Export of Manure Phosphorus and Nitrogen in Turfgrass Sod

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ABSTRACT

Regulatory mandates have increased demand for best management practices (BMPs) that will reduce nutrient loading on watersheds impaired by excess manure P and N. Export of manure P and N in turfgrass sod harvests is one BMP under consideration. This study quantified amounts and percentages of P and N removed in a sod harvest for different rates of manure and inorganic P and N. Six treatments comprised an unfertilized control, two manure rates with and without supplemental inorganic N, and inorganic P and N only. The treatments were applied to 'Tifway' bermudagrass (*Cynodon dactylon* L. × *C. transvaalensis* Burtt-Davey), '609' buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.], and 'Reveille' bluegrass (*Poa arachnifera* Torr. × *P. pratensis* L.) under field conditions. Comparisons among treatments revealed small variations of P and N content in clippings and the plant component of sod, but large variations in the soil component of sod for each turf species. In addition, 2 to 10 times more P and 1.3 to 5 times more N was removed in soil than in plant components of sod for the two manure rates with and without added inorganic N. Percentages of applied P and N in harvested sod were similar for the two manure rates with and without added N for each species, but differed among turf species for each P (46 to 77%) and N (36 to 47%). The large amounts and percentages of manure P and N removed by sod harvest support the feasibility of this BMP in efforts to reduce nutrient loads on watersheds.

Manure and wastewater disposal on land holdings of concentrated animal feeding operations (CAFOs) can contribute to P accumulation on fields and subbasins of watersheds. Large soil P concentrations contribute to a large P index (Lemunyon and Gilbert, 1993) and to relatively large probabilities of P loss in surface runoff from waste-application fields of the CAFOs (Jain, 1996). On the Upper North Bosque River watershed in Texas, USA, elevated P and N concentrations were reported in several reservoir and stream sites (McFarland and Hauck, 1999). The P and N concentrations in storm water runoff from the watershed were positively correlated with the percentage of land area occupied by dairy waste-application fields on selected subbasins.

Many states have developed recommendations for P applications to prevent nutrient losses in surface runoff (Sharpley and Tunney, 2000). In addition, advisory committees have joined with regulatory agencies to establish total maximum daily loads (TMDLs) for P and other potential contaminants of bodies of water on impaired watersheds. For example, a TMDL approved for the Upper Bosque River mandated a 50% reduction in soluble reactive phosphorus loading on the watershed (Texas Natural Resource Conservation Commission, 2001).

The management of P loads on fields and watersheds according to agronomic and regulatory limits appears to be a simple matter of balancing P imports with exports. Yet, there are economic implications when constraints are imposed on rates of manure disposal on fields adjacent to animal production. In many areas dominated by animal agriculture, there is simply no economically viable alternative to land application (Daniel et al., 1998). The cost of transporting manure more than short distances from the site of production often exceeds its nutrient value and large-scale transportation of manure from clusters of livestock operations to crop-production areas is not generally occurring.

Turfgrass sod is a high-value commodity that offers the potential for using manure P and N from CAFOs. The large gross income per hectare of turfgrass sod could pay the costs of transportation and application of manure on sod-producing areas. Another option is sod production on waste-application fields near manure sources. Rather than accumulating on field surfaces, P in plants and manure residues within the harvested sod layer could be exported from waste-application fields and watersheds on which livestock sources of P are concentrated (Wilkinson, 1997). Texas regulations are emphasizing manure export to reduce P loading and achieve total maximum daily load standards on impaired watersheds (Texas House Bill 2699, House Committee Report, http://www.capitol.state.tx.us/tlo/billnbr.htm).

Composted sewage sludge and other sources of organic waste have long been used to amend soil for turfgrass establishment and growth (Angle, 1994). Compost rates up to 200 Mg ha^{-1} were incorporated into topsoil or left on the soil surface for production of Kentucky bluegrass (*Poa pratensis* L.) and red fescue (*Festuca rubra* L.). Seedling establishment rate and soil pH, cation exchange capacity, aggregation, organic matter, and water content were increased after compost applications (Murray, 1981). In contrast, soil bulk density and sod weight per area unit were reduced. Unfortunately, compost nutrient content and removal in sod components were not measured.

In addition to improvements in the soil layer that enhance turfgrass maintenance and regrowth after harvest, manure sources of P and other nutrients can en-

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Abbreviations: BMP, best management practice; CAFO, concentrated animal feeding operation; STP, soil-test phosphorus.

hance turfgrass recovery and quality when harvested sod is transplanted. The use of composted sewage sludge has increased the aesthetic quality of turfgrass compared with turf fertilized with ammonium nitrate (Angle, 1994). Compost amendments helped maintain turfgrass color during summer drought and the addition of compost during sod production enhanced the overall quality of turfgrass for 510 d after sod was harvested and reestablished. In addition, the slow release of nutrients from raw and composted sewage sludge avoided the surge of growth and associated mowing costs inherent to inorganic fertilizer applications (Angle, 1994).

