MANAGEMENT OF NITROGEN AND COMPOSTED BIOSOLIDS TO CYCLE NUTRIENTS AND ENHANCE ENVIRONMENTAL QUALITY DURING PRODUCTION AND AFTER TRANSPLANTING TURFGRASS SOD

A Thesis

by

RONNIE WAYNE SCHNELL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2007

Major Subject: Agronomy

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Approved by:

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ABSTRACT

Management of Nitrogen and Composted Biosolids to Cycle Nutrients and Enhance
Environmental Quality During Production and After Transplanting Turfgrass Sod.
(May 2007)
Ronnie Wayne Schnell, B.S., Sam Houston State University
Chair of Advisory Committee: Dr. Donald M. Vietor

Land application of large, volume-based rates of municipal biosolids (MB) enhances soil physical properties and provides an alternative to disposal in landfills. Yet, topdressing or incorporation of the volume-based rates can increase non-point source losses of sediment and nutrients from excavated soils to surface waters. Research objectives were developed to evaluate the options for cycling of MB through turfgrass sod during production and after transplanting. The first objective was to compare the production of Tifway bermudagrass sod between fields grown with and without MB under increasing rates of supplemental fertilizer N. The second objective was to compare runoff losses between soils constructed with and without MB before planting to sprigs or sod transplanted from turfgrass grown in soil with and without incorporation of MB.

Incorporation of 25% by volume of MB in soil enhanced ($p < 0.001$) turfgrass coverage of the soil surface compared to soil without MB. In addition, amending soil with MB reduced wet and dry sod weights ($p < 0.001$) and increased soil water content ($p < 0.001$) at harvest compared to sod without MB. Runoff concentrations and mass loss of total dissolved P (TDP) were significantly greater ($P=0.001$) for MB-amended compared to un-amended sod. In addition, a linear relationship ($R^2 = 0.94$) was observed between water extractable soil P within the 0- to 2-cm depth and concentrations and mass loss of TDP in runoff. Similarly, runoff loss of NO_3-N was greater ($P = 0.05$) for soil mixed with 25% by volume of MB than soil alone and variation of NO_3-N loss among treatments was directly related to soil NO_3-N concentration within the 0- to 5-cm depth. In contrast, runoff concentrations of NH_4-N were directly related to inputs of N from turf clippings returned to soil rather than soil NH_4-N concentrations. Total Kjeldahl N (TKN) concentration in runoff was unrelated to soil N concentrations, but was linearly related to mass loss of sediment in runoff. Transplanted sod reduced sediment loss compared to sprigged soil during turfgrass establishment and MB-amended soil reduced sediment loss compared to soil without MB. In addition, the MB imported in sod or incorporated in soil before sprigging increased soil organic carbon and mean soil water content compared to sod or soil without MB over a 92 day period. Incorporation of MB within soil prior to planting fertilizer grown turfgrass sod enhanced water conservation and reduced nutrient loss compared to planting MB-grown sod on un-amended soils.

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CHAPTER I

INTRODUCTION

The system for cycling composted municipal biosolids (MB) to sod farms near cities and back to urban landscapes in transplanted sod accomplishes major tenets of sustainable agriculture. The system makes the most of nonrenewable resources at the interface between agricultural lands and expanding cities. The use of urban waste streams expands the natural resource base for agriculture, connects and integrates nutrient cycles between urban and agricultural landscapes, and produces a sod product that adds value to composted MB. Yet, additional research is needed to develop management practices for cycling of composted MB through sod that will enhance environmental quality and sustain the economic viability of farm operations.

The benefits of cycling composted MB from cities to turfgrass produced on agricultural land nearby include enhanced soil and water conservation during production and after sod is transplanted back to cities. Application of composted MB increases soil organic matter, improves water and nutrient retention, and enhances turfgrass establishment, growth and quality (Cisar, 1994, McCoy 1998). In addition, topdressing or incorporation of 25% by volume of composted MB to low quality soil can provide enough P and other essential nutrients to meet turfgrass requirements during

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This thesis follows the style of Journal of Environmental Quality.

production and after transplanting of sod (Hansen, 2005). Nutrients available from MB residues in transplanted sod reduce inorganic fertilizer requirements during sod establishment and potential runoff losses of soluble fertilizer sources of N and P (City of Austin, 2005).

Mineralization of organic N and P in residues of MB within sod can maintain turf color during production and after transplanting of sod (Garling and Boehm, 2001). In contrast, high C:N ratios of some sources of composted MB can immobilize N and delay green-up (Linde and Hepner 2005). Previous research indicates composted MB amendments can outperform one-time applications of inorganic fertilizer for establishment and development of turfgrass color and density (Linde and Hepner 2005, Rainey 2004). Yet, NO3-N concentrations and mineralization rates for organic N in composted MB or amended soil are typically not sufficient to achieve the rapid turfgrass establishment and recovery rates desired for sod production.

The benefits of cycling composted MB to sod produced on agricultural land and back to urban landscapes in transplanted sod can be offset by environmental risks. Repeated applications of composted MB at rates that meet the N requirements of crop plants can lead to undesirable accumulations of soil-P and metals in the sod layer (Cogger et. al. 2001). Although topdressing of composted MB during turfgrass production optimizes export of nutrients in the sod harvest that follows, surface concentrations of soil P can increase above regulatory limits. Increases in soil test P concentration within the sod layer are positively correlated with the concentrations of P in runoff water (Vietor et al., 2004). Dissolved P concentration in runoff of sod after transplanting from fields top-dressed with composted MB (1.2-cm depth) tend to be greater than turfgrass sprigged in soil mixed with the same volume (25% v/v) of composted MB (Hansen, 2005).

The total and extractable amounts of P and other nutrients in volume-based rates of composted MB need to be evaluated in relation to turfgrass requirements. The turfgrass requirements span both sod production and the duration of sod life after transplanting on urban landscapes. The P and other nutrients in composted MB can substitute for inorganic fertilizer applications and reduce energy costs associated with manufacture and transportation of the commercial fertilizers typically used on turfgrass (Brown and Leonard 2004). Regulatory or other P-based limits on composted MB rates allowed for turfgrass sod production could make it necessary to increase rates of inorganic fertilizer P applied after manure-grown sod is transplanted.

Although both productivity and economic viability of sod production can be enhanced on land near urban developments, MB cycling through sod will be sustainable only if environmental quality is protected. The purpose of this project is to evaluate the effects of MB on sod production and the environmental risks associated with contrasting practices for MB management during turfgrass establishment on urban landscapes. Imports of composted MB to urban landscapes through turfgrass sod rather than direct application to urban landscapes will likely reduce environmental risks and improve quality of turf.

An integrated system for cycling composted MB through turfgrass sod during production and transplanting was developed and evaluated. Composted MB was applied to increase soil organic matter, improve water and nutrient retention, and enhance turfgrass establishment, growth and quality (McCoy 1998). Replicated field experiments compared establishment rates of turfgrass sod amended with composted MB to sod grown with inorganic fertilizer only. In addition, interactions between fertilizer N rate and composted MB was evaluated. Turfgrass cover and quality, soil physical and chemical properties, and export of nutrients through sod harvests were quantified to evaluate composted MB as a resource for sod production. The replicated sod production plots were used to evaluate how natural biological cycles affect the fate of nutrients or organic matter from fertilizer, composted MB, and turfgrass biomass. Observations of turfgrass and soil properties demonstrated how cycling and export through turfgrass sod transforms urban waste into a valuable soil amendment. The integration of nutrient cycling, turfgrass sod production, and transplanting and marketing of sod in urban developments can create a system that enhances sustainability for both urban and agricultural communities.

After sod harvest, cycling of composted MB through turfgrass sod transplanted on urban landscapes is expected to conserve soil, water and nutrients compared to traditional seeding or sprigging methods. A replicated field experiment evaluated effects of contrasting turfgrass establishment practices on water retention, runoff, and quality for constructed urban soils. Sod transplanted from turf grown with and without incorporated composted MB was compared to turfgrass that is sprigged in a soil layer with or without incorporated compost. In addition, the sod with or without composted MB was transplanted on a soil layer prepared with and without incorporation of compost. The replicated experiment showed how cycling and import of composted MB with transplanted sod makes effective use of soil, organic matter, and nutrients and protects water quality. The conservation of these natural resources will enhance the quality of the environment, which is essential for the sustainability of urban landscapes. In addition, the use of organic amendments is expected to reduce applications of soluble inorganic fertilizers on transplanted sod and limit N and P losses through runoff compared to sod grown with inorganic fertilizers alone (Vietor et al., 2004).

CHAPTER II

EFFECTS OF COMPOSTED BIOSOLIDS AND NITROGEN ON TURFGRASS ESTABLISHMENT AND SOD HARVEST

Municipal sources of organic amendments, including composted MB, can be applied to improve soil physical and chemical properties and turfgrass establishment, growth and quality (McCoy 1998). Yet, the effects on turfgrass and soil properties will be dependent on the composition and quality of the composted MB source. High carbon to nitrogen ratio of composted MB limits turf growth rate and color due to immobilization of N (Linde and Hepner 2005). Previous reports indicate N mineralization rate is sufficient to warrant only partial reductions in fertilizer N rate (Flavel and Murphy, 2006). Fertilizer N rates need to be managed in relation to rates of selected compost sources to achieve rapid turfgrass growth and minimize the duration between sod harvests.

Quantifying turfgrass coverage is often accomplished through frequent subjective analysis by trained evaluators or the line-intersect method (Richardson et al. 2001). These methods are very time consuming and labor intensive, which may limit the frequency and precision of measurements taken. The high degree of random variation for both methods makes the results difficult to reproduce and often masks subtle differences among treatments. Another option for quantifying turfgrass coverage is to record the progression of turfgrass coverage with digital photographs and analyze with digital image analysis. Richardson et al. (2001) demonstrated that analysis of digital images with Sigma Scan (SPSS, Inc.) software could provide precise and rapid estimates of turfgrass coverage.

Digital image analysis was highly correlated with alternative methods of quantifying turfgrass coverage, yet avoided human bias in the analysis. Sigma Scan software is commercially available, but ImageJ software is available as an on-line applet or as a free downloadable program. ImageJ was created by Wayne Rasband of the National Institute of Mental Health. ImageJ and user created plug-ins are available at http://rsb.info.nih.gov/ij/. ImageJ software along with the threshold color plug-in is capable of performing analysis of turfgrass coverage similar to the method described by Richardson et al. (2001).

In addition to improving soil and sod properties during production, harvest and transplanting of MB-grown sod cycles organic matter and nutrients back to urban landscapes. Previous studies of manure cycling through sod harvests indicated up to 77% of total P and 47% of total N in surface applications of composted dairy manure were exported in a single sod harvest (Vietor et. al. 2002). Incorporation of composted MB within a 0 to 5-cm depth is expected to reduce the portion of applied nutrients removed in a single sod harvest (2-cm depth) compared to top-dressed compost. Smaller percentages of the incorporated MB are exported, but higher N and P rates in incorporated, volume-based MB applications enable N and P exports comparable to top-dressed MB. In addition, repeated sod harvests will remove additional portions of incorporated MB. A collateral benefit of compost incorporation is reduced potential runoff loss of nutrients after the harvested sod layer is transplanted. The portions of MB nutrients exported or lost during sod production will be used to evaluate current recommendations for volume-based rates of composted MB on turfgrass.

Objectives

I. Develop a method for evaluating turfgrass coverage among establishment treatments.

II. Evaluate effects of composted MB and fertilizer N on turfgrass coverage.

III. Quantify physical properties of sod and export of applied N and P in sod layer.

Materials and Methods

The design will comprise four replications of a factorial arrangement of three rates of inorganic fertilizer N with and without incorporation of composted MB during establishment of Tifway (Table 1). The composted MB will be incorporated to make up 25% by volume of soil within a 5-cm depth. The Tifway bermudagrass (*Cynodon dactylon* L. Pers. X *C. transvaalensis* Burtt-Davey) plots (3.0 m x 4.5 m) grown without composted MB received 30 kg ha^{-1} of P and 200 kg ha^{-1} of K as inorganic fertilizer before sprigging. The three inorganic N rates (0, 50 and 100 kg ha^{-1}) were assigned randomly to treatments with or without composted MB. The fertilizer N rates were applied shortly after sprigging and at monthly intervals when ambient temperatures favor rapid turfgrass growth. Turf was mowed weekly to a 2.5-cm height and clippings returned to the soil surface. Univariate analysis of variance was performed with SPSS 13.0 (SPSS Inc., Chicago, Illinois) to compare the factorial combinations of N rate with and without composted MB.

Table 1. Descriptions of treatments with and without MB amendments at varying rates of N.

Treatment	Fertilizer N Rate (kg ha^{-1})		
	0	50	100
No Composted MB	NC-0	NC-50	NC-100
25% by volume MB	WC-0	WC-50	WC-100

Digital photographs were taken throughout the establishment period of turfgrass. The images were digitally analyzed with ImageJ software using the "threshold color" plugin to determine the percent cover of turfgrass in each plot. The threshold color plugin was used to isolate the green or turfgrass portion of the plot. The image was converted to 8-bit and the threshold adjusted to include the entire "turf portion" of the image, already isolated by threshold color. Images were cropped to include only plot areas in analyses. The turfgrass area within plots was converted into red pixels and all other portions of the image were converted into white pixels. The software analyzed and quantified the proportion of red pixels, or turfgrass, in the selected area. ImageJ was calibrated with regression analysis of digital images of Tifway bermudagrass sod squares of known dimensions that were placed onto bare soil to represent from 0 to100% turfgrass coverage (Fig. 1).

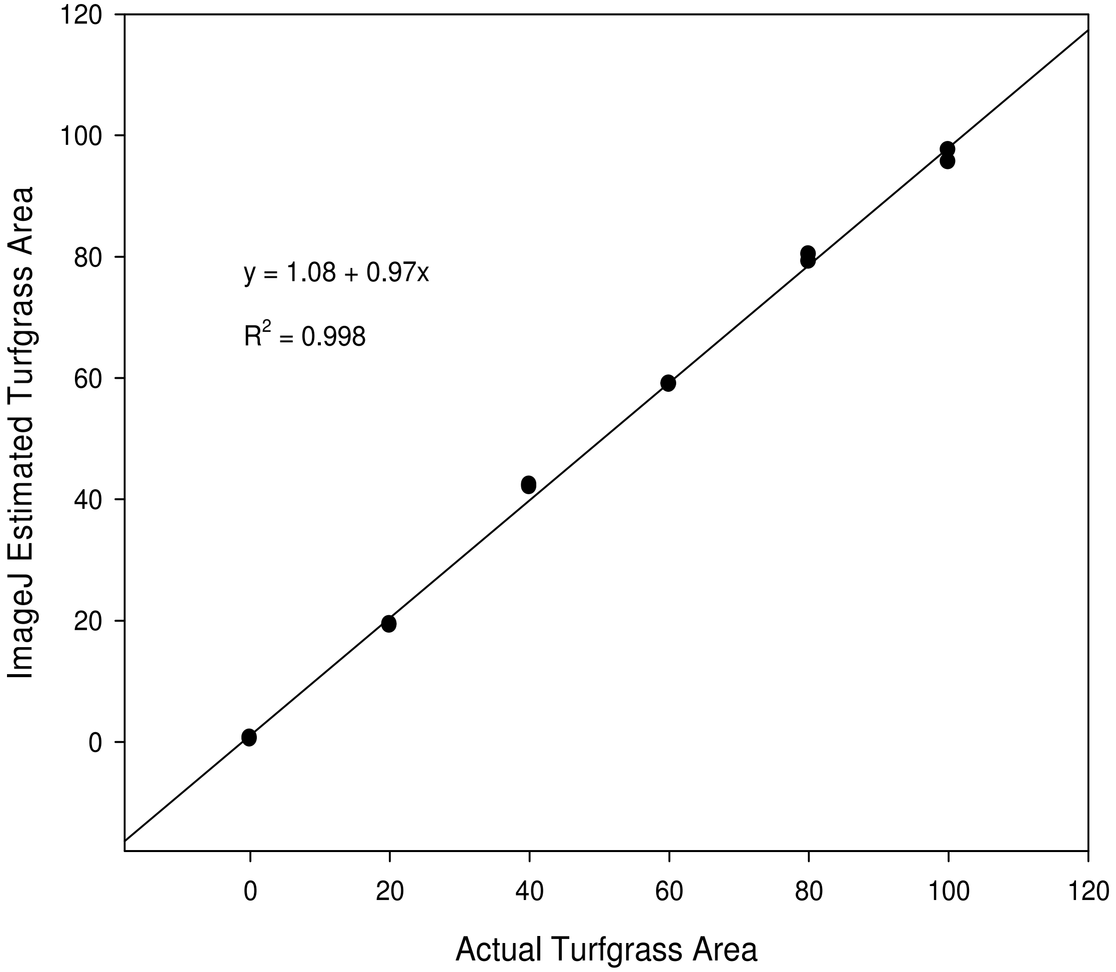

Figure 1. Relationship between actual turfgrass area and ImageJ estimated turfgrass area.

