. Exclosures (100 m^2) (unharvested and hayed) were placed side by side in paired low- and high-grazing pressure paddocks of each fertilization regime.

Fertilization was targeted to supply 200 kg N ha^{-1} yr^{-1} using one of the following strategies: (i) inorganically as NH_4NO_3 broadcast in split applications in May and July, (ii) with half assumed fixed and released by crimson clover cover crop during the winter–spring and the other half as NH_4NO_3 broadcast in July, and (iii) by broiler litter broadcast in split applications in May and July (Table 1). Phosphorus and K applications varied among treatments because excess P and K were applied with broiler litter to meet N requirements while inorganic phosphate and potash were applied based on soil-testing rec-

Table 1. Characteristics and rates of fertilizer sources applied.

	1994			1995			1996			1997			1998			5-yr mean	
Variable	May	July	Total	May	July	Total	May	July	Total	May	July	Total	May	July	Total	yr^{-1}	Eq†
	kg ha^{-1}																
Inorganic																	
N	110	101	211	101	101	202	118	132	250	118	120	238	113	111	224	225	103
P	0	0	0	24	0	24	24	0	24	24	0	24	7	0	7	16	7
K	0	0	0	47	0	47	93	0	93	93	0	93	28	0	28	52	24
Clover + inorganic																	
N	110	101	211	0	101	101	0	132	132	0	120	120	0	111	111	135	62
P	0	0	0	33	0	33	49	0	49	24	0	24	7	0	7	23	11
K	0	0	0	62	0	62	93	0	93	93	0	93	28	0	28	55	25
Broiler litter																	
N	96	99	195	85	131	216	101	64	164	124	99	223	79	93	172	194	89
P	43	76	118	62	79	141	59	53	112	36	33	69	76	102	178	124	57
K	57	113	169	113	130	243	82	86	168	50	64	115	63	77	140	167	76
Ca	56	95	151	95	87	182	62	74	136	41	48	89	42	53	96	131	60
Na	8	15	23	16	17	33	11	10	21	15	14	29	16	18	34	28	13
Mg	8	14	22	14	16	30	11	11	22	9	11	20	10	12	22	23	11
Al	2	24	26	10	43	53	9	3	13	1	2	3	1	5	6	20	9
Fe	3	14	18	8	26	35	6	4	10	2	3	4	2	4	6	15	7
Mn	2	2	4	2	3	5	2	2	4	1	1	2	1	2	3	4	1.6
Zn	1	1	2	2	1	3	1	2	3	1	1	2	1	1	2	2	1.1
Cu	1	2	3	1	2	3	1	1	2	1	1	2	2	1	3	2	1.1
	Mg ha^{-1}																
Dry mass	2.28	2.94	5.22	2.73	3.78	6.5	2.72	2.47	5.19	2.49	2.54	5.02	2.4	2.64	5.04	5.39	2461
	g water g^{-1} broiler litter dry mass																
Moisture	0.23	0.26	0.25	0.32	0.28	0.30	0.27	0.27	0.27	0.18	0.21	0.19	0.31	0.24	0.28	0.26	639

† Equivalent concentration of nutrient added, assuming 219 kg m^{-2} soil in 15-cm depth.

ommendations. Dolomitic limestone (2.2 Mg ha^{-1} 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 ≈10 kg ha^{-1} in October each year. All paddocks were mowed in late April following soil sampling and residue allowed to decompose [i.e., clover biomass in the clover + inorganic treatment and winter annual weeds (primarily *Lolium multiflorum* Lam. and *Bromus catharticus* Vahl.) in the other treatments].

Forage utilization regimes consisted of (i) unharvested (biomass cut and left in place at the end of the growing season), (ii) low grazing pressure (grazing to maintain high forage mass at a target of 3.0 Mg ha^{-1}), (iii) high grazing pressure (grazing to maintain low forage mass at a target of 1.5 Mg ha^{-1}), and (iv) hayed monthly at 4-cm height to remove aboveground biomass. Yearling Angus steers grazed paddocks 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. No grazing occurred in the winter. Animals were weighed, available forage determined, and paddocks restocked on a monthly basis.

Sampling and Analyses

Soil was sampled in November 1994 (end of Year 1), February 1996 (end of Year 2), October 1996 (end of Year 3), and October 1997 (end of Year 4) at depths of 0 to 6 and 6 to 15 cm with a 4.1-cm (i.d.) hydraulic probe. Sampling locations within grazed paddocks were within a 3-m radius of points on a 30-m grid. Due to the nonuniform dimensions of paddocks, sampling frequencies within a paddock varied from four to nine, averaging 7 ± 1. Two sampling locations were fixed within each hayed and unharvested exclosure. Soil was air-dried and ground to <2 mm in a mechanical grinder. In February 1999 (end of Year 5), soil was sampled in two different manners: (i) for extractable-soil nutrient cations from a composite of three cores (4.1-cm diam.) collected at a depth of 0 to 15 cm along each of three arcs at 5, 30, and 70 m from shades within grazed paddocks and from a composite of two cores randomly collected within unharvested and hayed exclosures and (ii) for total-soil nutrient cations from a composite of eight randomly selected areas 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 at depths of 0 to 3 and 3 to 6 cm following removal of surface residue. Sampling protocol in Year 5 was changed to accommodate other objectives related to spatial distribution of soil properties in response to animal behavior. Soil was oven-dried (55°C, 72 h) and gently crushed to pass a 4.75-mm screen in 1999. Subsamples within a paddock were composited before laboratory analyses in all years.