The benefits of manure applications on turf lend support to the BMP of using and exporting manure P and N through turfgrass sod production. Yet, the amounts and proportions of manure P and N removed through sod harvests need to be evaluated. Rather than focusing on P export through hay or clippings alone, this research investigated the feasibility of removing surface applications of manure with the layer of harvested sod. The specific objectives were to (i) quantify total P and N removal in clippings and soil and plant components of sod harvests of three turf species and (ii) compare P and N amounts in sod components and clippings between P rates available from inorganic or manure sources of P, with and without supplemental N fertilizer.

MATERIALS AND METHODS

Plot Design and Management

Four replications of six treatments made up a randomized complete block design for each of three turf species. The six treatments comprised an unfertilized control, two manure rates applied with and without supplemental inorganic N fertilizer, and a treatment of inorganic sources only of P and N. Soil-test phosphorus (STP) concentrations comparable with an agronomic threshold (Sharpley and Tunney, 2000) provided sufficient P in the inorganic-only treatment. Manure rates, split between two dates, were applied to evaluate potential removal and export of P at STP concentrations up to an environmental threshold near 200 mg P kg^{-1} of soil for manure treatments (Table 1) (Sharpley and Tunney, 2000). 'Tifway' bermudagrass and '609' buffalograss were established at the Texas A&M University (TAMU) Turf Field Laboratory in College Station, TX. 'Reveille' bluegrass was grown at the TAMU Research and Extension Center near Stephenville, TX. Plot areas of bermudagrass and bluegrass were 13.5 m^2 and buffalograss plots were 11.4 m^2.

Bermudagrass and buffalograss were established in the exposed Eg horizon of a truncated Boonville soil (fine, smectitic, thermic Chromic Vertic Albaqualf). Washed sand was rototilled to a depth of 12 cm prior to application of treatments. Total rates of manure P (Table 1) were split between two dates of manure application for each turf species. The initial applications of fresh dairy manure comprised P rates of 103 and 212 kg P ha^{-1} on bermudagrass and 125 and 200 kg P ha^{-1} on buffalograss. The respective manure rates were broadcast on the soil surface before planting of bermudagrass sprigs and buffalograss plugs in April 1998. Manure was stored in a static pile before the second annual application on these two turf species during March 1999. The bluegrass was hydroseeded on a tilled Windthorst fine sandy loam (fine, mixed, thermic Udic Paleustalf) in October 1998. A commercial source of composted dairy manure (Texas Best Compost, Dublin, TX) was applied to bluegrass in an initial application after seedling emergence during March 1999 and during July 1999. The initial manure application provided P rates of 110 and 220 kg ha^{-1}.

Total P of manure sources was determined to calculate manure rates. In addition, subsamples taken during application were analyzed to verify actual amounts of P and N applied (Table 1). The available nutrients in soil were determined through sampling of plots to a 7.5-cm depth before each manure application. Inorganic sources of N fertilizer were applied to designated treatments in increments of approximately 50

Table 1. Amounts of total N and P applied and removed in plant and soil components of sod harvest and change in extractable NO_3^- and P in soil to the 7.5-cm depth remaining after sod harvest.

	Nitrogen			Phosphorus		
Treatment	Applied	Removed	Soil NO_3^-†	Applied	Removed	Soil P†
	kg ha^{-1}					
			'Tifway' bermudagrass			
Low manure‡	695	266b§	8.2a	208	76b	−10.5c
High manure	1402	561a	9.4a	419	219a	36.6a
Low manure + N¶	907	363b	10.2a	210	106b	6.8bc
High manure + N	1643	575a	10.2a	427	209a	20.7ab
Inorganic fertilization#	202	122c	9.4a	0	19c	−43.4d
			Buffalograss			
Low manure	861	330b	12.4bc	252	136b	11.8b
High manure	1707	641a	15.5b	500	264a	35.6ab
Low manure + N	1127	426b	14.1bc	255	159b	6.6b
High manure + N	1973	588a	21.0a	503	281a	61.8a
Inorganic fertilization	256	157c	9.8c	0	21c	−52.0c
			Bluegrass			
Low manure	246	112cb	−0.9a	163	112b	22.7bc
High manure	495	260a	−0.3a	327	245a	26.1ab
Low manure + N	438	170b	0.6a	164	123b	17.0bc
High manure + N	682	328a	0.9a	325	286a	45.1a
Inorganic fertilization	190	47cd	0.3a	0	9c	4.0c

† Change in extractable soil content between sampling dates prior to treatments and after sod harvest.
‡ Manure only applied to provide N and P at rates specified.
§ Numbers followed by the same letter within a column for each species are not significantly different ($P = 0.05$).
¶ Inorganic N fertilizer applied with manure to provide N and P at rates specified.
# Inorganic N and extractable soil P provided N and P.

kg N ha^{-1} on three or more dates prior to sod harvest. Three inorganic N applications were applied to bluegrass, four to bermudagrass, and five to buffalograss. One application of potash provided 100 kg ha^{-1} of K to the inorganic-only fertilizer treatment for each species. A composite of soil samples from all plots was analyzed to quantify available soil P to the 7.5-cm depth for bermudagrass (75 kg P ha^{-1}), buffalograss (93 kg P ha^{-1}), and bluegrass (31 kg P ha^{-1}) prior to application of treatments. Soil NO_3–N concentrations in the composite samples were very low (1 to 5 mg kg^{-1} soil) for the three turf species.