Soil and composted MB were sampled before incorporation of composted MB or planting of turfgrass. Total N, P, and organic C; Mehlich-3 extractable P and cations; KCl-extractable NO_3-N and NH_4-N; and water-extractable P were analyzed by Texas Cooperative Extension Soil, Water, and Forage Testing Laboratory. The composted MB was mixed with soil to achieve 25% by volume and the volumes were weighed to quantify the mass of nutrients applied. The harvested sod layer and 5-cm soil depth below sod was sampled at harvest and analyzed to quantify total and extractable concentrations and mass of N, P, and organic C as described for soil and compost. Soil was washed from turfgrass of samples from the harvested sod layer in distilled water. The soil combined with wash solution and the turfgrass were dried, weighed, ground, and analyzed. Total N and P in turfgrass and soil total N, P, and organic C were quantified. In addition, soil concentrations of extractable P and cations, NO_3-N and NH_4-N, and water-extractable P was analyzed for the sod layer and depth below sod.

Turfgrass, composted MB, and soil samples were digested according to a modified Kjeldahl method. The NO_3-N and NH_4-N in composted MB and soil were extracted in 1M KCl. The concentrations of total N in digests and extractable NH_4-N were measured colorimetrically (Dorich and Nelson, 1984; Isaac and Jones, 1970). The NO_3-N was analyzed through cadmium reduction (Keeney and Nelson, 1982). Inductively coupled plasma optical emission spectroscopy (ICP) was used to measure total P in digests. The Mehlich 3 method was used to extract plant-available P and cations (K, Ca, Mn, Fe, Cu, and Zn) from composted MB and soil samples for ICP analysis (Mehlich, 1984). For water extracts of composted MB and soil, 4 g soil of soil was extracted in 40 ml distilled water for 1 hour on an orbital shaker. The dissolved reactive P in water extracts of composted MB and soil was determined colorimetrically within 24 hours of filtering (Pote and Daniel, 2000).

The General Linear Model (univariate) procedure in SPSS was used for analysis of variance (ANOVA) and mean separations among treatments. The ANOVA was used to evaluate treatment effects on soil water content and total N and P export in sod at harvest.

In addition, variation of soil concentrations of NO_3-N and NH_4-N, Mehlich-3 extractable P, cations, and water-extractable P among treatments was analyzed for the sod layer and depth below sod. A T-test was used to compare means for sod physical properties between MB-amended and un-amended soils.

Results

Turf Establishment

The percent turfgrass coverage at 2 weeks was greater ($p < 0.001$) for treatments receiving composted MB than for treatments without MB (Fig. 2). Turfgrass coverage ranged from 42 to 47% for MB-amended treatments and 24 to 34% for treatments without MB. The MB-amended treatments averaged 64% greater coverage than un-amended treatments at the 2-week sampling. The greater coverage could be attributed, in part, to greater sprig survival. Greater water retention in MB-amended soil could have reduced desiccation of sprigs compared to soil without MB.

Fertilizer N application did not start until the third week after planting and differences among treatments due to fertilizer N were not evident until week eight. At 8 weeks, turf coverage was 57, 67, 68, 70, 81 and 83 % for NC-0, NC-50, NC-100, WC-0, WC-50, and WC-100, respectively. Turfgrass coverage was 21% greater ($p < 0.001$) for MB-amended treatments than un-amended treatments. In addition, coverage was greater ($p < 0.001$) for treatments receiving fertilizer N than turfgrass established without fertilizer N. For treatments without MB, coverage was 18% greater with than without the topdressing of fertilizer N at 3 weeks. For MB-amended treatments, application of 50 or 100 kg fertilizer N ha^{-1} increased percent coverage 16% compared to without fertilizer N. Percent turf coverage was similar between fertilizer N rates of 50 and 100 kg N ha^{-1}. Turf coverage was greater ($p < 0.01$) for treatments with both MB and fertilizer N (50 and 100 kg ha^{-1}) than for MB only (0 kg N ha^{-1}) ($p < 0.01$) or the control without MB or fertilizer N. After week eight (Nov. 30), low temperatures prevented turfgrass growth until spring green-up.

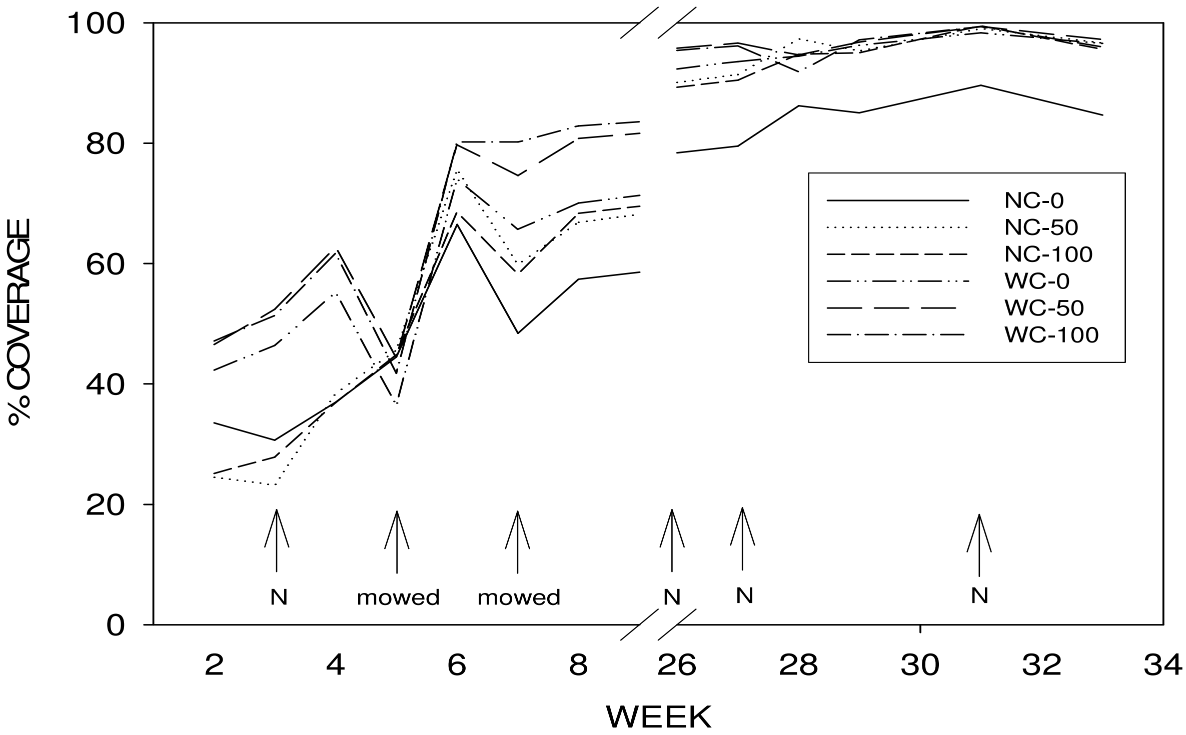

Figure 2. Progression of turfgrass coverage by week for all treatments determined by ImageJ analysis of digital photographs.

At week 27 after planting, percent turf coverage was 80, 91, 90, 94, 97, and 96 % for, respectively, treatments NC-0, NC-50, NC-100, WC-0, WC-50, and WC-100) (Fig. 2). Turf coverage for treatments amended with MB was 10 % greater ($p < 0.001$) than those without MB. In addition, fertilizer N applications contributed to greater ($p < 0.001$) coverage than treatments without fertilizer N. Combining MB with either rate of fertilizer N (50 and 100 kg ha^{-1}) increased percent coverage ($p < 0.005$) compared to fertilizer N alone (50 and 100 kg ha^{-1}). Yet, percent coverage did not differ between the high (100 kg ha^{-1}) and moderate (50 kg ha^{-1}) rates of fertilizer N . For the sampling date 31 weeks after planting, coverage was 98% or more and significantly greater ($p < 0.001$) for treatments amended with MB or fertilizer N than Tifway established without either nutrient source.

Over all sampling dates, rates of coverage were greater ($p < 0.001$) for MB-amended soil than un-amended soil with or without fertilizer N. No significant interaction between MB and N fertilizer was observed, yet both amendments did improve turfgrass coverage on the date's sampled compared to un-amended soils. Throughout the establishment period, the high rate of N (100 kg N ha^{-1}) provided no increase in rate of establishment over the moderate rate of N (50 kg N ha^{-1}). Results indicate that 50 kg N ha^{-1} is near the optimum rate of N for Tifway establishment with or without the use of composted MB.

Sod Properties

In addition to increasing turfgrass coverage rates, incorporation of 25% by volume MB reduced sod weight and increased soil water content at sod harvest. Although sod established without fertilizer N (0 kg N ha^{-1}) was harvested later and at a deeper depth (2.7

cm) than that grown with supplemental N, lower sod weight was observed for MB amended-sod without or with the four applications of fertilizer N. Mean wet weight of sod amended with composted MB (13.8 kg m^{-2}) was 19% less ($p = 0.001$) than sod grown without MB (17.0 kg m^{-2}) (Table 2). Mean dry weight was 33% lower ($p < 0.001$) for the MB-amended sod. Lighter sod is easier to handle and less expensive to transport. In addition, the reduced sod weights indicate less native soil is removed from production sites, which conserves soil and extends the longevity of sod production fields.

Greater ($p < 0.001$) mean water content (w/w) for the sod amended with composted MB (41.5%) than for un-amended sod (27.8%) contributed to the differences in sod wet weight. Greater sod water content could enhance sod survival after harvest and transplanting. In addition, water conservation of MB-amended sod could be greater than sod without MB during the establishment period after sod is transplanted.

Table 2. Weight and water content of turfgrass sod grown with and without composted MB.

Cutting Depth “cm”		**Wet Sod Wt. kg m^{-2}**		**Dry Sod Wt. kg m^{-2}**		**Water Content %**	
NC-0	2.7	18.13	17.03	14.66	12.34	19.1	27.8
NC-50	2.0	15.69		10.58		32.6	
NC-100	2.0	17.26		11.77		31.8	
WC-0	2.7	14.76	13.81	9.94	8.18	32.7	41.5
WC-50	2.0	14.25		8.05		43.5	
WC-100	2.0	12.65		6.54		48.3	
	T-Test P-value		< 0.001		< 0.001		< 0.001

Nutrients Exported With Sod Harvest

Total N applied to soils during turfgrass establishment without composted MB ranged from 0 to 400 kg ha^{-1} (Table 3). Total N applied to MB-amended soils ranged from 957 to 1368 kg ha^{-1}. Concentrations of total N in sod layer ranged from 598 to 715 mg kg^{-1} without MB amendment and 4083 to 4503 mg kg^{-1} in MB-amended soils. The total N export ranged from 146 to 198 kg ha^{-1} for sod harvested from Tifway bermudagrass established without composted MB and from 425 to 506 kg ha^{-1} for sod amended with MB. For Tifway established without composted MB, 49.5 to 72.9 % of applied total N was removed in a single sod harvest. For Tifway amended with MB, 31.1 to 52.8% of applied total N was exported in the initial sod harvest. The increase of fertilizer N rate from 50 to 100 kg ha^{-1} $month^{-1}$ during establishment without MB reduced the percentage of total applied N exported in sod from 72.9% to 49.5%. The reduced N recovery in sod indicated the 100-kg rate of fertilizer N exceeded crop uptake and reduced N-use efficiency. Similar differences in total N export were observed between the two fertilizer N rates applied to sod established with MB. For Tifway established without MB, 40 to 57% of N was in the soil portion of harvested sod layer. For MB-amended sod, 59 to 73% of the N exported in the sod harvest was in the soil portion. The portion of applied N taken up and exported in turfgrass was greater for Tifway established without MB than for Tifway supplied both fertilizer and MB sources of N.

Concentrations of total soil P in the harvested sod layer ranged from 132 to 193 mg kg^{-1} without composted MB and from 2096 to 2402 mg kg^{-1} in MB-amended soils. Concentrations of soil-test P ranged from 35 to 55 mg kg^{-1} in sod without MB and from

621 to 672 mg kg^{-1} in MB-amended sod layers. Although 30 kg fertilizer P was applied to Tifway established without composted MB, up to 40 kg of total P was exported in the initial sod harvest. The TP exported in un-amended sod ranged from 80 to 133% of applied fertilizer P (Table 3).

From 516 to 521 kg ha^{-1} of total P was applied to Tifway amended with composted MB, but only 158 to 265 kg total P ha^{-1} was exported in a single sod harvest. From 30.4 to 51.5% of applied total P was exported in the harvested sod layer (soil and turf) for MB-amended Tifway bermudagrass (Table 3). The large recovery of applied fertilizer P in the sod layer indicated uptake of inorganic P by turf and limited movement through the soil profile.

Table 3. Percentage of applied total N and P exported in sod harvest (soil + turfgrass).

	Nutrients Applied (kg ha^{-1})		**Nutrients Removed (kg ha^{-1}) by sod harvest**		**% Nutrients Exported ***	
	N	P	N	P	N	P
NC-0	0	30	155	40	-	133a
NC-50	200	30	146	24	73a	80b
NC-100	400	30	198	28	50b	95b
WC-0	958	516	506	266	53b	52c
WC-50	1161	518	440	183	38c	35c
WC-100	1368	521	425	158	31c	30c

*LSD significant at 0.05 level

For Tifway established without MB, 54 to 64% of total P exported in the harvested sod layer was in soil. From 79 to 81% of total P was in the soil portion of MB-amended sod. The uptake of P by Tifway represented a much larger proportion of the total P in the sod layer in treatments without MB than with the volume-based rate of composted MB.

Discussion

Incorporating composted MB (25% by volume) to a 5 cm depth accomplished the objective of enhanced ($p < 0.001$) turf establishment compared to soil without MB. Similarly, Linde and Hepner (2005) showed that incorporating a 5- to 7.5-cm depth of compost to a depth of 15 cm increased ($p < 0.05$) coverage rates and density of turf compared to a 2.5-cm depth or controls without compost. The enhanced turfgrass growth in response to large, volume-based rates of compost was due, in part, to improvements in soil physical properties. Compared to treatments without compost, SOC content was increased 2 to 4 times after incorporation of the 5- to 7.5-cm depths of compost in previous studies (Linde and Hepner, 2005). In addition, incorporation of the volume-based compost rates reduce soil bulk density and increase cation exchange capacity and water retention (McCoy 1998). Therefore, incorporation of composted MB was a feasible option for enhancing soil physical properties and turfgrass establishment during sod production and on low quality soils on urban landscapes.

The volume-based rates of composted MB can supply N and P amounts in excess of turf requirements. Previous observations indicated topdressings of a blend of composted

MB and yard waste enhanced turfgrass color, growth, and foliar N concentrations for up to 5 wk (Garling and Boehm, 2001). Yet, the duration of turf color enhancements varied in response to N content of composts. A comparison between N sources applied during bermudagrass sod production indicated N uptake and N-use efficiency was 2 times greater for water-soluble fertilizer N than pelletized biosolids (Barton et al., 2006). Gaudreau et al. (2002) reported ratings of turf color and density were 20% higher for turfgrass top-dressed with inorganic N and P fertilizer than for treatments top-dressed with a P-based rate of composted manure only. Observations in the present study indicated not all of the N forms in composted MB were immediately available and N mineralization rates were not sufficient to maximize turf performance (Sims, 1990). The four applications of fertilizer, each 50 kg N ha^{-1}, enhanced turf coverage compared to MB-amended soils without fertilizer N. Previous studies of composted manure cycling through turfgrass sod indicated supplemental fertilizer N reduced the time between harvests to 60% of sod grown with manure only (Vietor et al., 2004b). To maximize the growth potential of turf due to improved soil physical properties and water retention in MB amended soils, fertilizer N should be supplemented according to turf requirements.

