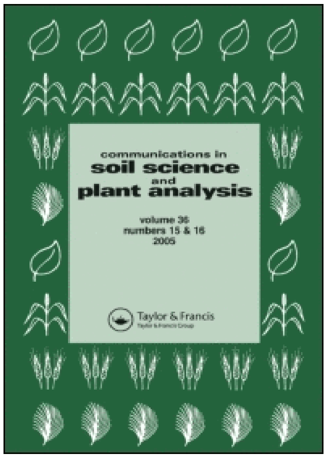

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Tillage and Forage System Effects on Forage Yields and Nutrient Uptake under Broiler Litter-Amended Soils

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Tillage and Forage System Effects on Forage Yields and Nutrient Uptake under Broiler Litter–Amended Soils

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Abstract: Planting and harvesting high-yielding forage grasses may remove phosphorus (P), copper (Cu), and zinc (Zn) from surface soils with a long history of broiler litter application. A study was conducted in Alabama's Sand Mountain region from 1998 to 2000 to determine tillage and forage systems best suited for removing nutrients from such overloaded soils. Tillage treatments included no-till, moldboard plowing, chisel plowing, and each combined with paraplowing. Forage treatments included bermudagrass (*Cynodon dactylon* (L.) Pers.) cv. Russell, tall fescue (*Festuca arundinacea* Schreb.) cv. Kentucky-31, and an annual rotation of ryegrass (*Lolium multiflorum* Lam.) and sorghum sudangrass (*Sorghum bicolor* L. Moench × *Sorghum vulgare sudanense*). The annual rotation produced highest yields and P uptake. Moldboard plowing the annual rotation further increased yields. It appears the annual rotation best removes P, Cu, and Zn via plant uptake. Tillage

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reduced P concentrations in the soil surface in the following order: moldboard > chisel > no-till.

Keywords: Forage grasses, tillage, nutrients, overloaded soils

INTRODUCTION

Application of poultry litter to local agricultural land is the most economical method of litter disposal. Though it is a beneficial fertilizer, long-term litter application can lead to build up of soil phosphorus (P) and metals such as copper (Cu) and zinc (Zn) (Kingery et al. 1994). Although the nitrogen (N)–P ratio of litter is 3:1, crop removal occurs at a ratio of 8:1 (Sharpley, Daniel, and Edwards 1993). Amounts of litter applied often exceed crop removal rates, resulting in soil surface P accumulations that are hard to deplete by crop uptake (Robinson and Sharpley 1996; Daniel et al. 1994).

Phosphorus is required for plant growth and occurs naturally in the soil. Additions of P increase the risk for surface water degradation. Phosphorus transported as surface runoff and erosion is the leading cause of fresh water eutrophication. Because of the addition of P to waters, algae grows at an excessive rate. Upon depleting the nutrients such as P, algae decompose, resulting in oxygen depletion and soluble nutrient release (Harper 1992). Noxious aquatic growth and fish kills occur in severe cases of eutrophication (Wood 1998). The uses of surface water in fisheries, industry, recreation, and drinking are all impaired.

Management approaches limiting P loss through agricultural nonpoint source pollution are most effective in preventing eutrophication (Sharpley et al. 1994). Tillage practices have been found to impact surface water quality by affecting both P concentrations in soil and losses. Tillage is the mechanical manipulation of soil to alter soil conditions for the purpose of weed control and incorporating soil amendments for improved crop production (Unger and Cassel 1991). Conservation tillage, which is being promoted for reducing soil erosion, leaves more than 30% of crop residues on the soil surface (MWPS 2000). Conservation tillage includes no-till and reduced tillage practices, which may include chisel plowing or disking. Conservation tillage is favored for its role in decreasing erosion and particulate P losses. Because soil amendments, such as poultry litter, and residues remain on the surface, dissolved P losses in surface runoff may increase (Andraski, Mueller, and Daniel 1985; Sharpley et al. 1994). Conventional tillage involves turnover of soil, incorporating crop residues and soil amendments into the soil profile. Because conventional tillage causes sediment to detach from the soil surface, erosion and particulate P losses are increased. The incorporation of surface material decreases losses of dissolved and total P (Römkens, Nelson and Mannering 1973).

Most studies to date correlate tillage to P in runoff, not soil P. Sharpley et al. (1991) found mean annual runoff concentrations of P were greater from no-till than reduced till, but both types of tillage were effective in reducing particulate P losses. Likewise, Andraski, Mueller, and Daniel (1985) found that no-till reduced erosion and P concentrations in runoff by 81%, and chisel plowing reduced concentrations 70%. Algal-available P relative to total P increased 26% for no-till and 6% for chisel plowing. Mueller, Wendt, and Daniel (1984) suggested that surface-applied manure and no-till were a poor combination. Griffith, Mannering, and Moldenhauer (1977) revealed that after several years of no-till on manured soils, soil-test P concentrations were six times greater than they were initially.

Römkens, Nelson, and Mannering (1973) suggested plowing soils every 3 to 4 years to redistribute soil P. Lower concentrations of dissolved P in runoff have been found from soils that were moldboard plowed (Römkens and Nelson 1974). Incorporating manure was found to decrease total P losses compared to broadcast application (Mueller, Wendt, and Daniel 1984). To decrease P accumulations at the surface and redistribute P into the root zone, P must be applied prior to tillage (Nichols, Daniel, and Edwards 1994). In many areas, poultry litter is applied to pastureland, which is rarely tilled. Few studies address tillage of pasturegrasses as a means of reducing P losses in runoff and erosion. Overseas studies have suggested that occasional tilling of pasturegrasses may loosen soils, allowing increased water infiltration and higher yields (Raper et al. 1997). There is conflicting evidence as to what type of tillage is most effective in reducing P accumulations in the soil and losses. One objective of this study was to determine the most effective tillage system to redistribute soil P under various Alabama pasture grass systems.

