Effect of Alum Treatments on Turfgrass Coverage and Runoff Losses during Establishment

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Abstract. Incorporation or top-dressing of composted biosolids (CB) can enhance turfgrass establishment and sod properties at harvest, but soil phosphorus (P) and nitrogen must be managed to protect water quality. Alum treatment of CB could reduce soluble P concentrations in amended soil and limit runoff loss of P. The objective was to evaluate CB and Alum effects on turfgrass coverage of soil and runoff losses during 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. var. dactylon × *C. transvaalensis* Burtt-Davey] establishment from sprigs or transplanted sod. Three replications of eight treatments comprised a complete randomized design. Four treatments were composed of 'Tifway' sprigged in soil with and without incorporation of CB and Alum. Four remaining treatments were sods harvested from 'Tifway' grown with and without top-dressed CB that were transplanted with and without a surface spray of Alum. Surface coverage of 'Tifway' sprigged in soil mixed with inorganic fertilizer or CB was comparable to transplanted sod 25 days after planting. In contrast, Alum incorporation acidulated soil, slowed coverage rates of sprigged 'Tifway', and increased NH_4-N runoff loss during early establishment in treatments without CB. Incorporation of Alum with CB or inorganic fertilizer in soil before sprigging reduced soil water-extractable P (WEP) more than 38% and reduced runoff loss of soluble reactive P (SRP) in three of four establishment treatments. Although SRP runoff loss from CB-amended sod was greatest among treatments, the Alum spray minimized SRP loss after transplanting. Alum effectively reduced runoff loss of SRP from CB, soil, and turfgrass sources during establishment from sprigs or sod. Additional field research is needed, but incorporated or surface sprays of Alum offer a potential new practice for mitigating runoff loss of SRP from establishing turfgrass.

Topdressing or incorporation of large, volume-based rates of composted biosolids (CB) can increase storage of soil organic carbon (SOC), supply essential mineral nutrients, and enhance turfgrass coverage during sod establishment and regrowth (Wright et al., 2005). Greater concentrations of soil total nitrogen (N) and phosphorus (P) and of soil-test P and potassium (K) were associated with greater SOC storage after transplanting CB-amended compared with fertilizer-grown 'Tifway' sod (Dai et al., 2009). The authors hypothesized greater soil-test concentrations of P and K in CB-amended sod could have increased turfgrass growth and contributions to the dissolved fraction of SOC.

Previous reports of turfgrass responses to CB applied before sprigging, seeding, or regrowth supported the hypothesis that both sod growth and quality could be improved.

Incorporation of 25% by volume of CB before sprigging increased 'Tifway' bermudagrass coverage 64% after 2 weeks and 23% after 8 weeks compared with soil without CB (Schnell et al., 2009). Similarly, incorporation of a 1.3-cm layer of CB within a 10- to 15-cm depth of excavated soil enhanced visual assessments of percent cover and clipping yields of seeded cool-season turfgrasses (Loschinkohl and Boehm, 2001). Top-dressing of dried biosolids at rates up to 100 Mg·ha^{−1} during regrowth of a tropical grass, kikuyu (*Pennisetum clandestinum* Hochst. Ex Chiov.), achieved higher than acceptable color ratings (Tesfamariam et al., 2009). In addition, top-dressing of the biosolids at rates up to 33 Mg·ha^{−1} enhanced kikuyu vigor and reduced soil removal and breakage in harvested sod compared with sod without biosolids. Similarly, incorporation of 25% by volume of CB before sprigging of 'Tifway' bermudagrass reduced wet sod weight 19%, dry sod weight 34%, and soil removal in harvested sod (Schnell et al., 2009).