Small rates of Trimec–Southern [2,4-dichlorophenoxyacetic acid, potassium-2-(2-methyl-4-chlorophenoxy) propionate, and 3,6-dichloro-2-methoxybenzoic acid] were applied to control broadleaf weeds until sod was dense enough to prevent weed invasion. Hand weeding of plots minimized the need for other chemical weed control.

Sampling

Turf was mowed to 2.5 cm and clippings were collected when grass height reached 7.5 cm. Clippings were removed and sampled on eight dates for bermudagrass, six dates for buffalograss, and seven dates for bluegrass prior to sod harvests. Fresh weights of clippings for each plot were measured and a random grab sample was removed and weighed before and after drying. Grab samples were dried in a forced-air oven at 60°C for at least 48 h before weighing. Dried samples were first ground in a Thomas rotary mill (Arthur H. Thomas Co., Philadelphia, PA) to pass a 2-mm screen. Samples were further ground in a UDY Cyclone Sample Mill (UDY Corporation, Fort Collins, CO) to pass a 0.5-mm screen.

Sod was cut at a 2.5-cm depth for each species after a dense turf was established. Commercial cutting depths are near 1 cm for turf grown on fine-textured soil and rolled before cutting. Bermudagrass and buffalograss sods were harvested during July 1999 and bluegrass was cut during October 1999. A cup cutter was used to randomly sample four plugs, 10 cm in diameter, from the sod of each plot. After sampling, plants and attached soil were washed and separated in an acidified (pH = 4) solution. The wash solution was combined with soil and the plant and soil components were dried in a forced-air oven at 60°C. The plant parts of sod were ground with the same methods used for the clippings. After drying, the soil component was weighed and pulverized through a soil grinder (Custom Laboratory Equipment, Orange City, FL). The dried and ground soil and plant samples were digested and analyzed for total N, P, K, and NO_3–N (soil only).

Sample Analysis

Manure samples, clippings, and plant and soil components of sod were digested according to Kjeldahl procedures in which a 0.25-g portion of ground sample was gradually heated to 350°C in the presence of $LiSO_4$, H_2O_2, and Se in concentrated H_2SO_4 (Parkinson and Allen, 1975). After dilution, total P in digests was analyzed through inductively coupled plasma optical emission spectroscopy (ICP) by the Texas A&M University Soil and Forage Testing Laboratory. Total N in the digest was analyzed by a Technicon (Tarrytown, NY) Autoanalyzer II (Feagley et al., 1994; Isaac and Jones, 1970; McGeehan and Naylor, 1988).

Extractable or STP of soil sampled to the 7.5-cm depth was analyzed at the Texas A&M University Soil and Forage Testing Laboratory. The P was extracted in acidified ammonium acetate–ethylenediamine tetracetate (EDTA) (Hons et al., 1990) and the ICP was used to measure P in the filtered extract. The STP concentration quantified treatment effects on soil remaining after sod harvest. Similarly, STP was used previously to quantify both agronomic and environmental thresholds for agricultural soils (Sharpley and Tunney, 2000).

Nitrate nitrogen of ground soil samples and NH_3–N of manure were extracted with a modified version of Keeney and Nelson (1982). A 2-g scoop of soil or a subsample of fresh manure and 20 mL of 0.1 *M* KCL were mixed in a 160-mL plastic cup. The solution was shaken for 10 min at 185 oscillations per minute. Following shaking, the solution was filtered through Whatman (Maidstone, UK) No. 2 (or equivalent) filter paper. The filtrate was analyzed for NO_3–N with a Technicon 800 Autoanalyzer. The NO_3–N was analyzed through cadmium reduction, and the NH_3–N was determined colormetrically (Dorich and Nelson, 1984).

Statistical Analysis

The Statistical Analysis System (SAS) was used to analyze the data separately for each species (SAS Institute, 1993). Analysis of variance procedures were used to determine if amounts of P and N in turf clippings and sod components differed among treatments for each species. Fisher's test for least significant difference (LSD) was used to compare treatment means at the 95% confidence level. In addition, soil variables were compared between treatments to evaluate responses to manure and inorganic P and N sources. It was expected that no difference or possible growth enhancement would be observed among the manure and fertilizer treatments.

RESULTS AND DISCUSSION

Treatment Effects on Phosphorus Amounts in Sod

The P amounts removed in clippings and in plant and soil components of sod for bermudagrass (Fig. 1), buffalograss (Fig. 2), and bluegrass (Fig. 3) differed significantly among treatments ($P = 0.02$). Manure applications increased P amounts in plant components of sod compared with controls for the three turf species. In addition, applications of inorganic N fertilizer with the larger manure rate increased P amounts in clippings compared with control and fertilizer-only treatments for bermudagrass and bluegrass turf (Fig. 1 and 3). Yet, small variation of P amounts in clippings and plant components among treatments revealed limitations to P removal through plant uptake and growth (Fig. 1, 2, and 3).

