AMENDING CONSTRUCTED ROADSIDE AND URBAN SOILS WITH LARGE VOLUME-BASED COMPOST APPLICATIONS: EFFECTS ON WATER QUALITY

A Dissertation

by

NELS EDWARD HANSEN

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

DOCTOR OF PHILOSOPHY

December 2005

Major Subject: Agronomy

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ABSTRACT

Amending Constructed Roadside and Urban Soils with Large Volume-Based Compost
Applications: Effects on Water Quality. (December 2005)
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Mineral nutrients imported in composted dairy manure (CDM) and municipal biosolid (CMB) amendments for highway-rights-of-way and urban landscapes can pose a threat to surface water quality. Treatments were developed to evaluate recommendations for amending roadside and urban soils with compost at large volume-based rates. Texas Department of Transportation (TxDOT) recommendations were evaluated in 2002 and 2003. Municipal recommendations were evaluated in 2004. Treatments were imposed on 4 by 1.5-m field plots on a constructed soil with an 8.5% slope. Three TxDOT compost application methods were tested; incorporation at 25% by volume (CMT), topdressing over vegetation (GUC), and topdressing a 5-cm compost woodchip mix over bare soil (ECC). In 2003, a 12.5% CMT treatment was substituted for the GUC, and two contrasting composts were compared. In 2002, soil test phosphorus (STP) concentrations (mg kg^{-1}) were 291, 360, 410, and 1921 mg kg^{-1} in the 0 to 5-cm layer of a course textured CMT, fine textured CMT, GUC, and ECC treatments, respectively using CDM. In 2003, STP concentrations were 264, 439, 496, 623, 1115, and 2203 mg kg^{-1}, in the 0 to 5-cm layer after incorporation of CDM and CMB at the 12.5 and 25% volume-based rates, and topdressing the 5-cm CDM- or CMB-woodchip mix over bare soil, respectively. In 2004, contrasting CMB products, relatively low or high in total phosphorus (TP) were incorporated into the soil at 12.5 and 25% by volume, or imported in transplanted sod at the 25% by volume rate. The STP concentrations were 87, 147, 180, 301, 322, and 544 mg kg^{-1}, respective to the previously defined treatments. Runoff water from 14, 10, and 8 natural rain events was used to characterize nutrient and sediment transport in 2002, 2003, and 2004, respectively. Concentration of TDP in runoff water was highly variable for roadside treatments across rain events. Mass losses of TDP were similar after CDM or CMB were incorporated into the soil at 12.5 and 25% by volume. Compost incorporation was the most effective method for limiting TP loss in runoff. Roadway and urban soils are expected to contribute greater TP losses as P concentration increases in soils.

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NOMENCLATURE

CDM	Composted Dairy Manure
CMB	Composted Municipal Biosolids
CMT	Compost Manufactured Topsoil
DRP	Dissolved Reactive Phosphorus
ECC	Erosion Control Compost
GLM	General Linear Model
GUC	General-Use Compost
N	Nitrogen
P	Phosphorus
SDOT	State Departments of Transportation
STP	Soil Test Phosphorus
TDP	Total Dissolved Phosphorus
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
TxDOT	Texas Department of Transportation
WEP	Water Extractable Phosphorus

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CHAPTER I

INTRODUCTION

Linking dissolved phosphorus (P) and nitrogen (N) in surface water to specific sources is difficult. Yet, a majority of nonpoint nutrient pollution is attributed to agricultural and urban landscapes (Carpenter et al., 1998; Sharpley et al., 2001a). Identifying nutrient sources and pathways to surface water is crucial for understanding how position in the landscape (Sanchez and Boll, 2005; Sharpley et al., 2001b) and cultural practices contribute to eutrophication (Andraski et al., 2003; Daniel et al., 1998; Edwards and Daniel, 1994; Sharpley et al., 2001b). Many States in the US developed or are developing P indices to help assess the risk of P transport from specific sites to surface water. The likelihood of surface runoff dissolving bioavalable forms of P and transporting the nutrient off-site increases as soil test P (STP) concentrations increase in the soil (Schroeder et al., 2004; Tarkalson and Mikkelsen, 2004; Vadas et al., 2005). Similarly, as the distance to a surface water body decreases, the probability of runoff water carrying nutrient loads to the water body increases (Sharpley et al., 2001b). Repeated applications of inorganic and/or organic fertilizers can build up nutrient concentrations in the soil (Eghball et al., 1996). Single, large applications of inorganic and/or organic fertilizers can have the same effect. In either case, the undesirable result can be loss of nutrients, especially P and N in runoff water (Eghball and Gilley, 1999).

This dissertation follows the style of the Journal of Environmental Quality.

Yet, careful fertilizer management strictly matching applications rates to plant needs is difficult due to environmental and monetary constraints. Fertilizer management is further complicated when organic sources are used such as animal manures and municipal biosolids. There is a high degree of variability in the concentrations of nutrients in manure across animal species, time, and treatment. Best management practices can provide guidance for applying manures and biosolids while minimizing negative impacts on surface water quality (Sharpley et al., 2001a).

Beside chemical properties, manures and biosolids are also used to amend the physical properties of soils (Aggelides and Londra, 2000; Agostini et al., 2003). The added organic matter can increase water infiltration, percolation, and water holding capacity. Improving the structure protects soil from erosion and promotes plant growth. State Departments of Transportation utilize composted manures and biosolids to stabilize roadside soils during construction projects (Black et al., 1998). Sediment loss from unprotected soils is a major source of nonpoint pollution to surface waters from highway construction sites (Barrett et al., 1995). Although specifications for these roadside amendments are different between states (Black et al., 1998), a general method for amending soil with compost is consistent. The roadside amendments are specified as large volume- or depth-based application rates to soil. The intended purpose is to stabilize the soil quickly and promote rapid revegetation (Mitchell, 1997, Persyn et al., 2004, Glanville et al., 2004). Although, Glanville et al., (2004) and Persyn et al., (2004) conducted studies on nutrient and sediment transport in runoff water from compost amended roadside soils, few other sources are available to estimate nutrient and sediment loads to surface water. The roadside amendments are applied to landscapes constructed to maximize water runoff. In Texas, over 600,000 m^3 of compost products were applied to roadside soils as physical amendments in 2002 and 2003 (Sherman, 2003). The specifications for compost composition and application define three unique methods for amending roadside soils with compost (TxDOT, 1993). First, compost manufactured topsoil (CMT) is compost incorporated into soil, by up to 30% on a volume basis. Second, general use compost (GUC) compost applied evenly to vegetation with the limitation that vegetation cannot be completely covered. Third, erosion control compost (ECC) a blend of compost and woodchips spread evenly over a bare soil surface.

An evaluation of roadside soils amended with compost is needed to predict potential water quality impacts and develop corrective measures if required. The first two studies conducted in 2002 and 2003 evaluate the use of compost applications in large volume-based rates on roadside soils and the potential for nutrient and sediment transport in runoff water. The third study conducted in 2004, compared turfgrass sod production for large-scale use of CMB. The TxDOT specifications for using compost products were developed to dispose of waste, and stabilize and revegetate roadside soils (McCoy and Cogburn, 2001). Similarly, municipal programs have emerged to dispose of CMB and improve soil quality on urban landscapes (City of Austin, 2001). The "Water Wise Landscape and Soil Rebate Program" encourages incorporating CMB up to 25% by volume in low quality urban soils. Similar to the TxDOT programs for amending roadside soils, amending urban soils at large volume-based application rates may increase soil nutrient concentrations to excessive levels and promote nutrient loss, in dissolved and sediment-bound forms.

In the third study, CMB disposal was integrated with turfgrass sod production to provide an alternative best management practice. Flanagan et al., (1993) reported utilizing CMB in turfgrass sod production and other studies have evaluated turfgrass responses to CMB (Landschoot and Waddington, 1987). However, runoff water quality from sod transplanted from CMB-grown turf remains to be compared to soil amended with CMB prior to establishment of vegetation on urban landscapes.

The three experiments were conducted at the Turfgrass Field Laboratory, Texas A&M University, College Station, TX. Previous to these experiments, twenty-one runoff plots were constructed on an 8.5% slope on the disturbed remnants of a Boonville fine sandy loam. In 2002, 2003, and 2004, seven treatments were applied to the twenty-one plots and replicated three times. The runoff water was measured and sampled to quantify nutrient and sediment concentrations and loads from all plots. Chapters I and II evaluate the impact TxDOT specifications for amending roadside soils can have on runoff water quality. Chapter III compares the quality of runoff water between turfgrass sod imported with CMB and soil mixed with CMB at large volume-based rates on low quality soils in urban landscapes.

CHAPTER II

RUNOFF WATER QUALITY FROM CONSTRUCTED ROADSIDE SOILS RECEIVING LARGE VOLUME-BASED COMPOST APPLICATIONS

INTRODUCTION

State Departments of Transportation are required by the Clean Water Act to manage non-point source pollution associated with U.S. highways and right-of-ways. Non-point source losses of sediment and nutrients can occur from exposure of newly-constructed soils in highway right-of-ways to wind and water erosion (Flanagan et al., 2002; Benik et al., 2003; Persyn et al., 2004; Glanville et al., 2004). Potential non-point source pollution is greatest before and during vegetation establishment (Easton and Petrovic, 2004). Rapid stabilization of disturbed soil in right-of-ways is essential, but poor quality soil can limit vegetation reestablishment.

In Texas, highway construction contractors are required to reestablish vegetation on 70% of the disturbed areas or provide alternative practices for stabilizing soil (TCEQ, 2003). Erosion control practices, including vegetation reestablishment, must be in place no later than 21-d after cessation of on-site construction activities (TCEQ, 2003). To improve contractor compliance with State regulations, the Texas Department of Transportation (TxDOT) developed specifications for composted organic amendments used to remediate excavated soils (TxDOT, 1993). Three specifications for compost-based soil amendments were developed: 1.) Compost Manufactured Topsoil (CMT), 2.)

General-Use Compost (GUC), 3.) and Erosion Control Compost (ECC) (TxDOT, 1993). The CMT comprises 5 to 35% compost by volume incorporated in soil. The GUC is 100% compost topdressed at a 0.6-cm depth over existing vegetation. The ECC was initially specified to include 63% compost and 37% woodchips by volume, applied over a bare soil surface. The potential benefits of volume-based compost rates specified for CMT, GUC, and ECC were enhanced physical properties of soil and rapid reestablishment of vegetation (Mitchell, 1997). Similar to observations for agricultural soils (Cox et al., 2001; Wong et al., 1999), compost was expected to reduce bulk density and increased aggregate stability, soil porosity, and hydraulic conductivity in constructed soils.

Texas highway construction contractors quickly adopted regulatory specifications for compost use. Nearly applied 600,000 m^3 of diverse compost sources were applied in 2002 and 2003 (Sherman, 2003), including composted dairy manure (CDM). Adopting specifications for volume-based rates of CDM and other compost sources on roadsides coincided with concerns about nonpoint-source losses of manure sources of P from agricultural soils (Sharpley et al., 2004). Topdressing of raw or composted manure on agricultural soil increases concentrations of soluble P forms near the surface and potential nonpoint-source losses in surface runoff (Kleinman et al., 2002; Vietor et al., 2004). Incorporation of manure reduces potential transport of manure P in runoff compared to topdressing at equal rates. Yet, incorporation of repeated or large applications of manure can raise soluble P concentrations near the soil surface and potential transport in runoff (Andraski et al., 2003). Topdressing or incorporating large volume-based rates of CDM specified for CMT, GUC, or ECC on roadsides could similarly contribute to nonpoint-source P losses to surface waters. Although, volume based rates of CDM can benefit soil physical properties and enhance revegetation on roadsides, potential losses of nutrients in runoff need to be evaluated.

The first objective was to quantify N, P, and sediment concentrations and losses in runoff water from soils amended with CDM according to TxDOT specifications for CMT, GUC, and ECC. Nutrient and sediment losses in runoff water were monitored for CDM-amended treatments before and after seeding of a perennial grass. The second objective was to evaluate relationships among P concentrations in the surface layer of amended soil and losses of P forms in runoff.

MATERIALS AND METHODS

Experiment Design

Twenty-one plots were previously constructed on an 8.5% slope of a Boonville fine sandy loam (fine smectitic thermic Vertic Albaqualf) at the Turfgrass Field Laboratory at Texas A&M University (Gaudreau et al., 2002; Vietor et al, 2004). A 10-cm border of 1.9-mm sheet metal was inserted 2.5 cm into the soil to isolate runoff water within each plot. The down-slope end of the plots narrowed to an H-flume, which directed runoff water to buried galvanized holding tanks (311 L capacity). Three replications of seven treatments comprised a randomized complete block design.

Physical requirements for CMT, GUC, and ECC treatments were established in TxDOT specification 1027 (TxDOT, 1993). Sand used in golf greens construction and a Weswood silty clay loam (fine, mixed, thermic Fluventic Ustochrept) provided contrasting soil textures for compost incorporation according to TxDOT specifications for CMT. Two CMT treatments comprised a volume-based mixture of 25% CDM and 75%, greens sand (CMT-Sand) or Weswood soil (CMT-Loam). The CMT was applied at a 5-cm depth on the excavated Boonville soil. The mass of CDM applied in CMT was 127 Mg ha^{-1}. A control for each CMT was 100% soil of each type applied at a 5-cm depth.

Topdressing a 0.6-cm depth (56 Mg ha^{-1}) of CDM on established bermudagrass (*Cynodon dactylon L.*) provided a GUC treatment (GUC-Grass). Established bermudagrass without CDM provided a control (Grass) for the GUC treatment. The ECC treatment was a 5-cm depth of the volume-based mixture of 63% compost and 37% woodchips. The mass of CDM applied in the ECC treatment was 333 Mg ha^{-1}.

Soil, compost, and woodchip volumes were measured and mixed thoroughly prior to application. The CDM volumes applied in CMT, GUC, and ECC treatments were weighed, sampled, and analyzed to compute nutrient application rates. After treatments were applied, plots were raked level and rolled to firm the treatment layer. Samples were taken from the treatment layer in each plot to quantify nutrient concentrations before the first runoff event.

Runoff was collected and sampled during 14 natural rain events before and after seeding of Princess bermudagrass (*Cynodon dactylon* (L.) Pers.) in CMT and ECC plots during 2002. Runoff volumes were measured and subsampled at the conclusion of rain events or before collection tanks overflowed. Rainfall depths for each event were recorded at an onsite rain gauge and subtracted from the depth of runoff collected in the uncovered collection tanks. Part I of the study comprised samples collected after each of the six natural rain events producing runoff from all treatments before seeding. Part II of the study was initiated on 8 August 2002 after seeding. Soil and the CDM mixtures in CMT and ECC treatments were reapplied on plots after Part I according to TxDOT specifications to replace erosion losses before seeding. Bermudagrass seed was broadcast and incorporated into a 0.5-cm depth of soil, CMT, and ECC treatments. Plot areas were irrigated to promote seedling germination and vegetation establishment. The plots were irrigated as needed between storm events to promote seedling establishment and growth without runoff. Soil was sampled to a 5-cm depth after the final recorded storm event of Part II on 4 November 2002.

Sampling and Analysis

A 500-mL water sample was collected after thorough mixing of the runoff volume suspended sediment. Runoff water samples were stored at 4°C if filtered within a 24-hr period or frozen if filtering was delayed. Each 500-mL sample was thoroughly mixed and filtered through a 0.7 μm glass filter under vacuum. The sediment on filters was dried and weighed. The glass fiber filter was used to enable digestion of the entire sediment fraction for analysis of total N and P for selected runoff events (Parkinson and Allen, 1975).

Similar to sediment, runoff filtrate was digested to quantify total N and P. Concentrations of total dissolved P (TDP) (< 0.7 μm) and total particulate P (PP) (Haygarth and Sharpley, 2000) in respective digests were analyzed through inductively coupled plasma optical emission spectroscopy (ICP). The TKN in digests and the NO_3-

N of the filtrate were measured colorimetrically (Dorich and Nelson, 1983; Isaac and Jones, 1970) and through cadmium reduction in an auto analyzer (Dorich and Nelson, 1984). When TKN concentrations in filtrate were small (< 10 mg L^{-1}), TDP and NO_3-N concentrations in filtrate were analyzed through ICP and the auto analyzer, respectively, without digestion. Concentrations in filtrate were adjusted to account for rainfall dilution of runoff from plots collected in the uncovered tanks. The malachite-green assay was used to measure dissolved reactive phosphorus (DRP) concentrations in runoff after six of the eight rainfall events in Part II (D'Angelo et al., 2003).

Extractable soil test phosphorus (STP) and NO_3-N in soil samples were analyzed at the Texas A&M University Soil, Water, and Forage Testing Laboratory. An acidified ammonium-acetate-EDTA extraction was used to estimate plant-available P (Hons et al., 1990). Soils extracted and tested according to this procedure do not exhibit an agronomic response to P fertilizer at STP values > 42 mg P kg^{-1}. Soil nitrate was extracted and analyzed according to methods described by Dorich and Nelson (1984).

A portion of the above-ground biomass of bermudagrass was harvested to determine differences in grass growth among treatments. Sub-samples were dried, weighed, digested, and analyzed to quantify total N and P. Roots and rhizomes were considered below ground biomass and were separated from the soil sampled to the 5-cm depth through washing of soil cores, drying, and weighing.