In addition to enhancing sod establishment and properties, CB amendments can benefit established turfgrass and transplanted sod. Top-dressing of composted manure at rates up to 99 m³·ha^{−1} on established cool-season turfgrass increased clipping yields during midsummer, green color retention during fall, and green-up rate in spring compared with controls receiving inorganic N (Johnson et al., 2006a). Similarly, top-dressings during spring on golf course fairways enhanced cool-season turfgrass growth, color ratings, and foliar N concentrations for 50 d or more (Garling and Boehm, 2001). The effects of top-dressed compost on turf color, foliar N content, and growth were attributed to N and other nutrients applied in large, volume-based rates (Garling and Boehm, 2001; Johnson et al., 2006a; Tesfamariam et al., 2009). Moreover, the nutrients and SOC removed with sod harvested from turfgrass grown with CB could reduce inorganic fertilizer requirements and enhance water retention during establishment of the transplanted sod (Schnell et al., 2009; Vietor et al., 2002, 2004).

Although beneficial to soil and sod properties, large, volume-based rates could contribute to nonpoint source losses of dissolved mineral nutrients in runoff during production and after transplanting of sod. Under field conditions, runoff loss of total dissolved P (TDP) from 'Tifway' bermudagrass planted as sprigs or sod, with or without CB or manure, was directly related to soil-test P and water-extractable P (WEP) concentrations in soil (Hansen et al., 2007; Vietor et al., 2004). In addition, runoff loss of TDP and soluble reactive P (SRP) on the 8.5% slope was greater for the sod transplanted from 'Tifway' top-dressed with a volume-based CB rate (1.3-cm depth) than turfgrass grown without CB (Hansen et al., 2007). Similarly, top-dressing of composted manure at rates up to 99 m³·ha^{−1} on a 1% to 2% slope of bluegrass (*Poa pratensis* L.) increased NH_4-N loss in runoff (Johnson et al., 2006b). In contrast, runoff loss of total N and P or dissolved and inorganic P concentrations in runoff of simulated rain were similar between bluegrass top-dressed with the 99-m³ rate and controls. Volume-based CB rates could be reduced to decrease soil concentrations and nonpoint source losses of P and N after transplanting of sod or sprigging. Yet, value-added benefits of CB to turfgrass coverage rates and sod properties will be compromised. Management practices are needed to reduce solubility and potential transport of dissolved nutrients in runoff and drainage from CB-amended soil and sod.

Treatment with lime and/or metal salts during the CB production process provides one option for lowering soluble P in CB and amended soils (Penn and Sims, 2002). If CB is derived from solids recovered from biological treatment of wastewater, the metal salts could be incorporated before application of CB to soil. Previous laboratory studies indicated aluminum sulfate (Alum) incorporated in biologically derived biosolids at an Al:P molar ratio near one minimized WEP concentration (Huang and Shenker, 2004). Alum effects on WEP of CB and turfgrass

biomass were similarly evaluated in mixtures through laboratory incubations (Vietor et al., 2009). Alum rates ranging from 0 to 0.15 g·g^{-1} sample were dissolved in water before mixing with CB or clippings and incubation for 24 h. Compared with controls without Alum, water-extractable P concentration was reduced most (99% for CB and 53% for clippings) at a rate of 0.1 g Alum/g CB or clippings. The Al^{+3} derived from Alum amendments can be a growth-limiting factor in acidic soils, but field studies of cool-season forage grasses indicated Alum treatment of top-dressed poultry litter did not affect yield (Moore and Edwards, 2005). Although not previously evaluated for turfgrass, Alum could be mixed with CB before topdressing or incorporation in soil for sod establish ment (Moore et al., 2000). Another option is spraying or top-dressing of Alum on CB-amended sod. Surface application of Alum to sod or established turfgrass could reduce P solubility and runoff loss from both CB and turfgrass sources. Yet, effects on turfgrass growth and P solubility and transport need to be evaluated during turf establishment from sod or sprigs.

The objective was to evaluate CB and Alum effects on turfgrass coverage of soil and runoff losses of water, sediment, and dissolved P and N during establishment of 'Tifway' bermudagrass through transplanting of sod or sprigging. In addition, relationships between soil and runoff concentrations of N and P were analyzed.