Manure applications similarly increased P removal in the soil component of sod, but the P content in soil was 2 to 10 times greater than in plant components of sod for the three turf species (Fig. 1, 2, and 3). In previous studies of potted bermudagrass turf, P in residues of applied poultry litter was 10 times greater than in turf stubble and roots (Wilkinson, 1997). In the present study, corresponding increases between P in the soil component of sod and P rates in manure indicated soil P comprised dairy manure residues for each turf species.

Treatment Effects on Nitrogen Amounts in Sod

Similar to P, total N amounts in clippings and soil and plant components of sod differed among treatments ($P = 0.02$) for the three turf species. Greater N than P amounts in clippings and the plant component of sod

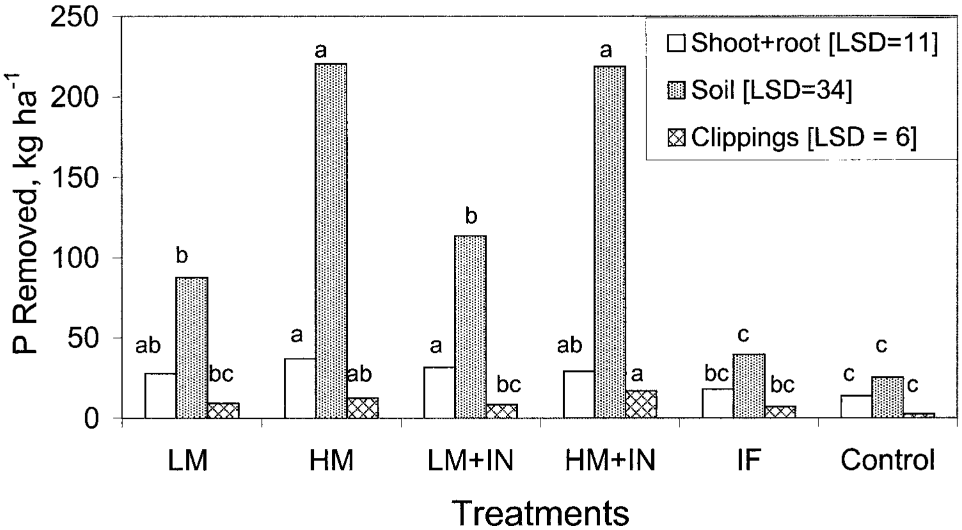

Fig. 1. The amount of P removed in bermudagrass clippings during production and in plant (shoot + root) and soil components of a single sod harvest for replicated manure and fertilizer treatments. The treatments comprised low manure (LM, 208 kg P ha^{-1}) and high manure (HM, 419 kg P ha^{-1}) rates without inorganic N, similar manure rates plus inorganic N (LM + IN and HM + IN), inorganic N fertilizer only (IF), and an unfertilized control. Bars representing clippings or a sod component with the same letter are not statistically different (P = 0.05).

were observed for all treatments (Fig. 4, 5, and 6). Larger plant requirements and uptake of N relative to P probably contributed to these differences. Total N amounts in bluegrass clippings and shoots and roots of sod were greater for the two manure rates with added inorganic N than manure without added N. The sum of manure and inorganic N sources contributed to more N accumulation than either N source alone (Fig. 6). Yet, variation of N in clippings and plant components among treatments was relatively small compared with variation of N in the soil component of sod for each turf species (Fig. 4, 5, and 6).

Relatively large increases of N in the soil component of bermudagrass (54%), buffalograss (43%), and bluegrass (63%) sod were observed in response to doubling of manure rates. For each turf species, N amounts in the soil component of sod ranged from 1.3 to 5 times greater than in the plant component of sod harvested from manure treatments. Doubling of manure rate increased N substantially more in soil than in plant components of sod. In contrast, comparative increases of N in soil and plant components of sod were similar after applications of inorganic N. Larger increases of N in soil than in plant components of sod that received manure indicated that soil contained most of the N from manure residues. The previous studies of potted bermudagrass indicated that N in manure residues, not soil N, made up most of N not removed in tops, stubble, and roots 112 d after applications of fresh or composted poultry litter (Wilkinson, 1997).