Plant available P, when not lost from the system, may be utilized by crops and pasture grasses. Because poultry litter is commonly disposed on pastures, forage harvest offers removal of excessive P, Cu, and Zn and may be a solution to alleviate surface soil nutrient accumulations. On pasture grasses, plants can utilize P from manure through an entire growing season (Barnes, Miller, and Nelson 1995). Removal of P by bermudagrass and tall fescue are estimated at 35–45 kg P ha^{-1} and 30 kg P ha^{-1}, respectively (Edwards and Daniel 1992). Annual ryegrass has a high P removal rate and may consume more P than needed in high P soils (Robinson 1996). Litter has been shown to increase yields for both tall fescue and coastal bermudagrass (Edwards and Daniel 1993; Honeycutt, West, and Phillips 1988). Evers (1999) found that broiler-litter applications increased bermudagrass yields by 20% and improved nutrient uptake. Wood, Torbert, and Delaney (1993) also found an increase in bermudagrass yield and hay quality. Lucero et al. (1995) reported increased dry-matter yields and P uptake for tall fescue with increasing poultry manure application rates. Accumulations of soil P have not been found to harm pasturegrass productivity (Kingery et al. 1994). Although tillage of pasture grasses is unusual, tillage can place nutrients in the root zone for increased crop use while decreasing surface soil P (Moore et al. 1998). The other objective of this study was to determine the most effective forage system in removing P via plant uptake under selected tillage systems.

MATERIALS AND METHODS

Study Site

The study was conducted from April 1998 to May 2000 at the Sand Mountain Agricultural Experiment Station near Crossville, Ala. (34.26 °N, 86.03 °W). The chosen site was a long-term littered pasture. Litter was applied at approximately 6 Mg ha^{-1} yr^{-1} for 10 years prior to the study. The soil on the site is classified as Hartsells fine sandy loam (fine-loamy, silicious, thermic, Typic Hapludult). Selected soil properties at the study site upon initiation of the study are found in Table 1.

Treatment and Plot Management

The experiment design was a split–split plot with deep noninversion tillage as main plots, surface tillage as subplots, and forage system as subsubplots. Deep noninversion tillage treatments consisted of paraplowing to 40 cm and no paraplowing (Table 2). Surface tillage treatments included no-till, moldboard plowing to 30 cm followed by disking, and chisel plowing to 35 cm followed by disking (Table 2). Forage system treatments included an annual rotation of sorghum–sudangrass hybrid and annual ryegrass, Russell bermudagrass (a warm season perennial), and Kentucky-31 tall fescue (a cool season perennial) (Table 2). In addition, a control plot was left

Table 1. Selected soil characteristics at each depth sampled upon initiation of the study at the Sand Mountain substation near Crossville, Ala.

Depth (cm)	Texture	pH	Total N (g kg^{-1})	Organic C (g kg^{-1})	P^a (g kg^{-1})
0–5	Sandy loam	5.43	1.2	40.0	648
5–10	Sandy loam	5.16	0.5	14.5	273
10–15	Sandy loam	5.36	0.3	7.8	211
15–30	Sandy loam	5.35	0.2	4.2	137
30–60	Sandy loam	5.10	0.1	2.2	33
60–90	Sandy loam	4.61	0.1	1.0	5

[a]Mehlich I extractable.

Table 2. Description of treatments applied to each sub-subplot in one replication at the Sand Mountain substation near Crossville, Ala.

Treatment	Deep inversion tillage	Surface tillage	Forage system
1	No paraplow	No-till	Annual rotation
2	No paraplow	No-till	Bermudagrass
3	No paraplow	No-till	Tall fescue
4	No paraplow	Chisel	Annual rotation
5	No paraplow	Chisel	Bermudagrass
6	No paraplow	Chisel	Tall fescue
7	No paraplow	Moldboard	Annual rotation
8	No paraplow	Moldboard	Bermudagrass
9	No paraplow	Moldboard	Tall fescue
10	Paraplow	No-till	Annual rotation
11	Paraplow	No-till	Bermudagrass
12	Paraplow	No-till	Tall fescue
13	Paraplow	Chisel	Annual rotation
14	Paraplow	Chisel	Bermudagrass
15	Paraplow	Chisel	Tall fescue
16	Paraplow	Moldboard	Annual rotation
17	Paraplow	Moldboard	Bermudagrass
18	Paraplow	Moldboard	Tall fescue
19	Control	Control	Control

untreated with an existing bermudagrass stand. Each treatment was replicated four times for a total of 76 subplots. Individual plots were 3 m $\times$ 10 m. The center 2 m of each plot was planted to forage, allowing for a 1.0-m border between each.

Prior to applying tillage treatments, existing grasses were killed with glyphosate, with the exception of the control plots. Tillage treatments were applied on 27 April 1998 upon death of existing grasses. Seeding of fescue at a rate of 34 kg ha^{-1} and seeding of sorghum-sudangrass at a rate of 67 kg ha^{-1} followed on 5 May 1998. Bermudagrass was sprigged on 14 May 1998. After final harvest of the sorghum–sudangrass in October 1998, ryegrass was seeded at a rate of 28 kg ha^{-1} on 30 October 1998. Tall fescue was overseeded at this time and again on 20 October 1999 to improve the stand. The rotation was repeated with the seeding of sorghum–sudangrass on 7 June 1999 and ryegrass on 20 October 1999. Plots were managed to minimize weed growth using picloram/2,4-D applied at 3 L ha^{-1}. Ammonium nitrate was added to all plots at a rate of 67 kg N ha^{-1} to meet crop N requirements in spring of 1999 and 2000. Throughout the duration of the project, no P was applied to the plots.