Statistical Analysis

The General Linear Model (GLM) procedure of SAS (SAS Institute, Inc., 2000) was used for analysis of treatment differences in runoff depth, sediment mass loss, and nutrient concentration and mass in runoff components and grass. Fisher's least significant difference (LSD) was used to compare treatment means (SAS Institute, Inc., 2000). Runoff water depths, nutrient concentration, and sediment mass loss were analyzed using the same procedures and tests. Regression analysis was used to quantify the relationship between soil test P and P mass loss in runoff water during rainfall events before and after seeding of bermudagrass. Regression analysis was also used to evaluate the relationship between mean dissolved reactive phosphorus (DRP) concentration and mean TDP concentration in runoff water from six selected runoff events in Part II.

RESULTS AND DISCUSSION

Part I

Soil

Concentrations of STP were elevated relative to grass requirements (Sims et al., 2000) after topdressing or incorporating CDM at rates specified for the CMT, GUC, or ECC roadside treatments (Table A-1). Grass is not expected to respond to increasing manure P rate above a STP concentration near 42 mg kg^{-1} soil (TCE, 2000). Compared to controls at the start of the experiment, the volume-based CDM rates increased STP concentration 4 times for GUC applied to grass (GUC-Grass), 10 times for CDM mixed with the sandy clay loam (CMT-Loam), 22 times for CDM mixed with sand (CMT-Sand), and 47 times for ECC. James et al. (1996) similarly observed an increase in STP from 36 to 251 mg kg^{-1} after repeatedly incorporating annual beef manure applications.

Applying CDM at volume-based rates increased (α=0.05) NO_3^--N concentrations in the amended soil layers of the CMT and ECC treated plots, but not for the GUC application on grass (GUC-Grass) (Table A-1). Samples removed shortly after treatments were applied indicated NO_3^--N concentration in the amended layer of CMT and ECC treatments increased from 3 to 8 times that of agronomic recommendations for grass sod (TCE, 2000b).

TDP, NO_3^--N, and TKN Concentrations

Six rainfall events produced 120-mm of total rainfall before seeding bermudagrass. A significant event by treatment interaction term necessitated analysis of variation of TDP and NO_3^--N concentrations among treatments within each event (Table A-2). Rain event 1, 2, and 6 were selected for discussion providing examples of nutrient concentrations in runoff soon after treatments were imposed and at the end of the sampling period from plots without vegetation. Although the concentrations of TDP in runoff water were high in Event 1, incorporating or topdressing of CDM did not increase (P=0.05) TDP concentrations above the controls. The TDP concentrations in runoff declined from Event 1 to Event 2. The TDP concentration was greater (P=0.05) for CDM topdressed on grass (GUC-Grass) than the other treatments amended with CDM during Events 2 and 6 (Table A-2). During the last event before seeding, topdressing of CDM on grass (GUC-Grass) was the only roadside amendment that increased (P=0.05) TDP concentration above the control (Table A-2). Similar to comparisons between CMT and soil alone in the present study, DRP concentrations in runoff of simulated rain were not different between unamended soils and soils mixed with three different manure sources at a P rate of 100 kg ha^{-1} (Kleinman et al., 2004).

Concentrations of NO_3-N and TKN (not shown) in the amended layer and runoff revealed an additional environmental impact of high CDM rates on roadside embankments. Greater (P=0.05) TKN concentrations in the surface applied CDM (Table A-1) were associated with greater (P=0.05) mean NO_3^--N concentration in runoff water from GUC-Grass during Event 1 and ECC during Event 2, compared to the other treatments (Table A-2). In addition, the large rate of CDM applied in the ECC layer and incorporated in the CMT-Sand and CMT-Loam increased TKN concentration in runoff compared to the respective controls and the GUC-Grass treatment on Event 1 and 2, but not 6. Glanville et al. (2004) previously reported mean soluble NO_3-N and NH_4-N concentrations were consistently greater for a layer of composted biosolids than for other compost sources or a layer of topsoil. There was large variation in the NO_3^--N concentration across rain events for the same treatments (Table A-2). For example, the NO_3^--N concentration was low for the ECC treatment in Event 1, yet increased nearly 50 times in Event 2. The concentrations were not consistent enough to determine a pattern for all treatments.

Depth of Water; Nutrient and Sediment Losses

Incorporation of CDM did not reduce (P=0.05) runoff water depth compared to soil without CDM in Events 1, 2, and 6 (Table A-2). Runoff depth was similarly unaffected in a comparison between soil alone and soil amended with fresh manure (Andraski et al., 2003). Kleinman et al. (2004) observed that surface applications of swine slurry or poultry or dairy manure at a TP rate of 100 kg ha^{-1} did not reduce runoff from a silt loam and loam soil compared to soils without slurry or manure applications.

Topdressing CDM over vegetation (GUC-Grass) did not reduce (*P*=0.05) runoff water depth compared to vegetation without CDM in Events 1, 2, and 6 (Table A-2). Runoff water depth from the ECC and CMT-Sand was lower (*P*=0.05) than runoff depth from the GUC-Grass in the first two events.

Established grass sod can restrict runoff water loss (Gross et al., 1990). Yet initially, the greatest (*P*=0.05) runoff depths were from the Grass and GUC-Grass treatments in Event 1, including the CMT-Loam in Event 2 (data not shown). Incorporation of CDM with the Sand (CMT-Sand) and topdressing CDM on the constructed slope (ECC) reduced (*P*=0.05) runoff water depths in Events 1 and 2. A similar application of a 5- or 10-cm depth of composted biosolids on a compacted roadside slope delayed runoff of simulated rain (95 mm h^{-1}) 21 min. longer than a 15-cm depth of topsoil applied on a compacted soil layer (Persyn et al., 2004). Yet, after runoff of simulated rain began, the steady state rate of water loss was comparable between the layers of composted biosolids and topsoil before vegetation was established. Runoff depths among treatments were similar in Event 6. Variation of total runoff depth among treatments indicated ECC and CMT-Sand enhanced water infiltration and storage in the initial rain events after construction, than the loam soil with and without CDM and CDM topdressed on grass (GUC-Grass).

Although TDP concentrations were similar among CMT-Sand, ECC, and GUC-grass treatments (Table A-2), the mass loss of TDP from GUC-Grass was greater (*P*=0.05) than from ECC and CMT-Sand (Table A-3). In addition, relatively small runoff depths for the ECC and CMT-Sand treatments limited mass loss of TKN in the filtrate portion of runoff (*P*=0.05) compared to established grass without or with CDM (GUC-Grass) (Table A-2). Although mean runoff depth of the ECC treatment was low, high NO_3-N concentrations in runoff contributed to mass loss of NO_3^--N similar to treatments for which runoff depths were large (Table A-3).

Large sediment losses can occur after soil is disturbed and left unprotected against rain and water runoff before seeding and vegetation establishment (Dabney et al., 2004). The CMT-Loam contributed greater (*P*=0.05) sediment mass loss in runoff water than the CMT-Sand and the ECC in Events 1, 2, and 6 (data not shown). In addition, sediment mass loss from the CMT-Loam exceeded the related Loam control in Events 2 and 6. In Event 1 the rain fall depth was 15-mm and resulted in 3.4 g m^{-2} sediment mass loss from the CMT-Loam. The rain fall depth in Event 2 was 27-mm and sediment mass loss increased to 119 g m^{-2}. In contrast to this, the ECC contributed 0.2 g m^{-2} in sediment mass loss to runoff water in Event 2. The treatment by event interaction term was not significant for sediment-bound TP (*P*=0.0860) or TKN (*P*=0.1155). Similar to sediment mass loss, the CMT-Loam contributed the greatest mean TP and TKN mass loss (mg m^{-2}) in runoff water before seeding bermudagrass (data not shown). This related well to the sum of TP and TKN mass losses presented in Table A-3. A strong correlation between suspended solids and TP loss during previous runoff studies of soil mixed with manure indicated erosion was a dominant process in P transport (Kleinman et al., 2002).

When TDP in runoff and TP loss in sediment are summed, the total P loss in runoff was greatest for CMT-Loam (530 mg P m^{-2}) and GUC-Grass (355.7 mg m^{-2})

treatments. These total P losses indicate large, volume-based rates of CDM on roadside construction sites can be problematic whether applied as CMT or GUC. Surface sealing, poor water infiltration, and large runoff depth and sediment losses contributed to large total P loss from the CMT-Loam in this study (Chiang et al., 1994). In contrast, the large TDP concentration, rather than sediment-bound P, combined with large runoff depths to yield large total P losses from GUC topdressed on established grass. Similarly, DRP accounted for 64% of the total P in runoff from surface-applied manure during simulated rain application on soil in packed boxes (Kleinman et al., 2002).

Part II

TDP, NO_3^--N, and TKN Concentrations

Runoff water from eight natural rain events was collected and sampled to evaluate water, nutrient, and sediment losses during the period of vegetation reestablishment on the CMT and ECC treatments. The total rainfall depth over the eight rain events after seeding was 289-mm. Generally, rainfall events in Part II produced greater rainfall depths than those recorded in Part I of the study. Analysis of nutrient concentrations in runoff during Events 7, 8, 10, and 14 are included in the discussion to provide assessment of runoff events soon after seeding and then spaced at the mid-point and end of sample collection (Table A-4). Topdressing CDM on the GUC-Grass and ECC treatments was expected to increase TDP concentrations in runoff (Gaudreau et al., 2002; Kleinman et al., 2002; Vietor et al., 2004). Yet, in Event 7 the TDP concentration in runoff was lower for the GUC-Grass and ECC than the Grass (Table A-4). After Event 7, TDP concentration in runoff did fit the expected results for the GUC and ECC

(Table A-4). Although the largest TDP concentration in runoff water was observed in Event 8 for the CMT-Sand treatment, consistently high mean TDP concentrations in runoff water were observed for the ECC treatment (Table A-4). Glanville et al. (2004) reported increases in runoff concentrations of soluble P up to 24 times greater for layers of composted biosolids than for unamended topsoil on simulated roadsides. They also reported that the mean dissolved P concentration in runoff from a biosolids layer was 3.10 mg L^{-1} (Glanville et al., 2004) which was lower than TDP concentration in runoff from the ECC in Event 8, 10, and 14.

Although the mean TDP concentration in runoff was high for the ECC treatment (Table A-4) over the eight rain events, the low runoff depth limited total mass loss of TDP (Table A-5). In contrast, large and somewhat variable runoff depths contributed to large and similar TDP losses in runoff between ECC and all treatments except for the unamended sand (Table A-5). Incorporating CDM into the surface soil layer was expected to minimize differences in runoff concentrations of TDP between CMT and respective unamended controls (Kleinman et al., 2002). While, mean TDP concentration (mg L^{-1}) in runoff water from CMT-Loam was not different (P=0.05) than the control after Event 7, differences were observed (P=0.05) for the CMT-Sand and the respective control for all but one event after seeding bermudagrass (Table A-4). Large, volume-based rates of CDM incorporated into soil contributed to large increases in STP, which were associated with differences in runoff concentrations of TDP between CMT and control soils (Table A-1).

Similar to TDP, the NO_3^--N concentrations in runoff were consistently highest in runoff from the ECC treatment (Table A-4). In addition, the general trend across all treatments was a decrease in NO_3^--N concentrations for the eight rain events after seeding bermudagrass. The notable exception occurred in Event 8 for both NO_3^--N and TDP concentrations in runoff from the CMT-Sand treatment (Table A-4). In Event 8, the NO_3^--N concentration in runoff from the CMT-Sand was about 20% greater than from the ECC treatment. Concentrations of TKN in runoff were relatively low after seeding. Topdressing or incorporating CDM into soil increased (P=0.05) the TKN concentration in runoff from the CMT-Sand treatment only.

Sum of Water, Nutrient, and Sediment Losses

Incorporating CDM into soil at 25% by volume in the CMT-Sand and CMT-Loam treatments did not reduce (P=0.05) the depth of runoff water compared to the soils alone (Table A-5). Similarly, runoff depth was not reduced compared to an untreated control when CDM was topdressed over established bermudagrass (GUC-Grass). Yet, the 5-cm layer of CDM mixed with woodchips in the ECC treatment reduced (P=0.05) runoff water loss compared to all but the CMT-Sand treatment during bermudagrass establishment.

Although TDP losses in runoff water were similar among treatments, the percentage of DRP in runoff water varied based upon whether the CDM was incorporated into soil or surface applied. The percent DRP in TDP transported in runoff was relatively high for treatments topdressed with ECC or GUC. The percentages of TDP recovered as DRP were 65% for ECC and 75% for GUC-Grass. In contrast, the percentage of TDP in the DRP fraction decreased to 50% for CMT-Sand and 55% for CMT-Loam treatments. These two treatments had CDM incorporated into the soil at 25% by volume. In previous comparisons between topdressed and incorporated dairy manure, Kleinman et al., (2004) reported DRP was 64% of total P in runoff from topdressed manure but 9% of total P in runoff from incorporated manure. Both the present and past studies indicated incorporation increased the portion of DRP adsorbed to soil particles.

Incorporating CDM (25% by volume) in CMT-Sand and CMT-Loam treatments did not reduce mass loss of sediment in runoff water compared to unamended Sand and Loam after seeding bermudagrass (Table A-5). A 50-mm rainfall event, 7 d after seeding, yielded 62% and 82% of the total sediment loss during grass establishment for CMT-Sand and CMT-Loam, respectively (data not shown). Sediment loss during a second 50-mm rainfall event 53 d later increased cumulative sediment loss to more than 86% of the total loss during establishment for CMT-Sand and CMT-Loam. In contrast, topdressing ECC on the excavated slope limited sediment loss to 4% of that from the layer of sandy clay loam soil (Table A-5).

The increases in mass loss of sediment after (Part II) compared to before seeding (Part I) was attributed to the greater rain and runoff depths after seeding (Tables A-3 and A-5). Yet, mass loss of sediment in runoff from GUC-Grass and ECC were similar despite the differences in runoff depth before and after seeding. Persyn et al. (2004) similarly reported interrill erosion rates from mulch blankets of composted biosolids were reduced and the time to runoff delayed compared to conventional soils applied on roadsides.

Low sediment loss limited mass loss of TP in the sediment fraction transported from ECC and established vegetation (GUC-Grass and Grass) (Table A-5). Conversely, relatively high sediment loss from CMT-Sand and Sand contributed to greater mass loss of TP than that of Grass treatments with and without GUC and ECC. Relatively low TP concentrations in digests of Loam (62 mg kg^{-1}) and CMT-Loam (141 mg kg^{-1}) limited TP mass loss, even though sediment loss from the Loam and CMT-Loam was greatest (P=0.05) among treatments for a 50-mm rain event 7 d after seeding and summed over all rain events (Table A-5). A texture analysis was not performed on the sediment load, but a large portion of the sediment loss from Loam and CMT-Loam may comprise silt, which contains far less adsorbed P than the clay fraction. In contrast, particulate forms of CDM could make up a large fraction of sediment loss and contribute to larger TP concentrations in sediment of runoff from CMT-Sand (757 mg kg^{-1}) than from CMT-Loam (141 mg kg^{-1}) during the same 50-mm rain event 7 d after seeding.

Variation of runoff depth diminished differences in mass loss of NO_3^--N and TKN among treatments after seeding (Tables A-3 and A-5). Greater runoff depths did increase NO_3^--N and TKN losses after seeding (Part II) as compared to before seeding (Part I). Runoff depth and concentration of NO_3^--N from the CMT-Loam combined to increase (P=0.05) mass loss of NO_3^--N compared to other treatments (Table A-5). Similar to treatment effects on TP loss in sediment, TKN loss in sediment was greater fro CMT-Sand and Sand than the Loam, CMT-Loam, and Grass. During 50-mm rain events 7 and 60 d after seeding, relatively large mean TKN concentrations in sediment from Sand and CMT-Sand treatments (0.8 and 2.5 g kg^{-1}, respectively) contributed to greater mass loss of TKN than the Loam and CMT-Loam treatments. Both CDM and plant sources of organic N in CMT-Sand and Sand could have increased (P=0.05) TKN loss compared to sediment of Loam and CMT-Loam treatments during bermudagrass establishment (Table A-5).

Soil Analysis

Analyses of soil sampled to the 5-cm depth after the final rainfall event on 4 November 2002 indicated topdressed and incorporated CDM treatments increased (P=0.05) TKN, total P (TP), and STP similar to samples at the start of the experiment (Table A-1). The increases in STP observed in soil of CMT-Sand, CMT-Loam, GUC-Grass, and ECC could be indicative of risks that excess soil P in roadside treatments pose to surface waters (Sims et al., 2000). The STP and TP concentrations in the ECC layer, which were more than two times greater than CMT or GUC treatments, indicated the layer of CDM mixed in woodchips could pose the greatest environmental risk.

Plant uptake, runoff, and leaching losses over 14 rainfall events reduced NO_3^--N concentration in the soil compared to initial concentrations (Table A-1). Only the NO_3^--N concentrations in ECC and CMT-Loam remained greater (α=0.05) than the other treatments. Yet, the effect of CDM amendments on soil remained evident in a comparison of soil TKN among treatments (P=0.05) (Table A-1). Although the TKN fraction is less water soluble than NO_3^--N in soil, increases in TKN may contribute to increased concentration and loss of TKN in the sediment fraction of runoff. Despite soil

TKN differences among treatments, variation of soil TKN was not related to variation of TKN loss in sediment among treatments before and after seeding (Tables A-1, A-3, and A-5). As expected, the bulk density of the ECC treatment was lower (*P*=0.05) than CMT, GUC, and unamended soils (Table A-1).