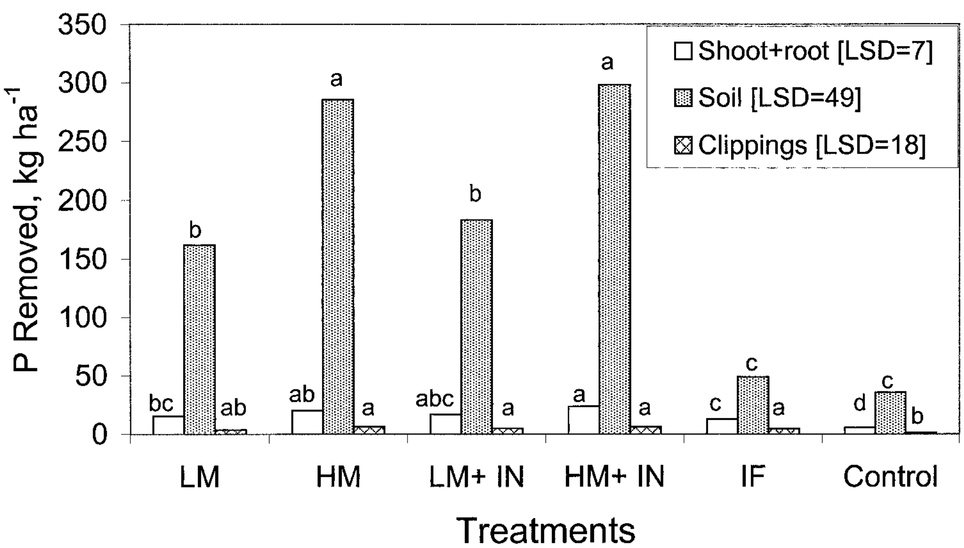

Fig. 2. The amount of P removed in buffalograss clippings during production and in plant (shoot + root) and soil components of a single sod harvest for replicated manure and fertilizer treatments. The treatments comprised low manure (LM, 252 kg P ha^{-1}) and high manure (HM, 500 kg P ha^{-1}) rates without inorganic N, similar manure rates plus inorganic N (LM + IN and HM + IN), inorganic N fertilizer only (IF), and an unfertilized control. Bars representing clippings or a sod component with the same letter are not statistically different (P = 0.05).

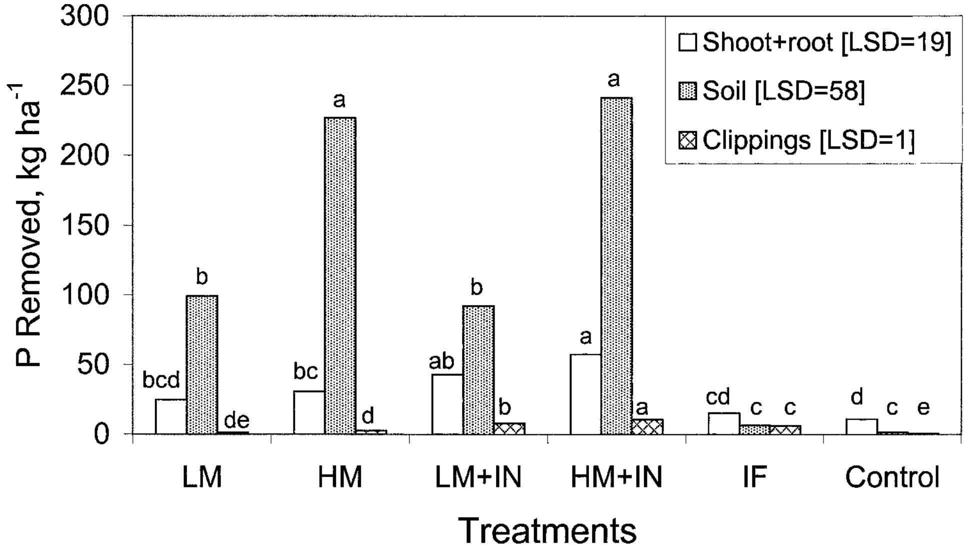

Fig. 3. The amount of P removed in bluegrass clippings during production and in plant (shoot + root) and soil components of a single sod harvest for replicated manure and fertilizer treatments. The treatments comprised low manure (LM, 163 kg P ha^{-1}) and high manure (HM, 327 kg P ha^{-1}) rates without inorganic N, similar manure rates plus inorganic N (LM + IN and HM + IN), inorganic N fertilizer only (IF), and an unfertilized control. Bars representing clippings or a sod component with the same letter are not statistically different (P = 0.05).

Phosphorus Removal in Sod

The feasibility of removing manure and fertilizer sources of P during a single sod harvest from each turf species was evaluated through comparisons between application rates and amounts in plant plus soil components of sod (Table 1). The starting or available P amounts in soil were discounted through subtraction of amounts in control sod from amounts removed in sod of other treatments. After discounting, the amounts of P removed in sod differed significantly ($P = 0.01$) among treatments comprising different rates of manure and inorganic sources of P. The amounts removed in sod were proportional to P amounts applied prior to harvests (Table 1). Yet, percentages of applied P removed in sod of a selected turf species were similar between the two manure rates with and without inorganic N. Of the P applied in manure, 46% was removed in sod of bermudagrass, 57% in sod of buffalograss, and 77% in sod of bluegrass. Relatively small P amounts in clippings of buffalograss (Fig. 2) contributed to the larger percentage of P removed in buffalograss than in bermudagrass sod. The application of composted manure could have contributed to greater P removal in bluegrass sod than occurred after fresh manure applications to the bermudagrass and buffalograss. Although no P was applied to the treatment receiving inorganic-only fertilizer, application of N fertilizer contributed to net P removal in sod after discounting P removed in control sod.