Plant Sampling and Analysis

All subsubplots were harvested using a sickle bar mower with time and frequency depending on forage system in the 1998 and 1999 growing seasons. A center strip measuring 1 m × 8 m was harvested from each subsubplot. The freshly cut forage was immediately weighed on a large portable scale. Biomass samples of approximately 1000 g were randomly collected from the total harvested, placed into tared brown paper bags, and weighed for fresh weight. The remaining stand of grass was then removed from the plots. Subsequent to each harvest, samples were dried at 60°C for 48 h for dry-weight determination. Dry-matter yield was then calculated for each subsubplot. Dried plant samples were ground to pass a 1-mm mesh screen using a Wiley mill (Thomas Scientific, Phila, Penn.). To determine total P, Cu, and Zn in the plant tissue, samples were dry-ashed, digested with hydrochloric acid (HCl) (Hue and Evans 1986), and analyzed via inductively coupled argon plasma spectroscopy (ICAP 9000, Thermo Jarrell Ash, Franklin, Mass.). Uptake of P, Cu, and Zn was calculated by multiplying forage nutrient content by dry-matter yield.

Soil Sampling and Analysis

Soil samples were taken from all subsubplots following tillage treatments on 19 and 20 May 1998 and again on 9 and 10 May 2000. Using a tractor-mounted Giddings hydraulic probe, three cores to 90 cm were collected in each subsubplot. Each core was divided by depth in the following increments (cm): 0 to 5, 5 to 10, 10 to 15, 15 to 30, 30 to 60, and 60 to 90. Each depth increment was composited within the subsubplot. Soil samples were dried in an oven at 60°C 4 four days and screened to pass a 2-mm sieve. Total soil P was quantified using a 4M nitric acid (HNO_3) digestion procedure (Bradford et al. 1975). Mehlich I P was determined by extracting soils with a dilute double-acid solution [(0.05 N HCl and 0.025 N sulfuric acid (H_2SO_4)] and analyzing by ICAP (Hue and Evans 1986). Soil pH was measured on 1:1 soil/water slurries with a pH meter having a glass electrode.

Statistical Analysis

Statistical analyses were conducted using the general linear model (GLM) procedure (SAS Institute, 1990) for a split–split plot design. The GLM procedure was performed on yield and nutrient uptake for all subsubplots in each growing season and all years combined. Sources of variation for soil included deep tillage, surface tillage, forage, and their interactions. Each sampling depth was analyzed separately. Least significant differences (LSD) were computed to demonstrate differences among treatment means. All statistical tests were performed at the $\alpha = 0.10$ significance level. Where interactions are significant, main effects composing the interaction are not discussed separately.

RESULTS AND DISCUSSION

Yield

Plots were planted with pasturegrasses, common to the region. Bermudagrass and tall fescue are high-yielding hay crops, and both sorghum-sudangrass and annual ryegrass are used for hay and silage (Robinson 1996). All treatments significantly affected forage yields in both growing seasons. A deep noninversion tillage by surface tillage interaction was exhibited in 1998–1999 (Figure 1a). When paraplowed, moldboard plowing produced significantly higher yields than chisel plowing or no-till. When not paraplowed, both moldboard and chisel plowing yielded significantly higher than no-till. In the 1999–2000 growing season, this interaction did not occur. The interaction was again significant for the total yields for the duration of the study (Figure 1b). When paraplowed, moldboard plowing produced significantly higher yields than both chisel plowing and no-till. No differences between surface tillages existed under no paraplowing. Research has shown that paraplowing can have benefits over inversion tillage for permanent pasture. Loosening of soils can increase water infiltration and plant growth (Raper et al. 1997). Carter and Kunelius (1998) found that paraplowing to 20 cm gave a negative yield response likely due to root injury during tillage. If tillage is done prior to planting, as in this study, damage to roots may be eliminated.

A surface tillage by forage interaction was significant for yields in the 1998–1999 and 1999–2000 growing seasons and the total project yields (Figure 2a). In 1998–1999, yields were greatest for the annual sorghum–sudangrass/ryegrass rotation followed by bermudagrass, then tall fescue. The rotation, being composed of drought tolerant-sorghum–sudangrass and high-yielding, adaptable ryegrass (Barnes, Miller, and Nelson 1995), was very productive in year 1. Because of high summer temperatures and periods of drought, the tall fescue did not establish well, resulting in poor yields. Bermudagrass is a warm season, deep-rooted, drought-resistant grass, which makes it more equipped to yield well under these conditions (Ball, Horeland, and Lacefield 1996). Surface tillage did not alter yields for bermudagrass and fescue. Annual rotation yields were higher under surface tillage in the following order: moldboard > chisel > no-till. This may be due to greater seed-to-soil contact needed to produce a good stand (Barnes, Miller, and Nelson 1995). In 1999–2000, the bermudagrass stand was much more successful, with yields becoming equal to those of the annual rotation (Figure 2b). Wood, Torbert, and Delancy (1993) found that the residual