Materials and Methods

Design and sampling. Three replications of eight establishment treatments were installed on surface-soil collected from a Boonville fine sandy loam (fine smectitic thermic Vertic Albaqualf) (83% sand, 11% silt, and 6% clay). Soil was packed within 5-cm depth increments in box lysimeters (44 cm length × 33 cm width × 15 cm depth), which were randomly assigned to locations on a greenhouse bench. Greenhouse photosynthetic photon flux densities ranged up to 1000 µmol·m^{-2}·s^{-1} and mean hourly temperatures ranged from 21 to 32 °C during the period of study. Mehlich-3 soil test concentrations before treatment were 13 mg·kg^{-1} for NO$_3$-N, 11 mg·kg^{-1} for P, and 63 mg·kg^{-1} for K. Four treatments comprised 'Tifway' sprigged in the soil with and without incorporation of CB (Table 1). Before planting of 1.9 kg fresh sprigs/m^2, one volume of CB was mixed with three volumes of soil (0.25 m^3·m^{-3}) with or without incorporation of a solution that provided 0.1 g Alum (1 g Al/kg Alum) per gram of dry CB in soil. The CB (Dillo Dirt), obtained from the City of Austin in September, was applied at 12.5 kg·m^{-2}. Total nutrient concentration in CB was 24 g·kg^{-1} for N, 12.7 g·kg^{-1} for P, and 7 g·kg^{-1} for K.

For 'Tifway' sprigged in soil without CB, a solution of super triple P (0–46–0) fertilizer, which provided 5 g P/m^2 with or without Alum, was incorporated in soil. The Al mass available from Alum in solution equaled the sum of soil-test P in the lysimeter and the applied rate of inorganic fertilizer P in solution. In addition to fertilizer P, 10 g·m^{-2} of K was applied as potash (0–0–60) to the 'Tifway' sprigged without CB. In four remaining treatments, a 2-yr-old regrowth of 'Tifway' sod was cut at the 2.5-cm depth of a sandy loam soil on an exposed E$_g$ horizon of a truncated Boonville fine sandy loam (Schnell et al., 2009) and transplanted on lysimeters. The sod was produced with and without a topdressing of CB (1.5 kg dry Dillo Dirt/m^2) at the start of the growing season in April 2008 and was irrigated with groundwater (pH = 9.2). The transplanted sod was established in lysimeters with and without a surface application of Alum solution (0.5 L) (Table 1). The Alum rate sprayed on 'Tifway' sod was based on the sum of the CB (1.5 kg·m^{-2}) top-dressed in April and biomass returned in clippings (0.5 kg·m^{-2}) during repeated mowing to a 4-cm height in the 2008 growing season. Similar to sprigged treatments, the Alum rate was 0.1 g·g^{-1} top-dressed CB plus clippings. Total nutrient concentration in the CB collected for top-dressing in April was 18 g·kg^{-1} for N, 4 g·kg^{-1} for P, and 7 g·kg^{-1} for K. In addition, the harvested sod layer was sampled before transplanting and total and soil-test N and P concentrations were analyzed after soil was washed from turfgrass and the soil plus wash solution was dried at 60 °C. Mean total soil nutrient concentration in sod transplanted from turf top-dressed with CB was 4058 mg·kg^{-1} for N, 1760 mg·kg^{-1} for P, and 685 mg·kg^{-1} for K. All eight lysimeter treatments received 25 kg·ha^{-1} of fertilizer N as ammonium sulfate (21–0–0) 6 d after planting. Lysimeters were irrigated by hand to balance evapotranspiration losses under greenhouse conditions. Daily irrigation with filtered water comprised 300 mL (2.1 mm) for sprigged 'Tifway' and 500 mL (3.4 mm) for transplanted sod during the first 7 d after planting and was 3.4 mm·d^{-1} for all treatments thereafter.