In previous studies of potted bermudagrass turf, substantially larger recoveries of P in stubble, roots, and

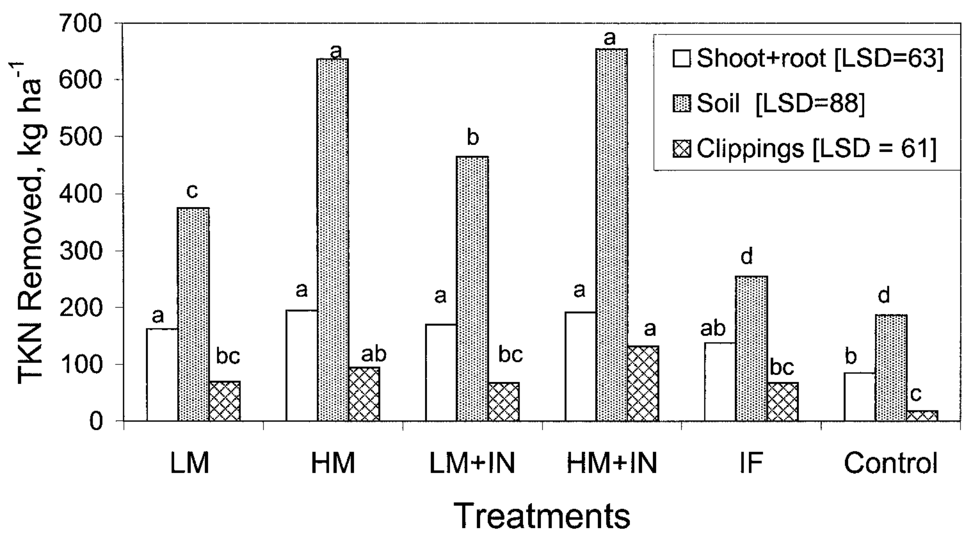

Fig. 4. The amount of N removed in bermudagrass clippings during production and in plant (shoot + root) and soil components of a single sod harvest for replicated manure and fertilizer treatments. The treatments comprised low manure (LM, 695 kg N ha^{-1}) and high manure (HM, 1402 kg N ha^{-1}) rates without inorganic N, similar manure rates plus inorganic N (LM + IN and HM + IN), inorganic N fertilizer only (IF), and an unfertilized control. Bars representing clippings or a sod component with the same letter are not statistically different (P = 0.05).

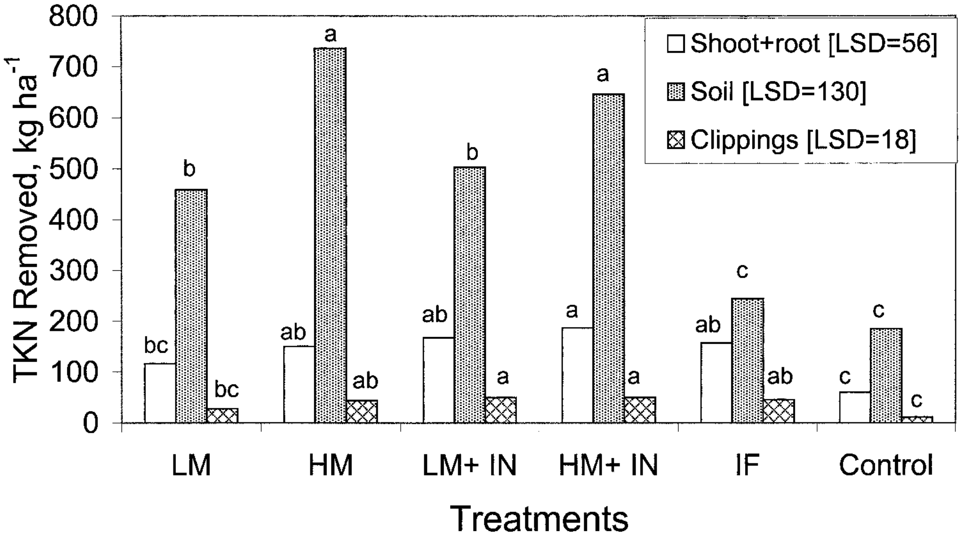

Fig. 5. The amount of N removed in buffalograss clippings during production and in plant (shoot + root) and soil components of a single sod harvest for replicated manure and fertilizer treatments. The treatments comprised low manure (LM, 861 kg N ha^{-1}) and high manure (HM, 1707 kg N ha^{-1}) rates without inorganic N, similar manure rates plus inorganic N (LM + IN and HM + IN), inorganic N fertilizer only (IF), and an unfertilized control. Bars representing clippings or a sod component with the same letter are not statistically different (P = 0.05).

manure residue were observed for composted in comparison with fresh poultry-litter applications on potted bermudagrass turf (Wilkinson, 1997). Despite negligible increases in soil, only 37% of P applied in fresh poultry litter was recovered in grass components and manure residues of potted bermudagrass turf at a P rate near 400 kg ha^{-1}. The amount and downward mobility of organic forms of P in fresh poultry or dairy manure could contribute to greater P leaching out of the sod layer than occurs for composted manure sources (Sims et al., 1998). Even smaller recoveries of P sources (≤20%) occur when plant tops only of forage bermudagrass are harvested after fresh manure applications (Sanderson and Jones, 1997).