Relationship of STP to P Loss in Runoff

Similar to previous reports, variation of the sum of TP in sediment and TDP in runoff among CMT and GUC treatments and controls was directly related to variation of STP concentrations within the 0 to 5-cm depth before and after seeding (Fig. B-1) (Kleinman et al., 2004; Schroeder et al., 2004). However, a large increase of mean STP in the soil surface layer after amending it with the ECC did not increase the sum of TP in sediment and TDP in water as predicted in a regression analysis of other treatments. The 5-cm layer of CDM mixed with woodchips in ECC effectively limited the portion of sediment P lost in runoff. As a result, the relationship between variation of STP and that of the sum of TP loss in sediment and TDP loss in water differed between ECC and other roadside treatments. The acidified NH_4OAc-EDTA extraction for STP determinations in the present study (Hons et al., 1990) was not indicative of potential water quality impacts across the CMT, GUC, and ECC treatments evaluated in the present study (Sims et al., 2000).

Turfgrass Response

Bermudagrass establishment and growth was affected by the roadside treatments imposed before seeding. Incorporation of the volume-based CDM application rate into the sand (CMT-Sand) increased biomass productions compared to the control (Sand)

(Fig. B-2). In contrast, biomass production was similar between the Loam and CMT-Loam. Surface sealing of the CDM-amended (CMT-Loam) and unamended Loam soil limited water infiltration during irrigation and rain events, which slowed and limited seedling germination and establishment (Cook and Nelson, 1986). Rapid water infiltration wetted the Sand, CMT-Sand, and ECC, which favored seed germination and plant establishment. The nutrients and organic matter supplied in large, volume-based CDM application rates, enhanced turfgrass seedling growth in CMT-Sand and ECC (Table 2-1 and Fig. 2-2). Topdressing a smaller volume-based CDM application rate (0.5-cm depth) on established bermudagrass in the excavated Boonville soil (GUC-Grass) did not increase biomass production compared to the Grass control or unamended Sand and Loam soils. Soil tests at the beginning and conclusion of runoff monitoring indicated low soil NO_3^--N concentrations limited biomass production of the established Grass treatments.

CONCLUSIONS

Monitoring runoff depth, and concentrations and mass losses of N, P, and sediment during natural rain events on an 8.5% slope revealed benefits of incorporating or topdressing CDM on roadsides before and after seeding. A 5-cm layer of CDM mixed with woodchips (ECC) reduced runoff depth compared to an equal depth of soil (Loam or Sand) or established grass with (GUC-Grass) or without (Grass) a 0.6-cm depth of CDM topdressed over the surface. In addition, sediment loss from the ECC treatment was less than the 5-cm depth of sandy clay loam soil with (CMT-Loam) and without (Loam) incorporated CDM. Moreover, the surface layer of ECC enhanced bermudagrass establishment and biomass production compared to sand alone (Sand), CMT-Loam, and Loam treatments.

Despite observed benefits, topdressing or incorporating CDM at the volume-based rates specified for roadsides increased concentrations of P and N forms in soil and runoff water to levels that could pose environmental risk. The topdressed layer of ECC increased mean TDP and NO_3^--N concentrations in runoff more than CMT-Loam in which CDM was incorporated to the 5-cm depth. Yet, incorporating CDM at 25% by volume into the CMT-Loam and CMT-Sand increased TDP and NO_3^--N concentrations in runoff water compared to respective soil types without CDM.

The tradeoff between depth and nutrient concentration of runoff was evident in treatment effects on mass loss of N and P. The low runoff depth for ECC limited mass losses of TDP and NO_3^--N to amounts comparable or less than incorporated (CMT-Sand or CMT-Loam) or topdressed CDM (GUC-Grass). Conversely, large runoff depths and NO_3^--N concentrations led to greater losses of NO_3^--N than other treatments after seeding. Similarly, tradeoffs occurred between mass loss and TP concentration of sediment. Large sediment mass and TP concentrations contributed to greater mass loss of TP from the CMT-Loam than other treatments before seeding. Low TP concentration limited mass loss of TP in sediment from CMT-Loam compared to ECC and CMT-Sand after seeding.

Extractable soil P (acidified NH_4OAc-EDTA) in the 0 to 5-cm depth could be used as an indicator of negative environmental impacts by roadside treatments. Mass loss of the sum of TDP and TP in sediment was directly related to the STP concentrations of CMT-Sand, CMT-Loam, GUC-Grass, and the controls, respectively. In contrast, low runoff depths limited mass loss of TDP and TP in sediment from ECC even though STP was three times greater than other treatments amended with CDM. Additional studies are needed to evaluate compost sources other than CDM and roadside specifications that will improve soil conditions and vegetation reestablishment without potentially negative environmental impacts.

CHAPTER III

QUANTIFYING NUTRIENT AND SEDIMENT TRANSPORT IN RUNOFF WATER FROM COMPOST AMENDED ROADSIDE SOILS

INTRODUCTION

State Departments of Transportation (SDOT) are mandated to manage highway construction projects as non-point pollution sources. Disturbed soil at construction sites can be eroded and transported in surface runoff when exposed to direct rainfall. Sediment loads are often the greatest fraction of soil components in runoff water from the highway construction sites (Barrett et al., 1995). Consequently, management practices at construction sites are designed to control sediment loss in storm water runoff. Silt fences, straw mulch, and material blankets are among practices construction firms use to control erosion (Benik et al., 2003). Increasingly, SDOT have developed specifications for application of compost products used to stabilize soil and promote revegetation (Mitchell, 1997, Persyn et al., 2004, Glanville et al., 2004). Persyn et al. (2004) reported 5- and 10-cm blankets of composted biosolids, yard waste, or industrial waste lowered losses of runoff water and sediment compared to losses from compacted subsoil or imported topsoil at highway construction sites. In a complementary report, Glanville et al. (2004) reported decreased nutrient losses in runoff water when compost products were surface applied as opposed to leaving the soil bare.

Compost amendment specifications vary among SDOTs, which broadly define source and rate requirements for construction contractors. Generally, compost application rates are depth- and volume-based, including limits on the maximum rate. Although compost material is required to meet Class A biosolid standards, requirements or limits on nutrient concentrations or rates in applied compost are not often specified. Yet, large depth- and volume-based applications can increase nutrient concentrations in amended soil above plant requirements and contribute to nonpoint source losses in surface runoff (Carpenter et al., 1998).

In Texas, the Department of Transportation (TxDOT) developed three specifications for soil and surface compost amendments on highway construction sites. Compost manufactured topsoil (CMT) is defined as a volume-based blend of 25% compost and 75% topsoil, which is applied at a depth specified by site engineers after excavation work is finished. Erosion control compost (ECC) is a 5-cm blanket of a volume-based blend of 50% compost and 50% woodchips applied evenly over bare soil. General use compost (GUC) is specified as 100% compost top-dressed without completely covering existing vegetation. The CMT, ECC, and GUC specifications were developed to enable construction contractors to control sediment loss in runoff water and minimize the duration of vegetation reestablishment.

Composted dairy manure (CDM) and composted municipal biosolids (CMB) are routinely used by construction contractors to comply with TxDOT and urban specifications for amendment of excavated soils (Austin City Connection, 2005). Specifications for volume-based rates do not change with respect to compost source, but variation of nutrient concentration and form among CDM and CMB sources could affect nonpoint-source losses in runoff (Maguire et al., 2001, Sharpley and Moyer, 2000). For example, increasing concentrations of extractable P in CDM or CMB sources applied to soil can increase dissolved P concentrations in runoff, particularly when compost sources are surface applied (Kleinman et al., 2002, Withers et al., 2001). Similarly, incorporation of volume-based CDM or CMB rates could increase extractable soil P concentration and concentrations of dissolved P in runoff (Kleinman et al., 2004; Schroeder et al., 2004, Vadas et al., 2005). In some cases, manure application can increase dissolved P loss more than inorganic fertilizers (Tarkalson and Mikkelsen, 2004; Vietor et al., 2004). Yet, manure amendments can be applied without pronounced P loss in runoff water if adequate crop residues remain on the soil surface (Andraski et al., 2003).

Differences between nutrient-based rates recommended for agronomic crops and volume-based compost rates specified for CMT, ECC, and GUC raise questions about potential nutrient and sediment loss in runoff water from highway construction sites. Although systems integrating compost-use with soil stabilization on roadsides provide an option for use of animal and municipal waste streams, potential impacts on water quality need to be evaluated. This study was initiated in 2003 to evaluate TxDOT specifications for CDM and CMB use in roadside amendments. The objectives of this study were to i) quantify nutrient loading rates to soil following the CMT and ECC specifications, ii) compare runoff concentration or losses of sediment, P, and nitrogen

(N) among CMT and ECC treatments during natural storm events, and iii) relate P loss in runoff water to soil P concentrations.

MATERIALS AND METHODS

Experimental Design

A Boonville fine sandy loam (fine smectitic thermic Vertic Albaqualf) was previously graded to an 8.5% slope for installation of 21 plots on the Texas A&M University Turfgrass Field Laboratory, College Station, Texas. (Gaudreau et al., 2002; Vietor et al, 2004). A 10-cm width of 1.9-mm sheet metal was inserted 2.5 cm into the soil to isolate and channel runoff from each plot through an H-flume into an uncovered 311-L tank. The long dimension of 1.5-m by 4-m (6 m^2) plots was oriented parallel to the slope. A randomized complete block design comprised 3 replications of seven treatments. Six treatments represented TxDOT specifications for application or CDM or CMB on roadsides (TxDOT, 1993). Two compost sources derived from Class A biosolids, CDM and CMB, were selected. Each of these contrasting compost sources was incorporated with a Weswood sandy clay loam soil (fine, mixed, thermic Fluventic Ustochrept) at volume-based rates of 12.5% and 25% within a 5-cm depth to provide four CMT treatments (Table 1). In addition, 5-cm depths of mixtures of equal volumes of wood chips and each CDM and CMB were topdressed on excavated soil in two ECC treatments. An existing stand of unfertilized bermudagrass (*Cynodon dactylon* (L.)) was the seventh or control treatment.

Treatments were installed and seeded on 22 April 2003. All materials were thoroughly mixed, weighed, and sampled for analysis prior to application (Table 1). In addition, soil within 0 to 5-cm depth of treatments was sampled after the final runoff event for analysis. The CMT and ECC treatments were raked and rolled to optimize seedling emergence and plant growth in the amended layer. A seed mix of 50-g bermudagrass and 50-g T-587 Bluestem (*Dicanthium annulatum* (Forssk.)) was broadcast over each plot area. Daily irrigation was applied to achieve seedling emergence and prevent water stress to establishing grass seedlings without runoff between rainfall events until 31 August 2003.

Sampling and Analysis

Runoff water was sampled after each of 10 natural rainfall events that yielded measurable runoff from all plots. Runoff depths were measured and water was thoroughly mixed in collection tanks for sampling (500-mL) at the conclusion of rainfall events or before any of the tanks overflowed. An onsite rain gauge provided rainfall depths. Rainfall depth was subtracted from runoff depths to compensate for rainfall collected in open collection tanks. After collection, water samples were stored at 4°C and filtered through glass fiber filters (< 0.7 µm) under vacuum within a 24-hr period. Samples were frozen if stored for more than 24 hr before filtering. Filter weights were subtracted from dry weights of sediment plus filters before analysis. Filters with sediment were ground and digested for analysis of total N and P in runoff after selected rainfall events (Parkinson and Allen, 1975).

Total and dissolved forms of P and N in filtrate were analyzed for all runoff events. Inductively coupled plasma optical emission spectroscopy (ICP) was used to measure total dissolved P (TDP) in digests of filtrate and total P (TP) in digests of sediment (Haygarth and Sharpley, 2000). Total Kjeldahl nitrogen (TKN) in digests of filtrate and sediment and $NO3^-$-N in filtrate were measured colorimetrically (Dorich and Nelson, 1983; Isaac and Jones, 1970) and through cadmium reduction in an auto analyzer (Dorich and Nelson, 1984). When TKN concentrations in filtrate were less than 10 mg L^{-1}, TDP and NO_3-N concentrations in filtrate were analyzed through ICP and the auto analyzer, respectively, without digestion. Nutrient concentrations in filtrate were adjusted to account for dilution from rainfall in the uncovered tanks. A malachite-green assay was used to quantify dissolved reactive phosphorus (DRP) concentrations in filtrate within 72 hr after filtering and storage at 4°C (D'Angelo et al., 2003).

Concentrations of total and extractable forms of P and N in soil samples were analyzed in the Texas A&M University Soil, Water, and Forage Testing Laboratory, College Station, Texas. An acidified NH_4OAc-EDTA extraction method was used to measure soil-test P (STP) (Hons et al., 1990). Increased grass growth is not expected from P fertilizer added to soils at STP greater than 42 mg P kg^{-1} (TCE, 2000). In addition, 1 g soil P was extracted in 10-mL distilled water for 1 hr on an orbital shaker. The ICP was used to measure TP in digests and STP and water-extractable P (WEP). Soil nitrate was extracted and analyzed as described by Dorich and Nelson (1984).

The bermudagrass/bluestem grass mix was mowed at a 7.5-cm height and clippings were weighed and sampled to compare growth rates and nutrient uptake among treatments. Sub-samples were dried, weighed, digested, and analyzed to quantify total P and N similar to sediment (McGeehan and Naylor, 1988). Roots, rhizomes, and crowns below the mowing height were washed from soil sampled to the 5-cm depth, then dried, and weighed.

Statistical Analysis

The General Linear Model (GLM) procedure of SAS (SAS Institute, Inc., 2000) was used for analysis of variance of runoff depth, nutrient concentration in soil and runoff, and mass loss of sediment and nutrients among treatments over ten runoff events. Fisher's least significant difference (LSD) was used to compare treatment means (SAS Institute, Inc., 2000). Regression analysis was used to relate variation of STP and to that of P mass loss in runoff over the ten runoff events during grass establishment. A t-test was performed to detect significant differences between CMB sources by comparing the slopes of the regression lines (Kleinbaum and Kupper, 1978).

RESULTS AND DISCUSSION

Soil

The bulk density of CDM (1.34 Mg m^{-3}) was greater than CMB (0.79 Mg m^{-3}) which nearly doubled the mass of CDM compared to CMB applied as volume-based rates in CMT and ECC treatments (Table A-6). The comparatively greater bulk density of CDM was attributed to soil scraped and hauled with raw manure from confined dairies to composting facilities (Eftoda and McCartney, 2004). In contrast, the rates of TN and TP applied in CMB to roadside soils were greater (P=0.05) than in CDM at the same volume-based application rate (Table A-6). Except for the 12.5% rates of CDM, incorporation of CDM and CMB increased (P=0.05) TP concentration in the 0 to 5-cm soil layer (Table A-6). In addition, topdressing of CMB in ECC treatments increased

(*P*= 0.05) TP concentration in the soil surface with respect to the control and CMT treatments (Table A-6). Similarly, the ECC treatment increased (*P*=0.05) TN concentration in the soil surface (0 to 5-cm) compared to (Table A-6).

Topdressing or incorporation of CDM and CMB at rates recommended for ECC and CMT increased (*P*= 0.05) STP above the control, except for CDM incorporated at 12.5% by volume (Table A-6). The STP concentrations in the 0 to 5-cm layer of all CDM- and CMB-amended treatments exceeded agronomic concentrations for grass sod. The STP concentrations from ECC treatments were 25 times greater for CDM and 50 times greater for CMB than agronomic soil P concentrations (Table A-6). Although not always significant (*P*= 0.05), STP concentration in soils amended with the CMB were consistently greater than those amended with CDM. In contrast, water extractable P (WEP) concentration in soil of the ECC treatment topdressed with CDM was greater (*P*=0.05) than ECC containing CMB.

Grass Response

Grass seedling emergence occurred quickly on all treated plot areas. The old world bluestem seedlings dominated in the mixture and represented a majority of the clipped biomass during the first and second harvest. In the first harvest, incorporation of CDM or CMB did not increase clipped biomass of CMT treatments compared to the control. Yet, clipping mass harvested from the ECC treatment was greater (*P*=0.05) than the control. During the second harvest clipping yields were greater (*P*= 0.05) for the 12.5% rate of CDM or CMB in CMT than the control. In addition, clipping yields of the CMT comprising 25% CDM were greater (*P*=0.05) than the control. In contrast, yields were similar for 25% by volume CMB, ECC from CDM or CMB, and the control. Four months after seeding, there was little variation of above ground biomass yields among treatments amended with CDM or CMB.