Reducing soil bulk density and increasing sod water content provides benefits that extend beyond the establishment period. Incorporation of volume based rates of MB reduced sod weight 33% and increased sod water content 49%. Johnston et al. (2006) demonstrated that as compost rate increased, bulk density decreased and volumetric water content increased. Similarly, Aggelides and Londra (2000) observed bulk density was reduced 19.7% for a loam soil and 16.7% for a clay soil, in addition to increased water content and retention. The reduced sod weight at harvest in the present study reflected reductions in bulk density for soil amended with composted MB. The reduced bulk density and sod weight indicate less native soil will be removed during harvest of MB-amended sod. In addition, the increases in soil water content and retention for sod grown with composted MB compared to without will reduce susceptibility to drought injury prior to and after transplanting of sod. It could be argued that sod grown in firmed soil only can be thinner than MB-amended sod and be less expensive to transport, but it will likely be more susceptible to drought injury (McCarty 2006, IFAS extension publication).

Less native soil is exported in harvests of MB-amended sod, but the amount and proportion of applied mineral nutrients exported with sod need to be determined for volume-based MB rates. The initial sod harvest removed 31.1 to 52.8% of the N applied in composted MB and inorganic fertilizer. A 35% greater harvest depth for MB-amended sod without fertilizer N contributed to the greater ($p < 0.05$) percentage of N export (52.8%) than MB-amended sod supplemented with split applications of fertilizer N (38 and 31 %). Similar to previous comparisons between organic and inorganic N sources, mean percentages in the range of applied N recovery were greater for sod grown with inorganic N (49.5 to 72.9%) rather than composted MB plus fertilizer N (Barton et al., 2006). Conversely, increasing fertilizer N rate from 50 kg ha^{-1} to 100 kg ha^{-1} reduced the exported percentage of applied N 18% for MB amended soils and 32% for fertilizer grown sod. The application of fertilizer N in excess of turf requirements increased susceptibility to leaching losses below the harvested layer.

Vietor et al. (2002) found that surface applied P-based rates of compost resulted in 30% of applied N being exported in manure + fertilized grown bermudagrass sod while 59% of N was exported in fertilizer-grown bermudagrass sod. The recovery of applied N in that study was lower than what was observed in this study. In the present study, concentration of N found in the soil at the beginning of the study was not subtracted out which would reduce the percentage of applied N exported as was observed by Vietor et al. (2002). The incorporation of MB in soil may have reduced volatilization losses of NH_3 compared to surface applied manures where up to 94% reduction of NH_3-N was reported under field conditions (Vietor et al. 2002). However, the N exported in the turf portion of the sod was similar for both studies.

A major portion of N export through sod harvest comprises the soil layer. Harvest of a soil layer enables export of recalcitrant organic N forms that resist mineralization during production of the sod crop. Previous studies of soluble fertilizer-N recovery in harvested bermudagrass forage reported N uptake efficiencies of 72 to 80%, which were directly related to dry matter yield (Brink et al. 2004). The N amount exported in 4 forage harvests (400 to 500 kg ha^{-1}) was similar to that of one sod harvest. Similar to turfgrass production, supplemental N is required for maximum forage yields of bermudagrass (Read et al. 2006). Yet, slow rates of mineralization limit recovery of organic N sources in forage harvests. Only 25% of annual applications of manure N was recovered in forage harvests over 4 yr for bermudagrass (*Cynodon dactylon* L. Pers) over-seeded with winter wheat (*Triticum aestivum* Thell cv. Wintex) in central Texas.

The export of MB sources of P through sod harvest is much greater than previous reports of manure P export through forage harvests. The amount of P exported in forage is dependent on dry matter yields and is a small proportion of the amount applied in manures with or without the additional N (Read et al. 2006, Brink et al. 2004). Only 20% or less of annual applications of manure P was recovered during 4 years of forage harvests from bermudagrass over-seeded with wheat (Sanderson and Jones, 1997). For incorporated MB in the present study, 30.4 to 51.5% of applied P was exported in the initial sod harvest. Similar to nitrogen, percent uptake and export of inorganic fertilizer P, which included antecedent soil P, were much greater (80 to 133%) than MB sources of P and dependent on depth of harvest. Another study of top-dressed, P-based rates of composted manure on Tifway bermudagrass fields indicated 1.5 to 3.4 times more P was exported than was applied (McDonald, 2005). The manure-P top-dressed on the clay soil did not move below the harvested sod layer, but was susceptible to loss in runoff.

Incorporation of MB in soil permits the use of large volume based rates to improve soil bulk density and water holding capacity. By incorporating MB, the MB residuals are diluted with soil to a depth that extends beyond the layer harvest by sod. The percentage of incorporated P exported by sod harvest is reduced compared to topdressing, but potential runoff losses are limited.

CHAPTER III

RUNOFF LOSSES AND CONSERVATION DURING TURFGRASS ESTABLISHMENT ON URBAN SOILS

Volume-based rates of municipal sources of organic amendments can increase soil water holding capacity and nutrient concentration and enhance turfgrass establishment (Cisar 1994). The maximum benefit for water-holding capacity during turf establishment on sandy soil occurred at 30% by volume of composted MB. Yet, soil water holding capacity is only one component of soil quality. Large increases in soil organic C and soil P and cation concentrations in compost-amended soil could contribute to nonpoint-source pollution on urban landscapes (Fleming and Cox, 2001, Jacinthe et al., 2004, Vietor et al., 2004). Imports of composts, topsoil, and mulches were previously identified among causes of elevated nutrient losses in runoff from residential construction sites on watersheds in North Carolina (Line et al., 2002).

Due to the potential negative environmental impacts of composted MB use, practices for management of composted MB on agricultural and urban landscapes need to be evaluated to minimize environmental risk. Methods may include incorporation of composted MB directly to urban landscapes prior to planting of sod or seed or import of composted MB residues through transplanted sod. Incorporation of composted MB can reduce potential runoff loss of N, P, organic C, and cations in surface runoff compared to surface application after sprigging of turfgrass (Kleinman et al., 2002). Importing sod transplanted from turfgrass grown in soil mixed with composted MB could further reduce runoff loss of water and nutrients during turfgrass establishment (Beard and Green, 1994). Yet, mineralization and dissolution of N, P, organic C, and cations in the transplanted sod layer could contribute to long-term runoff losses from sod grown with high rates of composted MB (Vietor et al., 2004). Although not previously evaluated, another option is transplanting of fertilizer-grown sod on soil mixed with a volume-based rate of composted MB. These contrasting practices for turfgrass establishment need to be evaluated to identify the best option for an integrated system that uses composted MB as a resource without detrimental effects on environmental quality.

The concentrations and mass loss of N, P, organic C, and cations in runoff depend on properties of composted MB used to amend soil and extractable nutrient concentrations in soil. The nutrients in compost available for transport in runoff or percolation depend, in part, on methods used to produce MB and the bulking agents added during composting of MB (Maguire et al., 2001, Penn and Sims, 2002). If organic C and P forms applied in composted MB are relatively insoluble or retained within the sod layer, large rates could pose less risk to water quality than fertilizer or manure applications (Maguire et al., 2001). Wastewater treated with Fe, Al, or lime prior to composting can reduce extractable P compared to biosolids derived without metal-salts or Ca. Dissolved P concentrations and mass loss of P in runoff were directly related to soil-test P and water-extractable P concentrations in soil amended with composted MB during turf establishment (Hansen, 2005). Relationships between soil and runoff concentrations can be used to identify factors that affect runoff losses from contrasting establishment treatments.

Objectives

I. Compare turf responses, soil water retention, and runoff losses of sediment, P, N, organic C and cations among contrasting establishment methods on constructed urban soils.

II. Relate extractable P, N, organic C and cation concentrations in the amended soil layer of establishment treatments to total and dissolved concentrations and mass losses of N, P, organic C, and cations in surface runoff over seven rain events.

Materials and Methods

Three replications of seven turf establishment treatments comprised a randomized block design (Table 4). Plots were blocked according to background concentrations of soil-test P before establishment treatments were imposed. Two sprigged treatments represent Tifway bermudagrass establishment on constructed urban soil. The sprigs were planted in sandy loam soil with and without incorporation of composted MB. Four options for turf establishment and composted MB cycling through transplanted sod made up additional treatments. Tifway bermudagrass sod was transplanted from turf grown (33 weeks) with or without composted MB. The sod with or without composted MB was transplanted on a sandy loam soil layer prepared with and without incorporation of composted MB.

For amended treatments, the composted MB was incorporated to make up 25% by volume of soil in which transplanted sod was grown and on which sprigs were planted or sod transplanted. The plots established with and without composted MB, through transplanting of compost- or fertilizer-grown sod or sprigging, were compared to a control. The control was made up of sod transplanted from turfgrass grown with low N inputs on a soil layer without composted MB. The seven treatments were installed on an 8.5% slope excavated from a Boonville fine sandy loam soil (fine smectitic thermic Vertic Albaqualf). Sheet metal borders isolated plots (1.5 m x 4 m) and channeled runoff through H-flumes into 311-L tanks for measurement and sampling of runoff volumes.

Table 4. Treatment descriptions.

MBSod/MBSoil	High N, MB-amended sod transplanted on MB-amended soil.
HNFSod/MBSoil	High N, fertilizer-grown sod transplanted on MB-amended soil.
MBSod/Soil	Moderate N, MB-amended sod transplanted on soil without MB.
SprigMBSoil	Sprigged, MB-amended soil.
SprigSoil	Sprigged without MB in soil.
HNFSod/Soil	High N, fertilizer-grown sod transplanted on soil without MB.
MNFSod/Soil	Moderate N, fertilizer-grown sod transplanted on soil without MB.

Turfgrass was mowed to a 2.5-cm height when shoots elevated to 7.5 cm. Clippings were collected, weighed, sub-sampled for analysis of water and nutrient concentration, and returned to plots. Sub-samples were dried, weighed, ground, and composited over dates for analysis of total P and N.

Soil within amended layers and sod were monitored after soil, composted MB, and Tifway sprigs or transplanted sods were applied on the excavated slope and after the final runoff event. Soil bulk density and water content was determined gravimetrically. Soil was sampled at depths of 0 to 5 cm and 0 to 2 cm for analysis of total N and P and organic C, NO3-N, Mehlich-3-extractable P and cations, and water extractable. The 0- to 2-cm depth represented nutrients available from the imported sod or the surface soil layer. Soil removed from the 0- to 5-cm depth represented both imported sod and the soil layer on which sod was transplanted. Dielectric aquameter sensors and a data logger were used to monitor soil water content at 6-hour intervals to obtain the daily average within the amended soil layer of one replication of the seven establishment treatments.

Runoff volumes were measured and sampled after each of seven natural rain events during turf establishment. Runoff samples were centrifuged within 24 hr of sampling and the supernatant filtered (< 0.45 μm) for analysis of dissolved N and P forms. Unfiltered water samples from runoff were sub-sampled for digestion and analysis of total Kjeldahl N (TKN) and total P, cations, and organic C (Parkinson and Allen, 1975; Pote and Daniel, 2000). Turf clippings, composted MB, and soil samples were dried, weighed, and sub-sampled for digestion and analysis of total N, P, and organic C. The total N in digests was measured colorimetrically (Dorich and Nelson, 1984). Total organic C of composted MB and soil was quantified through automated dry combustion with CO_2 analysis. The Mehlich 3 method and distilled water was used to extract P and cations from composted MB or soil (Sims, 2000; Crouse et al. 2000). ICP was used to analyze total P in digests and dissolved P and cations in filtrate of runoff samples and extracts of composted MB and soil. The NO_3-N in filtrate of runoff samples and in KCl extracts of composted MB and soil were analyzed through cadmium reduction. An OI Analytical Model 700 total organic C (OI Analytical, College Station, Texas) analyzer was used to analyze water-extractable organic C in filtrates of runoff. Molybdate-reactive phosphorus (DRP) in runoff samples and in extracts of composted MB and soil was determined colorimetrically within 24 hours of extraction or filtering (Pote and Daniel, 2000).

The General Linear Model (univariate) procedure in SPSS was used for Analysis of variance (ANOVA) and mean separations of physical or chemical characteristics of soil, runoff, and turf clippings among treatments and runoff events. Regression analysis was used to relate concentrations and mass losses of total dissolved P, molybdate reactive P, dissolved organic C, and cations in runoff to concentrations of Mehlich-3 and water-extractable P, cations, and total organic C in soil sampled after the final runoff event. These regression relationships were used to evaluate variation of source factors that affect runoff loss, including interactions between P, cations, and organic C that are associated with establishment treatments.

Results

Sediment and Water

Rainfall and runoff amounts were measured to determine the proportion of rainfall lost through surface runoff. The percentage of rainfall retained in the soil after sprigging of Tifway (SprigSoil) (32.9%) was lower than all other treatments ($p < 0.05$). Incorporation of composted MB in soil below transplanted sod (MBSod/MBSoil and HNFSod/MBSoil) enabled retention of a greater ($p < 0.10$) portion of rainfall over seven runoff events (57.2 to 57.8%) than sod transplanted on soil without MB (47.7% for

MBSod/Soil and 47.3% for HNFSod/Soil and MNFSod/Soil). Rainfall retention was similar between treatments in which both sod and the subtending soil contained MB (MBSod/MBSoil) and those in which MB was incorporated in soil only (HNFSod/MBSoil and SprigMBSoil). Retention of rainfall during turfgrass establishment could reduce runoff volumes and nutrient loss during turfgrass establishment.

Amendment of sod or soil with composted MB contributed to greater ($p < 0.05$) percent soil water than treatments without MB. Mean percent soil water (w/w) over a 92 day period starting July 10 was 17.3 for (MBSod/MBSoil), 19.8 for HNFSod/MBSoil, 16.0 for MBSod/Soil, 16.9 for SprigMBSoil, 9.5 for SprigSoil, 12.3 for HNFSod/Soil, and 15.6 MNFSod/Soil (Appendix B). Greater soil water retention could enable greater biomass production and improved turf quality when rainfall is limiting.

Total sediment loss over seven rain events (g m^{-2}) was greatest ($P < 0.001$) among the establishment treatments for sprigged Tifway without MB (SprigSoil). In addition, total sediment loss from sprigged Tifway amended with MB (SprigMBSoil) was greater ($p < 0.01$) than transplanted sod with or without MB in sod or subtending soil (MBSod/MBSoil, HNFSod/MBSoil, MBSod/Soil, and HNFSod/Soil). Mean total sediment loss (g m^{-2}) was 1.79 for (MBSod/MBSoil), 1.19 for HNFSod/MBSoil, 1.98 for MBSod/Soil, 21.58 for SprigMBSoil, 63.89 for SprigSoil, 2.62 for HNFSod/Soil, and 4.07 for MNFSod/Soil.

Phosphorus

Within the 0- to 5-cm depth, concentrations ranged from 19 to 382 mg kg^{-1} for soil-test P (STP), 5 to 22 mg kg^{-1} for water extractable P (WEP), and 152 to 1433 mg kg^{-1} for total P (TP) (Table 5). Within the 0- to 2-cm depth, concentrations ranged from 10 to 635 mg kg^{-1} for STP, 5 to 48.9 mg kg^{-1} for WEP, and 99 to 1761 mg kg^{-1} for TP (Table 5). Within the top 2 cm of soil, STP concentrations were greater for sod transplanted from turfgrass grown with than without composted MB. Sampling to a 5-cm depth diluted STP, concentrations for treatments in which MB-grown sod was transplanted on soil without MB. In contrast, sampling to a 5- rather than 2-cm depth increased STP for treatments in which sod without MB was transplanted on soil constructed with 25% by volume composted MB. The variation of STP concentration between sampling depths was important when relating concentrations in soil and runoff.

Table 5. Total P (TP), soil-test P (STP), and water-extractable P (WEP) concentrations (mg kg^{-1}) of soil within 0- to 2-cm and 0- to5-cm depths of turfgrass establishment treatments (See Table 4 for description of treatments).