Soil bulk density was calculated from the oven-dried soil weight and coring device volume for samples at a depth of 0 to 6 cm. Bulk density at a depth of 6 to 15 cm was not determined but assumed to be 1.5 Mg m^{-3}. Soil pH was determined in 1:2 soil/water (w/v) with a glass electrode. Extractable-soil cations at depths of 0 to 6 and 6 to 15 cm at the end of Years 1 to 4 and at a depth of 0 to 15 cm at the end of Year 5 were determined in double acid (0.05 *M* HCl + 0.0125 *M* H_2SO_4) with inductively coupled plasma spectroscopy (ICPS). Total elemental analysis of soil collected at depths of 0 to 3 and 3 to 6 cm at the end of Year 5 was determined with ICPS following digestion (1 g of soil in a mixture of 10 mL of concentrated nitric acid + 5 mL of concentrated perchloric acid) with heating on a hot plate for 5 min beyond the time when white, dense perchloric acid fumes appeared. The University of Georgia Agricultural and Environmental Services Laboratory conducted all pH and ICPS analyses.

Analysis of variance was conducted for each depth within a year separately to identify differences due to main effects of fertilization (three levels) and forage utilization (four levels) and their interactions (SAS Inst., 1990). Across-depth analyses were from sums adjusted for bulk density and soil volume of depth increments. Across-year analyses considered year as an additional blocking criterion. Preplanned orthogonal contrasts were (i) inorganic/clover + inorganic vs. broiler litter and (ii) inorganic vs. clover + inorganic for the fertilization main effect and (i) unharvested/hayed vs. low and high grazing pressure, (ii) unharvested vs. hayed, and (iii) low vs. high grazing pressure for the forage utilization main effect. Contrasts for interactions were factorial combinations of the main-effect comparisons. Linear regression of soil properties with time was used to test for (i) significant changes with time and (ii) significant differences in soil responses with time assuming a common intercept. All effects were considered significant at $p \leq 0.1$.

RESULTS AND DISCUSSION

Averaged across sampling events during the first 5 yr of management, interactions between fertilization and forage utilization regimes were significant for at least one preplanned contrast statement concerning soil pH at 6 to 15 cm, extractable-soil K at 6 to 15 cm, extractable-soil Ca at both depths, extractable-soil Mg at both depths, extractable-soil Zn at 6 to 15 cm, and extractable-soil Cu at 0 to 6 cm (Table 2). Overall, the interactions were relatively minor, except for Ca at 0 to 6 cm ($P < 0.01$) where extractable-soil Ca under ungrazed management was 599 ± 48 mg kg^{-1} with inorganic and clover + inorganic fertilization and 747 ± 83 mg kg^{-1} with broiler litter fertilization while under grazing management was 696 ± 58 mg kg^{-1} with inorganic and clover + inorganic fertilization and 640 ± 33 mg kg^{-1} with broiler litter fertilization. The reason for this interaction appears likely to be due to the same observation made with regards to extractable-soil P at this site (Franzluebbers et al., 2002) where two of the three replications for the unharvested broiler litter treatment were unknowingly allocated to *hot spots* in the field resulting from previous land use activities (e.g., small feedlots, farmstead, septic system, etc., with concentration of organic nutrients). Most of the other less significant interactions were possibly due to this same effect. Therefore, the analysis of soil properties with time in this study became even more critical to elucidate the effects of fertilization and forage utilization. Temporal analyses should have been less affected by this nonuniform initial distribution.

Fertilization Impacts on Soil pH and Extractable-Soil Nutrient Cations

Soil pH at 0- to 15-cm depth under inorganic fertilization was lower than under clover + inorganic and broiler litter fertilization during the first 3 yr but not thereafter (Fig. 1). This initial discrepancy among treatments could have been due to a random treatment allocation interaction with landscape position since there were no other

Table 2. Soil pH and extractable-soil nutrient cation concentrations (mg kg^{-1}) as affected by soil depth, fertilization, and forage utilization regime (UH = unharvested, LG = low grazing pressure, HG = high grazing pressure, and H = hayed) averaged across four sampling dates during the first 5 yr of management.

Soil		Inorganic				Clover + inorganic				Broiler litter				
Property	Depth	UH	LG	HG	H	UH	LG	HG	H	UH	LG	HG	H	LSD (P = 0.1)
	cm													
pH	0 to 6	6.05	6.16	6.22	6.25	6.49	6.48	6.41	6.53	6.27	6.28	6.41	6.35	0.20†
	6 to 15	6.07	6.13	6.19	6.38	6.56	6.56	6.23	6.62	6.49	6.23	6.47	6.53	0.25
							mg kg^{-1}							
K	0 to 6	107	86	110	70	89	108	100	67	132	133	132	91	24
	6 to 15	66	49	70	41	55	65	59	42	89	87	73	46	16
Ca	0 to 6	550	648	692	582	664	779	665	600	806	617	663	688	144
	6 to 15	437	471	520	452	471	544	492	478	757	468	476	554	196
Mg	0 to 6	86	97	120	95	95	114	95	87	110	105	118	106	20
	6 to 15	77	77	102	84	75	91	85	74	87	76	90	79	20
Zn	0 to 6	1.2	2.7	1.4	1.0	1.4	2.7	1.4	1.2	7.2	5.2	5.7	4.2	2.4
	6 to 15	0.6	1.5	0.6	0.5	0.7	1.6	0.8	0.8	5.0	1.8	1.1	1.7	2.5
Mn	0 to 6	73	66	54	80	85	67	98	81	123	141	111	115	44
	6 to 15	61	55	44	73	76	67	80	69	102	111	89	92	33
Cu	0 to 6	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	1.6	2.2	5.3	1.3	2.2
	6 to 15	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.7	0.7	0.6	0.7	0.1