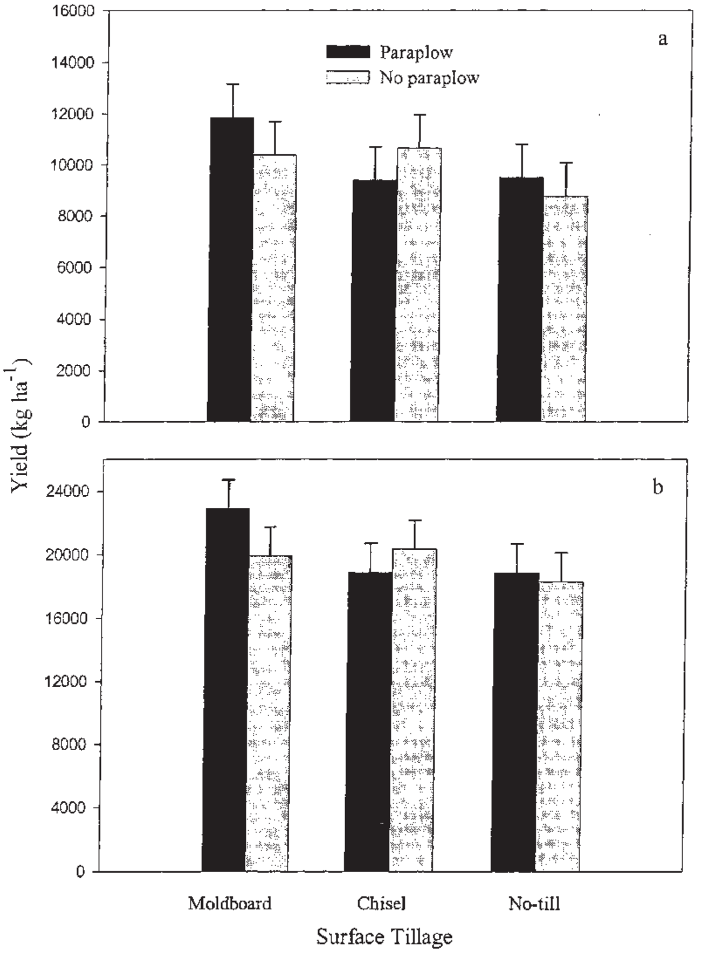

Figure 1. Mean forage yields at the Sand Mountain substation near Crossville, Ala., as (a) affected by deep and surface tillage during the 1998–1999 growing season and (b) the total for the duration of the study. Bars are $LSD_{0.10}$.

effects of poultry litter resulted in high yields of bermudagrass. Bermudagrass and the annual rotation had significantly higher yield than tall fescue in 1999–2000. Again, yields for bermudagrass and fescue did not vary with surface tillage. The annual rotation produced significantly higher yields under the moldboard system than under the chisel and no-till systems.

The total yields for the combined growing seasons demonstrate results parallel to the 1998–1999 season (Figure 2c). The annual rotation generated the highest yields followed by bermudagrass and tall fescue. Moldboard plowing resulted in highest yields within the rotation. Because the rotation was quick to establish each season and harvested over a much

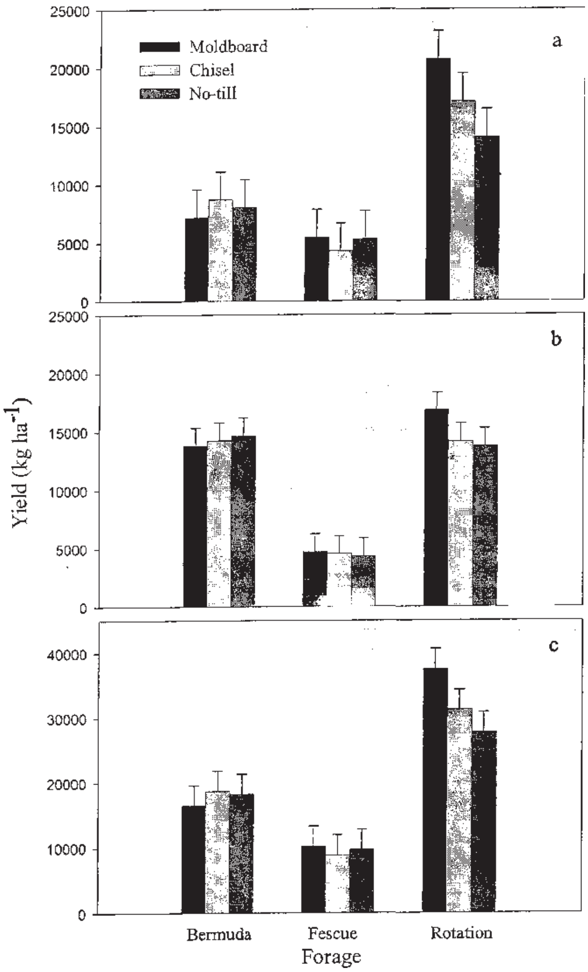

Figure 2. Mean forage yields at the Sand Mountain substation near Crossville, Ala., as (a) affected by surface tillage and forage during the 1998–1999 growing season, (b) during the 1999–2000 growing season, and (c) the total for the duration of the study. Bars are $LSD_{0.10}$.

longer period of time, greater yields were to be expected. Once better established, the bermudagrass and tall fescue may become more productive.

Nutrient Removal

Nutrient accumulations in surface soil are removed from the system either by runoff and erosion or by plant uptake. To reduce the contribution to surface-water contamination, removal from the system by plant uptake of P, Cu, and Zn is of great importance. Significant differences among treatments occurred for P, Cu, and Zn uptake. Because plant-tissue content of nutrients usually varies little, most differences found were probably due to yield (Robinson 1996).

In 1998–1999, a significant surface tillage by forage interaction existed for P uptake (Figure 3a). The annual rotation removed significantly more P than bermudagrass and fescue. The amount of P removed from the latter two forages did not vary by surface tillage. Phosphorus uptake for the annual rotation was significantly greater under moldboard and chisel systems than no-till. Tillage may have placed more P in the root zone, enhancing plant uptake. In the 1999–2000 growing season, P uptake was affected by forage type only (Figure 3b). Phosphorus removal was greatest in the following order: annual rotation > bermudagrass > tall fescue. Ginting et al. (1998) reported that tillage type did not affect P uptake on manured soils. A surface tillage by forage interaction was present for the total P removed for the duration of the study (Figure 3c). The annual rotation removed a larger quantity of P compared to bermudagrass and fescue. Robinson (1996) found that ryegrass is prone to luxury consumption of P in high P soils. Annual ryegrass and sorghum–sudangrass can remove P at an estimated 60–85 kg P ha^{-1} yr^{-1} and 18 kg ha^{-1} yr^{-1}, respectively (Edwards and Daniel 1992; Robinson 1996). These removal rates are comparable to those seen here. There were no significant differences between P uptake from bermudagrass and fescue, nor were there any differences owing to tillage system. Bermuda and tall fescue have similar P removal rates estimated at 40 kg ha^{-1} and 30 kg ha^{-1}, respectively (Edwards and Daniel 1992). Both perennials appear to remove less P that the rotation according to these numbers. Phosphorus uptake from the rotation was greater under moldboard and chisel plowing than no-till. Where high P uptake under moldboard plowing most likely results from yield, the nearly equal P uptake under chisel plowing probably results from a high tissue P content, because yields for the rotation were significantly less under chisel plowing compared to moldboard plowing (Figure 2).