	STP 0 to 2 cm	WEP 0 to 2 cm	TP 0 to 2 cm	STP 0 to 5 cm	WEP 0 to 5 cm	TP 0 to 5 cm
MBSod/MBSoil	621	45.2	1761	382	22	1351
HNFSod/MBSoil	55	15.1	149	236	14.9	754
MBSod/Soil	635	48.9	1705	249	15.7	608
SprigMBSoil	307	13.2	977	347	13.2	1433
SprigSoil	10	5	99	19	5	152
HNFSod/Soil	35	12.6	167	28	5.5	160
MNFSod/Soil	35	12.6	167	38	6.2	169

Mean runoff concentration of DRP for Tifway sprigged in soil mixed with MB (SprigMBSoil) was greater ($p < 0.05$) than Tifway sprigged without MB in soil (SprigSoil). In contrast, DRP concentration in runoff from SprigMBSoil was less ($p < 0.005$) than sod transplanted with or without MB on soil constructed with or without MB (MBSod/MBSoil, HNFSod/MBSoil, MBSod/Soil). Mean DRP concentrations (mg L^{-1}) in runoff were 2.265 for MBSod/MBSoil, 1.618 for HNFSod/MBSoil, 2.804 for MBSod/Soil, 0.842 for SprigMBSoil, 0.274 for SprigSoil, 0.691 for HNFSod/Soil, and 0.515 mg L^{-1} for MNFSod/Soil. In addition, a significant interaction ($p < 0.001$) between treatment and date was observed for DRP. The interaction was attributed, in part, to clustering of rain events within two time periods. Four rain events occurred during June 16 to 22 and three events during July 3 to 5. In addition, rainfall depths during the final two rain events in July were greater than depths of previous rain events. The rainfall depths from June 16 to 22 were 1.92, 1.88, 3.92, and 1.93 cm. Amounts from July 3 to 5 were 1.9, 7.5, and 6.5 cm. The mean DRP concentration was greatest ($p < 0.001$) during the first rain event of each cluster and typically declined over subsequent rain events (Fig. 3). For example, the DRP concentration of runoff from the MBSod/MBSoil treatment declined from 4.0 mg L^{-1} on June 16 to 1.9 mg L^{-1} on June 22. Similarly, runoff DRP concentration for MBSod/MBSoil decreased from 3.34 on July 3 to 0.69 mg L^{-1} on July 5. Similar trends were observed for treatments with and without composted MB.

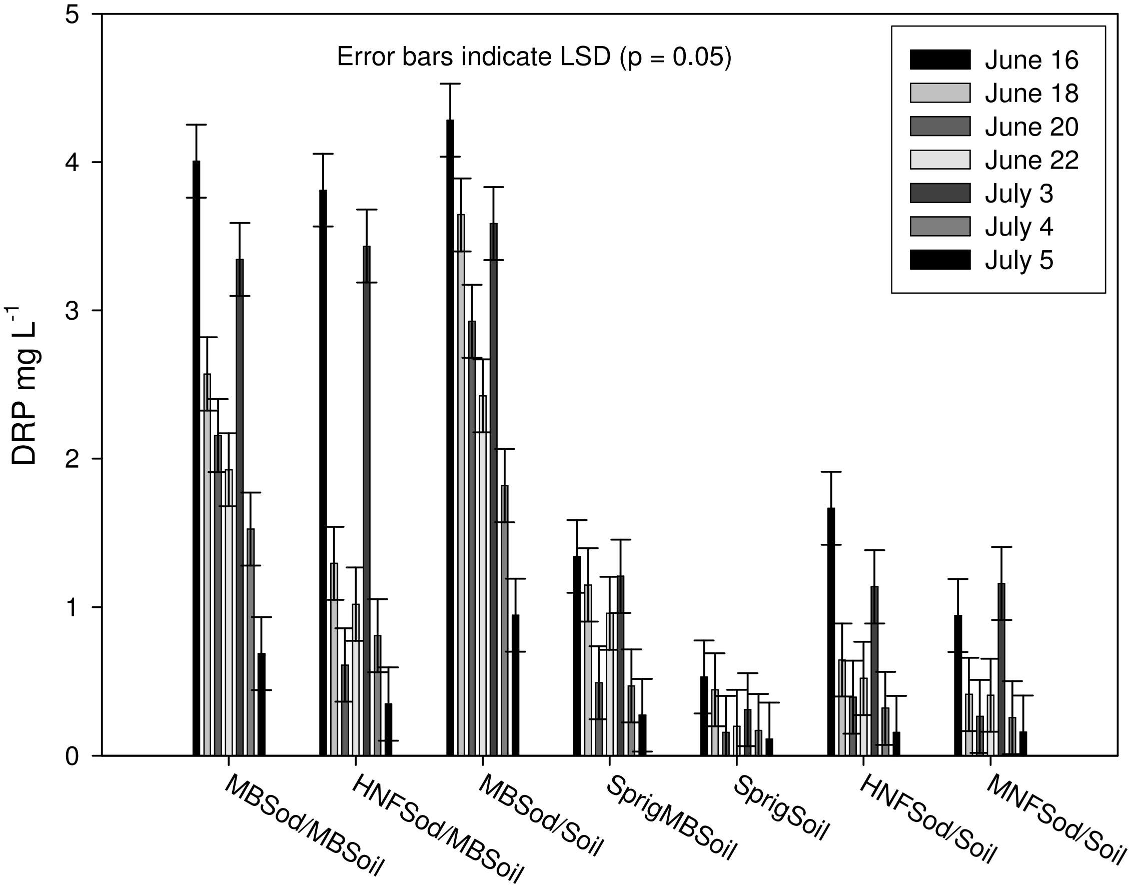

Figure 3. Dissolved reactive P (DRP) concentration in runoff water emanating from turfgrass establishment treatments by date. See Table for description of treatments.

Runoff concentrations of both total dissolved P (TDP) and TP varied among the establishment treatments (Fig. 4). Mean TDP concentration in runoff ranged from 0.92 to 3.26 mg L^{-1} among treatments amended with composted MB and from 0.42 to 0.90 mg L^{-1} among treatments without MB. Mean TP concentrations ranged from 1.30 to 3.29 mg L^{-1} among treatments amended with composted MB and from 0.63 to 1.05 among treatments without MB. Mean TDP concentration in runoff was greater ($p < 0.005$) for the three treatment combinations in which transplanted sod or soil beneath sod were amended with composted MB (MBSod/MBSoil, HNFSod/MBSoil, and MBSod/Soil) than the other four treatments. In addition, mean TDP concentration in runoff from transplanted sod amended with MB (MBSod/MBSoil and MBSod/Soil) was greater ($p < 0.005$) than sod without MB transplanted on soil with MB (HNFSod/MBSoil).

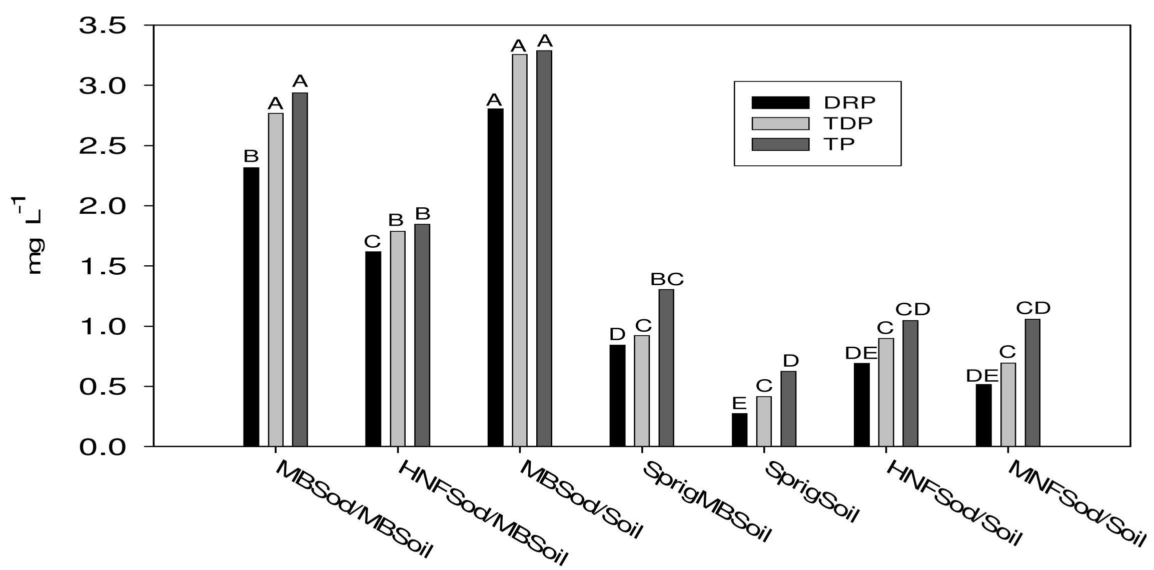

Figure 4. Mean runoff concentrations of Total P (TP), Total Dissolved P (TDP), and Dissolved Reactive P (DRP) for establishment treatments over seven runoff events. Letters above bars indicate mean separation using LSD ($p = 0.05$). See Table 4 for description of treatments.

Similar to DRP, mean concentrations of TDP and total TP in runoff declined from initial through subsequent rain events within the clusters of events in each June and July. The trend among rain events indicated consecutive runoff events within each cluster removed a portion of soluble and sediment-bound P near the soil surface. Yet, mineralization of P and the greater depths of runoff events in July contributed to increased runoff concentrations of TDP and TP from the fourth event in June to the initial event in July.

Over seven runoff events, mass loss of TP was greater ($p < 0.001$) for sod transplanted from Tifway bermudagrass grown with composted MB (MBSod/MBSoil and MBSod/Soil) than all other treatments. In addition, mass loss of TP was greater for MBSod/MBSoil and MBSod/Soil than Tifway sprigged in soil mixed with MB (SprigMBSoil). Mean mass loss of TP (mg m^{-2}) was 41.3 for MBSod/MBSoil, 21.1 for HNFSod/MBSoil, 55.4 for MBSod/Soil, 15.7 for SprigMBSoil, 12.7 for SprigSoil, 14.8 for HNFSod/Soil, and 12.7 for MNFSod/Soil. Variation among transplanted sod treatments revealed rainfall interactions with the sod layer and soil on which sod was placed. Rainfall interactions with the transplanted sod layer contributed to greater ($p<0.05$) mass loss of TP from MB-amended sod transplanted over soil without MB (MBSod/Soil) than from fertilizer-grown sod on soil without MB (HNFSod/Soil). Conversely, incorporation of composted MB in the constructed soil beneath MB-grown sod (MBSod/MBSoil) reduced ($p<0.05$) TP mass loss compared to MB-grown sod transplanted on soil without MB. The incorporation of MB in soil beneath transplanted sod (MBSod/MBSoil) increased water retention. The increased water retention could have contributed to biomass production and P uptake that was 5 times greater for sod transplanted on soil with MB than on soil without MB.

For one treatment in which incorporation of composted MB within soil beneath transplanted sod was the largest imported source of TP, mass loss TP in runoff was affected. The TP mass loss from HNFSod/MBSoil was greater ($p < 0.05$) than medium-N sod or sprigs planted on soil without MB (MNFSod/Soil and SprigSoil). In contrast, mass loss of TP was similar for sod grown with inorganic P and high N whether transplanted on soil with (HNFSod/MBSoil) or without MB (HNFSod/Soil).

Mass loss of TDP and DRP over seven runoff events was greater ($p < 0.05$) for treatments in which transplanted sod or subtending soil was amended with composted MB (MBSod/MBSoil, HNFSod/MBSoil, and MBSod/Soil) than for the other four treatments (Table 6). Yet, TDP mass loss from sprigged Tifway amended with MB (SprigMBSoil) was similar to sprigged and transplanted sod treatments without composted MB. Mean mass loss of TDP (mg m^{-2}) was 37.8 for MBSod/MBSoil, 19.1 for HNFSod/MBSoil, 52.8 for MBSod/Soil, 10.2 for SprigMBSoil, 7.2 for SprigSoil, 11.8 for HNFSod/Soil, and 9.1 for MNFSod/Soil. Mean mass loss of DRP (mg m^{-2}) was 29.3 for MBSod/MBSoil, 16.3 for HNFSod/MBSoil, 44.1 for MBSod/Soil, 9.6 for SprigMBSoil, 5.1 for SprigSoil, 8.8 for HNFSod/Soil, and 6.6 for MNFSod/Soil.

Table 6. Cumulative mass loss (mg m^{-2}) for all treatments.

	TP mg m^{-2}	TDP mg m^{-2}	DRP mg m^{-2}
MBSod/MBSoil	1652.00 b[†]	1512.18 b	1171.41 b
HNFSod/MBSoil	885.28 c	802.37 c	684.17 c
MBSod/Soil	2327.13 a	2216.69 a	1850.27 a
SprigMBSoil	658.16 cd	428.53 d	401.49 d
SprigSoil	532.24 d	302.04 d	214.42 d
HNFSod/Soil	623.35 cd	496.36 d	368.65 d
MNFSod/Soil	533.94 d	381.20 d	278.78 d

[†] Mean separated by LSD ($p = 0.05$)

Regression analysis indicated a linear relationship between concentrations of soil WEP within a 2-cm depth (depth of the imported sod layer) and of TDP in runoff accounted for the largest portion of observed variation ($R^2 > 0.92$) (Fig. 5). A direct linear relationship between concentrations of TDP in runoff and WEP within the 5-cm depth was similarly observed, but the coefficient of determination was reduced ($R^2 < 0.66$). As was evident in variation of runoff concentrations and losses of TDP among treatments, the regression analysis indicated rainfall interaction with the 2-cm soil depth was a major determinant of runoff concentrations of TDP. Conversely, incorporation of MB deeper into the soil profile reduces interaction with rainfall and reduces runoff loss of TDP. A similar relationship was observed between soil WEP concentrations (2-cm depth) and cumulative mass loss of TDP over the seven runoff events (mg m^{-2}) (Fig. 5). Consistent with previous reports (Torbert et al. 2002), variation of WEP provided the best fit to concentration and mass of runoff TDP. Yet, variation of WEP was closely related to other soil P concentrations, including TP ($R^2 = 0.89$) and DRP ($R^2 = 0.85$).

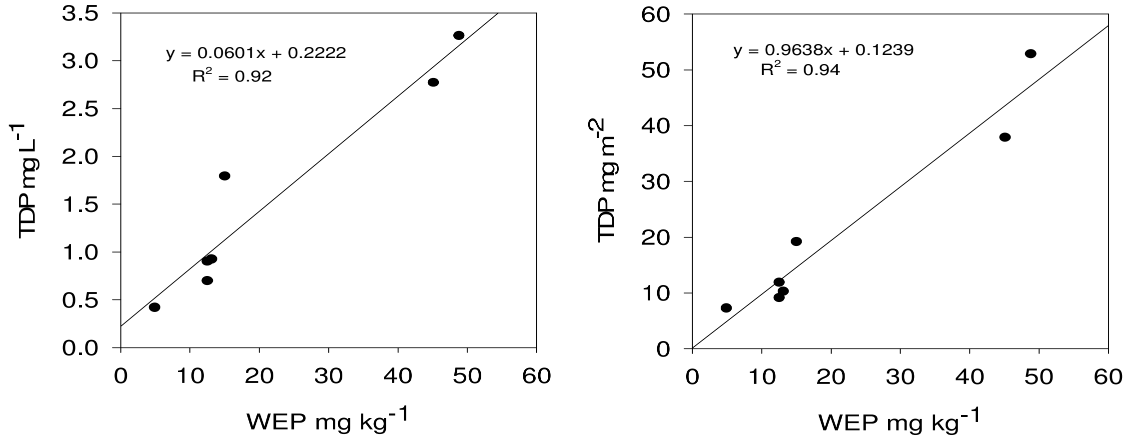

Figure 5. Relationships between soil WEP concentration (2-cm depth) and concentration (mg L^{-1}) and mass loss (mg m^{-2}) of TDP in runoff.

Nitrogen

As with phosphorus, soil sampling depth affected concentrations of TKN, NH_4 and NO_3 due to variation across layers of transplanted sod and constructed soil with and without composted MB. At a 2 cm sampling depth (representing sod layer), TKN concentrations ranged from 580 mg kg^{-1} (SprigSoil) to 3510 mg kg^{-1} (MBSod/MBSoil) (Table 7). The TKN concentrations were more than 3 times greater for treatments amended with MB in the 0- to 2-cm layer than for treatments without MB. The soil NO_3-N concentrations ranged from 2.0 mg kg^{-1} (SprigSoil) to 28.1 mg kg^{-1} (SprigMBSoil). The NO_3-N concentration in composted MB (133 mg kg^{-1}) contributed to greater soil NO_3-N concentration sampled from SprigMBSoil shortly after sprigging.