Applied Nitrogen Removal in Sod

Similar to P, N application rates were compared with the sum of N amounts in plant and soil components of sod (Table 1). The N amounts in unfertilized sod (control) were subtracted from amounts in sod from manure and fertilizer treatments to discount soil N available before treatments were started. The amounts of N removed in sod differed significantly (P = 0.01) among the treatments comprising different rates of manure and inorganic sources of N. The amounts removed were directly dependent on the amounts applied during the period preceding sod harvest (Table 1). Yet, the percentages of N recovered from a particular N source were similar. Of the treatments receiving fresh or stored

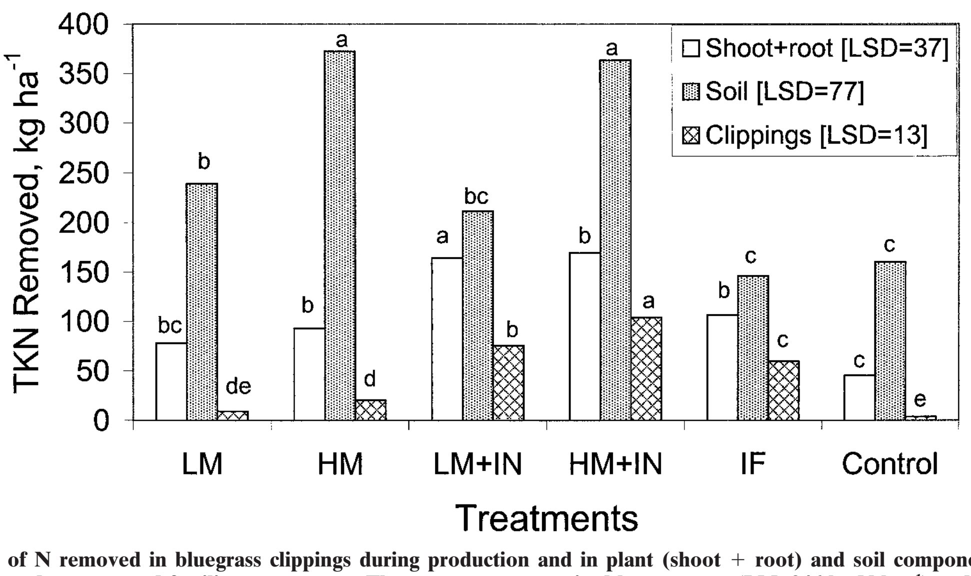

Fig. 6. The amount of N removed in bluegrass clippings during production and in plant (shoot + root) and soil components of a single sod harvest for replicated manure and fertilizer treatments. The treatments comprised low manure (LM, 246 kg N ha^{-1}) and high manure (HM, 495 kg N ha^{-1}) rates without inorganic N, similar manure rates plus inorganic N (LM + IN and HM + IN), inorganic N fertilizer only (IF), and an unfertilized control. Bars representing clippings or a sod component with the same letter are not statistically different (P = 0.05).

manure only on bermudagrass and buffalograss, 37 to 40% of the applied N was recovered in sod. Similarly, 30 to 39% of N applied as both manure and inorganic N fertilizer was removed in sod of these two turf species. In previous studies of potted bermudagrass turf, N rates similar to those of the fresh dairy manure in the present study were applied as fresh poultry litter (Wilkinson, 1997). Of N applied as fresh poultry litter, only 21 to 34% was removed in the total for stubble, roots, and manure residue from pots.

The percent N removal within sod components for N applied as inorganic fertilizer only on bermudagrass and buffalograss (59–61%) was greater than N applied through manure sources only (Table 1). Greater removal of inorganic N of fertilizer than N of manure applications was expected because fertilizer and soil NO_3–N were soluble and largely available for root uptake. When N amounts in sod were added to those of clippings (Fig. 4 and 5), the percentage removal of applied inorganic N was comparable with that of tops, stubble, and roots after fertilizer applications on potted bermudagrass turf (Wilkinson, 1997). Similar recoveries of fertilizer N have been reported for annual harvests of a forage bermudagrass (*Cynodon dactylon* L. Pers. 'Coastal') (Matocha et al., 1973), which comprised N in tops only.

The amounts of N applied as composted dairy manure and removed in bluegrass sod were less than amounts applied in fresh manure and removed in bermudagrass and buffalograss sod (Table 1). The N amounts removed in bluegrass sod differed significantly ($P = 0.01$) among N rates and sources and were proportional to amounts applied. Yet, the percentages of N removed in sod were similar for treatments that received manure only (43 and 53%) and greater than bermudagrass and buffalograss. Additions of inorganic N with manure did not significantly increase amounts or percentages of applied N in the sod harvest of bluegrass.

Composting of dairy manure before application on the bluegrass could have reduced N losses from the sod layer compared with fresh and stored manure applications on the other two turf species. The previous studies of potted bermudagrass indicated that composting of poultry litter before applications substantially increased the percentage of N recovered in stubble, roots, and manure residue compared with fresh poultry litter (Wilkinson, 1997). Volatilization losses of NH_3 from the fresh dairy manure in the present study could have contributed to greater N loss and reduced N recovery in sod of the bermudagrass and buffalograss. Sampling of the fresh manure during and 24 h after application revealed a 94% reduction of NH_3–N concentration under field conditions. Sanderson and Jones (1997) previously reported up to 35% loss of total N from fresh dairy manure, presumably as ammonia volatilization, under field conditions.