Uptake of Cu was affected by surface tillage and forage treatments. In the 1998–1999 growing season, a significant surface tillage by forage interaction occurred, and the annual rotation removed the most Cu (Figure 4a). Moldboard and chisel plowing resulted in significantly more Cu being taken up by the rotation than to no-till. Bermudagrass uptake of Cu was significantly higher under chisel plowing compared to moldboard plowing but was not different from no-till. Surface tillage did not affect Cu removal of tall fescue. In 1999–2000, there were no significant differences in Cu uptake. The total uptake of Cu for the duration of the study was affected by forage only. Overall, the annual sorghum–sudangrass/ryegrass rotation removed more Cu than both bermudagrass and fescue (Figure 4b). Kingery et al. (1993) reported higher concentrations of Cu in tall fescue tissue on littered

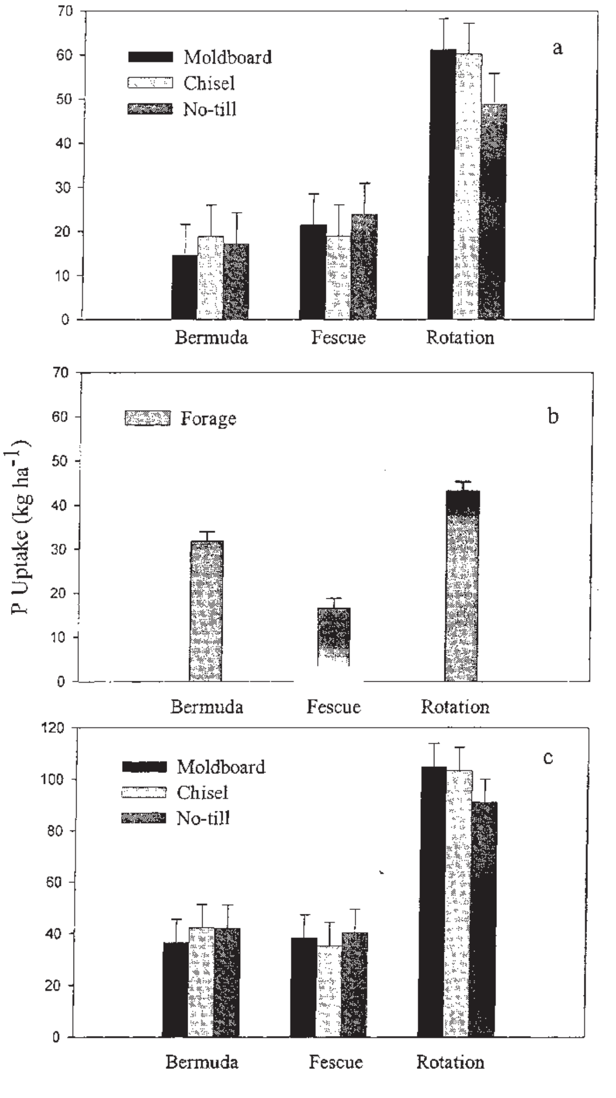

Figure 3. Mean P uptake for forages at the Sand Mountain substation near Crossville, Ala., (a) during the 1998–1999 growing season, (b) during the 1999–2000 growing season, and (c) the total uptake for the duration of the study. Bars are $LSD_{0.10}$.

pasture compared to nonlittered pastures, revealing the potential for elevated forage Cu concentrations.

Zinc uptake by forages followed a very similar trend to P uptake. During the 1998–1999 season, a surface tillage by forage interaction existed (Figure 5a). The rotation removed a significantly larger amount of Zn than did bermudagrass and tall fescue. Moldboard plowing and chisel plowing

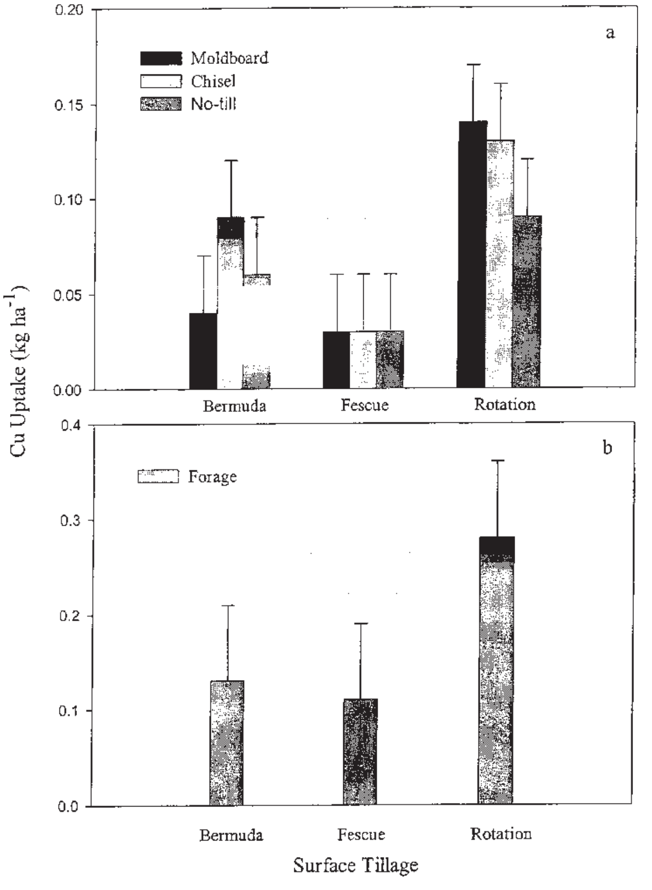

Figure 4. Mean copper uptake for forages at the Sand Mountain substation near Crossville, Ala., (a) during the 1998–1999 growing season and (b) the total uptake for the duration of the study. Bars are $LSD_{0.10}$.