† Underlined least significant difference (LSD) values indicate significance between at least two means based on orthogonal contrast statements.

obvious explanations. The initial discrepancy prompted us to apply limestone to inorganic treatments in 1995 and 1996 (i.e., before grazing in Years 2 and 3) to correct for this difference in acidity. At the end of 5 yr of management, soil pH was not different among fertilization treatments. Based on regression with a common intercept among fertilization regimes, soil pH increased with time under clover + inorganic fertilization at a depth of 0 to 6 cm, declined with time under inorganic fertilization at a depth of 6 to 15 cm, and declined with time under inorganic and broiler litter fertilization at a depth of 0 to 15 cm (Table 3). Declining pH with inorganic and broiler litter fertilization was likely due to acidity released during nitrification of NH_4^+, either supplied inorganically or as organic compounds. Coastal bermudagrass produces optimally at a soil pH of 5.0 (Robinson, 1996), indicating that despite the declining soil pH with time, bermudagrass production should not have been limited by acidity.

Extractable-soil K concentration was significantly greater with broiler litter than other fertilization regimes at the end of 3 and 5 yr of management (Fig. 1). Extractable-soil K remained unchanged with time under inorganic and clover + inorganic fertilization regimes but increased significantly with time at all soil depths to 15 cm under broiler litter fertilization (Table 3). Broiler litter supplied the equivalent of 76 mg K kg^{-1} soil (0 to 15 cm) yr^{-1}, but the rate of increase in extractable-soil K (5 mg kg^{-1} yr^{-1}) was only 7% of that supplied, suggesting that plant uptake, leaching, and mineral fixation provided heavy demands on K supply. Supplying the equivalent of 25 mg K kg^{-1} soil (0 to 15 cm) yr^{-1} with inorganic and clover + inorganic fertilization was able to prevent a significant decline in available soil K (Tables 1 and 3). The initial extractable-soil K level of 76 mg K kg^{-1} soil (0 to 15 cm) was categorized in the medium soil test range (i.e., 50 to 100 mg K kg^{-1} soil) by the University of Georgia Cooperative Extension Service. At the end of 5 yr, fertilization with broiler litter elevated the extractable-soil K level almost into the high soil test range (i.e., 100 to 175 mg K kg^{-1} soil).

Extractable-soil Ca and Mg concentrations at 0- to 15-cm depth were unaffected by fertilization regime throughout the study (Fig. 1). At a depth of 0 to 15 cm, extractable-soil Ca remained unchanged with time, but

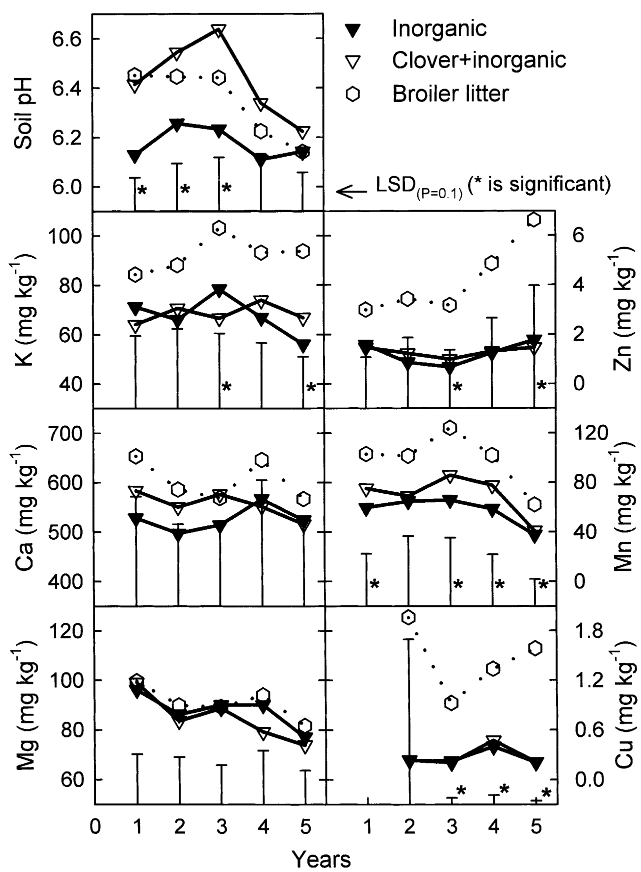

Fig. 1. Soil pH and extractable-soil nutrient cations at a depth of 0 to 15 cm as affected by fertilization regime during the first 5 yr of management. Vertical bars are least significant difference (LSD) at p = 0.1 to separate fertilization regimes within a year.