At the 5 cm sampling depth, TKN concentrations ranged from 677 mg kg^{-1} (SprigSoil) to 2647 mg kg^{-1} (MBSod/MBSoil) (Table 7). The TKN concentrations in MB-amended treatments were more than 2 times greater than those of treatments without MB. Variation of NH_4-N and NO_3-N concentrations among treatments followed similar trends. Concentrations ranged from 3.5 to 40.6 mg kg^{-1} for NO_3-N and from 2.8 to 16.2 mg kg^{-1} for NH_4-N.

Table 7. Concentration of N forms at specified soil sampling depths for contrasting turfgrass establishment practices. See Table 4 for description of establishment practices or treatments.

	TKN mg kg^{-1} 2-cm depth	NO_3-N mg kg^{-1} 2-cm depth	TKN mg kg^{-1} 5-cm depth	NO_3-N mg kg^{-1} 5-cm depth	NH_4-N mg kg^{-1} 5-cm depth
MBSod/MBSoil	3510	9.5	2647	40.6	16.2
HNFSod/MBSoil	750	3.8	1677	49.6	13.1
MBSod/Soil	3295	8.8	1310	15.6	10.4
SprigMBSoil	2270	28	2560	28.6	15.7
SprigSoil	580	2.0	677	4.5	2.8
HNFSod/Soil	773	3.3	760	4.3	7.3
MNFSod/Soil	598	3.3	767	3.5	9.8

In addition to differences among treatments ($p < 0.001$), an interaction ($p < 0.001$) between rain event and treatment was statistically significant ($P=0.001$). As observed for TP, STP, and SRP, NO_3 concentration in runoff declined over rain events within each of two clusters of rain dates (Fig. 6). During the first cluster of four rain events, runoff concentrations of NO_3-N on June 16 ranged from 0.9 mg L^{-1} (MBSod/Soil) to 6.2 mg L^{-1} (SprigMBSoil). During the fourth rain event on June 20, NO_3-N concentrations ranged from <0.01 mg L^{-1} (HNFSod/Soil) to 1.1 mg L^{-1} (HNFSod/MBSoil). The trend of declining NO_3-N concentration was observed during three rain events from July 3 to 5. From July 3 to the final runoff event (July 5), NO_3-N concentration declined from 0.24 to 0.03 mg L^{-1} for MNFSod/Soil and from 3.1 mg L^{-1} to 0.17 mg L^{-1} for HNFSod/MBSoil (Fig. 6).

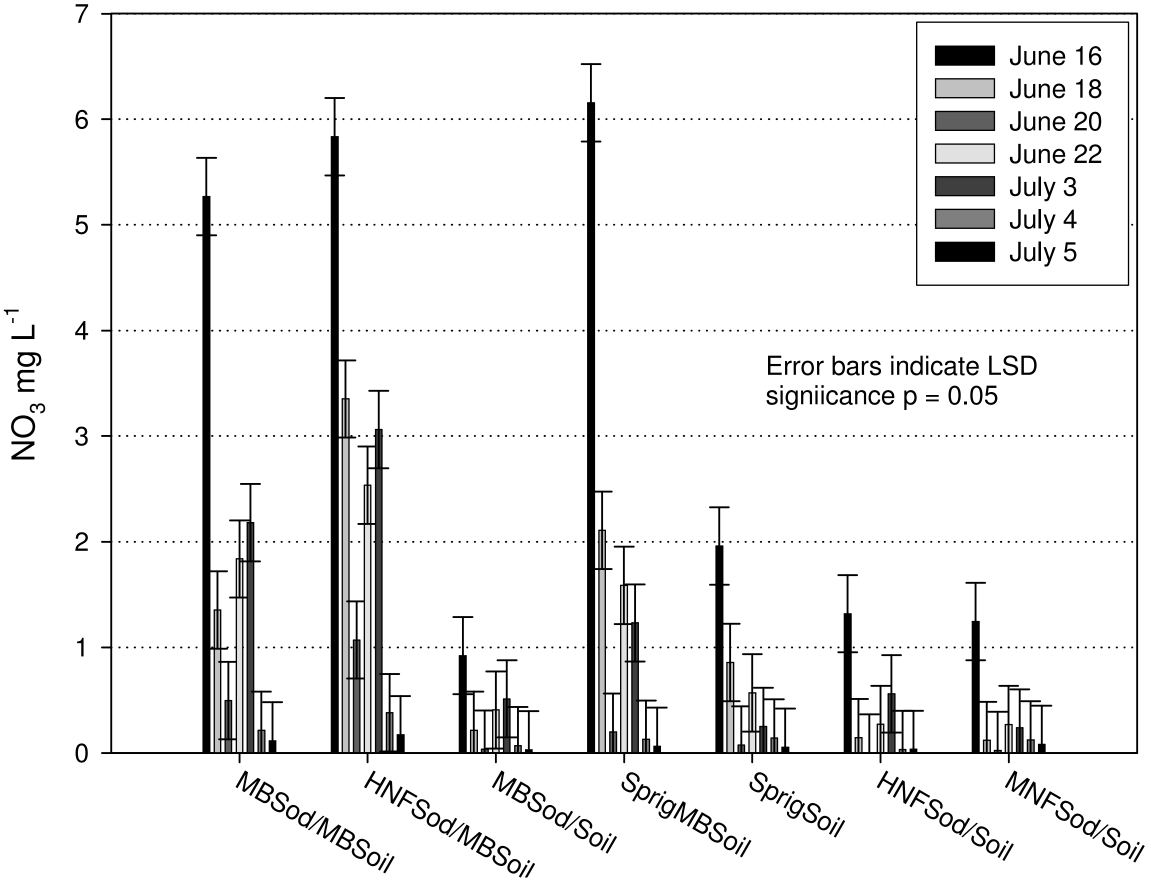

Figure 6. Mean runoff concentrations of NO_3-N on seven sampling dates for each establishment treatment. See Table 4 for description of treatments.

Mean runoff concentration of NO_3-N differed ($p<0.001$) among treatments on June 16, 18, 22 and July 3 ($p < 0.001$), but were relatively low and similar among treatments on June 20, July 4 and 5. The decline of runoff concentrations of NO_3-N after the initial rain event was likely due to runoff loss of mobile N pools during the initial rain event of each cluster. Mineralization of N from within the soil profile could have increased the pool of mobile N available for transport during the initial rain event of the second cluster (July 3) of rainfall events.

Table 8. Mean NO_3-N concentrations for establishment treatments during selected rain events. See Table 4 for description of treatments.

NO_3 (mg L^{-1})	June 16	July 3
MBSod/MBSoil	5.268 a[†]	2.181 a
HNFSod/MBSoil	5.835 a	3.061 ab
MBSod/Soil	.921 b	.513 c
SprigMBSoil	6.155 a	1.232 bc
SprigSoil	1.960 b	.250 c
HNFSod/Soil	1.319 b	.560 c
MNFSod/Soil	1.245 b	.238 c

[†] Means separated by LSD ($p = 0.05$).

For June 16, runoff concentrations of NO_3-N were 2 to 6 times greater ($p < 0.005$) for MBSod/MBSoil, HNFSod/MBSoil, and SprigMBSoil than the other four treatments (Table 8). The lower and similar runoff concentrations of NO_3-N between MBSod/Soil and MNFSod/Soil was attributed, in part, to moderate rates of soluble N application before either sod source was transplanted on the constructed soil without MB. In addition, Tifway uptake of NO_3-N could have been comparable to mineralization rates of N in MB and turfgrass residues. During the initial rain event (July 3) of the second cluster of three rain dates, runoff concentrations of NO_3-N were greater ($p < 0.05$) for MBSod/MBSoil, HNFSod/MBSoil, and SprigMBSoil compared to other treatments.

Similar to observations for TP, TDP, and SRP, variation of runoff concentrations of NO_3-N among treatments was indicative of rainfall interactions with soluble N forms near and below the soil surface of establishment treatments. Mean runoff concentration of NO_3-N was greater ($p = 0.001$) for HNFSod/MBSoil than all other treatments. Although lower than HNFSod/MBSoil, mean runoff concentrations of NO_3-N were similar between MBSod/MBSoil and SprigMBSoil and greater ($p = 0.001$) than the other four treatments (Fig. 7).

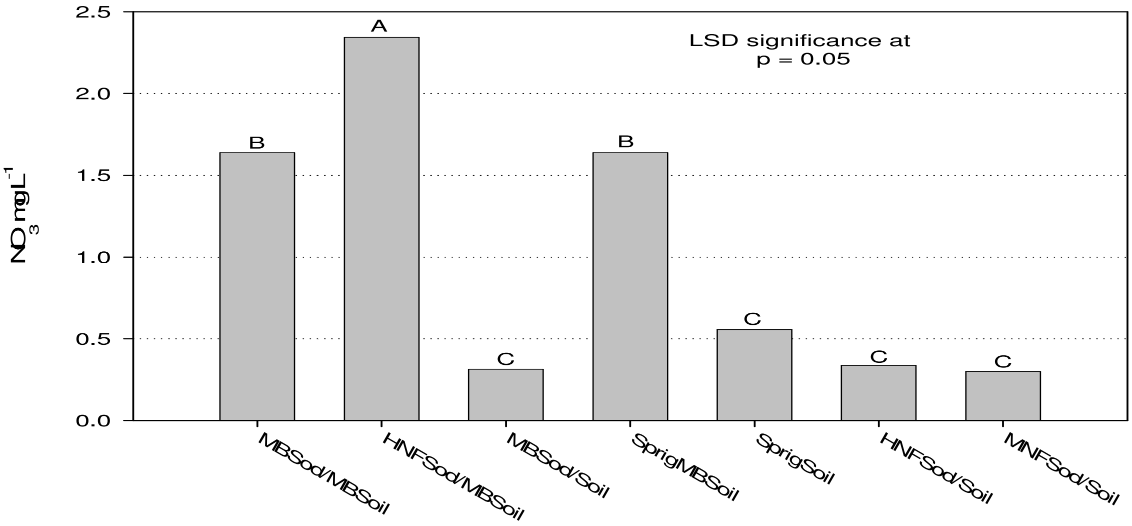

Figure 7. Mean runoff concentrations of NO_3 for establishment treatments over seven runoff events. See Table 4 for description of treatments.

Regression analysis indicated variation of runoff concentrations of NO_3-N were directly related ($R^2 = 0.89$) to soil NO_3-N concentrations within the 0- to 5-cm depth. In contrast, variation of soil NO_3-N within the 0- to 2-cm depth) accounted for little of the variation ($R^2 = 0.13$) of runoff concentrations of NO_3-N. Another factor influencing concentration of NO_3-N in runoff water is uptake by Tifway turf. As with phosphorus, MB amended soil improved turfgrass biomass production and potential uptake of NO_3-N within the sod layer compared to sod or soil without composted MB during the period preceding the sampling date for soil. Soil NO_3 concentration was linearly ($R^2 = 0.97$) related to uptake of N by turfgrass, determined by the cumulative mass TKN in returned clippings.

Variation of runoff concentrations of NH_4-N among treatments and runoff events was similar to that of NO_3. Treatment effects on runoff concentration of NH_4-N and an interaction between rain event and treatments were significant ($p < 0.001$). The runoff concentration of NH_4-N differed ($p < 0.05$) among establishment treatments on June 18 and 22 and July 3, but not on other rain dates. After the initial rain event of each cluster of rain dates, NH_4-N concentration declined over the subsequent events of each cluster (Fig. 8). On June 16, NH_4-N concentrations ranged from 0.89 to 5.34 mg L^{-1} for treatments with MB amendments and from 0.61 to 1.33 mg L^{-1} for treatments without MB. During the fourth rain date (June 20) of the first cluster, NH_4-N concentrations declined to the range of 0.08 to 0.44 mg L^{-1} in MB amended treatments and 0.06 to 0.17 mg L^{-1} for treatments without MB. A similar trend was observed during the second cluster of rain events from July 3 to 5. On July 3, NH_4-N concentrations ranged from 1.24 to 4.72 mg L^{-1} in MB-amended treatments and 0.99 to 1.54 mg L^{-1} in treatments without MB (Fig. 8). On July 5, runoff concentrations of NH_4-N declined to the range of 0.32 to 0.66 mg L^{-1}.

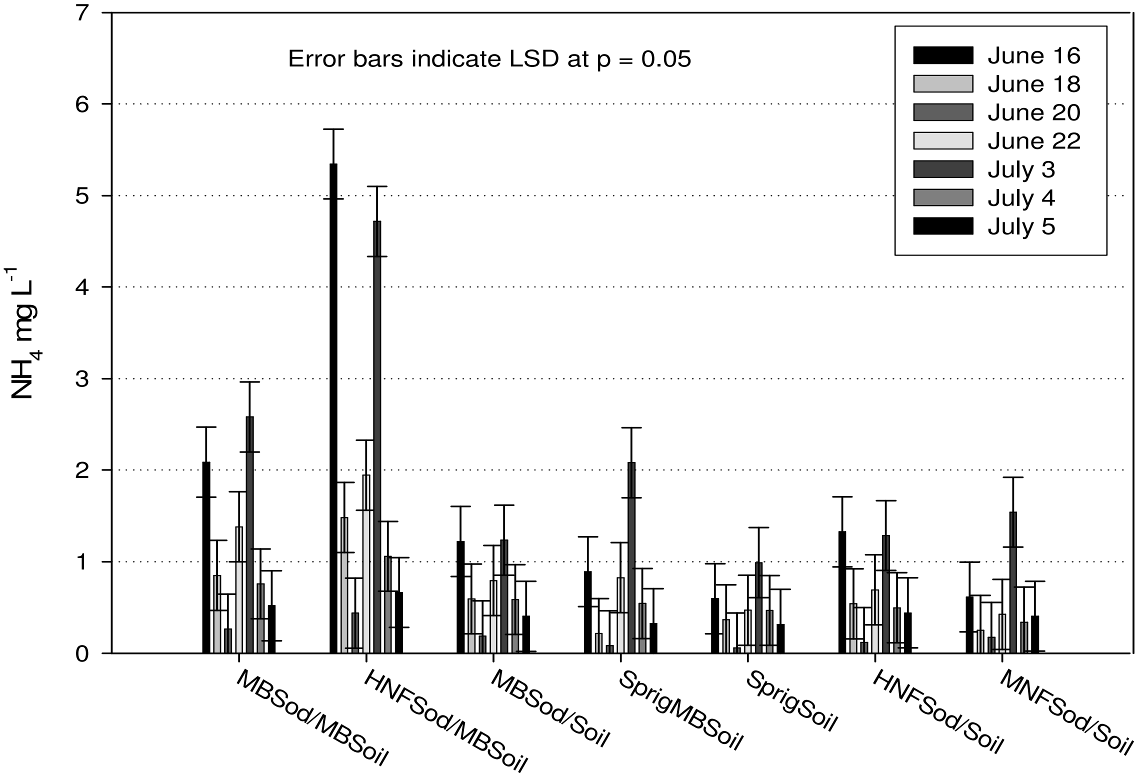

Figure 8. Mean runoff concentrations of NH_4-N for contrasting establishment treatments during each of seven rain events after planting. See Table 4 for description of treatments.

The mean concentrations of NH_4-N in runoff over seven rain events for MBSod/MBSoil (1.21 mg L^{-1}) and HNFSod/MBSoil (2.24 mg L^{-1}) were greater ($p < 0.005$) than the other five treatments. The mean NH_4-N concentration in runoff for the other five treatments ranged from 0.47 to 0.72 mg L^{-1}. Low runoff concentrations of NH_4-N were observed even though these five treatments included transplanted sod and soil amended with composted MB as well as treatments without MB. The greater mean NH_4-N concentrations in runoff from MBSod/MBSoil and HNFSod/MBSoil could be attributed, in part, to greater mineralization of N from clippings and turfgrass biomass compared to the other five treatments (Figure 9). Turfgrass was mowed and clippings weighed and returned to soil on June 16 and 26. Greater NH_4-N concentration was observed on June 16 and July 3, which were the rain events following the return of turfgrass clippings to all treatments. For most treatments, NH_4-N concentration was greater on July 3 than on June 16.