TDP and NO_3^--N Concentrations in Runoff

A significant rain event by treatment interaction term (*P*=0.05) in the model necessitated analysis of variation of TDP and NO_3^--N concentrations in runoff water among treatments for individual rain events. The variation of concentration of TDP in runoff among treatments was consistent across runoff events even though rain depths differed greatly (Table A-7). Five rain events distributed throughout the sampling period illustrated the variations in runoff concentrations of TDP and NO_3^--N among treatments (Tables A-7 and A-8). The mean TDP concentrations in runoff water differed (*P*= 0.05) among treatments for each of the five events (Table A-7). Incorporating CDM at 25% by volume in the soil increased (*P*= 0.05) TDP concentrations in runoff compared to the control during Event 1 and 3 (Table A-7). In contrast, mean TDP concentration in runoff from CMT treatments mixed with 12.5% by volume CDM or CMB and 25% CMB were similar to the control. The concentrations of TDP observed in runoff from ECC treatments comprising CDM or CMB were consistently greater than the CMT treatments (Table A-7). In addition, the greater soil WEP for ECC containing CDM was associated with greater TDP in runoff from ECC with CDM than ECC with CMB on four of the sampling dates (Table A-6 and A-7).

Although compost source affected TDP concentration in runoff from ECC treatments, TDP concentration in runoff water from CMT was similar between the CDM and CMB incorporated into the soil (Table A-7). Incorporating compost with soil (CMT) can decrease dissolved P concentrations compared to surface applications (Sharpley, 1985). However, incorporation of CDM or CMB in soil increased soil nutrient concentrations, which could contribute to increasing nutrient losses in runoff water (Schroeder et al., 2004; Tarkalson and Mikkelsen 2004; Kleinman et al., 2004; Pautler and Sims 2000; Vietor et al., 2004).

The NO_3^--N concentrations in runoff were relatively low and declined over the series of ten rain events (Table A-8). Mean NO_3^--N concentrations in runoff water did not differ between treatments comprising similar compost application methods and rates (Table A-8). During the first runoff event, NO_3^--N concentrations in runoff from ECC comprising CMB and CMT mixed with 25% by volume CDM and CMB were greater (P=0.05) than the control. During events 8 and 10, runoff concentrations of NO_3^--N remained greater for the ECC containing CMB than CMT treatments and the control (Table A-8). Glanville et al. (2004) conducted a similar study of roadside amendments utilizing compost products and reported that NO_3^--N concentrations in runoff water were often below 0.2 mg L^{-1}. After the first rain event, NO_3^--N concentrations in runoff were similar to those reported by Pote et al. (2003) (0.57 mg L^{-1}) in runoff from poultry litter incorporated into grassland soils.

Runoff, Nutrient, and Sediment Losses

The total depth of rainfall for the ten rain events was 281-mm. Total runoff losses were indicative of water infiltration capacities of the seven treatments (Table A-9). Roadside treatments did not effectively reduced runoff water losses below that of the established bermudagrass. Topdressing of the ECC containing CMB did reduce runoff depth compared to the 12.5% by volume rate pf CDM and CMB and the 25% rate of CDM (Table A-9). In addition, compost source did affect runoff depth from plots amended to the ECC specification. The surface application of a 5-cm layer of CMB and woodchips (1:1 by volume) lowered (*P*=0.05) the total runoff depth compared to ECC using CDM (Table A-9). Similar studies of surface-applied compost before establishment of vegetation on simulated roadsides indicated both biosolids and yard-waste sources delayed and reduced runoff depth compared to excavated soil (Persyn et al., 2004).

The TDP losses in runoff water were summed over the ten rain events for each treatment (Table A-9). Except for the 25% by volume rate of CDM, incorporation of compost sources in CMT treatments limited cumulative TDP losses to amounts comparable to the established bermudagrass control. Greater (*P*=0.05) TDP losses in runoff from the 25% rates of CMB was associated with greater soil TP and STP of this CMT treatment compared to the control (Tables A-6 and A-9). Topdressing of compost and woodchips in the ECC treatments increased (*P*=0.05) TDP losses in runoff to 3 times that of the control for CMB and 6 times the control for CDM. Conversely, Glanville et al. (2004) reported decreased P loss in runoff water from surface-applied compost treatments that reduced runoff water losses compared excavated surfaces with or without a topsoil layer. Similar to differences in soil WEP between CDM- and CMB-amended ECC, cumulative TDP loss from ECC containing CDM was greater than ECC with CMB (Tables A-6 and A-9). Similar to previous studies, incorporation of compost sources into the surface 0 to 5-cm of soil (CMT) reduced TDP losses in runoff compared to ECC treatments (Tarkalson and Mikkelsen, 2004).

Except for the 12.5% rate of CMB in CMT, incorporation and topdressing of CDM and CMT in respective CMT and ECC treatments increased cumulative DRP loss compared to the control (Table A-9). Similar to TDP losses, DRP loss in runoff from the ECC treatments was greater than the CMT treatments in which CDM or CMT was incorporated with soil. In addition, DRP loss was greater for ECC and 25% y volume CMT treatments missed with CDM than with CMB (Table A-9).

The DRP fraction in runoff water comprised a majority of the TDP for all treatments. For example, 55% of the TDP in runoff water from the control was DRP (Table A-9). The DRP losses increased to 80% of TDP in runoff water from the ECC treatment using CMB as the compost source. The greater (P=0.05) DRP in runoff from ECC for CDM than CMB corresponded to differences in soil WEP between the ECC treatments (Table A-6 and A-9). The DRP is the fraction of P in surface water considered most available to aquatic plants and may contribute to accelerated eutrophication at concentrations orders of magnitude less than observed in this study (Carpenter et al., 1998).

Incorporating CDM at the 25% by volume application rate was the only treatment contributing greater NO_3^--N loss than the control. Yet, the sum of TKN losses over ten events was greater (P= 0.05) for both ECC treatments than CMT treatments and the bermudagrass control (Table A-9). The greater TKN losses from ECC reflected the soil TKN concentrations of ECC compared to other treatments. Overall, the greatest

(*P*=0.05) NO_3^--N and TKN losses occurred in Event 1 for the seven roadside treatments observed in this study (data not shown).

The ECC blanket comprising compost and woodchips successfully limited soil erosion during each of the ten rain events observed in this study. Cumulative sediment loss from the ECC treatments was comparable to established bermudagrass in the control and less (*P*=0.05) than CMT treatments (Table A-10). The ECC treatments reduced cumulative sediment loss to 5% of loss from CMT treatments. The reductions observed in this study were 3 times greater than reductions of steady state interrill erosion rate reported for a 5-cm blanket of biosolids compost (Persyn et al., 2004).

Sediment mass loss was a major contributor of P to runoff water from all treatments, including the control. Although the ECC treatments limited sediment mass loss, TP loss in sediment was greatest (*P*=0.05) for ECC comprising CDM and woodchips (Table A-10). The material lost as sediment in runoff from the ECC was most likely compost and therefore contributed to the large P loss to surface water; even though, relatively small quantities of sediment were lost. The TP loss in sediment from ECC containing CMB was less (*P*=0.05) than ECC with CDM and similar to CMT amended with CMB and the 25% by volume rate of CDM. The variation of TP loss in sediment reflected variation of soil TP concentrations among CMT treatments and the control (Tables A-6 and A-10). Conversely, TP loss in sediment for ECC containing CDM was greater than the CMB amended ECC though soil TP was 3 times greater for the ECC containing CMB (Tables A-6- A-10). The ECC treatment comprising CMB contributed as great or greater (*P*= 0.05) sediment-bound TP mass loss in runoff water as the CMT treatments (Table A-10).

In contrast to TP loss in sediment, TN loss in sediment transported in runoff was similar between ECC treatments and the control (Table A-10). Incorporating CMB at the 12.5% rate and CDM at the 25% rate in CMT resulted in greater TKN mass loss than the ECC treatments. Losses of TKN in the sediment fraction were comparable to dissolved TKN in runoff water for the four CMT treatments in which CDM and CMB were incorporated in soil (Tables A-9 and A-10).

Relationship between Soil and Runoff P

The corresponding variation between nutrient losses in runoff and soil concentrations indicates soil could be sampled to predict runoff losses. Relating P concentrations in the soil to P in runoff can be site and soil specific (Schroeder et al., 2004; Sharpley, 1995; Vadas et al., 2005). Yet, the relationship between soil P and P in runoff can be used to predict P transport from soils in a watershed (Vadas et al., 2005). The TDP and sediment-bound P losses were summed over ten rain events for each treatment in 2003 and related to soil P concentrations (Fig. B-3, B-4, and B-5). Variation of TP loss in runoff was analyzed in relation to variation of measurements of soil P to identify and evaluate indicators of the potential environmental impacts of varied rates and specifications for CDM and CMB use on roadsides (Sims et al., 2000). Mass losses of TP for the control, CMT, and ECC treatments were regressed against mean WEP, STP, and TP in samples of the surface 0 to 5-cm soil depth after Event 10 (Fig. B-3, B-4, and B-5). A linear relationship was observed between each measure of soil P and mass loss of TP over 10 runoff events. The slopes of the regression lines were not significantly different (*P* = 0.05) for CDM and CMB correlated to WEP, STP, or TP concentrations in soil. Yet, the slopes of relationships between TP in soil and TP (Fig. B-5) in runoff and between STP and TP in runoff (Fig. B-4) varied between CDM and CMB sources used to amend soil. In contrast, slopes of regression equations relating WEP to TP loss in runoff were similar between compost sources (Fig. B-3). Similar to previous comparisons among varied sources of livestock manure (Sharpley and Moyer, 2000) WEP was an effective environmental indicator of potential enrichment of surface runoff after land application of CDM or CMB.

CONCLUSIONS

Amending newly constructed roadside soils with compost products is gaining acceptance by many SDOTs in the U.S. The goal is to protect roadside soils from water erosion after construction through incorporation of compost into the soil at large volume-based rates (CMT) or topdressing a compost-woodchip mix over bare soil (ECC). The specifications for CMT and ECC comprise large, volume-based rates and contrasting application methods without limits on nutrient concentration, form, and content of constituent compost sources. In this study, large nutrient loads were imported to roadside soils in CDM and CMB mixed with soil in CMT and with woodchips in ECC treatments. Although ECC limited sediment losses, sediment contributed to large TP loss in surface runoff. In addition, the ECC application increased total and extractable P concentrations in the soil and concentrations of TDP in runoff water. The ECC treatments contributed the highest P losses in runoff and CMT contributed the highest N losses in runoff over ten rain events. The ECC and CMT are among non-point P and N sources on watersheds that need careful evaluation to determine potential impacts to surface waters. Importantly, roadside soils are constructed in zones that promote rapid water runoff and transport to provide safe driving conditions. Increasing concentrations of P in the soil were directly related to increasing total P loss in runoff water from roadside soils. The linear relationships between WEP, STP, and TP concentrations in the soil and total P loss in runoff water imply the need to limit soil nutrient concentrations to protect water quality. In this study, the CMT and ECC specifications using CDM and CMB led to excessive P concentrations in the soil, which contributed to the large P losses observed in runoff. Only a small fraction of the TN loss in runoff was attributed to NO_3^--N. A majority of the NO_3^--N was transported in runoff water during the first rain events after roadside soil construction. Further studies are needed to quantify long-term water-quality impacts of amending roadside soils with compost according to SDOT specifications, including the CMT and ECC.

CHAPTER IV

CYCLING COMPOSTED MUNICIPAL BIOSOLIDS THROUGH TURFGRASS SOD PRODUCTION: WATER QUALITY

INTRODUCTION

Municipalities and related industries produce and market composted municipal biosolids (CMB) as soil amendments for establishment of vegetation, including turfgrass, on commercial and residential landscapes and sports fields (City of Austin, 2001; Dickerson, 1999; Milwaukee Municipal Sewerage District, 2004). Recycling CMB across urban landscapes diverts waste streams from landfills and facilitates nutrient and carbon cycling. Historically, reports of CMB use in turfgrass management systems focused on plant responses to amended soils (Schlossberg and Miller, 2004; Loschinkohl and Boehm, 2001; O'Brien and Barker, 1995; Flanagan et al., 1993). The CMB amendments decreased incidence of disease, enhanced color, reduced establishment time, and delayed water stress of turfgrass established on disturbed urban soils and sod production fields (Boulter et al., 2002; Loschinkohl and Boehm, 2001; Garling and Boehm, 2001; Smith, 1996; Murray et al., 1980).

Evaluations of turfgrass establishment and municipal programs promoting CMB use on low-quality soils have included studies of depth- or volume-based rates. For example, the City of Austin, Texas recommends incorporation of 25% by volume of CMB into a 15-cm depth of soil or topdressing of a 0.6-cm depth of CMB (City of

Austin, 2001). Similarly, large volume-based CMB rates were used to enhance soil physical properties for turf establishment on poor quality soils (Landschoot, 1995; Cisar, 1994, Angle, 1994). Yet, little information concerning nutrient losses in surface runoff from soils amended with the large volume-based CMB rates is available.

Line et al. (2002) identified imports of compost and mulches on residential soils among factors increasing nutrient loss in runoff water from urban construction sites. Nutrient losses in runoff water from amended soil and turf are expected to increase as nutrient concentrations in soil increase, whether applied as inorganic or organic fertilizer sources (Easton and Petrovic, 2004; Vietor et al., 2004; Gaudreau et al., 2002). The nutrient loads in urban runoff are considered a major source of non-point surface water pollution (Carpenter et al., 1998).

The potential contribution of volume-based CMB rates to nonpoint-source nutrient losses in surface runoff from urban landscapes needs to be evaluated. In addition, the traditional approach of mixing with CMB with urban soils prior to sprigging or seeding of turfgrass needs to be compared to the practice of importing CMB in sod transplanted for turfgrass fields grown with CMB (Vietor et al., 2004). A previous study indicated transplanted sod delayed runoff of simulated rain more than wood or fiber blankets applied to 8% or larger slopes on simulated construction sites (Krenitsky et al., 1998). The comparison of runoff losses between CMB-amended soil and CMB-amended sod will contribute to development of optimal practices for minimizing sediment and nutrient losses during revegetation and stabilization of soils on urban construction sites. The objectives of this study were: (i) quantify and compare export of total and extractable P and N in sod harvests among turfgrass sources produced with inorganic fertilizer and two sources and rates of CMB, (ii) quantify and compare P and N runoff losses between sod transplanted from CMB-produced turfgrass and turfgrass sprigged in CMB amended soil, and (iii) relate runoff concentrations and mass losses of P to extractable soil P concentrations of turf establishment treatments.

MATERIALS AND METHODS

Turfgrass Sod Production

Sod production treatments were imposed under irrigated conditions at the Texas A&M University (TAMU) Turfgrass Field Laboratory, College Station, TX between May and August 2004. Six treatments were replicated four times in a randomized complete block design. Individual plots measured 3.0 m by 4.5 m. Treatments differed with respect to P source and rate. The treatments comprised a control (0 kg P ha^{-1}), inorganic P fertilizer (50 kg P ha^{-1}), and two CMB sources topdressed at 12.5 and 25% by volume (v/v) of a 5-cm depth of soil. The two CMB sources were available for purchase from the cities of Austin and Bryan, Texas. The total P (TP) concentration on a wet weight basis in the Austin source (7.8 g kg^{-1}) was two times greater than that of the Bryan source (3.6 g kg^{-1}). The Austin source was designated as High-P and the Bryan source as Low-P CMB. The two CMB rates represented 50 and 100% of the volume-based rates recommended for urban soils in Austin, Texas. The CMB was topdressed after sprigging Tifway bermudagrass [*Cynodon dactylon* (L.) Pers. *x C. transvaalensis* Burtt-Davy, var. Tifway] in a 5-cm depth of imported loamy sand. The loamy sand was applied over an exposed E_g horizon of a truncated Boonville fine sandy loam soil (fine smectitic thermic Chromic Vertic Albaqualf). Total and extractable P and N concentrations in the 5-cm layer of loamy sand and in CMB sources were analyzed prior to treatment applications. Inorganic N fertilizer was applied as ammonium sulfate $(NH_4)_2SO_4$ to all plots at rate of 50 kg N ha^{-1} on 15, 24 June; 2, 13, 23 July; and 16 August 2004 to promote rapid turf establishment.

Turf was mowed to 3 cm when grass height reached 8 cm. Turfgrass sod was harvested to a 2.5-cm depth on 26 August 2004. Four 10-cm diameter plugs were sampled from each plot. The plugs were used to estimate total P and N amounts in soil and plant components and extractable P and N in the soil component of the harvested sod layer. Plant and soil components of sod were separated in an acidified (pH=4) wash solution to reduce N loss. The wash solution was combined with soil and dried at 60 C. Dried soil and plant components were weighed, ground, sub-sampled, and analyzed.

Runoff Water Quality

Experimental Design and Sampling

Runoff water quality was compared between transplanted sod and CMB-amended soil on an 8.5% slope excavated from the Boonville soil at the TAMU Turfgrass Field Laboratory. A randomized complete block design comprised three replications of seven treatments that were installed on 1.5 m by 4-m plots (Gaudreau et al., 2002; Vietor et al., 2002; Vietor et al., 2004). A 10-cm width of sheet metal was inserted to a 2.5-cm depth around plot perimeters to isolate and channel runoff through individual H-flumes into uncovered 311-L tanks. Except for an established bermudagrass (*Cynodon dactylon* L.) control, plot surfaces were excavated to a 5-cm depth to simulate a disturbed urban landscape before treatments were imposed. Three treatments consisted of the bermudagrass control and sod transplanted from turf top-dressed with a 1.2-cm depth of High-P or Low-P CMB. Four additional treatments comprised Tifway sprigged into a 5-cm depth of sandy-clay loam soil (fine, mixed, thermic Fluventic Ustochrept) mixed with 12.5% or 25% by volume of the High-P or Low-P CMB source.