Table 3. Temporal changes in soil pH and extractable-soil K, Ca, and Mg concentrations as affected by fertilization, forage utilization (UH = unharvested, LG = low grazing pressure, HG = high grazing pressure, and H = hayed), and soil depth during Coastal bermudagrass management. (Note: Regressions for 0 to 6 and 6 to 15 cm were based on available data from Years 1 to 4 while regressions for 0 to 15 cm were based on data from Years 1 to 5.)

Fertilization	Forage utilization	pH			K			Ca			Mg		
		0 to 6 cm	6 to 15 cm	0 to 15 cm	0 to 6 cm	6 to 15 cm	0 to 15 cm	0 to 6 cm	6 to 15 cm	0 to 15 cm	0 to 6 cm	6 to 15 cm	0 to 15 cm
						Intercept							
					mg kg^{-1} soil								
All	All	6.3	6.5	6.5	96	57	76	575	561	581	103	94	100
						Slope							
					mg kg^{-1} soil yr^{-1}								
Inorganic	UH	−0.07*	−0.17***	−0.13***	5.0	3.5	0.5	−2	−44*	−28*	−5.0*	−6.6**	−6.5***
	LG	−0.03	−0.13***	−0.09***	−3.9	−2.5	−3.2†	43*	−35†	−8	−0.6	−6.6**	−4.8***
	HG	−0.02	−0.11***	−0.06**	5.0	4.8*	0.8	50**	−17	4	6.1**	1.6	0.1
	H	−0.01	−0.04	−0.05**	−9.3**	−6.2**	−9.2***	10	−39*	−24†	−2.7	−3.8†	−4.5**
Clover + inorganic	UH	0.07*	−0.01	−0.02	−1.9	−1.2	−2.2	33†	−41*	−26*	−2.9	−8.5***	−7.6***
	LG	0.07*	0.02	0.00	4.4	3.5	1.8	79***	−8	14	4.0†	−1.9	−1.3
	HG	0.03	−0.11***	−0.07**	3.2	2.4	1.1	39	−28	−4	−2.9	−4.1*	−3.8**
	H	0.08*	0.04	0.00	−10.1**	−5.5*	−8.2***	13	−34†	−22†	−5.9**	−8.1***	−7.7***
Broiler litter	UH	−0.03	−0.02	−0.05**	13.1***	12.6***	7.3***	75***	68***	45***	1.2	−3.0	−2.9*
	LG	−0.01	−0.10**	−0.07***	12.4***	11.5***	9.7***	17	−36†	−17	1.0	−6.1**	−3.8**
	HG	0.02	−0.02	−0.04*	12.1***	6.8**	7.8***	30†	−30	−10	5.0*	−1.7	−1.4
	H	0.01	−0.01	−0.03	−1.5	−4.3†	−5.0**	32†	−2	−1	0.2	−5.2**	−4.2**
LSD (P = 0.1) among fertilization × forage utilization means		0.08‡	0.07	0.05	8.4	5.5	4.3	42	46	30	5.5	4.8	3.3
Inorganic	Mean	−0.03	−0.11***	−0.08***	−0.8	−0.1	−2.8†	25*	−34*	−14	−0.6	−3.8**	−3.9***
Clover + inorganic	Mean	0.06**	−0.01	−0.02	−1.1	−0.2	−1.9	41**	−28*	−9	−1.9	−5.7***	−5.1***
Broiler litter	Mean	−0.00	−0.04	−0.05***	9.0**	6.6***	5.0**	39**	0	4	1.8	−4.0**	−3.1**
LSD (P = 0.01) among fertilization means		0.06	0.06	0.03	6.5	4.7	3.6	31	34	22	4.1	3.5	2.4
Mean	UH	−0.01	−0.06**	−0.07***	5.4*	5.0***	1.9	35**	−6	−3	−2.2	−6.0***	−5.6***
	LG	0.01	−0.07**	−0.05***	4.3†	4.2**	2.8*	46***	−26*	−3	1.5	−4.9***	−3.3***
	HG	0.01	−0.08***	−0.06***	6.7**	4.7**	3.2**	40***	−25†	−3	2.7†	−1.4	−1.7†
	H	0.03	0.00	−0.03*	−6.9**	−5.3***	−7.5***	18	−25†	−16†	−2.8†	−5.7***	−5.4***
LSD (P = 0.01) among forage utilization means		0.06	0.05	0.03	5.6	3.6	2.7	27	31	20	3.7	3.3	2.3

* Significance from zero at p = 0.05.
** Significance from zero at p = 0.01.
*** Significance from zero at p = 0.001.
† Significance frmo zero at p = 0.1.
‡ Underlined least significance difference (LSD) values indicate significance among comparisons.

Table 4. Temporal changes in extractable-soil Zn, Mn, and Cu concentrations as affected by fertilization regime, forage utilization (UH = unharvested, LG = low grazing pressure, HG = high grazing pressure, and H = hayed), and soil depth during 'Coastal' bermudagrass management. (Note: Regressions for 0 to 6 and 6 to 15 cm were based on availabe data from Years 1 to 4 while regression for 0 to 15 cm were based on data from Years 1 to 5.)