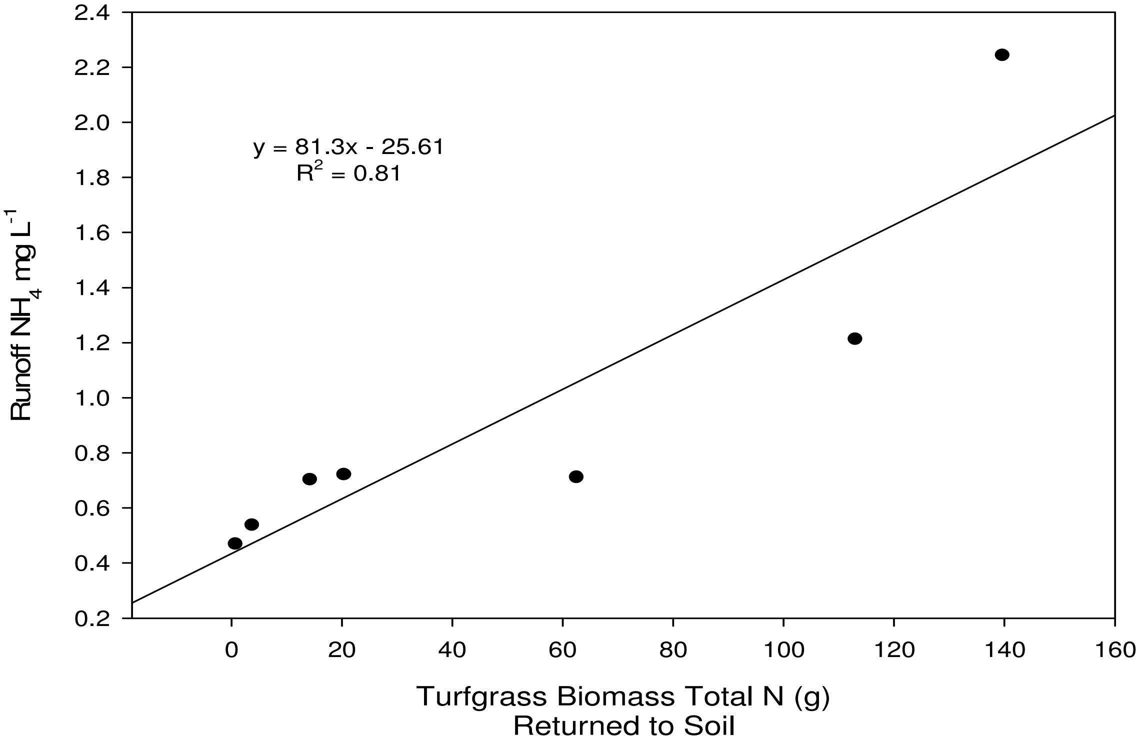

Figure 9. Relationship between turfgrass biomass TKN returned and mean NH_4-N concentration in runoff.

Runoff concentrations of TKN differed ($p < 0.001$) among establishment treatments and an interaction ($p < 0.001$) was observed between treatment and rain. An ANOVA within runoff events indicated runoff concentration of TKN differed ($p < 0.001$) among treatments except on July 4 and 5. As with other forms of N, runoff concentration of TKN generally declined after the initial rain event within each cluster of rain dates (Figure 10). The range of mean TKN concentration declined from June 16 (9.2 to 20.6 mg L^{-1}) to June 20 (6.2 to 12.9 mg L^{-1}). Mean runoff concentration of TKN over seven runoff events was greatest ($p < 0.005$) for sprigged treatments and sprigged un-amended soil had greater mean concentration than MB-amended sprigged ($p = 0.003$). Mean runoff TKN concentration of sprigged treatments over seven runoff events was 10.5 mg L^{-1} for MB-amended soil and 12.2 mg L^{-1} for soil without MB. Mean TKN concentrations in runoff were lower for the sods transplanted from turfgrass grown with or without MB (6.4 – 8.5 mg L^{-1}).

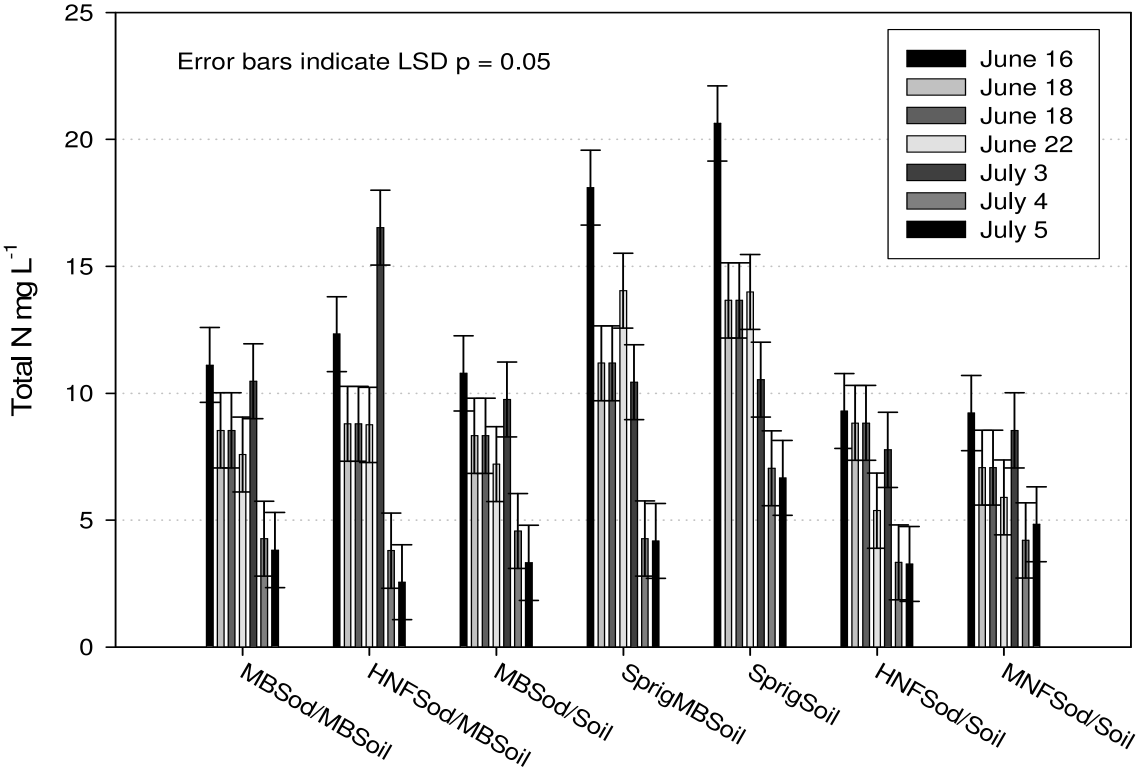

Figure 10. Mean runoff concentrations of TKN for establishment treatments during each of seven runoff events. See Table 4 for description of treatments.

Although imports of composted MB as transplanted sod or a soil amendment increased TKN of soil (Table 7), runoff concentration of TKN was more closely related to sediment loss (Figure 11). The greatest sediment loss was observed for the sprigged treatments with or without incorporation of composted MB. Similarly, runoff concentration of TKN was greater for the sprigged treatments with MB (10.5) and without MB (12.2 g L^{-1}). Digestion and analysis of the sediment filtered (< 0.7 μm) from runoff water revealed greater concentrations of sediment-bound TKN in runoff from sprigged treatments (531 to 622 μg L^{-1}) than from transplanted sod (35 to 47 μg L^{-1}). Although incorporation of composted MB increased soil TKN concentration three-fold within the 0- to 5-cm depth compared to soil without MB (Table 7), neither sediment or TKN concentrations in runoff differed between the two sprigged treatments. Importing composted MB in transplanted sod reduced both sediment and TKN concentration in runoff compared to the sprigged treatments.

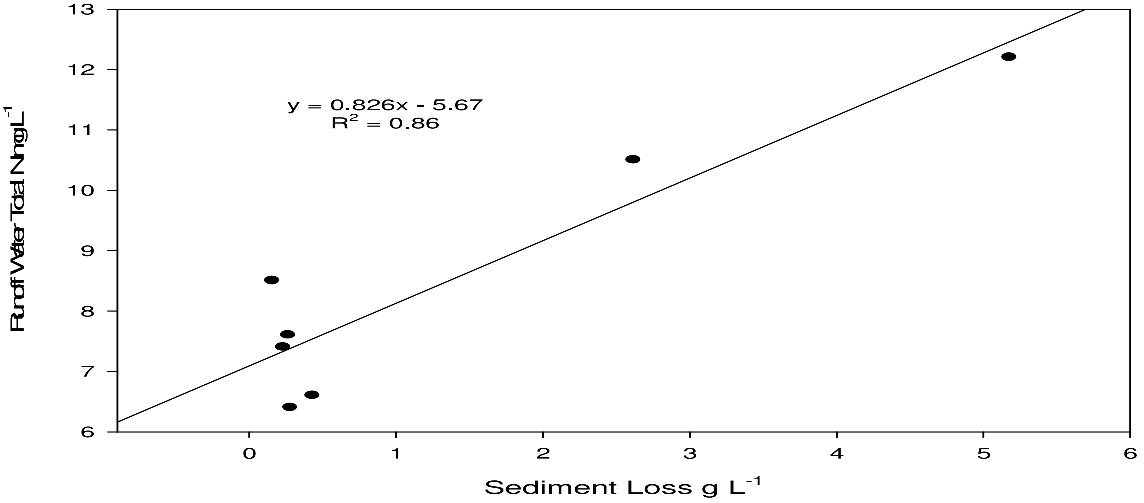

Figure 11. Relationship between mean runoff concentrations or TKN and sediment in runoff.

Mass loss N was affected by runoff volume and concentrations of soluble and sediment-bound forms in runoff water. Runoff volume was directly related to rainfall depth and varied among treatments. Mean runoff volume over the seven runoff events was greater ($p < 0.05$) for the sprigged treatment without MB (SprigSoil) than the six other treatments. For moderate rainfall amounts (< 2.0 cm) on June 16, 18, 22 and July 3, mass loss reflected the trend of decreasing mean concentration for respective N forms across runoff events. In contrast, large rainfall depths on June 3 (3.92 cm) and July 4 (7.5 cm) and 5 (6.5 cm) produced spikes in mass loss of NH_4-N and TKN.

Mean mass loss of NO_3-N over seven runoff events was greatest ($p < 0.001$) among the establishment treatments for HNFSod/MBSoil at 20.4 mg m^{-2}. Mass loss of NO_3-N in runoff was similar between MBSod/MBSoil (12.9 mg m^{-2}) and SprigMBSoil (13.4 mg m^{-2}) and greater ($p < 0.05$) than that of the remaining four treatments. On dates of moderate rain and runoff depth (June 16 and 18), mass loss of NO_3-N was similar among HNFSod/MBSoil (44.7 mg m^{-2}), MBSod/MBSoil (36.9 mg m^{-2}), SprigMBSoil treatments (44.7 mg m^{-2}), but NO_3-N loss was less ($p < 0.05$) for remaining four treatments. On July 3, mean mass loss of NO_3-N was similar among treatments and ranged from 1.6 – 5.2 mg m^{-2}. The large depths of rain (7.5 and 6.5 cm) and runoff on July 4 and 5 diluted NO_3-N concentrations and precluded differences in NO_3-N mass loss among treatments. For the moderate rain depths over the four rain events in June, interaction of rainfall with the surface layer likely solubilized and reduced the NO_3-N available for transport during consecutive rain and runoff events. Cumulative mass loss for NO_3-N over seven rain events is shown in Table 9.

Mean mass loss of NH_4-N over the seven runoff events was greatest ($p < 0.001$) for HNFSod/MBSoil at 22.6 mg m^{-2} followed by losses that were similar among MBSod/MBSoil (13.7 mg m^{-2}), MBSod/Soil (11.6 mg m^{-2}), and HNFSod/Soil (10.9 mg m^{-2}). Mean mass loss of NH_4-N in runoff was similar among sprigged treatments (SprigSoil and SprigMBSoil) and control sod (MNFSod/Soil) and were the lowest among the seven treatments (<9.6 mg m^{-2}). Similar to NO_3-N, reductions in mass loss of NH_4-N from the initial rain event through July 3 reflected the trend of NH_4-N concentration in runoff. On July 4 and 5, increased depths of rainfall and runoff contributed to greater mass loss of NH_4-N for all treatments than previously sampled runoff events. Cumulative mass loss for NH_4-N over seven rain events is shown in Table 9. The mean mass loss of NH_4-N from June 16 to July 3 ranged from 4.3 to 17.5 mg m^{-2}.On July 4 and 5, the range of mass loss of NH_4-N was 14.8 to 35.3 mg m^{-2}. In addition to higher rainfall depth, a return of turfgrass clippings to soil coincided with the 202 to 386% increase in mass loss of NH_4 on July 4 and 5 compared to lower rainfall depths of previous runoff events.

The mean TKN mass loss in runoff over seven runoff events was greatest ($p < 0.001$) for SprigSoil at 248 mg m^{-2} and was similar among the six other treatments within the range from 92 to 125 mg m^{-2}. Variation of TKN mass loss corresponded with that of sediment loss and both variables reflected differences in rainfall and runoff depth among the seven runoff events. For rain events during June and on July 3, TKN mass loss ranged from 71 – 223 mg m^{-2}. The increased rainfall and runoff depths on July 4 and 5 increased TKN mass loss to a range of 130 – 310 mg m^{-2}. The greater rain and runoff depths on July

4 and 5 contributed to a 139 to 253% increase in the mass loss of TKN compared to previous rain events.

In the comparison among treatments, sources of variation of mass loss of sediment proved insight concerning treatment effects on TKN mass loss. For sprigged treatments (SprigSoil and SprigMBSoil), incorporation of 25% by volume of composted MB increased water holding capacity of soil and enhanced establishment rates of turfgrass. By the first runoff event (June 16), the sprigged turfgrass covered 45% of soil amended with MB, but only 40% of soil without MB. On June 28, after the first cluster of rain events and the second time turf was mowed, turfgrass covered 95% of the soil amended with MB, but only 52% of the soil without MB. The enhanced coverage of MB amended soils reduced soil exposure to runoff and transport processes for sediment. As a result, mass loss of sediment and TKN from SprigMBSoil was similar to treatments comprising transplanted sod with and without MB amendments.

Table 9. Cumulative mass loss of N over seven runoff events.

	TKN mg m^{-2}	NO_3 mg m^{-2}	NH_4 mg m^{-2}
MBSod/MBSoil	690.86 bc[†]	90.09 b	95.72 b
HNFSod/MBSoil	644.52 c	142.91 a	158.06 a
MBSod/Soil	829.12 bc	23.36 d	80.97 b
SprigMBSoil	876.57 bc	93.96 b	54.43 c
SprigSoil	1736.12 a	61.35 c	66.98 bc
HNFSod/Soil	683.18 bc	21.68 d	76.26 b
MNFSod/Soil	757.05 bc	28.58 d	53.71 c

[†] Means separated by LSD ($p = 0.05$)

Carbon

Soil organic carbon (SOC) within the 5-cm depth was greatest ($p < 0.001$) for treatments in which the entire depth was amended with 25% by volume of composted MB. Mean SOC concentrations of 3.0 g kg^{-1} for MBSod/MBSoil and 2.9 g kg^{-1} for SprigMBSoil were greater than treatments in which only a 2-cm depth of sod or soil was amended. For treatments in which either the surface layer (0 to 2 cm depth) or constructed soil below the 2-cm depth was amended with MB, SOC concentration within the 5-cm depth was reduced. The SOC concentration was 1.66 g kg^{-1} for MBSod/Soil, which was less ($p < 0.001$) than treatments amended throughout the 5-cm depth but greater ($p< 0.001$) than treatments without MB. Similarly, the SOC of HNFSod/MBSoil was 1.68 g kg^{-1} was less than MBSod/MBSoil and SprigMBSoil but greater than three un-amended treatments. The SOC concentrations of treatments without MB ranged from 0.55 – 0.72 g kg^{-1} (Appendix A).

The variation of mean SOC concentration among treatments was reflected in variation of dissolved organic carbon (DOC) concentration in runoff over the seven rain events. Mean DOC concentrations in runoff from MBSod/MBSoil (35.9 mg L^{-1}) and MBSod/Soil (37.9 mg L^{-1}) were greater ($p < 0.001$) than the other five treatments. The mean runoff concentration of DOC for HNFSod/MBSoil (26.7 mg kg^{-1}) was, in turn, greater ($p < 0.001$) than all sprigged or un-amended treatments. The mean DOC concentration was lowest ($p < 0.001$) among treatments for SprigSoil at 7.6 mg kg^{-1}.