Discounting N removed in the sod harvest from the control and excluding N in clippings, relatively small amounts of N were removed in bluegrass sod when inorganic N only was applied (Table 1). Yet, the combination of N in clippings and N in the sod harvest for the treatment fertilized with inorganic N did yield a percent removal comparable with that of N removed in sod of manure treatments. Irrigation was applied weekly rather than daily to replace evapotranspiration of bluegrass. Large and infrequent water applications could have contributed to leaching of inorganic N forms and reduced NO_3–N in concentrations in the sod layer of the Windthorst fine sandy loam.

Extractable Phosphorus and Nitrate Nitrogen in Soil after Sod Harvest

Amounts of STP and NO_3–N within the 7.5-cm depth were measured before manure and fertilizer were applied and after sod harvest. The change in P amount between the two sampling dates differed among treatments ($P = 0.01$) (Table 1). The larger manure rate, with or without inorganic N fertilizer, contributed to greater STP gains in soil remaining after sod harvests than either the smaller manure rate or the treatment fertilized with inorganic N alone (Table 1). These treatment differences were consistent across the three turf species.

The increase in the NO_3–N content of the 7.5-cm soil layer remaining after sod harvest differed significantly among treatments applied to buffalograss. The larger manure rate plus inorganic N fertilizer contributed to greater increases in soil NO_3–N than other treatments. Five applications of inorganic N on the fertilizer-only treatment for buffalograss contributed to increases of NO_3–N within soil remaining after sod harvest.

Application of fertilizer N only reduced STP within the 7.5-cm depth of soil remaining after harvest of buffalograss and bermudagrass sod. These STP reductions during sod production with inorganic N only were attributed to P removal in clippings and sod and reaction of inorganic P with clay in the 5- to 7.5-cm depth of the truncated Boonville soil. The sum of STP reductions for the fertilizer-only treatment and STP increases for each manure treatment provided estimates of net P additions of manure to soil remaining after harvest of sod. The percentage of applied manure P available as STP in soil remaining after sod harvests averaged 19% for bermudagrass, 22% for buffalograss, and 10% for bluegrass.

Extractable NO_3–N and P contents of soil remaining after sod harvests can result from previous mineralization of manure P and N during the period of sod production. Yet, concentrations are not indicative of potential mineralization of the organic P remaining in soil after sod harvest (Haney et al., 2001). Previous estimates of decay series for dairy manure (Klausner et al., 1994) and of bermudagrass uptake of N from manure (Sanderson and Jones, 1997) indicated that approximately 10% of the manure N in soil could be available for the next sod crop. The mineralization and availability of manure P to the next sod crop is expected to be comparable with manure N (Sanderson and Jones, 1997). Yet, mineralization and plant uptake will not be necessary for removal of P and N of manure residues within the next layer of harvested sod.

Implications in Phosphorus and Nitrogen Management

The comparative amounts of P and N among clippings and plant and soil components of sod illustrated the principal advantage of exporting manure P and N through sod. As manure rates doubled, increases in P and N removal were most pronounced for the soil component of sod, which included manure residues. Increases of P and N amounts in clippings and in shoots and roots of sod were relatively small compared with the increases in the soil component. Similarly, annual forage harvests of Coastal bermudagrass overseeded with wheat (*Triticum aestivum* emend Thell) removed only 103 of 721 kg ha^{-1} of total P applied as dairy manure over 4 yr (Sanderson and Jones, 1997).

The corresponding increases between P rates applied in manure and P removal in sod will help CAFOs and turf producers comply with mandates for reduced nutrient loading on fields and watersheds. This BMP, which removes manure residue and P and N in direct proportion to application rates, can raise the regulatory upper limit for P and N amounts applied and removed through annual crop harvests. Previous regulatory limits were based on expected P and N amounts in aerial parts of plants. These limits could be increased substantially through removal of manure residues with the soil component of sod harvests. Moreover, increasing the rates of inorganic N applied with composted manure to levels greater than the present study could increase turf growth rates and enable harvest of more than one sod crop per year. The 200 kg P removed in 1 ha of bermudagrass sod represents the total P excreted annually in the manure of 10 dairy cows (Van Horn et al., 1994).

Composting of manure prior to application avoided odors, volatilization losses of NH_3–N, and high counts of pathogenic microorganisms associated with surface applications of fresh dairy manure. In addition, the dried, granular texture of composted manure was easier to mechanically dispense on plots. Yet, incorporation to a soil depth of 15 cm prior to turf establishment would overcome problems identified for fresh manure and would allow application of larger P and N rates than surface applications. Several turf crops could be produced to remove and export the layers of P and N incorporated from one large manure application.

Large amounts of manure P and N can be exported through sod harvests, but P and N transport in surface runoff during sod production and after transplanting of sod needs to be evaluated for this BMP. In addition, P and N losses to ground and surface waters through leaching and subsurface drainage could occur. Finally, the costs and benefits of manure sources of P and N need to be quantified in relation to budgets for turf and dairy production and environmental compliance.

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