Fertilization	Forage utilization	Zn 0 to 6 cm	Zn 6 to 15 cm	Zn 0 to 15 cm	Mn 0 to 6 cm	Mn 6 to 15 cm	Mn 0 to 15 cm	Cu 0 to 6 cm	Cu 6 to 15 cm	Cu 0 to 15 cm
						Intercept				
						mg kg^{-1} soil				
All	All	2	1	1	89	73	94	1.8	0.2	0.7
						Slope				
						mg kg^{-1} soil yr^{-1}				
Inorganic	UH	−0.4	−0.3	−0.1	−4.4	−3.4	−10.2	−0.45	0.04	−0.12
	LG	0.1	0.0	0.2	−8.0	−5.8	−11.4	−0.46	0.05	−0.12
	HG	−0.3	−0.3	−0.0	−12.3	−9.2	−14.5	−0.44	0.05	−0.11
	H	−0.4	−0.3	−0.1	−3.3	−0.5	−8.1	−0.46	0.03	−0.12
Clover + inorganic	UH	−0.3	−0.2	−0.1	−1.4	0.4	−7.5	−0.45	0.05	−0.11
	LG	0.2	0.1	0.2	−7.3	−0.9	−9.8	−0.45	0.06	−0.11
	HG	−0.3	−0.2	−0.0	3.2	3.6	−5.6	−0.45	0.06	−0.11
	H	−0.4	−0.2	−0.1	−1.8	−0.3	−8.5	−0.44	0.04	−0.12
Broiler litter	UH	1.9***	1.4	1.6	10.7	9.4	0.3	−0.03	0.17	0.13
	LG	1.2***	0.1	0.6	19.6	14.0	2.9	0.14	0.19	0.19
	HG	1.2***	−0.1	1.1	7.6	5.1	−3.6	0.77	0.15	0.32
	H	0.7*	0.1	0.5	8.1	7.3	−1.0	−0.11	0.15	0.09
LSD (P = 0.1) among fertilization × forage utilization means		0.8†	0.5	0.5	11.8	9.7	7.4	1.18	0.08	0.27
Inorganic	Mean	−0.2	−0.2	−0.0	−7.0	−4.7	−11.1	−0.45	0.04	−0.12
Clover + inorganic	Mean	−0.2	−0.2	0.0	−1.9	0.7	−7.8	−0.45	0.05	−0.11
Broiler litter	Mean	1.3***	0.4	1.0	11.5	8.9	−0.3	0.19	0.16	0.18
LSD (P = 0.1) among fertilization means		0.5	0.4	0.3	8.2	6.6	5.0	0.92	0.07	0.21
Mean	UH	0.4	0.3	0.5	1.6	2.1	−5.8	−0.31	0.09	−0.03
	LG	0.5	0.1	0.3	1.4	2.4	−6.1	−0.26	0.10	−0.01
	HG	0.2	−0.2	0.3	−0.5	−0.2	−7.9	−0.04	0.08	0.03
	H	−0.0	−0.1	0.1	1.0	2.2	−5.9	−0.34	0.07	−0.05
LSD (P = 0.1) among forage utilization means		0.5	0.4	0.3	7.4	6.0	4.5	0.94	0.06	0.21

* Significance from zero at p = 0.05.
*** Significance from zero at p = 0.001.
† Underlined least significant difference (LSD) values indicate significance among comparisons.

extractable-soil Mg declined significantly under all fertilization regimes (Table 3). Plant uptake, leaching, and mineral fixation were likely reasons for this decline in Mg concentration with time.

Extractable-soil Zn, Mn, and Cu concentrations at 0- to 15-cm depth were significantly greater with broiler litter than other fertilization regimes, primarily beginning at the end of 3 yr of management (Fig. 1). Broiler litter supplied a small quantity of these elements (2 to 5 kg ha^{-1} yr^{-1}; Table 1). At a depth of 0 to 15 cm, extractable-soil Zn and Cu remained unchanged with time under inorganic and clover + inorganic fertilization regimes but increased significantly with time under broiler litter fertilization (Table 4). Extractable-soil Mn declined significantly with time under inorganic and clover + inorganic fertilization regimes but remained unchanged with time under broiler litter fertilization. The supply of Zn in broiler litter (1.1 mg kg^{-1} yr^{-1}) was matched almost entirely with an increase in extractable-soil Zn at a depth of 0 to 15 cm (1.0 mg kg^{-1} yr^{-1}) (Tables 1 and 4). As expected, accumulation of extractable-soil Mn and Cu was much less than the rates supplied in broiler litter (<20%), due likely to significant elemental transformations with soil minerals and organic matter.

Forage Utilization Impacts on Soil pH and Extractable-Soil Nutrient Cations

Soil pH at a depth of 0 to 15 cm was variably affected by forage utilization regime during the 5 yr of this study (Fig. 2). Soil pH under unharvested management was lower than under haying at the end of 4 yr and was lower than under all other forage utilization regimes at the end of 5 yr. From regression, soil pH at a depth of 0 to 15 cm declined significantly under all forage utilization regimes when averaged across fertilization regimes, with the decline significantly greater under unharvested and high grazing pressure than under haying (Table 3). The similar soil pH response to unharvested and low and high grazing pressures in this study is consistent with the lack of difference in soil pH observed at the end of 4 yr of light vs. heavy livestock grazing in South Africa (Allsopp, 1999). However, at the end of 10 yr, soil pH tended to decline with higher sheep grazing intensity in New Zealand (Scott, 2000).