Similar to the trends for N and P forms, the runoff concentrations of DOC varied among runoff events and tended to decline after the initial rain event (June 16 and July 3) for each cluster of rain events. On June 16, DOC in runoff from MBSod/Soil (62.3 mg L^{-1}) was greater ($p < 0.05$) than MBSod/MBSoil (53.6 mg L^{-1}), which was greater ($p < 0.05$) than HNFSod/MBSoil (43.9 mg L^{-1}). The amendment of the sod layer or constructed soil beneath sod for these three treatments contributed to greater ($p<0.05$) runoff concentrations of DOC than the other five establishment treatments. A DOC concentration of 14.7 mg L^{-1} for SprigSoil was lowest ($p < 0.05$) among the seven treatments.

By June 22, mean DOC concentration in runoff from the seven treatments had decreased 43 to 62% compared to June 16. The runoff concentration of DOC for MBSod/MBSoil (30.8 mg L^{-1}) and MBSod/Soil (28.9 mg L^{-1}) remained greater ($p < 0.01$) than other treatments and that of SprigSoil (5.6 mg L^{-1}) remained lowest. A similar trend of declining DOC concentration was observed between July 3 and 5. Runoff concentrations of DOC ranged from 10.1 to 61.8 mg L^{-1} on July 3 and from 3.7 to 12.4 mg L^{-1} on July 5.

The variation of runoff concentrations of DOC among treatments could be attributed to decomposition of MB and turf biomass and clippings and to soluble root exudates from turfgrass roots. The relatively large DOC concentrations in runoff from MB-amended soil and sod indicated MB was a source of DOC. Yet, spikes in runoff concentrations of DOC on June 16 and July 3 for treatments producing relatively large biomass indicated decomposition of turf clippings was a potential source of DOC.

The large increases of SOC and of associated runoff concentrations of DOC for treatments amended with composted MB overshadowed DOC derived from decomposition of clippings and root exudates from growing turfgrass. In addition, DOC contributions from turfgrass clippings and root exudates were expected to be greater for the high turfgrass densities of transplanted sod than for sprigged treatments. To relate runoff concentrations of DOC to the varied sources of SOC, sprigged and sodded treatments where analyzed separately. The contribution of MB to increases of SOC and runoff concentration of DOC is evident for the sprigged treatments with and without incorporation of MB (Fig. 12). A linear equation provided the best fit ($R^2 = 0.97$) for the relationship between variation of SOC and runoff concentration of DOC for SprigSoil and SprigMBSoil treatments. The contributions of both MB and turfgrass C sources to concentrations of SOC and of DOC in runoff reduced the portion of variation of DOC ($R^2 = 0.63$) accounted for in variation of SOC (Fig. 12). Differences of biomass production and turfgrass growth rate among MB-amended and un-amended sod treatments may have contributed to variation in DOC production and loss in runoff.

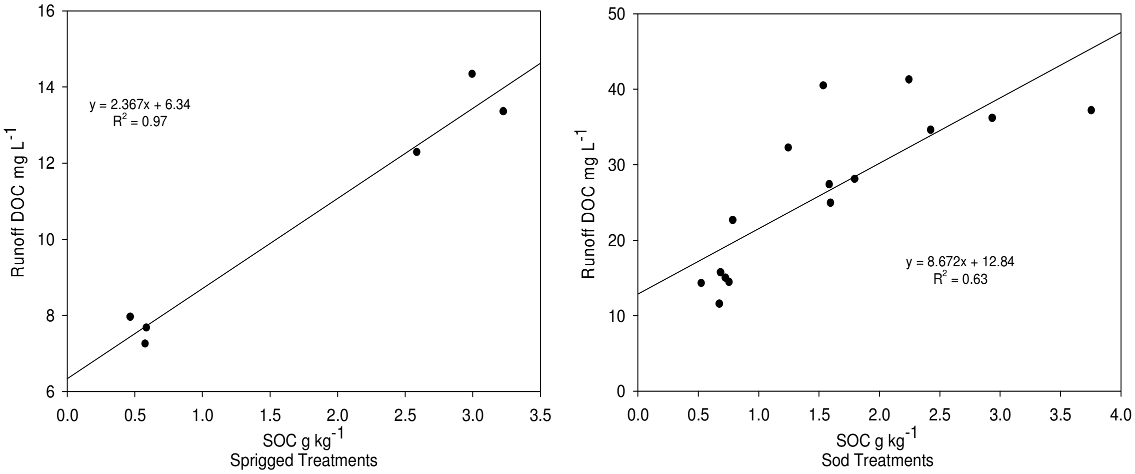

Figure 12. Relationship between mean concentrations of SOC and of DOC in runoff for sprigged and sod treatments.

Cations

Cations could potentially interact with P in soil and affect runoff concentrations of P. Total soil Mg, Ca and Fe were quantified in digests of soil sampled from treatments after the final runoff event. The concentrations of total Ca and Mg within the 0- to 2-cm soil depth were directly related MB amounts imported as sod or compost. The MB amendments within the 0- to 2-cm depth of MBSod/MBSoil, MBSod/Soil, and SprigMBSoil increased total Mg concentrations to a range of 1364 to 1462 mg kg^{-1}. In contrast, total Mg concentrations ranged from 416 to 715 mg kg^{-1} for those treatments without MB in the 0- to 2-cm depth (HNFSod/MBSoil, SprigSoil, HNFSod/Soil, MNFSod/Soil) total. Similar to Mg, MB amendments increased total Ca concentrations within the 0- to 2-cm depth to a range of 16945 – 26235 mg kg^{-1} for MBSod/MBSoil, MBSod/Soil and SprigMBSoil. In contrast, total Ca concentrations ranged from 1855 – 2221 mg kg^{-1} for HNFSod/MBSoil, SprigSoil, HNFSod/Soil and MNFSod/Soil without MB in the 0- to 2-cm depth. Given MB amendments were the principal source of total P, Ca, and Mg, variation to total soil P concentration was linearly related to that of Ca (R^2 = 0.99) and Mg (R^2 = 0.91) within the 0- to 2-cm depth.

In contrast, variation of soil total P concentration within the surface layer was unrelated to total soil Fe concentration (R^2 = 0.27). Soil total Fe concentrations were similar among treatments and ranged from 5361 – 7635 mg kg^{-1} within the 0- to 2-cm depth and from 7121 – 8259 mg kg^{-1} to a depth of 5 cm. The analyses indicate soil rather than composted MB was the principal source of Fe and of variation of total soil Fe concentration among treatments. Although addition of MB to soil or sod did not result in significant differences in soil Fe concentration among treatments, addition of MB diluted soil Fe concentrations while increasing total P concentration. The MB amendments reduced ($p < 0.001$) the molar ratio of Fe:P within the 0- to 2-cm soil depth for MBSod/MBSoil, MBSod/Soil and SprigMBSoil (1.7, 1.7 and 2.9 respectively) compared to HNFSod/MBSoil, SprigSoil, HNFSod/Soil and MNFSod/Soil (ranged from 19.7 to 22.4). Within the 0- to 5-cm soil depth, the Fe:P ratio of MB-amended treatments was lower ($p < 0.001$), ranging from 3.0 – 7.0, than the range observed for treatments without MB (25.0 – 26.5).

Although MB amendments were a major source of soil Mg, variation of runoff concentrations of Mg were not related to MB use in the establishment treatments. Mean runoff concentration of total Mg was greater ($p = 0.001$) for sprigged treatments, with or without MB amendments, than for sodded treatments with or without MB. Total Mg concentration in runoff ranged from 3.4 to 5.6 mg L^{-1} for SprigSoil and SprigMBSoil and from 1.3 to 2.0 mg L^{-1} for sodded treatments over the seven runoff events. In addition, the mean total Mg concentration in runoff was linearly ($R^2 = 0.96$) related to sediment loss. Given soil rather than MB was the principal source of total Fe, the direct linear relationship between total Fe concentration in runoff ($R^2 = 0.93$) and sediment loss was expected. In addition, total Fe concentration in runoff was greatest ($p < 0.001$) for SprigSoil (30.8 mg L^{-1}), a treatment without MB that established slowly. Runoff concentrations of the other six treatments were relatively low and ranged from 0.9 – 4.2 mg L^{-1}.

As the molar ratio of mean total Fe:P declined to near 1 in soil due to MB amendments in selected treatments, the mean concentration of TP in runoff increased (Fig.

13). The volume-based rate of MB increased soil total P within the 0- to 2-cm depth to concentrations that diminished potential sorption of P to non-crystalline Fe compounds within soil. The decreasing soil Fe:P ratio was inversely related to total soil P concentrations. A similar relationship between Mg:P in soil and runoff concentration and loss of TP was observed. Unlike the Fe:P ratio, the Mg:P ratio was lowered in MB-amended treatments due to additions of both Mg and P. The Mg:P ratio in MB-amended soil reflected the ratio in the MB. As a result, relationship between the Mg:P ratio of soil and runoff loss of TP is due to an existing relationship between Mg and TP in soil. This data suggest that soil total P concentration in soils with and without volume-based MB rates is a more useful indicator of potential runoff loss of P than Fe:P and Mg:P ratios. Relating oxalate extractable fractions of Fe and other cations to saturation and runoff loss of P may prove more effective than concentrations of total cations (Schroeder et al. 2004).

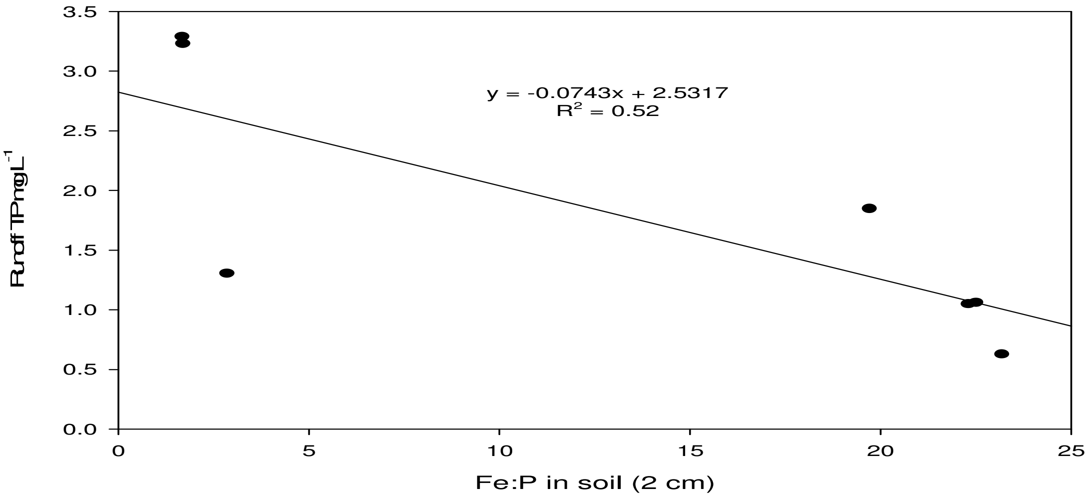

Figure 13. Relationship between Fe:P in soil and runoff loss of TP.

Discussion

Compared to transplanted sod, sediment loss from sprigged treatments was 27 times greater without composted MB and 9 times greater with composted MB. Incorporation of MB into soil reduced sediment loss 66% compared to soil without MB. The lower sediment loss for soil mixed with MB in sprigged treatments was similar to a 120% reduction of sediment loss observed after surface applications of compost in conventional tillage and cropping systems (Wortmann and Walters 2006). Greater rates of coverage for sprigged turfgrass amended with MB contributed to the reduced sediment loss over the seven runoff events compared to soil sprigged without incorporation of MB. Similar to the present study, Persyn et al. (2004) found sod formed by vegetated road banks with or without MB and incorporation of MB into soil of un-vegetated road banks reduced sediment loss compared to un-vegetated road banks without incorporation of MB in soil.

Comparisons between transplanted sod and sprigged Tifway, with and without composted MB amendments in the 0- to 2-cm and deeper depths, revealed options for limiting runoff loss of water, sediment, and nutrients. As reported previously for animal manures, incorporating MB into soil decreased runoff loss of P compared to MB near the soil surface (Kleinman et al. 2002). Transplanting MB grown sod on soil with and without incorporation of MB causes STP and TP concentration to vary greatly between the 0- to 2-cm depth and below 2 cm. Concentrations of STP and TP in transplanted sod were more than 10 times greater with than without composted MB. Although 25% by volume of MB was incorporated throughout the soil layer of the sprigged treatment, concentrations of STP were 51% lower and TP 43% lower than that of MB amended sod within the 0- to 2-cm depth.

Previous studies indicated concentrations within the 0- to 5-cm depth were most closely related to runoff concentrations and losses of P (Torbert et al., 2002). Yet, MB amendments differed between 0- to 2-cm and 2- to 5-cm depths for transplanted sod treatments in the present study. Sampling across depths with and without MB diluted concentrations of P forms compared to sampling within a depth mixed with MB. In addition, rainfall interactions with the 0- to 2-cm depth were a major source of variation of runoff concentrations and losses of P forms. Even for the sprigged treatment, greater concentrations of P forms at 0- to 5-cm sampling depth than at 0- to 2-cm indicated P uptake in turf roots and leaching through the soil profile could have reduced P concentrations in the surface layer. Leaching of P through coarse textured soils to a depth of 30 cm was reported Eghball (2003) and low recoveries (through sod harvest) of P from surface applied manure on a sandy loam soil was reported by Vietor et al. (2002).

Vietor et al. (2004) demonstrated the slope of linear relationships between STP and mass loss of dissolved P was greater for sprigged than sodded treatments sampled to a depth of 7.5 cm. The soil on which sod was transplanted was uniform among treatments and did not confound variation among sodded treatments sampled at depths below the sod layer. When concentrations of P are uniform in the soil below sod treatments, depth of sampling is not as critical as observed in the present study. When variation occurs within and below the sod layer, the best way to compare a variety of turf establishment methods with and without MB in sod or soil is to sample the depths near the surface that interact with runoff water.

The variation of nutrient concentrations among treatments with and without MB in the 0- to 2-cm depth affected variation of concentration and loss of nutrients in runoff. The observations for establishment treatments in the present study are consistent with previous reports of a direct relationship between runoff loss of P and P concentration in soil (Torbert et al. 2002) and manure amendments (Kleinman et al. 2002). Under simulated rainfall, Kleinman et al. (2002) demonstrated WEP concentration in top-dressed manure was directly related to SRP concentration in runoff. In the present study, variation of concentration and mass loss of P forms in runoff were similarly best related to variation of soil WEP concentration within the 0- to 2-cm depth ($R^2 < 0.94$).

Compared to MB-amended sods, relatively low runoff concentrations TP, TDP, and DRP and soil concentrations of TP, STP, and WEP were observed over seven runoff events for sods without MB. Similarly, incorporation of MB in soil doubled runoff concentration of TDP compared to soil without MB in sprigged treatments. The benefits of incorporating MB in soil during production of sod before transplanting or before sprigging was evident in comparing turfgrass that was top-dressed with composted manure during production or sprigging. Runoff concentrations of TDP for sod transplanted from fields top-dressed with composted dairy manure (Vietor et al., 2004) were two times greater than that of sod transplanted from soil mixed with volume-based MB rates. Similarly, TDP concentration in runoff from sprigged Tifway top-dressed with composted manure was 9.5 times greater than soil mixed with 25% by volume of MB in the present study.

The previous study of runoff from sods transplanted from fields grown with and without top-dressed manure revealed the opportunity to eliminate soluble fertilizer P applications on manure-grown sod (Vietor et al., 2004). Annual applications of soluble fertilizer P to sod transplanted from fields grown with inorganic fertilizer P is a potential nonpoint-source of TDP in runoff. Similar to manure-grown sod (Vietor et al., 2004), annual applications of soluble P fertilizers are unnecessary for establishment and maintenance of MB-amended sod. Easton and Petrovic (2004) also demonstrated that soluble inorganic fertilizers may result in concentrations and loss of P from turfgrass greater than organic sources.

Comparing transplanted sod and Tifway established through sprigging, with and without MB amendments demonstrates the affect biological processes have on cycling of nitrogen in soil and potential loss in runoff. In the present study, no fertilizer N was applied to sod after transplanting or to Tifway established through sprigging. Concentration of NO_3-N in soil was related to uptake of N by turfgrass and loss in runoff. Mineralization of N in composted MB and of turf clippings cycled back to soil resulted in variations of concentration and forms of N found in soil and in runoff by the final sampling date.