resulted in greater Zn uptake for the rotation than did no-till. Uptake by tall fescue was not altered by surface tillage. Bermudagrass produced greater Zn uptake under the chisel plowing system than under moldbaord plowing but did not differ from no-till. Forage type affected Zn uptake in 1999–2000 (Figure 5b). Zinc uptake was significantly higher in the following sequence: annual rotation > bermudagrass > tall fescue. Uptake for this season was also significantly affected by surface tillage, although there was no interaction with forage system. Chisel plowing resulted in an uptake of 0.55 kg Zn ha^{-1}. This was significantly greater than Zn uptake under moldboard plowing and no-till, removing 0.47 kg Zn ha^{-1} and 0.46 kg Zn ha^{-1}, respectively. A significant surface tillage by forage interaction occurred for total Zn uptake over the duration of the study

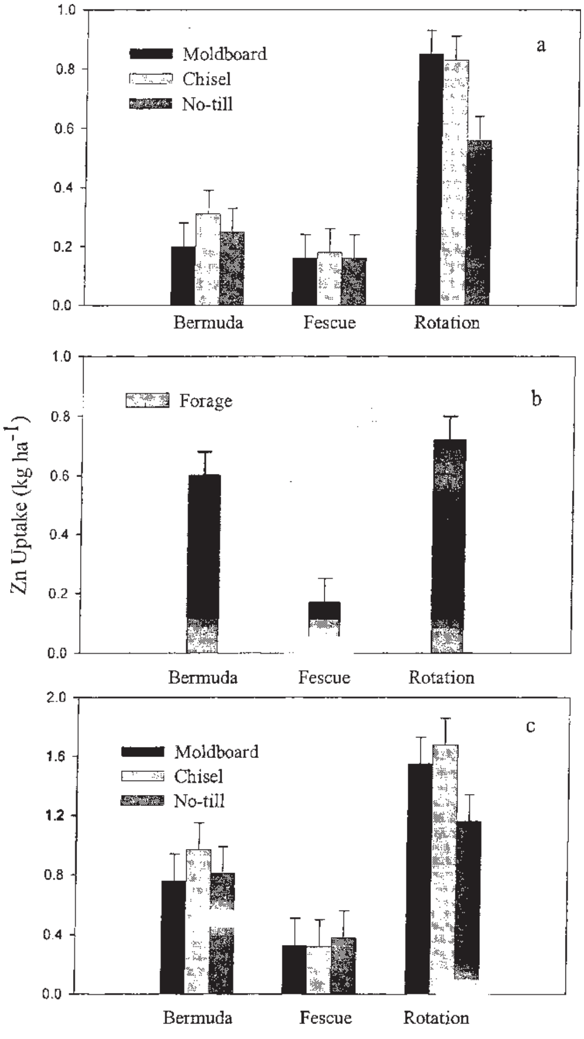

Figure 5. Mean Zn uptake for forages at the Sand Mountain substation near Crossville, Ala., (a) during the 1998–1999 growing season, (b) during the 1999–2000 growing season, and (c) the total uptake for the duration of the study. Bars are $LSD_{0.10}$.

(Figure 5c). Zinc uptake by the rotation exceeded that of both bermudagrass and fescue. Moldboard and chisel systems resulted in greater uptake than no-till for the rotation. Zinc uptake by bermudagrass was greatest in combination with chisel plowing compared to moldboard. Uptake by fescue did not differ by surface tillage. Kingery et al. (1993) found that tissue Zn concentrations in tall fescue from littered pastures were not different from nonlittered pastures and levels were in an adequate range for livestock consumption.

Soil Phosphorus

Several forms of soil P were measured, and differences between treatments occurred for each form upon initial sampling in 1998 and final sampling in 2000 and for the change in concentration between sampling dates. In 1998, forages were not established at the time soils were sampled; therefore, differences between forage systems were not analyzed.

Total P, which represents P in both dissolved and particulate phases, measured as high as 1000 mg kg^{-1} at the surface. O'Halloran (1993) found concentrations similar to these in soils treated with dairy manure. In sandy loam soils, organic P is estimated to make up 21–26% of total P (O'Halloran 1993). Total P has been correlated with sediment-bound P lost through soil erosion (Mueller Wendt, and Daniel 1984). Deep noninversion tillage significantly affected total soil P concentrations (Table 3). In 1998, paraplowing the soil reduced P concentrations at 0–5 and 5–10 cm. Upon sampling in 2000, paraplowing reduced P concentrations at 30–60 cm only, likely due to a downward movement of P stimulated by paraplowing in 1998. A significant change in concentration between sampling years occurred in the 0- to 10-cm depth. Over time, paraplowing the soil caused a slight increase in P concentrations at the surface where no paraplowing decreased concentrations (Table 3). It is unclear as to why paraplowing increased surface soil total P in this study.

Surface tillage and forage selection significantly affected total soil P concentrations. In 1998, moldboard plowing reduced P concentrations at the surface 0–5 cm by half compared to chisel plowing and no-till (Table 4). This decrease occurred because of the soil profile inversion caused by moldboard plowing. Surface-applied poultry litter was transferred from the

Table 3. Mean total soil P concentration at (mg kg^{-1}) each sampling depth as affected by deep tillage in 1998 and 2000 and the change in concentration (ΔP) between sampling years at the Sand Mountain substation near Crossville, Ala.

	Soil depth (cm)					
Treatments	0–5	5–10	10–15	15–30	30–60	60–90
1998						
Paraplow	810	571	505	362	159	76
No paraplow	980	655	529	386	171	77
2000						
Paraplow	818	610	555	453	200	98
No paraplow	843	615	535	450	234	81
ΔP						
Paraplow	7.9	38	50	90	41	16
No paraplow	−139	−42	4.3	61	62	1.6

Table 4. Mean total soil P concentration at the 0- to 5-cm depth in 1998 and 2000 and the change in concentration (ΔP) between sampling years at the Sand Mountain substation near Crossville, Ala.