ImageJ analysis of digital photographs of lysimeter surfaces was used to quantify 'Tifway' coverage of soil during establishment as described previously (Schnell et al., 2009). ImageJ software was downloaded from the National Institutes of Health (http://rsbweb.nih.gov/ij/download.html). Lysimeter surfaces were photographed from a 50-cm height at 18, 25, and 32 d after sprigging. Shadows within photographs of the dense tiller population of sods reduced green turf estimates below 100%, but coverage was complete and similar (P = 0.001) among sodded treatments on each sampling date. Turfgrass was cut at the soil surface of lysimeters after the second rain event and clippings were dried, weighed, and analyzed. After turfgrass was clipped, five 2-cm diameter soil cores were removed from 0- to 5-cm and 5- to 15-cm depths of each lysimeter. Cores from each lysimeter were composited within depths, dried, and ground for analysis of total and extractable N and P forms. For the analysis of soil WEP within the 0- to 5-cm depth, 1 g soil was extracted in 10 mL distilled water while shaking for 1 h and filtered (less than 0.45 µm).

Simulated rain (10 cm·h^{-1}) was applied through an oscillating, indoor, multiple-intensity rainfall simulator at 20 and 37 d after planting of sod or sprigs on box lysimeters (Birt et al., 2007). Lysimeters were positioned on a metal frame beneath the rainfall simulator to impose a soil-surface slope of 15%. The runoff volume from each lysimeter was collected from a flume attached to the downslope lysimeter wall, measured, and sampled after each of three consecutive 8-min intervals during each simulated rain event. Samples were refrigerated after collection and filtered (less than 0.45 µm) within 12 h for analysis. Sediment collected during filtration of runoff samples was dried and weighed. Concentrations of dissolved N and P forms in filtrate were analyzed and the product of runoff volume and concentration was used to compute mass losses.

Runoff, soil, composted biosolids, and turfgrass analysis. A microwell plate reader or inductively coupled plasma optical emission spectroscopy (ICP) was used to measure concentrations of soluble N or P forms in filtrate of runoff and extracts of soil. A colorimetric assay was used to measure filtrate concentrations of SRP, which included inorganic P, on the plate reader (Lopez and Vargas-Albores, 2003; Pote and Daniel, 2000). As the operational definition of SRP implies, this soluble P fraction was expected to be more available to biota, including algae

Table 1. Mean yield of clippings and nutrient uptake of turfgrass and pH, Mehlich-3 P (STP), water-extractable P (WEP), and NO$_3$-N in soil sampled from the 5-cm depth for 'Tifway' bermudagrass established through sprigging (Sp) or transplanted sod (Sd) in box lysimeters.[z]

Abbrev.	Yield	Turf TN	Turf TP	pH	STP	Soil WEP	Soil NO$_3$-N
	(g·m^{-2})				(mg·kg^{-1})		
SpIF	136 b[y]	5.6 b	0.5 c	7.2 c	23 c	2.5 de	2.0 a
SpIF-Al	71 b	2.4 c	0.2 d	4.1 e	40 c	0.5 e	1.7 a
SpCB	145 b	6.4 b	0.7 bc	7.8 b	318 a	6.7 ab	2.3 a
SpCB-Al	154 b	6.7 b	0.7 bc	7.6 bc	347 a	4.1 cd	1.7 a
SdIF	481 a	9.8 a	0.8 b	8.5 a	23 c	6.7 ab	2.3 a
SdIF-Al	481 a	9.5 a	0.7 bc	6.2 d	20 c	0.9 e	2.7 a
SdCB	425 a	10.1 a	1.3 a	8.5 a	311 a	8.1 a	1.7 a
SdCB-Al	429 a	9.3 a	1.1 a	8.1 ab	234 b	5.0 bc	2.3 a
P	0.001	0.001	0.001	0.001	0.001	0.001	NS

[z]'Tifway' was established with inorganic fertilizer (IF) or composted biosolid (CB) with or without Alum (Al).
[y]Means followed by the same letter within columns were not significantly different (P = 0.05).
NS = nonsignificant.

in surface waters, than organic and sediment-bound forms of P (Haygarth and Sharpley, 2000). Similarly, SRP was available for chemical reactions in soil and water, including precipitation with hydrolysis products of Alum after surface application on 'Tifway' sod or mixing with CB or soil.