Total N (TN), nitrate-N (NO_3^--N), total P (TP), Mehlich-3-extractable P (STP), and water extractable P (WEP) of amended soil and transplanted sod were measured at the start and end of the runoff sampling period. Runoff volumes of eight rainfall events were measured and sampled from 28 August 2004 through 1 April 2005. Runoff was sampled immediately after rain events or before collection tanks overflowed. The samples were stored in a refrigerator at 4°C or placed on ice prior to centrifuging a 100-mL sub-sample. Centrifuging and filtering were initiated within 24-h of runoff, except for the first rain event on 28 August 2004. Samples from the first event were refrigerated for 36-h at 4°C prior to centrifuging. The sub-samples were centrifuged at 3600 rpm for 30 minutes. The supernatant was decanted and filtered (<0.45-µm) for analysis of total dissolved P (TDP) and dissolved reactive P (DRP). Subsamples of filtrate were submitted to the Texas Cooperative Extension Soil, Water, and Forage Testing Laboratory for analysis of total Kjeldahl nitrogen (TKN), NO_3-N, and TDP. The sediment recovered during centrifuging and filtering was dried, weighed, and ground for analysis and computations of TP and TKN in sediment transported in runoff water.

Three plugs (10-cm diameter and 5-cm deep) were sampled from plots after the final runoff event to compare turfgrass root and shoot biomass among treatments. The plugs were washed in an acidified solution (pH=4) to separate plant tissue from soil and CMB residues.

Sample Analysis

Turfgrass, CMB, sediment, and soil samples were digested according to a modified Kjeldahl method (Parkinson and Allen, 1975). The TKN concentration in digests was measured colorimetrically (Dorich and Nelson, 1983). The Mehlich 3 method was used to extract plant-available P from compost sources and soil (Mehlich, A. 1984). The NO_3-N in compost and amended soil was extracted as described by Keeney and Nelson (1982). In addition, NO_3-N and P in CMB and soil were extracted in distilled water to quantify nutrients susceptible to loss through leaching and runoff. An auto-analyzer was used to quantify NO_3-N in extracts through cadmium reduction (Dorich and Nelson, 1984). Concentrations of TP in digests and TDP in extracts of soil and filtrate of runoff were analyzed through inductively coupled plasma optical emission spectroscopy (ICP). The DRP in water samples and extracts of CMB and soil was determined colorometrically within 24 h of filtering (D'Angelo et al., 2001).

Statistical Analysis

Analysis of variance (ANOVA) (SAS version 9.0) and mean separations among treatments were conducted for sod production and runoff experiments (SAS Institute Inc, 2000). In addition, ANOVA among treatments was completed for individual runoff events if interactions between treatments and sampling dates were significant (P=0.05) for the runoff experiment. Regression analysis was used to evaluate the relationship of mean TDP concentration and mass losses of TDP in runoff during eight rain events to STP and WEP concentrations in soil. A T-test was performed to detect significant differences between slopes of the regression relationships for the two CMB sources (Kleinbaum and Kupper, 1978).

RESULTS AND DISCUSSION

Turfgrass Sod Production

The turfgrass sod was harvested on 26 August 2004 four months after bermudagrass sprigs were planted. Although NO_3-N was applied in CMB and five fertilizer applications totaling 300 kg N ha^{-1} (Table A-11), mean NO_3^--N concentrations (mg kg^{-1}) in the harvested sod layer were low (Table A-12). The NO_3-N concentrations on a wet basis in High-P CMB were 34% greater than Low-P CMB, but NO_3-N concentrations in soil of the sod layer did not differ among treatments at harvest (Table A-12).

Low NO_3-N concentrations within and below the harvested sod layer were similar for the control and CMB-amended treatments indicating turf plants used a major portion of applied NO_3-N during turf establishment (Table A-12). In contrast to the low concentrations of soil NO_3-N, top-dressing of the two sources and rates of CMB increased (*P*=0.05) soil TKN concentration within the harvested sod layer compared to treatments receiving only inorganic-N and inorganic-P fertilizers (Table A-12). Doubling the volume-based rates of respective CMB sources increased (*P*=0.05) soil concentrations of TKN. Yet, TKN concentration in soil beneath the sod layer was similar between CMB-amended treatments and the control.

Amending sod production plots with CMB, even at 12.5% by volume, increased STP to concentrations 5 times greater than recommended agronomic levels. In addition, top-dressing of both rates of the two CMB sources increased (P=0.05) STP of the harvested sod layer compared to the control and sod top-dressed with 50 kg ha^{-1} of fertilizer P (Table A-12). Moreover, increasing the rate of either CMB source from 12.5 to 25% by volume increased the STP concentrations in the sod layer. For each CMB rate, STP was greater (α=0.05) in the sod layer amended with High-P than with Low-P CMB (Table A-12). Similar STP concentrations between the control and CMB-amended treatments within the 5-cm depth of soil below the sod layer indicated STP applied in CMB was largely exported with the sod harvest.

Similar to changes in STP, the 25% by volume rates of both CMB sources and the 12.5% rate of the High-P CMB increased TP in the sod layer compared to the control and fertilizer-grown sod (Table A-12). Despite large TP increases in soil within the sod layer, TP in the 5-cm depth of soil below the sod layer were similar to the control. The single sod harvest effectively removed the TP applied in CMB. In previous studies of manure export through sod up to 77% of TP in topdressings of composted manure was exported through a single sod harvest of Reveille bluegrass (*Poa arachnifera* Torr. X *P. pratensis* L.) (Vietor et al., 2002).

The dry weight of Tifway bermudagrass biomass (Mg ha^{-1}) in the sod layer was similar (P=0.05) among treatments and ranged from 10 to 14 Mg ha^{-1} (dry wt).

Topdressing CMB at volume-based rates (12.5 and 25% of the surface 5-cm) over establishing sprigs did not limit bermudagrass growth compared to applications of inorganic fertilizer only to promote establishment. The control plot receiving only inorganic N fertilizer and yielded biomass similar to other treatments, indicating P concentrations in the soil of control plots were not limiting.

Runoff Water Quality

Soil and Runoff Depth

Increases of soil nutrient concentrations above that of annual crop requirements can contribute to loss of dissolved and sediment-bound nutrients in runoff water (Carpenter et al., 1998). Contrasting establishment treatments in the present study contributed to increased concentrations and potential runoff loss of soil nutrients. The NO_3-N and TKN concentrations in sod transplanted from turf topdressed with CMB were greater (P=0.05) than sprigged treatments in which soil was mixed with the two rates of Low-P CMB (Table A-13). For each CMB source, top-dressing and import with transplanted sod increased (P=0.05) TKN concentration compared to equal and lesser rates that were incorporated within the 5-cm soil depth of sprigged treatments. In addition to reducing concentration of NO_3-N or TKN near the soil surface, incorporation could reduce potential transport and loss in surface runoff (Table A-13).

Concentrations of extractable P forms in the 5-cm depth were similarly greater (P=0.05) for transplanted sod than sprigged treatments in which CMB was incorporated. Concentrations of WEP, a potential indicator of P loss through leaching or runoff, were greater for sod containing topdressed CMB than for soil mixed with the respective CMB

(Table A-13) (Sharpley and Moyer, 2000). In addition, doubling the volume based CMB rate mixed with soil increased WEP for the respective CMB. Variation of STP among treatments was similar to WEP, except the 12.5% rate of Low-P CMB was not different from the 25% rate or control. In contrast to NO_3-N, STP concentrations exceeded agronomic P levels (50 mg kg^{-1}) for all treatments amended with CMB (Table A-13).

Variation of runoff depth and concentration and mass loss of N and P forms and sediment was analyzed separately for each runoff event to accommodate a significant (*P*=0.05) interaction between treatments and runoff events (Table A-14). Rainfall depths varied between 12 and 49 mm and totaled 210 mm during the eight events. Yet, runoff depth varied among treatments on the first event only, 2 d after treatments were imposed (Table A-15). Runoff depth was 2 times greater (*P*=0.05) for transplanted sod than for the established bermudagrass control and turf sprigged into soil mixed with the 12.5% rate of High-P CMB on the first date. Runoff depth did not differ among the two sources and rates of CMB incorporated in sprigged treatments (data not shown). The magnitude of treatment differences in runoff depths diminished as Tifway bermudagrass established on the sprigged treatments. The portion of rainfall recovered in runoff declined from 67% to 25% from the first to last runoff event.

Concentrations in Runoff

Concentrations of TDP in runoff water differed (*P*=0.05) among treatments during each of eight rain events (Tables A-14 and A-15). During the first two rain events, TDP concentrations in runoff from transplanted sod were greater (*P*=0.05) than the control and sprigged treatments amended with CMB (Table A-15). In addition, TDP concentration in runoff was greater (*P*=0.05) for sod amended with Low-P CMB than for High-P CMB. The difference in runoff concentration of TDP between the two sod sources for the first two events occurred despite similar WEP concentrations within the 5-cm depth of these two treatments (Table A-13).

During five subsequent runoff events, comparative soil WEP concentrations were reflected in similar TDP concentrations in runoff between the two sod sources (Tables A-13 and A-15). In addition, greater TDP concentrations in runoff from transplanted sod than from the control and sprigged treatments amended with CMB were consistent with soil WEP differences between treatments (Tables A-13 and A-15). Moreover, greater STP concentrations in the sampled layer of transplanted sod than for sprigged plots for a respective CMB is consistent with greater TDP concentration in runoff from transplanted sod. The results indicate CMB incorporation in soil can reduce the quantity of P dissolved and transported in runoff water (Daverede et al., 2004; Pote et al., 2003; Sharpley 1985). In addition, CMB products high in TP could be incorporated at volume-based rates recommended for urban soils without increasing TDP concentration in runoff compared to lesser CMB rates or established bermudagrass supplied inorganic nutrients (Tarkalson and Mikkelsen, 2004). Moreover, variation of TDP concentration in runoff among all treatments was small on a sampling date seven months after treatments were imposed (Table A-15).

The TKN concentration in filtrate was indicative of mass loss of dissolved N in runoff among establishment treatments. Although an interaction between treatment and rainfall event was significant (*P*=0.05), the ranking of mean TKN concentrations in runoff among treatments was similar over rain events (data not shown). During four runoff events after treatments were applied, mean TKN concentration in runoff was greater (*P*=0.05) for sod transplanted from turf grown with High-P CMB (11.2 mg L^{-1}) than for turf grown with low-P CMB (8.8 mg L^{-1}). During five runoff events, mean TKN concentration in runoff from sod grown with High-P (12.2 mg L^{-1}) and Low-P CMB (10.0 g L^{-1}) were greater (α=0.05) than the control and soil mixed with either CMB source (5.5 mg L^{-1}) before sprigging. The ranking of runoff concentration of TKN among treatments over the first six runoff events was similar to treatment differences in soil TKN concentration (Table A-13).

Low NO_3^--N concentrations in runoff were consistent with low soil test concentrations of NO_3-N among establishment treatments (Table A-13). The NO_3-N concentrations were generally less than 1.0 mg L^{-1} for all treatments during each rain event (data not shown). The NO_3^--N concentration in runoff water differed among treatments on only two of eight runoff events (Table A-14). Easton and Petrovic (2004) reported runoff concentrations up to 10 mg L^{-1} in runoff from a 7 to 9% slope after application of natural organic N (100 kg ha^{-1}) sources, including biosolids, during early turf establishment. Yet, their organic N sources were top-dressed on newly seeded cool-season perennial grass rather than incorporated in soil or imported with sod.

Mass Losses in Runoff

Although variation of magnitude of treatment differences in mass loss of TDP contributed to an interaction between treatment and event, the mean rank among treatments was consistent among events (Table A-14). The mean mass loss of TDP in runoff from transplanted sod was less (*P*=0.05) for the Low-P CMB (96 mg m^{-2}) than the High-P CMB (153 mg m^{-2}) sod source during only two of eight rain events. In addition, mean TDP mass loss (mg m^{-2}) in runoff was consistently greater for sod grown with High-P (106 mg m^{-2}) or Low-P CMB (76 mg m^{-2}) than from a control and sprigged treatments amended with volume-based CMB rates (26 mg m^{-2}). Similar treatment differences were observed for mass loss of TDP summed over the eight runoff events (Table A-16). Variation of the sum of total mass loss of TDP among treatments indicated incorporation of either CMB source effectively limited TDP mass loss compared to CMB imported with transplanted sod (Tarkalson and Mikkelsen, 2004). Vietor et al. (2004) reported greater TDP losses in runoff water when composted dairy manure was applied to sprigged bermudagrass rather than imported with transplanted sod. In contrast to the present study, the composted dairy manure was topdressed on sprigged treatments rather than incorporated.

A major portion of TDP mass loss was in the DRP fraction for all treatments (Table A-16). The DRP mass loss (mg m^{-2}) was greatest over eight rain events for transplanted sod used to import CMB (Table A-16). Yet, the fraction of TDP mass loss, composed of DRP was 50% lower in runoff from the transplanted sod than from CMB mixed in the 0 to 5-cm soil layer. The DRP mass loss in runoff from sprigged treatments ranged between 57 and 77% of the TDP mass loss over eight runoff events (Table A-16).

Sediment loss in runoff varied among treatments during the first two runoff events after treatments were established and on Nov 1 (Table A-14). Totaled over eight runoff events, sediment loss was less (α=0.05) for transplanted sod than for three sprigged treatments in which CMB was mixed with soil (Table A-16). The total mass of sediment was 2 to 3 times greater for sprigged compared to transplanted sod treatments.

Mean mass losses of TP and TKN in sediment were not different among treatments over the first six rain events (Table A-14). Yet, cumulative mass loss of TP and TKN in the sediment fraction was greater for sod transplanted from turf grown with High-P CMB than the other sod source or sprigged treatments amended with either CMB source (Table A-17). Analyses of soil sampled from the 0- to 5-cm depth indicated greater TP and STP concentrations in sod grown with High-P CMB contributed to greater mass loss of TP in sediment from High-P sod than from other treatments. Mass loss of TP in sediment and mean STP in sod grown with High-P CMB were more than 70% greater than the next lower mean of each variable for other establishment treatments (Tables A-13 and A-17). Similarly, mass loss of TKN in sediment was 118% greater and soil TKN concentration was 52% greater for sod grown with High-P CMB than for the second ranking treatment (Tables A-13 and A-17). Incorporation of both CMB sources in soil limited mass loss of TKN and TP in the sediment fraction of runoff to amounts similar to the established bermudagrass control.

The sums of mass losses of TP and TKN in sediment were similar in magnitude to mass losses of TDP and TKN in runoff water for sprigged treatments in which CMB was incorporated (Tables A-16 and A-17). In contrast, import of Low-P CMB in transplanted sod reduced sediment-bound losses to 49% of dissolved TKN and to 22% of TDP. Yet, the high TKN and TP concentrations in sod imported from turf grown with

High-P CMB diminished differences between mass losses of sediment-bound and dissolved N and P forms (Tables A-13 and A-17). Mass loss of TKN in sediment was 76% of dissolved TKN and TP in sediment was 56% of TDP in runoff water (Tables A-16 and A-17).

Similar to variation of concentrations, NO_3-N mass losses were low compared to TKN and differed among treatments during only three runoff events (Table A-14). The sum of mass losses over eight runoff events indicated NO_3-N mass loss from transplanted sod and sprigged treatments amended with High-P CMB were greater than the established bermudagrass control (Table A-16). Yet, variation of mass loss of NO_3-N was not related to variation of soil-test or runoff concentrations of NO_3-N among treatments.

Relationship between Soil and Runoff Losses

Mean concentration and mass loss of TDP in runoff were regressed against WEP and STP for each treatment replication (Figs. B-6 and B-7). Previous evaluations have questioned the utility of STP alone for managing the risk of direct P loss in runoff from fertilizers and organic wastes applied to soil (Sims et al., 2000). Eghball et al. (2002) reported runoff losses of dissolved P forms were not well correlated to STP concentrations just after organic nutrient sources are applied. In contrast, Vietor et al. (2002) reported a positive, direct relationship between mean TDP loss in runoff water and STP for sod transplanted from turfgrass top-dressed with P-based rates of composted dairy manure. A similar study of P transfer in runoff after application of biosolids and fertilizer indicated P release was related to amounts extracted in water (Withers et al., 2001).

Variation of mean TDP concentration in runoff for eight runoff events sampled during the present study was positively and directly related to variation of both soil WEP and STP concentrations among CMB amended treatments (Figs. B-6 and B-7). Yet, the relationship between extractable P forms and TDP in runoff differed between compost sources (Fig. B-7).The predicted mass loss of TDP in runoff was less for treatments amended with Low-P than High-P CMB as soil WEP concentration increased above 12 mg kg^{-1} (Fig. B-6). Conversely, predicted TDP concentration in runoff was less for High-P than Low-P CMB as STP concentration increased above 500 mg kg^{-1} (Fig. B-7). In contrast, relationships between soil WEP and TDP concentration and between STP and TDP mass loss in runoff were similar between Low-P and High-P CMB (Fig. B-6 and B-7). Variation of the relationships between extractable soil P forms and TDP concentrations and losses in runoff reveal both the utility and limitations of extractable soil P tests alone for evaluations of the potential impacts of agricultural practice on water quality.