Treatments	1998 (mg kg^{-1})	Treatments	2000 (mg kg^{-1})	ΔP (mg kg^{-1})
Moldboard	572	Moldboard/bermuda	525	−47
		Moldboard/bescue	508	−125
		Moldboard/rotation	487	−27
Chisel	1062	Chisel/bermuda	1079	205
		Chisel/fescue	837	−288
		Chisel/rotation	869	−322
No-till	1050	No-till/bermuda	1001	−79
		No-till/rescue	1114	63
		No-till/rotation	1054	30
$LSD_{0.10}$	110		130	177

surface into the plow layer. Andraski, Mueller, and Daniel (1985) found total P losses were highest from conventional tillage due to this inversion. Under no-till and chisel plowing, P accumulations at the surface were not mixed into the plow layer. Chisel plowing reduced P concentrations compared to no-till at the 60- to 90-cm depth (data not shown), but these findings are likely anomalous and not of real environmental significance. The final sampling in 2000 resulted in a surface tillage by forage interaction at the surface 0–5 cm (Table 4). Phosphorus concentrations decreased according to the sequence moldboard > chisel > no-till. Again, moldboard plowing reduced concentrations by half when compared to no-till. Again, this was likely due to soil profile inversion. Under the chisel plowing and bermudagrass combination, P concentrations were significantly higher, matching those of no-till, than under chisel plowing with tall fescue or the annual ryegrass/sorghum–sudangrass rotation. At 5–10 cm, moldboard plowing reduced P concentrations to 537 mg kg^{-1} compared to chisel plowing (660 mg kg^{-1}), and no-till (641 mg kg^{-1}). Research has shown that under a no-till system, P can accumulate in the upper 2.5 to 15 cm (O'Halloran 1993).

There was also a surface tillage by forage interaction for the change in P concentration between sampling years at the 0- and 5-cm depth (Table 4). Under moldboard plowing, all forage treatments resulted in a decrease in P concentration over time. This decrease probably occurred because of either plant uptake of P or losses of sediment P via erosion, although vegetative cover tends to decrease erosion (MWPS 2000). Differences under the chisel system were significant among forages. Bermudagrass resulted in a substantial increase in P of 205 mg kg^{-1}, where both fescue and the rotation resulted in a significant decrease in P of approximately 300 mg kg^{-1}. This may be explained by the root systems of these forages. Both tall fescue and ryegrass are bunch-type grasses whose shoots remain isolated under each bunch. Bermudagrass is rhizomatous, meaning its shoots spread below ground (Turgeon 1999). When bunch type grasses are harvested, most of the crop residue is removed, including P taken up by the grass. When the bermudagrass is harvested, a great deal of plant material remains just under the surface. Decaying residue recycles organic P back into the soil. Ginting et al. (1998) reported that an increase in surface soil P after tillage may be due to P from plant residues. Under no-till, there was very little change in P concentration over time and no differences between forages occurred.

At the 15- and 30-cm depth, differences between treatments occurred for soils sampled in 2000 and for the change in P concentration from 1998 to 2000 (Table 5). In 2000, moldboard plowing increased P concentrations at this depth, most likely due to redistribution of the poultry litter into the plow layer. O'Halloran (1993) reported an increase in soil organic P at the plow layer from incorporation of dairy manure. There were no differences between chisel and no-till at this depth. An overall increase in P concentration occurred at this depth between sampling years as a result of P leaching stimulated by moldboard and chisel plowing (Table 5). The most significant increase occurred between moldboard plowing and no-till. Forage also affected the change in P at this depth, probably due to plant uptake. The annual rotation and bermudagrass treatments resulted in a significant increase in P concentration compared to tall fescue.

Although Römkens and Nelson (1974) reported no correlation between extractable soil P and total soil P, differences in P concentration with respect to treatments were similar between the two in this study. Mehlich I–extractable P estimates plant-available P by extracting aluminum- and iron-bound P from acidic soils like those in the southeastern United States (Sims, Hodges, and Davis 1998). A large body of research links soil-test P levels determined by Mehlich I extraction to P losses in surface runoff (Sharpley, Daniel, and Edwards 1996). Daniel et al. (1994) reported a highly linear relationship between STP in surface soil and soluble P lost in runoff from cropland and grassland watersheds. Mehlich I–extractable P

Table 5. Mean total soil P concentration at the 15- to 30-cm depth in 2000 and the change in concentration (ΔP) from 1998 to 2000 at the Sand Mountain substation near Crossville, Ala.

Treatments	2000 (mg kg^{-1})	ΔP (mg kg^{-1})	Treatments	ΔP (mg kg^{-1})
Moldboard	521	123	Bermuda	83
Chisel	435	69	Fescue	42
No-till	398	36	Rotation	103
$LSD_{0.10}$	62	59		39

concentrations at the surface initially reached 680 mg P kg^{-1}, grossly exceeding the range for optimum crop productivity. For initial samples, differences were found at the surface as a result of deep noninversion tillage (Table 6). At 0–5 and 5–10 cm, paraplowing resulted in lower P concentrations than no paraplowing. In 2000, paraplowing decreased P concentrations from 5 to 60 cm deep. This demonstrates the paraplow's ability to dilute P into the soil profile. Deep noninversion tillage had no effect on the change in P concentration between sampling dates.