Mineralization of N from MB in the amended layer of soil in sod or sprigged treatments resulted in a 15 fold increase in runoff loss of NO_3 compared to sod or sprigged establishment without MB. Incorporating MB into subsoil for establishment of turf through sod with and without MB or sprigs resulted in runoff NO_3-N concentrations similar to concentrations reported by Johnson et al. (2006) when topdressing large rates (99 m^3 ha^{-1})

of compost. However application of fertilizer N to turf for un-amended soil may result in NO_3-N concentration in runoff comparable to MB amended soils as reported by Johnson et al. (2006), Gaudreau et al. (2002). Amending soils with composted MB prior to establishment of sod or sprigs may enhance turfgrass biomass production and reduce runoff losses of NO_3-N compared to turf establishment using inorganic fertilizers only (Gaudreau et al. 2002).

MB amended sub-soils resulted in greater water retention and greater biomass production which cycled greater amounts of N back to the soil surface with the return of clippings. Concentration and amounts of TKN in turfgrass biomass was linearly related to NO_3-N concentrations in soil. Soil concentration of N was only one factor contributing to greater turfgrass biomass and uptake of N, greater soil water content of MB amended soils also contributed to greater biomass production. NH4 concentration and mass loss in runoff had a linear relationship ($R^2 = 0.81$) with the mass of TKN found in the clippings returned to the surface. Other than runoff events immediately following return of turf clippings, runoff NH_4 concentrations were similar to concentration reported by Johnson et al. 2006. The application of ammonium containing fertilizers contributes to large amounts of NH_4 in runoff which may mask the affect of turf clipping return on NH_4 loss. Gaudreau et al. (2004) found that NH_4 losses were greatest in rain events following the application of NH_4 containing fertilizers. On rain dates other than dates immediately following return of clippings, concentrations of NH_4 in runoff were similar among establishment methods and dates. Turfgrass quality may be enhanced and runoff loss of NH_4 reduced by management of turf clippings and fertilizer N for turf established through sod or sprigs with composted MB.

Concentrations of TKN in runoff were linearly related to amount and concentration of TKN in sediment. Sediment loss was related to turf coverage. Sod treatments had complete coverage and MB amended sprigged soil had achieved complete coverage by the fourth rain event. The rapid coverage compared to the sprigged treatment without MB resulted in significant reductions in sediment loss (Vietor et al. 2002). Similarly, Gaudreau et al. (2004) attributed runoff loss of TKN to density and coverage of turfgrass which reduced sediment loss. As reported by Vietor et al. (2002) TKN concentrations in sediment comprised only a small fraction of TKN in runoff yet concentrations in runoff were similar to concentration in sediment for the present study. Establishment of turf through sod or sprigs, with MB amendments may reduce runoff loss of TKN and sediment compared to un-amended sprigged soil.

Runoff loss of DOC was greatest for MB amended sod and sprigged soil. The DOC loss is attributed to MB additions and contributions from turfgrass. Due to the difference in turfgrass densities when comparing sprigged to transplanted sod treatments, generation of DOC from root exudates and decomposition of turf clippings is expected to be less for sprigged turf. For turfgrass established with MB, runoff concentrations of DOC were 2.5 times greater for establishment using sod compared to sprigging. For turfgrass establishment without MB, runoff concentration of DOC was 2.0 times greater for sod than for sprigged soils. Wright et al. (2005) reported that compost application resulted in an initial increase of DOC in soil with contributions from turfgrass playing a major role in sustaining DOC concentrations in soil and also observed seasonal variation associated with seasonal production of turfgrass. A relationship exist between SOC and DOC in soil (Zhang et al. 2006, Wright et al. 2005) and DOC only accounts for a small fraction of total soil organic carbon (Silveria 2005). The relationship between SOC and DOC in soil contributes to variation of DOC in runoff from turf established through sod or sprigging with and without composted MB. DOC concentrations in runoff were 2.0 or 1.75 times greater MB amended soils than for un-amended soils for establishment of turfgrass with sod or sprigs respectively. For MB-amended and un-amended sod treatments in the present study, the linear relationship between variation of SOC and DOC in runoff was poorer (R^2 = 0.63) than that of sprigged treatments (R^2 = 0.97). Differences of biomass production and turfgrass growth rate among MB-amended and un-amended sod treatments may have contributed to variation in DOC production and loss in runoff.

CHAPTER IV

SUMMARY

Cycling of composted MB between cities and turfgrass produced nearby on agricultural land could benefit sod production and the urban landscapes on which MB-grown sod is transplanted. The nutrients and organic matter applied in composted can enhance turfgrass establishment, growth and quality during production and after sod is transplanted back to cities. In addition, volume-based MB amendments can enhance soil and water conservation and improve sod properties (Cizar, 1994). The goal of cycling MB amendments through turfgrass sod is to maximize benefits of MB additions to soil while minimizing negative impacts to the environment.

In the present study, incorporation of MB at volume based rates enhanced percent coverage during establishment of Tifway bermudagrass sod. Yet, split applications of 50 kg fertilizer N ha^{-1} further improved percent coverage Tifway during fall and spring sampling dates. The four split applications of 50 kg N ha^{-1} each were near the optimum for production of a Tifway bermudagrass sod crop under the soil and climatic conditions of the present study. Increasing fertilizer N rates to 100 kg N ha^{-1} per application did not increase turfgrass coverage rates compared to the 50-kg rate. In addition to turfgrass requirements during establishment and re-growth, a substantial portion of the nutrients and organic matter in MB are harvested and transplanted back to urban landscapes in sod. For MB amended soils, 31 to 53% of applied N and 30 to 52% of applied P were exported through the initial sod harvest.

In addition to improving establishment rate of turf, MB amendments improved sod physical properties. Amending soil with MB at volume based rates reduced sod weight and increased sod water content at harvest. Reduced sod weight will aid in transportation of sod from production sites to markets and conserves native soil on which sod is produced. Removing less native soil may prolong the productivity of sod fields and diminish the effect of contrasting soil textures when transplanting sod on a variety of urban soils.

Exporting a large percentage of applied carbon and nutrients in the harvested sod layer extends the benefits of improved soil physical conditions to urban soils on which sod is transplanted. Yet, nutrients supplied in excess of turf uptake requirements are subject to loss in runoff. Variation of TP, STP and WEP in the sod layer (2-cm depth) and NO_3-N in the soil layer (5-cm depth) accounted for a major portion of variation in TP, TDP, and SRP concentrations and mass loss in runoff for contrasting turfgrass establishment practices on urban soils. As soil concentrations increased with the addition of MB in to the surface layer or sub-surface layer, runoff losses also increased. Despite incorporation of MB and increases in soil P forms within constructed soil below the sod layer, transplanting sod low in P on the soil layer limited mass loss of P forms in runoff.

Sprigging of Tifway in MB-amended soil reduced P loss in runoff compared to transplanting of MB grown sod on MB amended or un-amended soil and was similar to turf establishment without MB amendments. Transplanting of fertilizer-grown sod over MB-amended soil also reduced runoff loss of P compared to transplanting of MB grown sod. The MB amendments in the surface layer for any establishment method contributed to increased concentrations of NO_3-N in runoff. Incorporation of MB in constructed soil below the surface layer similarly increased runoff loss, but mean runoff concentrations of NO3-N for any turf establishment method that included MB was less than 2 mg L^{-1}. Mean runoff concentrations of NO3-N were less than 0.6 mg L^{-1} for Tifway established without MB amendments.

Variation of runoff concentrations of NH_4 among establishment treatments was not related to variation of soil NH_4-N concentration. Variation of runoff concentration of NH_4-N from differing establishment treatments was directly related to variation of TKN mass in turfgrass clippings returned to the soil surface. Intense rainfall interaction with turfgrass residues at the surface contributed to greater losses of NH_4 in runoff. The TKN biomass in turfgrass clippings and associated NH_4-N loss in runoff were relatively large for turf established on MB amended subsoil, sprigged or sodded. Incorporation of composted MB in subsoil limited runoff loss and improved soil water holding capacity beneath transplanted sod, which was associated with greater biomass production than treatments without MB in soil. MB grown sod transplanted on un-amended subsoil resulted in reduced biomass production and NH_4-N return in clippings.

Transplanted sod, with or without MB amendments, limited sediment loss compared to the sprigged treatments. Although MB amendments increased soil TKN concentration, variation of TKN loss in runoff among establishment treatments was related to variation of runoff loss of sediment rather than soil N. Use of sod with or without MB in the sod or subsoil limited sediment and TKN losses in runoff. Sediment loss was greater for sprigged than sodded treatments, but amending soil with MB reduced sediment and TKN loss in runoff compared to soil without MB.

Variation of sediment and nutrient concentration and loss among runoff events revealed the dynamics of interactions between rainfall and surfaces of establishment treatments. Consecutive rain events within a period of one week or less removed soluble nutrients applied in treatments or generated through mineralization from MB and plant residues at the soil surface. Concentrations in the initial runoff event were greatest followed by a steady decline in concentration during subsequent rain events. During a period between two clusters of rain events, mineralization of nutrients in MB and plant residues at the surface replenished soluble nutrients subject to loss in runoff. In addition to timing of rain events, increased rainfall depth contributed to increased sediment and TKN loss during the final two runoff events of the seven events sampled in this study.

Amending soil, sod or both with MB increased SOC 302 to 545% compared to treatments without MB. A combination of the increased SOC concentrations, turfgrass root exudates, and decomposition of plant residues contributed to variation of DOC concentration in runoff. Actively growing, dense turfgrass of established sod transplanted on MB amended and un-amended soils contributed to greater DOC loss in runoff than the incomplete turfgrass cover of sprigged treatments with and without MB. In addition to increased DOC concentrations, increased SOC concentration contributed to greater soil water content and retention in treatments amended with MB. Greater water infiltration rates for sod or subsoil amended with MB limits runoff loss during and after turfgrass establishment.

The studies of fate and transport of mineral nutrients, organic C, and sediment during production and after transplanting turfgrass sod revealed both benefits and risks of cycling MB between urban and agricultural landscapes. Amending sod or subsoil with MB improved potential water conservation in both agricultural and urban soils. In addition, MB amendments enhanced growth and performance of turfgrass compared to soil without MB. The MB amendments improved turf performance through enhanced water retention and nutrient availability within the root zone. Although the MB sources of nutrients benefit turfgrass growth, negative environmental impacts can occur. The volume-based rate of MB required to improve soil physical properties can provide N and P in amounts that greatly exceed turfgrass requirements. Incorporation of 25% by volume MB elevated concentrations of N and P forms in soil and sod, but similarly increased concentration and mass loss of N and P forms in runoff compared to treatments without MB. Transplanting of MB-grown sod on soil constructed with or without MB contributed to increased concentration and mass loss of dissolved N and P forms in runoff. Incorporation of MB in a coarse-textured soil exhibiting rapid water infiltration characteristics reduced runoff concentrations of dissolved N and P forms after sprigging compared to MB-grown sod. Yet, both sediment and TKN loss were greater for sprigged than sodded Tifway bermudagrass. In situations where slope causes loss of sediment and N to be a concern, transplanting of fertilizer grown sod on MB-amended soil may be the best option. Other options which involve MB grown sod transplanted on MB amended and un-amended soils could be suitable methods for turfgrass establishment if methods for limiting P loss in runoff are developed.

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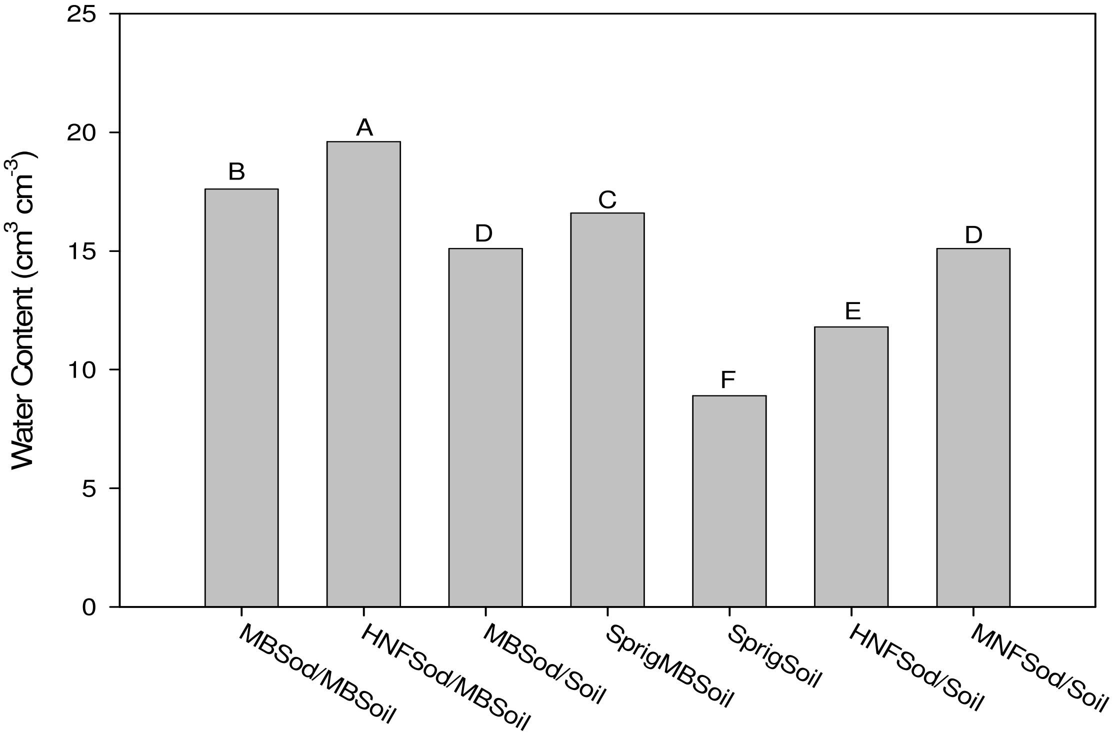
APPENDIX A

RUNOFF EXPERIMENT TREATMENT MEANS

	MBSod/ MBSoil	HNFSod/ MBSoil	MBSod/ Soil	Sprig MBSoil	SprigSoil	HNFSod/ Soil	MNFSod/ Soil
2 cm - Soil TKN mgkg^{-1}	3510	750	3295	2270	580	773	598
2 cm - Soil NO_3 mg kg^{-1}	9.5	3.8	8.8	28	2	3.3	3.3
2 cm - Soil WEPmg kg^{-1}	45.2	15.1	48.9	13.2	5	12.6	12.6
2 cm - Soil STP mg kg^{-1}	621	55	635	307	10	35	35
2 cm - Soil TP mg kg^{-1}	1761	149	1705	977	99	167	167
5 cm - Soil TKN mgkg^{-1}	2647	1677	1310	2560	677	760	767
5 cm - Soil NO_3 mg kg^{-1}	40.6	49.6	15.6	28.6	4.5	4.3	3.5
5 cm - Soil NH_4 mg kg^{-1}	16.2	13.1	10.4	15.7	2.8	7.3	9.8
5 cm - Soil WEPmg kg^{-1}	22	14.9	15.7	13.2	5	5.5	6.2
5 cm - Soil STP mg kg^{-1}	382	236	249	347	19	28	38
5 cm - Soil TP mg kg^{-1}	1351	754	608	1433	152	160	169
5 cm - Soil SOC g kg^{-1}	3.04	1.66	1.68	2.94	0.55	0.67	0.72
pH	7.8	7.7	8.3	8.0	8.3	8.5	8.7
Soil moisture	0.173	0.198	0.16	0.169	0.095	0.123	0.156
sediment loss	10.73	7.12	11.89	129.47	383.33	15.69	24.42
Runoff Volume L	30.96	34.32	47.01	38.67	72.08	53.73	50.49
Runoff DRP mg L^{-1}	2.32	1.62	2.80	0.84	0.27	0.69	0.51
Runoff TDP mg L^{-1}	2.77	1.79	3.26	0.92	0.42	0.90	0.69
Runoff TP mg L^{-1}	2.94	1.84	3.29	1.30	0.62	1.05	1.06
Runoff DOC mg L^{-1}	35.92	26.73	37.94	13.31	7.61	17.47	13.59
Runoff NO_3 mg L^{-1}	1.64	2.34	0.31	1.64	0.56	0.34	0.30
Runoff NH_4 mg L^{-1}	1.21	2.24	0.72	0.71	0.47	0.70	0.54
Runoff TKN mg L^{-1}	7.62	8.53	7.39	10.48	12.20	6.38	6.56
Clipping weight g	3538	3949	784	1729	49	580	175

APPENDIX B

SOIL MOISTURE FOR RUNOFF TREATMENTS JUNE 29 – SEPTEMBER 21



B1. Mean soil water content for contrasting turfgrass establishment methods over a 92 day period. Means separated by LSD (p = 0.05).

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