Tifway Bermudagrass

Tifway bermudagrass biomass (Mg ha^{-1}), comprised the above ground portion and roots harvested from the 0 to 5-cm soil layer of treatments. Biomass was consistently greater (P=0.05) for transplanted sod than for sprigged treatments. Importing the Low-P CMB in turfgrass sod produced the highest biomass (dry wt) at 17 Mg ha^{-1}. Importing the High-P CMB in turfgrass sod yielded 13 Mg ha^{-1} in biomass.

The biomass yield after incorporating CMB into the soil at the 12.5% volume based rate was 6 and 8 Mg ha^{-1} for the Low-P and High-P CMB, respectively. Similarly, the biomass yield after incorporating CMB at the 25% volume based rate was 6 Mg ha^{-1} for the Low-P CMB and 7 Mg ha^{-1} High-P CMB. The biomass yield was calculated approximately 3-mo after treatments were imposed on the runoff plots. Yield differences between sod and sprigged treatments are attributed to the delay of leaf area development for sprigged compared to sodded bermudagrass. Further study is needed to determine how biomass yield differs between transplanted and sprigged bermudagrass turf during establishment.

CONCLUSIONS

Variation associated with nutrient concentration of CMB and different rates and methods of CMB application affected nutrient export through bermudagrass sod harvests and impacts of sod on water quality. Topdressing of volume-based rates of contrasting CMB sources enabled complete removal of applied N and P forms in a single sod harvest. Yet, sod transplanted from turf topdressed with volume-based CMB rates contributed to greater soil and runoff concentrations and mass loss of N and P forms than volume-based CMB rates incorporated in soil. Although import of CMB in transplanted sod reduced sediment loss compared to CMB-amended soil sprigged with bermudagrass, imports of CMB in sod contributed to runoff loss through dissolved and sediment fractions. The high concentrations of TKN, TP, STP, and WEP in sod amended with High-P CMB were consistently associated with greater mass loss of the respective nutrients in runoff compared to CMB-amended soil in sprigged treatments. Conversely, incorporation of CMB in soil minimized variation of mass loss of TP and TKN in solution and sediment among sprigged treatments and the control even though CMB increased soil concentrations of P and N. Yet, regression analysis indicated concentrations of STP and WEP in transplanted sod or soil amended with CMB was directly and positively related to concentration and mass loss of TDP in runoff. Variation of the regression relationships indicated soil concentrations alone were not sufficient predictors of CMB impacts on water quality.

CHAPTER V

CONCLUSIONS

The importance of protecting newly exposed or disturbed soils from wind and water erosion cannot be overstated. Rainwater runoff and overland flow can transport large sediment loads to surface water bodies when soil is unprotected. Roadway soils and soils in urban landscapes are often compacted, further exacerbating the problem of runoff and sediment loss. There is a real need to develop management strategies at construction sites along highways and in the urban landscape to improve the physical quality of soil, thereby improving infiltration, water storage capacity, and limiting sediment losses. Large volume-based compost applications are currently recommended as a tool for improving soil physical properties and promoting vegetation establishment. The specifications developed for amending roadside soils require incorporation of compost (CMT) into the soil surface, topdressing over existing vegetation (GUC), or topdressing a compost-woodchip blend over a bare soil surface (ECC). Large compost volumes are imported to soil through the CMT, GUC, and ECC. Similarly, nutrient concentrations can increase to excessive levels in soil amended by CMT, GUC, and ECC. Concentrations of P and N in runoff water from compost-amended soils were increased to levels considered a risk to surface water quality associated with accelerated eutrophication. Topdressing CDM over existing vegetation increased TDP concentrations in runoff water more than incorporating or applying the compost-woodchip mix. Although TDP and NO_3^--N concentrations were high in runoff water from the ECC, the total losses were not greater than in runoff from the CMT or GUC. The ECC effectively limited runoff water and sediment loss, whereas, the CMT was not an effective method for limiting runoff water or sediment loss for the Loam soil used in this study. Topdressing compost over existing vegetation was also not an effective method for controlling runoff water.

In the 2002 study, the sum of TP mass losses in runoff increased as STP concentration increased n the surface 0 to 5-cm of soil of the CMT-Sand, CMT-Loam, GUC, and the related controls. The 2002 study evaluated runoff water quality before and during plant establishment on the roadside soils amended by CMT, GUC, and ECC. The ECC decreased runoff depths and sediment losses, which limited the TP loss in runoff even though TDP concentrations in runoff were higher than CMT or GUC. In contrast, the sum of TP mass losses in runoff water was highly correlated to WEP, STP, and TP concentrations in the soil for the CMT and ECC in 2003. The 2003 study evaluated runoff water quality during plant establishment on roadside soils amended by the CMT and ECC. The ECC did not restrict runoff water losses as was previously observed in 2002. In 2002 and 2003, only a small fraction of the total N loss in runoff water was attributed to NO_3^--N. However, rainfall was not evaluated for contributions of mineralized N to runoff. In 2003, CDM and CMB were compared and contrasted as were application rates for the CMT specification for amending roadside soils. Cutting the compost application rate by half did not lower nutrient losses compared to the 25% by volume application rate. The WEP concentration in the surface 0 to 5-cm layer of

CMT and ECC was the most effective method for predicting TP mass loss in runoff water for both CDM and CMB.

Developing systems that can manage increasing supplies of CMB and not pose a risk to the environment is critical. A turfgrass sod production system used to cycle CMB across agricultural and urban landscapes was evaluated in 2004. The P added in CMB applications to sod production fields was exported in transplanted sod. Although equal depths of compost were topdressed on the soil at the 12.5 and 25% volume-based rates, variation in nutrient content between CMB products affected the quantity of P applied and subsequently removed in harvested sod. After the sod was transplanted, a comparison was made using the same rates of CMB topdressed for sod production, but the CMB were incorporated into soil. Sprigs were planted for turfgrass establishment. By comparison, the TDP concentration and loss in runoff water was lessened by incorporating the CMB into the soil rather importing it in transplanted sod. In contrast, the NO_3^--N concentrations in runoff were variable in runoff from CMB incorporated into soil or imported in transplanted sod. The concentrations of P and N in the CMB were not good indicators of nutrient loss in runoff water if the CMB were incorporated into soil. Yet, the concentration of WEP and STP in the soil is positively correlated to TDP mass losses in runoff water during plant establishment.

The three studies reported in this dissertation were limited by time. Runoff water was sampled for water quality analysis during vegetation establishment on compost amended soils. A longer sampling period will enable studies of long-term mineralization effects and loss of N, carbon, and mineral nutrients effects on water quality after incorporating or topdressing CDM and CMB at large volume-based rates. The studies evaluating roadside amendments were also limited by climatic conditions. Texas has six climate regions that contrast in annual rainfall depths and characteristics. Further evaluation of compost amendment to roadside soils used in Texas is needed to develop specifications that balance the need of improving the physical characteristics of soil with abating nonpoint nutrient pollution to surface water. A long-term study evaluating P cycling in turfgrass, applying CMB at rates of up to 25% by soil volume is also needed. Little information is available describing the fate of P applied in CMB imported in harvested sod.

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APPENDIX A

Table A-1. Chemical and physical properties of soil amended with composted dairy manure (CDM) to meet Texas Department of Transportation (TxDOT) specifications for amending roadside soils with compost.

	May 2002				November 2002									
Treatment	Soil Test P		NO_3-N		Soil Test P		TP		NO_3-N		TKN		Bulk Density	
	mg kg^{-1}												g cm^{-3}	
Sand	12	g[†]	3	f	19	f	125	f	3	c	121	f	1.25	ab
CMT[‡]-Sand	272	c	141	c	291	d	457	cd	4	c	807	d	1.24	ab
Loam	55	e	13	e	74	e	370	de	4	c	466	e	1.28	ab
CMT-Loam	542	b	235	b	360	c	797	b	9	b	1138	bc	1.30	a
Grass	41	f	28	d	54	ef	246	ef	3	c	1047	c	1.25	ab
GUC[§]-Grass	177	d	5	f	410	b	625	bc	4	c	1241	b	1.22	b
ECC[#]	1921	a	343	a	1253	a	1792	a	12	a	3002	a	0.95	c

†Means in columns with different letters are significantly different at *P*= 0.05 by Fisher's test for least significant difference.

‡Compost manufactured topsoil (CMT): 75% soil and 25% CDM by volume, incorporated to a 5-cm depth.

§General use compost (GUC): 100% CDM by volume topdressed on existing vegetation.

#Erosion control compost (ECC): 33% untreated woodchips and 67% CDM by volume, as a 5-cm uniform layer.

Table A-2. Mean TDP and NO_3^--N concentrations in runoff water sampled after three selected rain events before seeding bermudagrass on roadside treatments (8.5% slope). The rainfall depths were 15, 27, and 27-mm, respectively in the three selected events before seeding bermudagrass in 2002.

	Event 1, 29 May			Event 2, 16 June			Event 6, 17 July		
Treatment	Runoff	TDP	NO_3^--N	Runoff	TDP	NO_3^--N	Runoff	TDP	NO_3^--N
	mm	mg L^{-1}		mm	mg L^{-1}		mm	mg L^{-1}	
Sand	0.6 c	9.4 a[†]	0.63 b	1.5 c	4.0 ab	3.92 b	21.6 a	1.6 b	0.02 b
CMT[‡]-Sand	0.9 c	9.4 a	0.34 b	0.7 c	2.7 bc	3.45 b	17.4 ab	2.5 b	0.40 b
Loam	1.2 bc	3.0 a	0.29 b	7.4 c	0.4 c	0.51 b	23.7 a	1.1 b	0.45 b
CMT-Loam	1.2 c	5.9 a	0.41 b	10.4 abc	2.2 bc	0.78 b	19.0 ab	2.3 b	6.40 a
Grass	6.5 a	4.4 a	1.56 b	18.5 a	2.3 bc	1.25 b	21.7 a	1.9 b	0.02 b
GUC[§]-Grass	4.0 ab	10.3 a	6.80 a	14.6 ab	6.4 a	1.21 b	17.0 ab	5.1 a	0.02 b
ECC[#]	0.5 c	7.0 a	0.30 b	0.5 c	2.4 bc	14.66 a	12.5 b	2.9 b	1.40 b

†Means in columns with different letters are significantly different at *P*=0.05 by Fisher's test for least significant difference.

‡Compost manufactured topsoil (CMT): 75% soil and 25% CDM by volume, incorporated to a 5-cm depth.

§General use compost (GUC): 100% CDM by volume topdressed on existing vegetation.

#Erosion control compost (ECC): 33% untreated woodchips and 67% CDM by volume, as a 5-cm uniform layer.

Table A-3. The sum of water, nutrient, and sediment losses in runoff from roadside soils during six rain events before seeding bermudagrass in 2002. The roadside soils (8.5% slope) were amended with composted dairy manure (CDM) according to specifications for incorporating (CMT), topdressing over vegetation (GUC), and topdressing a CDM-woodchip mix over bare soil (ECC).

	Runoff Water			Sediment		
Treatment	TDP	NO_3^--N	TKN	Mass	TP	TKN
	mg m^{-2}			g m^{-2}	mg m^{-2}	
Sand	59 b	10 c	135 c	170 bc	19 b	84 b
CMT[‡]-Sand	74 b	15 bc	124 c	43 c	127 b	323 b
Loam	44 b	25 bc	189 bc	340 b	116 b	193 b
CMT-Loam	134 b	186 a	231 abc	714 a	329 a	635 a
Grass	164 b	51 bc	357 ab	40 c	22 b	129 b
GUC[§]-Grass	332 a	50 bc	371 a	18 c	23 b	106 b
ECC[#]	58 b	114 ab	147 c	26 c	31 b	79 b

† Means in columns with different letters are significantly different at *P*=0.05 by Fisher's test for least significant difference.

‡ Compost manufactured topsoil (CMT): 75% soil and 25% CDM by volume, incorporated to a 5-cm depth.

§ General use compost (GUC): 100% CDM by volume topdressed on existing vegetation.

Erosion control compost (ECC): 33% untreated woodchips and 67% CDM by volume, as a 5-cm uniform layer.

Table A-4. Mean TDP and NO_3^--N concentrations in runoff water sampled in four selected rain events after seeding bermudagrass on roadside treatments (8.5% slope). The rainfall depths were 50, 25, 12.5, and 43-mm, respectively in the four selected events after seeding in 2002.

	Event 7 (15 August)		Event 8 (2 October)		Event 10 (9 October)		Event 14 (4 November)	
Treatments	TDP	NO_3^--N	TDP	NO_3^--N	TDP	NO_3^--N	TDP	NO_3^--N
				mg L^{-1}				
Sand	0.7 e	0.09 bc	3.6 c	1.26 c	0.3 b	0.31 b	0.7 c	0.01 b
CMT‡-Sand	2.3 c	1.67 b	13.6 a	7.65 a	2.5 b	0.74 b	2.3 b	0.14 b
Loam	1.6 d	0.01 c	2.1 c	0.87 c	1.1 b	0.40 b	0.7 c	0.01 b
CMT-Loam	5.9 a	0.62 bc	5.2 bc	1.69 c	2.5 b	0.78 b	1.1 c	0.25 b
Grass	4.5 b	0.43 bc	3.6 c	1.92 c	0.5 b	0.33 b	0.6 c	0.01 b
GUC§-Grass	2.5 c	0.91 bc	6.6 bc	2.42 bc	2.3 b	0.78 b	2.5 b	0.13 b
ECC#	1.2 de	5.55 a	8.7 b	5.99 ab	8.0 a	1.65 a	4.9 a	1.38 a

†Means in columns with different letters are significantly different at *P*=0.05 by Fisher's test for least significant difference.

‡Compost manufactured topsoil (CMT): 75% soil and 25% CDM by volume, incorporated to a 5-cm depth.

§General use compost (GUC): 100% CDM by volume topdressed on existing vegetation.

#Erosion control compost (ECC): 33% untreated woodchips and 67% CDM by volume, as a 5-cm uniform layer.

Table A-5. The sum of water, nutrient, and sediment losses in runoff from roadside soils during eight rain events after seeding bermudagrass in 2002. The roadside soils (8.5% slope) were amended with composted dairy manure (CDM) according to specifications for incorporating (CMT), topdressing over vegetation (GUC), and topdressing a CDM-woodchip mix over bare soil (ECC).

	Runoff Water					Sediment		
Treatment	Depth	TDP	DRP	NO_3^--N	TKN	Mass	TP	TKN
	mm	mg m^{-2}				g m^{-2}	mg m^{-2}	
Sand	198 ab[†]	197 a	71 a	23 b	645 a	590 b	464 a	6303 a
CMT[‡]-Sand	132 bc	466 a	239 a	61 b	597 a	305 bc	436 ab	5027 ab
Loam	217 a	234 a	121 a	84 b	733 a	1,138 a	132 c	444 c
CMT-Loam	177 ab	525 a	292 a	283 a	607 a	990 a	214 bc	381 c
Grass	214 a	410 a	180 a	72 b	783 a	48 c	57 c	332 c
GUC[§]-Grass	171 ab	496 a	374 a	91 b	789 a	29 c	59 c	325 c
ECC[#]	84 c	581 a	382 a	138 b	931 a	40 c	147 c	1319 bc

[†] Means in columns with different letters are significantly different at *P*=0.05 by Fisher's test for least significant difference.

[‡] Compost manufactured topsoil (CMT): 75% soil and 25% CDM by volume, incorporated to a 5-cm depth.

[§] General use compost (GUC): 100% CDM by volume topdressed on existing vegetation.

[#] Erosion control compost (ECC): 33% untreated woodchips and 67% CDM by volume, as a 5-cm uniform layer.

Table A-6. Compost mass and nutrient rates applied as composted dairy manure (CDM) and municipal biosolids (CMB) at TxDOT specified rates for roadside soils seeded to a mixture of bluestem and bermudagrass. In addition, soil nutrient concentrations for treatments amended with CDM and CMB are presented. The treatments comprised compost manufactured topsoil (CMT), erosion control compost (ECC), and an unfertilized control.

			Compost			Soil			
Treatment	Source	Rate	Mass	TP	TKN	TP	TKN	STP	WEP
		% volume	Mg ha^{-1}	kg ha^{-1}		mg kg^{-1}			
Control	NA	NA				254 e	1188 cd	80 e	17 d
CMT	CDM	12.5	62 d[†]	199 f	320 f	537 de	725 e	264 de	34 cd
CMT	CMB	12.5	28 f	408 d	468 e	875 cd	1035 de	439 cd	29 d
CMT	CDM	25	109 b	337 e	566 d	761 d	1059 de	496 cd	50 bc
CMT	CMB	25	50 e	810 b	865 c	1201 c	1515 c	623 c	33 cd
ECC	CDM	50	185 a	611 c	944 b	1773 b	2759 b	1115 b	77 a
ECC	CMB	50	100 c	1773 a	1712 a	5121 a	5212 a	2203 a	55 b

[†] Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

Table A-7. Mean TDP concentration in runoff water from compost amended roadside soils for selected rain events in 2003. The rain amounts for the select events were 23, 5, 18, 29, 50 mm, respectively. See caption of Table A-6 for treatment descriptions.