Extractable-soil K concentration at a depth of 0 to 15 cm was lower under hayed than under other forage utilization regimes throughout the 5 yr (Fig. 2). At a depth of 0 to 15 cm, when averaged across fertilization regimes, extractable-soil K declined significantly with

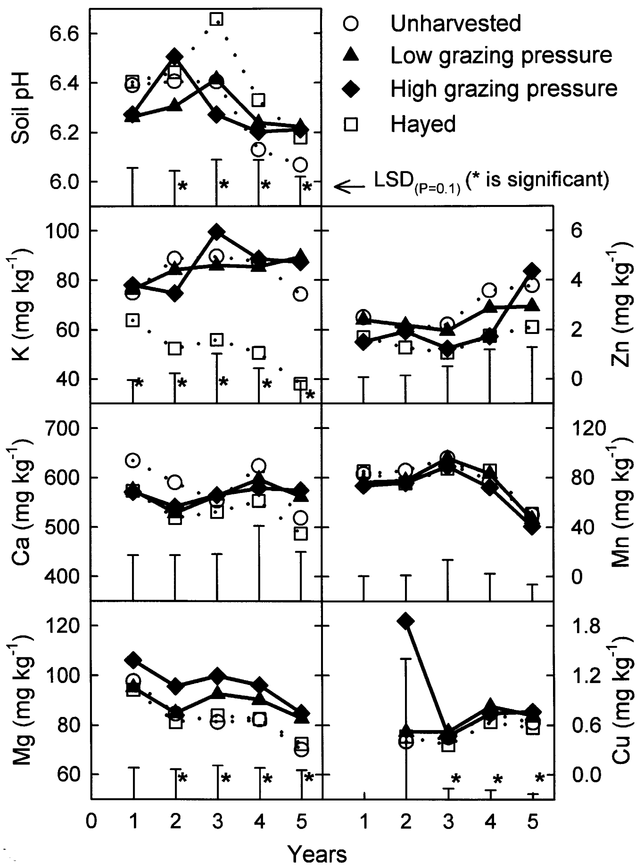

Fig. 2. Soil pH and extractable-soil nutrient cations at a depth of 0 to 15 cm as affected by forage utilization during the first 5 yr of management. Vertical bars are least significant difference (LSD) at $p = 0.1$ to separate forage utilization regimes within a year.

haying, remained unchanged with unharvested management, and increased significantly with low and high grazing pressures (Table 3). The higher K supply with broiler litter led to a significant increase in extractable-soil K with unharvested and low and high grazing pressure compared with no change with other fertilization regimes. Haying was expected to remove nutrients from the field in harvested forage. Based on 17 mg K g^{-1} of bermudagrass dry matter (Follett and Wilkinson, 1995) and an average hay harvest yield of 7.6 Mg ha^{-1} yr^{-1} (A.J. Franzluebbers, unpublished data, 2002), the demand for K with hay harvest (133 kg ha^{-1} yr^{-1}) would have been mostly met through fertilization (average of 91 kg ha^{-1} yr^{-1}) and the remainder through available soil K extraction from the surface 15 cm of soil (rate of decline in extractable-soil K was equivalent to 16 kg ha^{-1} yr^{-1}) as well as below the surface. At a depth of 0 to 15 cm, there were no differences in extractable-soil K among unharvested and low and high grazing pressures, suggesting that as long as forage residues (either undigested or digested) were returned to the paddock, significant recycling of K occurred to elevate levels above that under haying. Greater extractable-soil K occurred in the surface 7.5 cm of soil with sheep grazing than following a single year of pastoral fallow (Nie et al., 1997). In contrast, excluding moose (*Alces alces*) resulted in greater extractable-soil K than grazed areas at one of three sites in Michigan (Pastor et al., 1993).

Extractable-soil Ca, Zn, and Mn concentrations were not affected by forage utilization regime throughout the 5 yr (Fig. 2). At the end of 3 yr and onwards, extractable-soil Mg and Cu were higher under grazed than under ungrazed management systems. At a depth of 0 to 15 cm when averaged across fertilization regimes, extractable-soil Ca and Cu remained relatively unchanged with time (Tables 3 and 4). However, there was a significant increase in extractable-soil Ca at the soil surface (0 to 6 cm) with unharvested and low and high grazing pressures, suggesting that redistribution of Ca toward the organic matter–enriched surface soil was occurring. Our results of similar extractable-soil Ca concentration whether forage was unharvested or grazed are supported by observations of similar extractable-soil Ca between moose-grazed plots and 40-yr-old exclosures (Pastor et al., 1993). This result contrasts with the observations of Scott (2000), who found that extractable-soil Ca tended to be reduced with higher sheep grazing intensity.

At a depth of 0 to 15 cm when averaged across fertilization regimes, extractable-soil Mg and Mn concentrations declined significantly with time under all forage utilization regimes (Tables 3 and 4). Extractable-soil Zn increased significantly with time under all forage utilization regimes with broiler litter fertilization only, but more so under unharvested and high grazing pressures. The change in extractable-soil Zn with time at a depth of 0 to 6 cm was inversely proportional to the intensity of forage utilization, i.e., largest increase with unharvested management (no utilization), moderate increase with low and high grazing pressure (low and moderate utilization), and smallest increase with haying (high utilization). This result corroborates the observation of significantly greater Zn contained in stems of forages than in leaves (Pederson et al., 2002). Bermudagrass stem production and subsequent recycling of Zn in the paddock would have been greatest with unharvested forage followed by low grazing pressure and high grazing pressure. Haying would have removed Zn from the field.