Surface tillage affected Mehlich I–extractable P concentrations throughout the profile for the 1998 sampling (Table 7). In the surface 5 cm, moldboard plowing decreased P concentrations by 60% compared to chisel and no-till, reducing P concentrations to 254 mg kg^{-1}. There were no differences between chisel plowing and no-till at the surface. On soils amended with beef manure, moldboard plowing resulted in no accumulation of Olsen-extractable P at the 0- to 5-cm depth (Ginting et al. 1998). At 5–10 cm, chisel plowing had higher concentrations than no-till, most likely because chisel plowing buried some litter and residue below the surface. At 10–15 and 15–30 cm, moldboard plowing produced higher P concentrations than both chisel and no-till. Ginting et al. (1998) reported an increase in Olsen extractable P at the 5- to 10- and 10- to 15-cm depths from moldboard plowing. At 30–60 cm, P concentrations were higher under the chisel system than under no-till and moldboard. This may possibly be due to P movement stimulated by the extensive loosening of soil by the chisel plow into this region. In 2000, a surface tillage by forage interaction occurred at the surface depth (Table 8). Forage differences did not occur under moldboard and no-till. Bermudagrass resulted in a much higher P concentration in the 0- to 5-cm depth than fescue, and neither was different from the rotation under the chisel system. At 5–10 cm, chisel plowing resulted in an increase in P concentration compared to moldboard plowing, and at 10–15 cm the reverse effect occurred (Table 7). This effect was caused by the

Table 6. Mean Mehlich I–extractable P concentration at (mg kg^{-1}) each sampling depth as affected by deep tillage in 1998 and 2000 at the Sand Mountain substation near Crossville, Ala.

	Soil depth (cm)					
Treatments	0–5	5–10	10–15	15–30	30–60	60–90
1998						
Paraplow	476	264	230	128	34	6.8
No paraplow	621	333	254	183	37	7.6
2000						
Paraplow	301	216	196	152	29	3.6
No paraplow	374	254	222	196	60	3.9

Table 7. Mean Mehlich I–extractable P concentration (mg kg^{-1}) at each sampling depth as affected by surface tillage in 1998 and 2000 at the Sand Mountain substation near Crossville, Ala.

	Soil depth (cm)					
Treatments	0–5	5–10	10–15	15–30	30–60	60–90
1998						
Moldboard	254	308	309	191	24	7.5
Chisel	710	335	208	142	50	6.9
No-till	680	253	209	133	32	7.3
$LSD_{0.10}$	117	59	81	27	16	NS[a]
2000						
Moldboard	158	197	218	218	52	3.7
Chisel	413	268	219	164	48	3.7
No-till	441	240	191	141	33	3.8
$LSD_{0.10}$	94	41	NS	30	NS	NS

[a]NS = not significant.

tilling mechanism. At 15- to 30-cm deep, a forage effect also occurred. Tall fescue resulted in a soil P concentration of 152 mg kg^{-1}, significantly lower than both bermudagrass and the rotation (176 mg kg^{-1} and 194 mg kg^{-1}, respectively).

Table 8. Mean Mehlich I–extractable P concentration (mg kg^{-1}) at the 0- to 5-cm depth in 2000 and the change in concentration (ΔP) (mg kg^{-1}) between 1998 and 2000 at 0- to 5-cm and 15- to 30-cm depths at the Sand Mountain substation near Crossville, Ala.

	Soil depth (cm)		
	0–5		15–30
Treatments	2000	ΔP	ΔP
Moldboard/bermuda	161	−104	2.9
Moldboard/bescue	166	−122	−16
Moldboard/rotation	148	−62	92
Chisel/bermuda	478	−93	5.7
Chisel/fescue	340	−308	38
Chisel/rotation	420	−491	23
No-till/bermuda	407	−263	21
No-till/fescue	466	−246	−4.2
No-till/rotation	449	−211	8.3
$LSD_{0.10}$	80	196	57

Mehlich I–extractable P concentrations decreased from 1998 to 2000 under all tillage and forage systems at the surface depth (Table 8). This was probably due to plant uptake, but because other P losses were not measured in this study, it is impossible to know what fraction of this decrease was due to surface runoff or sediment loss. No differences between forages occurred under moldboard plowing and no-till. Under chisel plowing, decreases in P concentration were significantly greater for the rotation and fescue than for bermudagrass. Again, this is possibly due to the recycling of P back into the bermudagrass system. This interaction also occurred at the 15- to 30-cm depth (Table 8). Under chisel plowing and no-till, there were no significant differences between forages. Under moldboard plowing, however, there was a much larger increase in soil P concentration on plots treated with the rotation than bermudagrass and fescue plots. Overall, increases at this depth were not very substantial.

CONCLUSIONS

The annual rotation of ryegrass and sorghum–sudangrass produced significantly higher yields than bermudagrass and tall fescue in 1998–1999. Moldboard and chisel plowing resulted in greater yields for the rotation than did no-till. In 1999–2000, bermudagrass yields increased significantly, equaling those of the annual rotation. Tall fescue did not yield well because of climate conditions during the 2-year study. Phosphorus uptake was also higher under the rotation in both years compared to bermudagrass and fescue. Uptake was higher under moldboard and chisel-plowing systems for the rotation. Uptake for both Cu and Zn showed results similar to those of P uptake. For the duration of the study, the annual rotation was most effective in removing nutrients from the soil. If future bermudagrass yields match those of 1999–2000, it may be just as effective in P removal.

Initially, P concentrations in surface soil were extremely high. Phosphorus concentrations measured on no-till plots give a good indication of the excessively high P levels that can accumulate under long-term litter application. The system of moldboard plowing and disking successfully diluted P into the soil profile to approximately 60 cm. As a result of moldboard plowing, soil-test P concentrations at 0–5 cm decreased by 50% or more in 1998 when compared to no-till and the system of chisel plowing and disking. After 2 years, concentrations were further decreased at the surface on moldboard-plowed plots. In 2000, bermudagrass and chisel plowing resulted in an increase in soil P at the surface, whereas all other combinations resulted in a decrease. Paraplowing diluted P throughout the profile following tillage in 1998. Concentrations continued to decrease over time, as was seen from final sampling. More research regarding the paraplow would be necessary to draw conclusions about its use in redistributing soil P.

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