Amendment	Source	Rate	Rain Event				
			1 (5 June)	3 (14 June)	6 (4 July)	8 (11 August)	10 (31 August)
		% volume	mg L^{-1}				
Control	NA	NA	1.9 d[†]	2.2 d	1.8 c	3.2 b	2.6 c
CMT	CDM	12.5	2.7 d	3.2 cd	2.4 c	3.4 b	2.6 c
CMT	CMB	12.5	2.6 d	2.8 d	2.1 c	3.8 b	3.3 c
CMT	CDM	25	5.2 c	6.0 c	2.8 c	3.9 b	3.3 c
CMT	CMB	25	3.2 cd	3.4 cd	2.7 c	4.2 b	3.2 c
ECC	CDM	50	17.1 a	17.3 a	11.4 a	11.0 a	11.2 a
ECC	CMB	50	9.6 b	13.0 b	8.0 b	11.4 a	8.3 b

[†] Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

Table A-8. Mean NO_3^--N concentration in runoff water from compost amended roadside soils seeded to bluestem and bermudagrass for selected rain events in 2003. The rain amounts for the select events were 23, 5, 18, 29, 50 mm, respectively. See caption of Table A-6 for treatment descriptions.

			Rain Event				
Amendment	Source	Rate	1 (5 June)	3 (14 June)	6 (4 July)	8 (11 August)	10 (31 August)
		% volume	mg L^{-1}				
Control	NA	NA	0.59 d[†]	0.22 a	0.25 a	0.55 b	0.25 bc
CMT[‡]	CDM	12.5	1.20 bcd	0.48 a	0.51 a	0.64 b	0.23 c
CMT	CMB	12.5	1.10 cd	0.32 a	0.17 a	0.41 b	0.21 c
CMT	CDM	25	2.38 a	0.69 a	0.40 a	0.41 b	0.23 c
CMT	CMB	25	1.65 abc	0.47 a	0.25 a	0.40 b	0.21 c
ECC[§]	CDM	50	1.41 bcd	0.28 a	0.46 a	1.15 a	0.30 ab
ECC	CMB	50	2.01 ab	0.45 a	0.45 a	1.42 a	0.34 a

[†] Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

Table A-9. The sum of the dissolved nutrient loss in runoff water during ten rain events from roadside soils amended with composted dairy manure (CDM) and composted municipal biosolids (CMB) to enhance revegetation and reduce sediment loss after construction. See caption of Table A-6 for treatment descriptions.

Amendment	Source	Rate	Runoff	TDP	DRP	NO_3^--N	TKN
		% volume	mm	mg m^{-2}			
Control	NA	NA	156 bc[†]	301 d	165 e	45 b	775 b
CMT[‡]	CDM	12.5	194 ab	450 cd	303 d	86 b	786 b
CMT	CMB	12.5	178 ab	428 cd	272 de	59 b	815 b
CMT	CDM	25	206 a	637 c	450 c	140 a	1025 b
CMT	CMB	25	168 abc	440 cd	308 d	78 b	770 b
ECC[§]	CDM	50	178 ab	1845 a	1321 a	75 b	1756 a
ECC	CMB	50	137 c	1050 b	841 b	71 b	1549 a

[†] Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

Table A-10. The sum mass loss of sediment and associated TP and TKN in runoff water during ten rain events from roadside soils amended with composted dairy manure (CDM) and composted municipal biosolids (CMB). See caption of Table A-6 for treatment descriptions.

Amendment	Source	Rate	TP		TN		Sediment	
		% volume	mg m^{-2}				g m^{-2}	
Control	NA	NA	328	c[†]	115	b	111	cd
CMT[‡]	CDM	12.5	361	c	554	ab	525	b
CMT	CMB	12.5	439	bc	1373	a	398	b
CMT	CDM	25	646	b	1380	a	872	a
CMT	CMB	25	454	bc	664	ab	469	b
ECC[§]	CDM	50	965	a	60	b	44	d
ECC	CMB	50	681	b	16	b	11	d

[†] Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (P=0.05).

Table A-11. Rates of N and P applied to Tifway bermudagrass production plots in composted municipal biosolids (CMB) and inorganic fertilizers. Nutrient application rates were a function of volume-based rates (v/v) topdressed on the soil. The inorganic N fertilizer was applied to achieve rapid establishment and growth of Tifway bermudagrass.

	N rate		P rate	
	CMB	Fertilizer†	CMB	Fertilizer
	——— kg ha^{-1} ———			
Control	0	300	0	0
P fertilizer (50 kg ha^{-1})	0	300	0	50
Low-P CMB (12.5%)	325	300	130	0
High-P CMB (12.5%)	642	300	295	0
Low-P CMB (25%)	698	300	280	0
High-P CMB (25%)	1302	300	599	0

†The inorganic N source was $(NH_4)_2SO_4$ (21-0-0) and the inorganic P source was triple super phosphate (0-46-0).

Table A-12. Mean concentrations of nutrient forms in the harvested sod layer and the 5-cm depth of soil exposed after sod removal. The treatments comprised two rates (12.5% and 25% by volume) of two sources of composted municipal biosolids (High-P and Low-P), inorganic P fertilizer (50 kg ha^{-1}), and an unfertilized control. Treatments were imposed after sprigging of Tifway bermudagrass.

Treatment	Harvested sod layer							
	NO_3^--N		TKN		STP		TP	
	mg kg^{-1}							
Control	3.5	a†	640	d†	18	d	138	c
P fertilizer (50 kg ha^{-1})	3.3	a	658	d	27	d	103	c
Low-P CMB (12.5%)	4.3	a	2240	c	273	c	636	bc
High-P CMB (12.5%)	4.5	a	2770	bc	483	b	1196	b
Low-P CMB (25%)	5.0	a	3753	ab	427	b	1179	b
High-P CMB (25%)	7.8	a	4740	a	646	a	2120	a
	Remaining soil							
Control	9.0	a	482	a	38	a	112	a
P fertilizer	8.5	ab	415	a	37	a	105	a
Low-P CMB (12.5%)	7.5	ab	433	a	37	a	123	a
High-P CMB (12.5%)	5.8	b	437	a	42	a	133	a
Low-P CMB (25%)	6.5	ab	390	a	55	a	95	a
High-P CMB (25%)	5.8	b	450	a	44	a	130	a

†Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (P=0.05).

Table A-13. Mean concentrations of total Kjeldahl N (TKN), water extractable P (WEP), soil-test P (STP), and total P (TP) in the surface layer (0 to 5 cm) at the end of the runoff water sampling period. Tifway bermudagrass was established on an 8.5% slope through sprigging or transplanting of sod. Composted municipal biosolids (CMB) were incorporated (INC) at 12.5 or 25% by volume into the soil prior to sprigging or topdressed on turf before sod was harvested and transplanted (SOD).

Treatment	NO_3^--N		TKN		WEP		STP		TP	
	mg kg^{-1}									
Control	6.7	ab[†]	1863	cd	5.9	bc	32	d	368	e
Low-P INC-12.5%	2.7	b	1167	d	2.6	d	87	cd	526	de
High-P INC-12.5%	4.7	ab	1577	d	2.8	cd	147	c	756	cde
Low-P INC-25%	3.3	b	1957	cd	6.5	b	180	c	793	cd
High-P INC-25%	5.3	ab	2533	bc	6.1	b	301	b	1330	b
Low-P SOD	8.7	a	3040	b	13.7	a	322	b	1041	bc
High-P SOD	9.0	a	4550	a	13.9	a	544	a	2017	a

†Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

Table A-14. Analysis of variance among treatment for depth; concentrations of total dissolved P (TDP), NO_3-N, and dissolved total Kjeldahl N (TKN); mass loss of sediment and associated total P (TP) and TKN; and mass loss of TDP, NO_3-N, and dissolved TKN of runoff during each of eight rain events.

Event	Runoff	TDP	NO_3^--N	TKN	TDP	TP	NO_3^--N	TKN	Sed.-N	Sediment
	mm	mg L^{-1}			mg m^{-2}					g m^{-2}
28 Aug.	0.025	<0.001	NS	<0.001	<0.001	NS	NS	<0.001	NS	0.012
4 Oct.	NS[†]	<0.001	NS	0.012	0.001	NS	NS	0.002	NS	0.006
19 Oct.	NS	<0.001	NS	<0.001	0.001	NS	NS	0.001	NS	NS
25 Oct.	NS	<0.001	NS	<0.001	0.008	NS	0.026	0.009	NS	NS
1 Nov.	NS	<0.001	0.009	<0.001	0.002	NS	0.017	0.002	NS	0.019
17 Nov.	NS	<0.001	NS	0.001	<0.001	NS	NS	0.024	NS	NS
20 Nov.	NS	<0.001	NS	NS	0.001	0.036	0.018	NS	0.027	NS
1 Apr.	NS	0.015	0.008	NS	NS	0.031	NS	NS	0.007	NS

† NS = not significantly different at $P = 0.05$.

Table A-15. Mean TDP concentration in runoff water from sprigged bermudagrass after High- and Low-P sources of composted municipal biosolids (CMB) were incorporated into a 5-cm depth of soil (INC) or after sod (SOD) was transplanted from turf grown with High-P or Low-P CMB. Runoff water was produced by natural rain events on all listed dates.

Treatments	28 Aug.[†]	4 Oct.	19 Oct.	25 Oct.	1 Nov.	17 Nov.	20 Nov.	1 Apr. 2005
	mg L^{-1}							
Control	1.3 c[‡]	1.5 c	1.7 b	1.9 b	1.9 b	1.1 b	1.7 b	0.9 c
Low-P INC-12.5%	0.9 cd	1.5 c	1.9 b	2.2 b	2.0 b	1.1 b	2.6 b	1.7 bc
High-P INC-12.5%	0.6 d	1.2 c	1.7 b	2.0 b	1.8 b	1.0 b	1.9 b	2.0 b
Low-P INC-25%	0.9 cd	1.6 c	2.3 b	3.1 b	2.7 b	1.4 b	2.5 b	1.9 b
High-P INC-25%	0.9 cd	1.4 c	1.5 b	2.3 b	2.4 b	1.4 b	2.5 b	2.2 ab
Low-P SOD	5.3 a	7.5 a	6.0 a	6.8 a	5.4 a	4.2 a	5.6 a	1.7 bc
High-P SOD	4.1 b	5.7 b	5.9 a	6.6 a	5.4 a	4.1 a	5.0 a	3.1 a

† Runoff events occurred in 2004 unless otherwise noted.

‡ Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

Table A-16. Total depth and mass loss of total dissolved P (TDP), NO_3-N, and dissolved TKN in runoff totaled over eight rain events from 28 August 2004 to 1 April 2005. Treatments comprised High-P and Low-P sources of composted municipal biosolids incorporated (INC) at 12.5 and 25% by volume or top-dressed at 1.2-cm depth before harvest and transplanting of sod (SOD).

Treatment	Runoff	TDP	DRP	NO_3^--N	TKN
	mm	mg m^{-2}			
Control	70 a[†]	120 b	104 c	17 d	379 b
Low-P INC 12.5%	109 a	178 b	137 bc	34 bcd	486 b
High-P INC 12.5%	119 a	185 b	136 bc	63 ab	530 b
Low P INC 25%	107 a	220 b	141 bc	32 cd	518 b
High PINC 25%	117 a	222 b	127 bc	80 a	584 b
Low P SOD	98 a	536 a	267 ab	38 bcd	786 b
High P SOD	149 a	756 a	381 a	55 abc	1474 a

[†] Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

Table A-17. Total mass loss of sediment and sediment-bound TP and TKN in runoff totaled over eight rain events from 28 August 2004 to 1 April 2005. Treatments comprised High-P and Low-P sources of composted municipal biosolids incorporated (INC) at 12.5 and 25% by volume or top-dressed at 1.2-cm depth before harvest and transplanting of sod (SOD).

Treatment	Sediment		TP		TKN	
	g m^{-2}		——— mg m^{-2} ———			
Control	64	b[†]	94	b	291	b
Low-P INC 12.5%	242	a	209	b	452	b
High-P INC 12.5%	239	a	198	b	259	b
Low-P INC 25%	314	a	248	b	514	b
High-PINC 25%	185	ab	212	b	511	b
Low-P SOD	90	b	116	b	381	b
High-P SOD	91	b	422	a	1120	a

[†] Numbers followed by the same letters in columns are not significantly different according to Fisher's LSD means separation test (*P*=0.05).

APPENDIX B

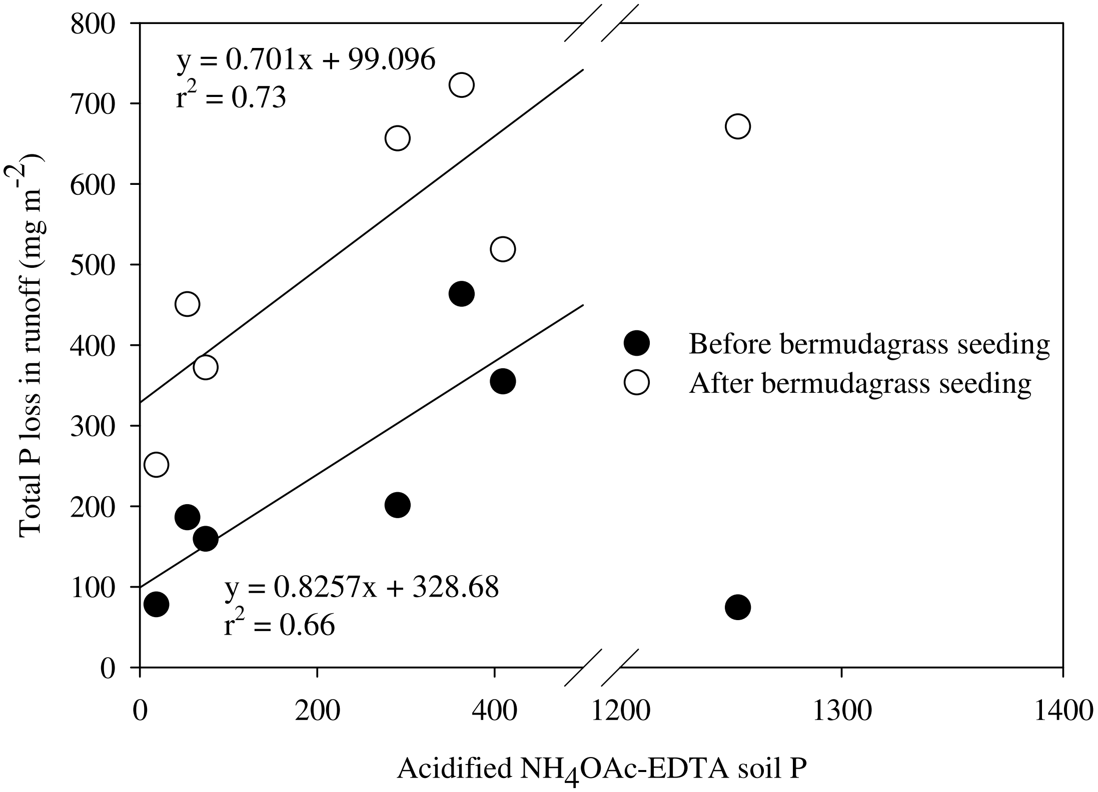

Fig. B-1. Total phosphorus (P) loss in runoff water plotted against acidified NH_4OAc-EDTA extractable P in roadside soils amended with composted dairy manure (CDM) on an 8.5% slope. The CDM was incorporated into soil (CMT), topdressed on grass (GUC), and surface applied in a woodchip mix (ECC) according to specification for amending roadside soils with compost.

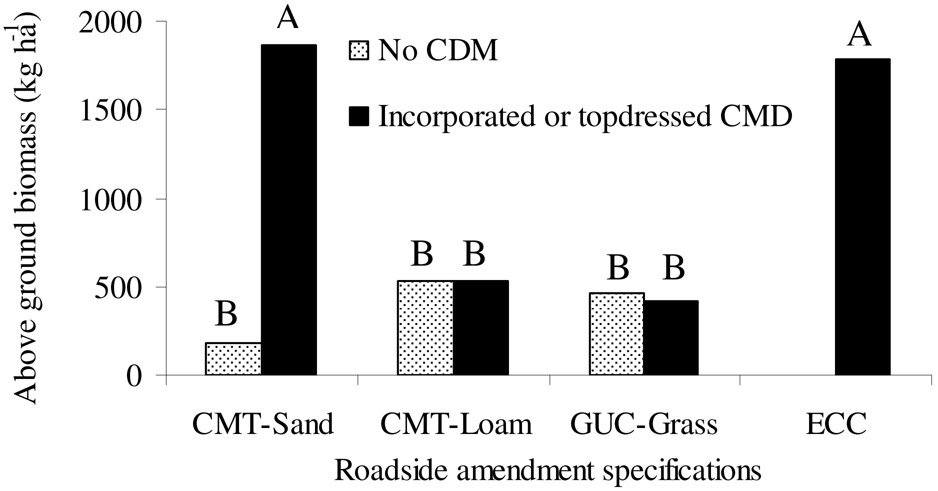

Fig. B-2. Bermudagrass clippings harvested between August and November 2002 on runoff plots amended by incorporating (CMT), topdressing over vegetation (GUC), and in a woodchip mix over bare soil (ECC) to meet specifications for amending soil with composted dairy manure (CDM).