Excluding sheep and rabbit (*Lepus* spp.) grazing from a pasture in New Zealand for 16 yr led to significantly higher extractable Mg in the surface 7.5 cm of soil compared with grazing but no effect on extractable-soil K and Ca (McIntosh and Allen, 1998). Excluding moose browsing for 40 yr also resulted in significantly higher extractable-soil Mg compared with grazing at two of three sites in a national park in Michigan (Pastor et al., 1993). In our study, the comparison between unharvested management and the two grazing pressures produced a lack of response to grazing for extractable-soil K, Ca, Zn, Mn, and Cu (Tables 3 and 4). In contrast to the results of the aforementioned studies, extractable-soil Mg with unharvested management declined more with time compared with grazing. It is unclear why our results differed so dramatically from previous studies with regards to Mg and were more consistent with regards to other cations.

Total-Soil Nutrient Cations

At the end of 5 yr of bermudagrass management, total-soil nutrient cations were variably affected by fertilization and forage utilization regimes (Table 5). The primary effect of fertilization regime was for greater quantity of total-soil Fe, Ca, and Mg under inorganic than under clover + inorganic or broiler litter fertilization. This effect was significant at a depth of 0 to 3 cm for all three elements and also at a depth of 3 to 6 cm for total-soil Fe. Concentration of total-soil Al and Fe were highly related to the concentration of the clay-sized fraction in soil (Fig. 3) while total-soil K, Ca, Mg, and Na were not closely related to clay concentration ($r^2 \leq 0.23$). Soils with high clay concentration tend to have high element concentrations other than Si (Helmke, 2000). Although three of the highest total-soil Fe concentrations occurred with inorganic fertilization, the distribution of total-soil Fe concentration within the inorganic fertilization treatment was similar to that of other fertilization treatments (Fig. 3), such that clay concentration (as a proxy for landscape position and soil erosion effect) was not likely the only explanation for the differences observed among treatments although an adequate explanation remains elusive. The wide distribution of clay, Al, and Fe concentrations among samples illustrates (i) the diversity of soil characteristics within a relatively small area from the variably eroded, sloping region of the Southern Piedmont USA and (ii) the landscape complexity that soil research in this region should be addressing.

With the application of 2.2 Mg ha^{-1} of dolomitic limestone twice to the inorganic fertilization treatment and once to the clover + inorganic fertilization treatment early in the study, the supply of Ca and Mg would have been 183 and 111 kg ha^{-1} yr^{-1} with inorganic fertilization, 92 and 55 kg ha^{-1} yr^{-1} with clover + inorganic fertilization, and 131 and 23 kg ha^{-1} yr^{-1} with broiler litter fertilization, respectively. The greater supply of Ca and Mg in the inorganic fertilization treatment likely contributed to the difference in total-soil Ca and Mg at a depth of 0 to 3 cm. Results from the two depths provide little evidence that Ca and Mg moved beyond the surface 3 cm of soil. The relatively generous application of Ca in broiler litter appeared to have possibly been in a more soluble form, such that accumulation was not limited to the soil surface like that with dolomitic limestone application.

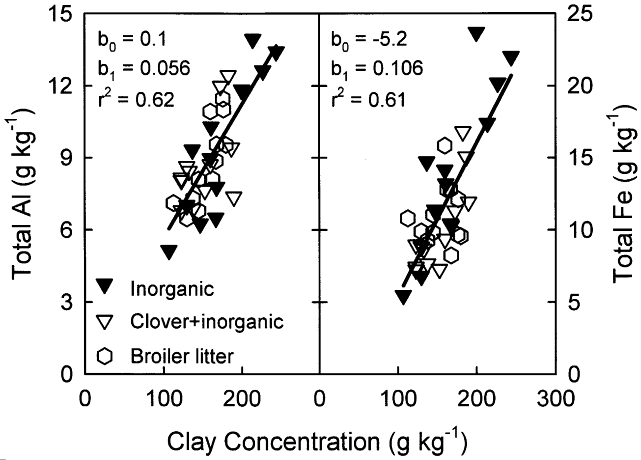

Fig. 3. Relationships of total-soil Al and Fe concentrations with clay-sized soil concentration at a depth of 0 to 3 cm in February 1999 at the end of 5 yr of management.

The other primary fertilization effect was for greater total-soil Na under broiler litter than under inorganic or clover + inorganic fertilization regimes at both soil depths (Table 5). Broiler litter supplied the equivalent of 13 mg Na kg^{-1} (0 to 15 cm) yr^{-1}, but accumulation of total-soil Na in the surface 6 cm was only about 15% of that applied, assuming the concentration under broiler litter was equal to that under other fertilization regimes and that no change in total-soil Na had occurred with time under inorganic or clover + inorganic fertilization. Leaching of Na below the soil surface likely occurred.

There were no significant fertilization effects on total-soil Al and K. Application of Al with broiler litter was minor, amounting to only 2% of the least significant difference (Tables 1 and 5). Despite three times higher application rate of K with broiler litter than with other fertilization treatments, total-soil K was not affected by

Table 5. Total-soil nutrient cation concentrations as affected by soil depth, fertilization averaged across forage utilization regimes, and forage utilization averaged across fertilization regimes at the end of 5 yr. (Note: Interactions between main effects were not significant, except for K at 0 to 3 cm.)

	Al		Fe		K		Ca		Mg		Na	
Management	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	0 to 3 cm	3 to 6 cm	0 to 3 cm	3 to 6 cm
	g kg^{-1} soil											
Fertilization regime												
Inorganic	9.4	11.4	14.1	15.2	0.47	0.45	2.04	0.74	0.73	0.36	0.019	0.020
Clover + inorganic	8.7	9.4	10.0	11.5	0.45	0.40	1.50	0.86	0.52	0.37	0.019	0.018
Broiler litter	8.8	10.6	11.0	12.9	0.51	0.45	1.24	0.80	0.38	0.35	0.029	0.028
LSD (P = 0.1)	2.6	2.3	3.6†	2.8	0.11	0.09	0.57	0.30	0.29	0.09	0.003	0.004
Forage utilization regime												
Unharvested	8.3	10.0	10.0	11.4	0.43	0.43	1.54	0.79	0.56	0.36	0.021	0.021
Low grazing pressure	8.6	10.0	12.2	13.7	0.49	0.44	1.70	0.86	0.55	0.37	0.022	0.021
High grazing pressure	10.3	11.9	14.6	16.9	0.60	0.48	1.85	0.84	0.59	0.39	0.028	0.027
Hayed	8.7	10.0	10.1	10.7	0.40	0.39	1.29	0.72	0.47	0.33	0.020	0.019
LSD (P = 0.1)	1.5	1.8	2.5	3.2	0.06	0.08	0.42	0.16	0.18	0.07	0.003	0.004

† Underlined least significant difference (LSD) values indicate significance between at least two means.

fertilization regime, and this lack of difference may have been due to the high demand for K by bermudagrass forage and its susceptibility to leaching. The lack of difference in total-soil K also contrasts with the positive effect of broiler litter fertilization on extractable-soil K.

The primary effect of forage utilization on total-soil nutrient cations was for higher levels with high grazing pressure compared with other treatments (Table 5). Total-soil Al, Fe, K, and Na at both 0- to 3- and 3- to 6-cm depths were greater with high grazing pressure than with other forage utilization regimes when averaged across fertilization regimes. Total-soil Ca was greater with high grazing pressure than with other forage utilization regimes only at a depth of 0 to 3 cm. Interestingly, total-soil Mg was not different among forage utilization regimes at either depth. These results suggest that continuous close grazing with high grazing pressure by cattle (but not overgrazing) kept soil nutrients concentrated near the soil surface through a closely integrated cycling of nutrients from soil to plant to animal to soil. The concomitant increase in organic matter at the immediate soil surface with high grazing pressure (Franzluebbers et al., 2001) appears to have acted as a sponge or filter that may have become increasingly reactive for cation transformations into stable organo-mineral complexes (Stevenson and Fitch, 1986).

The only other significant forage utilization effect on total-soil nutrient cations when averaged across fertilization regimes was for greater total-soil K under low grazing pressure than under haying at a depth of 0 to 3 cm (Table 5). This effect contributed to the only significant interaction between fertilization and forage utilization regimes on total-soil nutrient cations and was primarily due to the significantly positive grazing pressure response of total-soil K under clover + inorganic fertilization, mildly positive response under broiler litter fertilization, and no response under inorganic fertilization. The heavy demand for K with hay removal and the continuous recycling of K on the pasture with either low or high grazing pressure would explain the significant difference between hayed and grazed treatments.

SUMMARY AND CONCLUSIONS

The effects of 5 yr of bermudagrass management varying in fertilization and forage utilization regimes on soil nutrient cations were diverse. Application of broiler litter at 5.4 Mg ha^{-1} yr^{-1}, which supplied the equivalent of 194 kg N ha^{-1} yr^{-1}, led to 53% greater extractable-soil K, 58% greater extractable-soil Mn, 4.1 times greater extractable-soil Zn, and 7.6 times greater extractable-soil Cu concentrations than under inorganic and clover + inorganic fertilization regimes in the surface 15 cm of soil at the end of 5 yr. The temporal change in extractable-soil nutrient cations at a depth of 0 to 15 cm as a percentage of total applied with broiler litter was 7% for K and Ca, 18% for Cu, and 91% for Zn. Extractable-soil Mg and Mn did not accumulate with time even with broiler litter application. At the end of 5 yr, total-soil Fe, Ca, and Mg were 48 ± 14% greater with inorganic fertilization at a depth of 0 to 3 cm than with clover + inorganic and broiler litter fertilization, at least partially due to the need for greater dolomitic limestone application to equalize soil pH among fertilization regimes. Haying resulted in a 7.5 mg K kg^{-1} yr^{-1} decline in extractable-soil K, even with an average application of 42 mg K kg^{-1} yr^{-1} across fertilization regimes. Grazing with cattle increased extractable-soil K with the same inputs as with haying by 3.0 ± 0.3 mg K kg^{-1} yr^{-1}. Grazed management systems maintained higher levels of extractable-soil K and Mg and total-soil Fe, K, and Ca than ungrazed systems, suggesting that cycling of nutrients from soil to forage to cattle to soil in well-managed pastures could lead to significant improvement in long-term soil fertility. Moderate application of broiler litter was an effective means of supplying nutrient cations in addition to N and P and is recommended for pasture management systems designed to restore the fertility of eroded Ultisols.

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