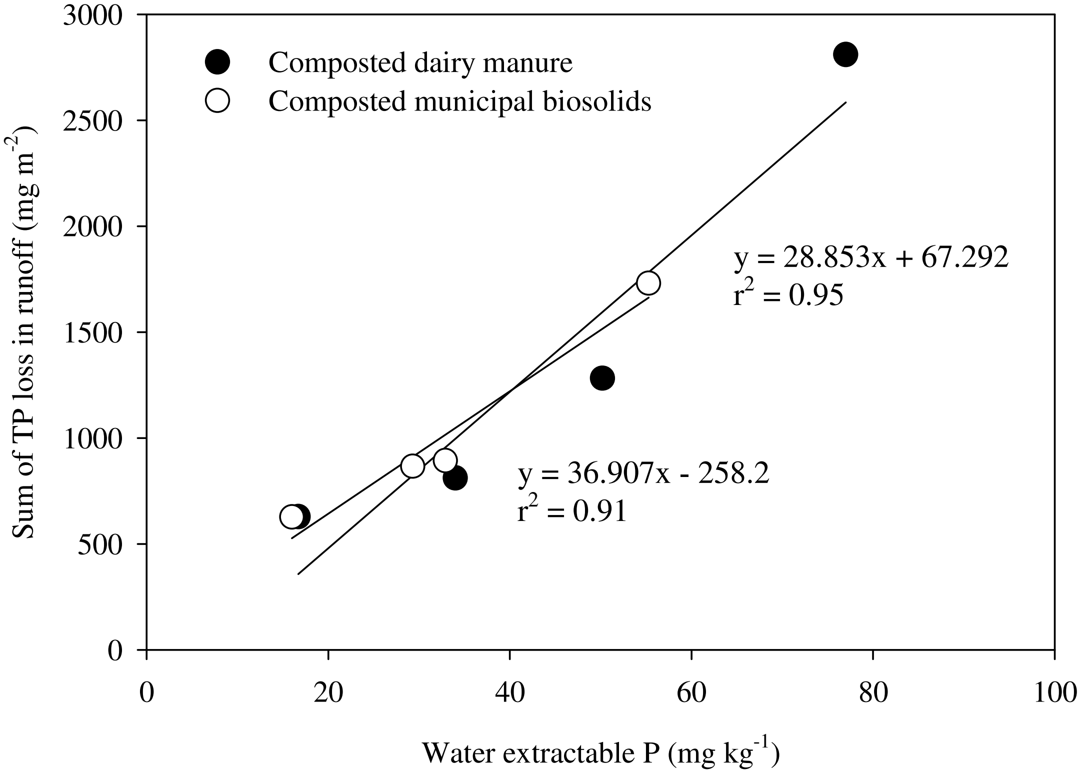

Fig. B-3. The sum of TP loss in dissolved and sediment fractions of runoff water over ten rain events compared to the concentration of water extractable P in the surface 0 to 5-cm layer of soil. Soil samples were taken after ten rain events in 2003 and represent roadside-soils amended with composted dairy manure and composted municipal biosolids according to TxDOT specifications.

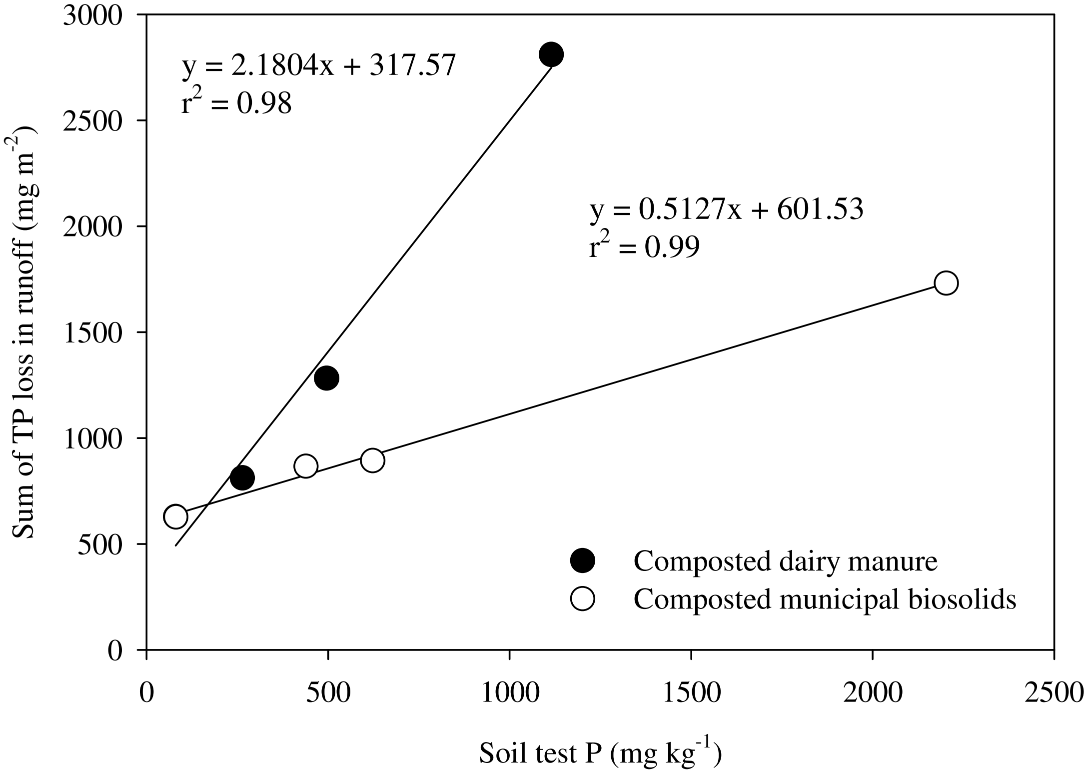

Fig. B-4. The sum of TP loss in dissolved and sediment fraction of runoff water over ten rain events compared to the concentration of acidified NH_4OAc-EDTA extractable soil P in the surface 0 to 5-cm layer of soil. Soil samples were taken after ten rain events in 2003 and represent roadside-soils amended with composted dairy manure and composted municipal biosolids according to TxDOT specifications.

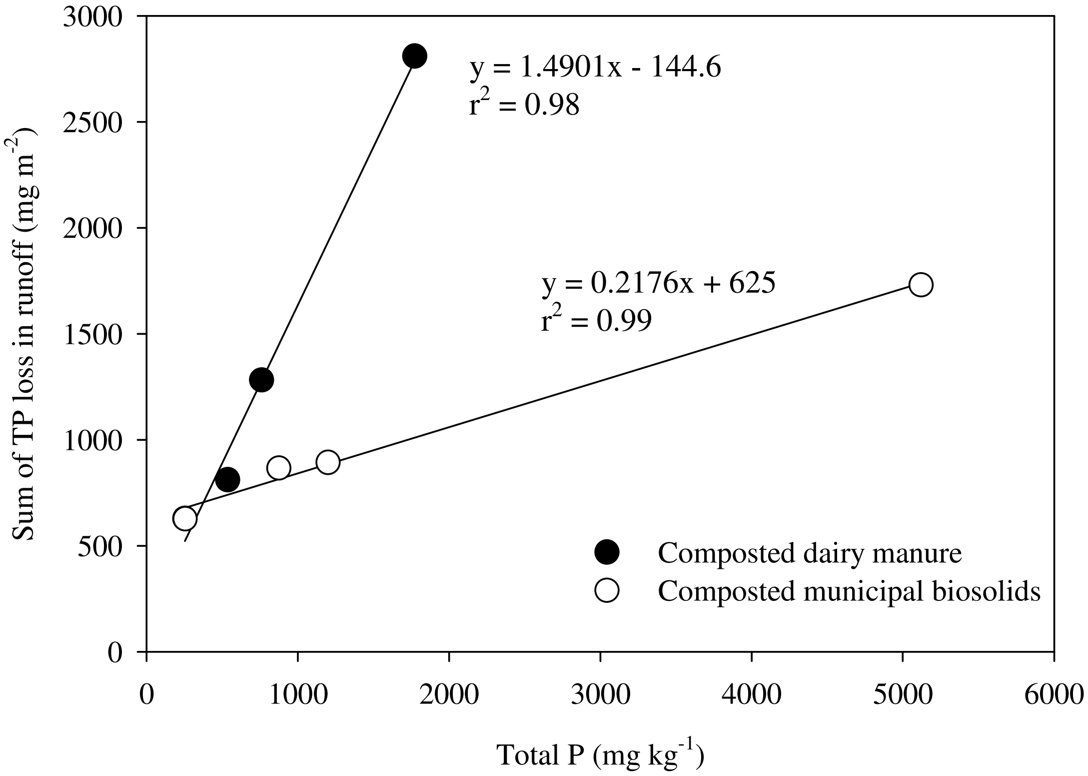

Fig. B-5. The sum of TP loss in dissolved and sediment fractions of runoff water over ten rain events compared to the concentration of digested soil P or total P in the surface 0 to 5-cm layer of soil. Soil samples were taken after ten rain events in 2003 and represent roadside-soils amended with composted dairy manure and composted municipal biosolids according to TxDOT specifications.

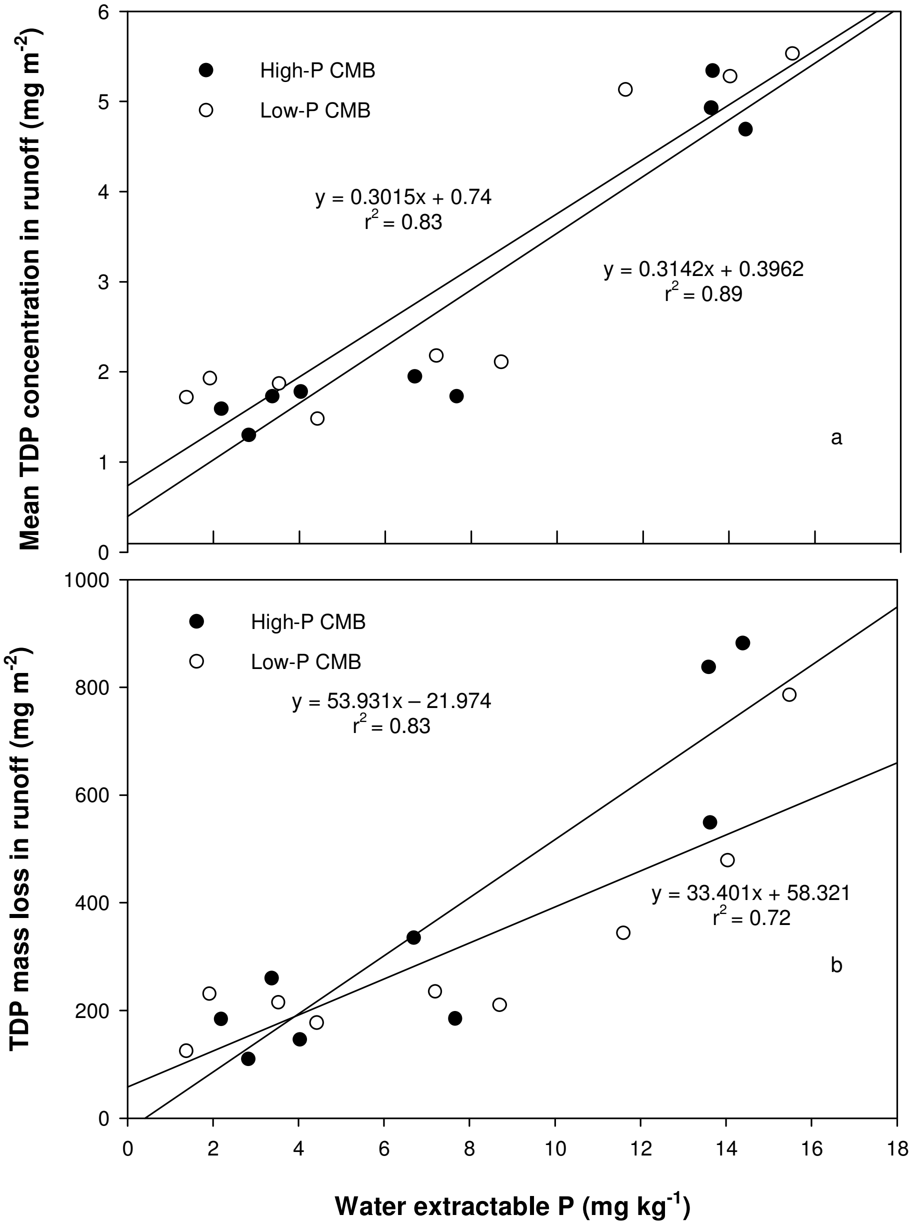

Fig. B-6. Mean concentration (a) and mass losses (b) of total dissolved P (TDP) in runoff water from eight rain events plotted against the water extractable P (WEP) concentration in the 0 to 5-cm soil depth. High-P and Low-P sources of composted municipal biosolids (CMB) were topdressed at a 1.2-cm depth before harvest and transplanting of sod or were incorporated at 12.5 and 25% by volume before sprigging of bermudagrass.

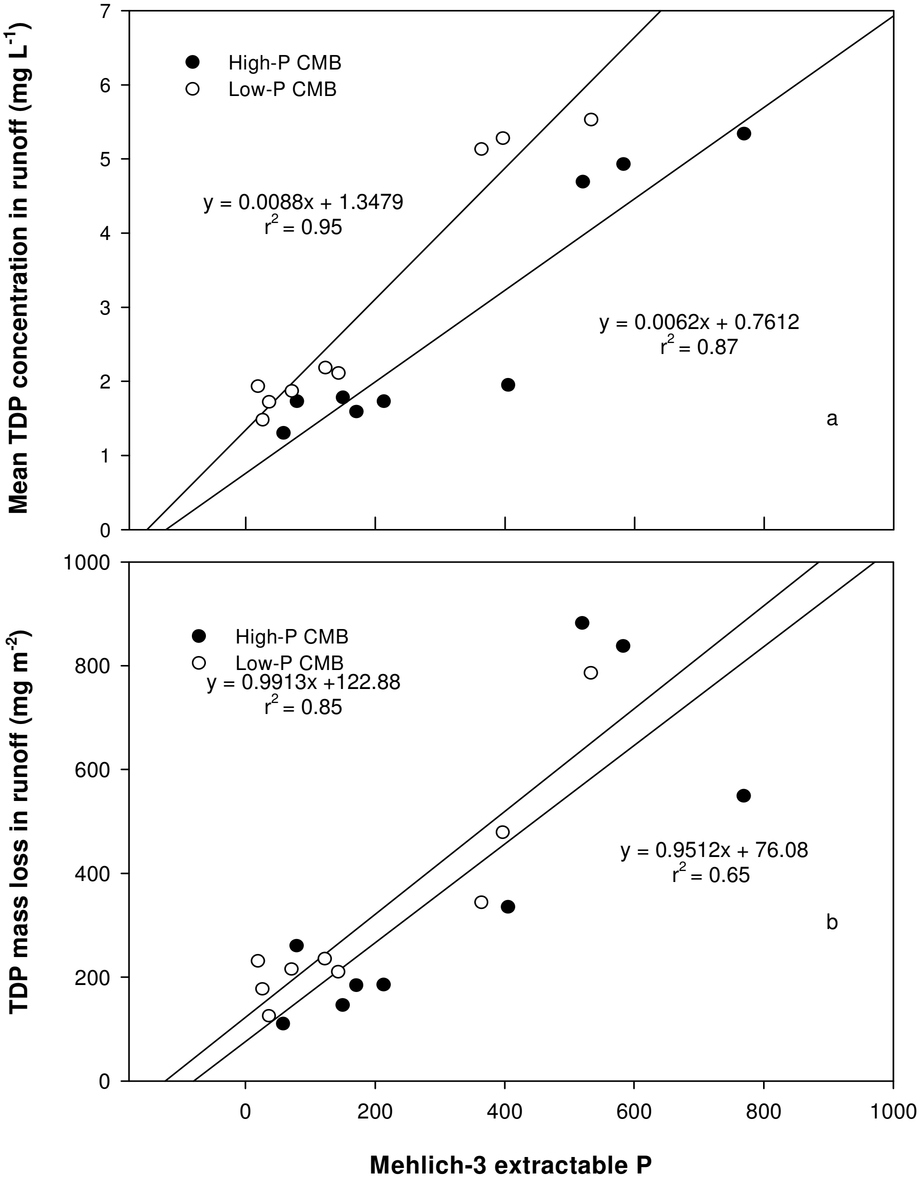

Fig. B-7. Mean concentration (a) and mass losses (b) of total dissolved P (TDP) in runoff water from eight rain events plotted against the soil-test P concentration (Mehlich-3) in the 0 to 5-cm soil depth. High-P and Low-P sources of composted municipal biosolids (CMB) were topdressed at a 1.2-cm depth before harvest and transplanting of sod or were incorporated at 12.5 and 25% by volume before sprigging of bermudagrass.

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Presentations

Hansen, N.E., D.M. Vietor, R.H. White, T.L. Provin, and C.L. Munster. 2005. Turfgrass sod production as a system for cycling composted municipal biosolids across urban and agricultural landscapes. Annual Southern Branch of American Society of Agronomy Meeting, San Antonio, TX.
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