The Texas AgriLife Extension's Soil, Water, and Forage Testing Laboratory analyzed N and P in soil, turfgrass, CB, and runoff filtrate. An Elementar VarioMAX analyzer (Hanau, Germany) was used to quantify total N in soil, CB, and turfgrass. Nitric acid digestion prepared soil, CB, and plant samples for ICP analysis of total P and K (Havlin and Soltanpour, 1989). In addition, the ICP was used to quantify P in Mehlich-3 extracts of soil (Mehlich, 1984). Soil NO_3-N was extracted as described by Keeney and Nelson (1982) and measured through cadmium reduction (Dorich and Nelson, 1984). For TDP measurements, runoff filtrate was digested (Parkinson and Allen, 1975) before ICP analysis. Soluble unreactive P (SURP) in filtrate was computed as the difference between TDP and SRP concentrations. Although the SURP contributed to runoff loss of dissolved P, organic P forms in this fraction were expected to be less reactive with Alum than SRP (Haygarth and Sharpley, 2000). For soluble N analysis of runoff filtrate on the plate reader, reduction with Devarda's alloy was used to quantify NO_3-N concentration and NH_4-N was measured colorimetrically (Sims et al., 1995).

Statistical analysis. Analysis of variance (ANOVA) was used to evaluate effects of time of rain event, sampling interval within each event, and establishment treatments with and without CB and Alum on soil, turfgrass, and runoff variables. The ANOVA was conducted separately for each rain event to accommodate interactions between treatments and rain events. Variables were averaged over the three sampling intervals within each rain event if interactions with treatments were not significant or if rankings among treatments were similar among intervals. Fisher's least significant difference test ($P = 0.05$) was used to compare means among sampling intervals and establishment treatments (SAS Institute Inc., 2000). Regression analysis was used to evaluate relationships among variation of soil and runoff concentrations of P.

Results and Discussion

Turfgrass coverage of soil. Compared with mean percent soil coverage for transplanted sods, which was similar ($P = 0.05$) among treatments with and without CB, mean percent cover of the sprigged 'Tifway' was lower ($P = 0.001$) 18 d after planting (Fig. 1). In addition, percent coverage of 'Tifway' sprigged in soil amended with Alum and inorganic fertilizer was less ($P = 0.001$) than that in sprigged treatments with CB or fertilized soil without Alum. Over the next 7 d, percent cover of sprigged treatments with CB or with inorganic fertilizer but no Alum increased to achieve coverage of soil comparable to that of transplanted sod. In

contrast, percent cover remained 39% lower ($P = 0.001$) for the sprigged treatment amended with inorganic fertilizer and Alum. At 32 d after planting, percent cover of the 'Tifway' sprigged in soil with inorganic fertilizer and Alum remained 15% lower ($P = 0.01$) than cover of transplanted sod and 11% lower than cover on sprigged treatments without Alum (Fig. 1).

Variation of dry weight of clippings collected 38 d after planting reflected the variation of percent cover among treatments at 32 d. Mean clipping yield for soil amended with inorganic fertilizer and Alum was 84% less than that of transplanted sod (Table 1). Although not statistically different ($P = 0.05$), mean yield was 48% less for 'Tifway' sprigged in soil with than without Alum. Analysis of clippings of 'Tifway' sprigged in soil amended with inorganic fertilizer, with or without Alum, indicated N uptake was 57% lower ($P = 0.001$) and P uptake was 60% lower ($P = 0.001$) with Alum (Table 1).

The potentially detrimental effects of Alum after hydrolysis to aluminum oxides $[Al(OH)_3]$ included acidulation of soil in sprigged and sodded treatments (Table 1). For sprigged 'Tifway' without CB, reduced soil pH was associated with the slower rates

of coverage and lower nutrient content of 'Tifway' on soil with than without Alum (Fig. 1; Table 1). The Alum hydrolysis products in soil could have inhibited 'Tifway' root growth directly in addition to forming insoluble precipitates with P forms in soil (Tisdale et al., 1993). Moreover, Al^{+3} could have replaced exchangeable H^+ and other cations on soil colloids, which further reduced soil pH. Mixing the Alum with CB reduced soil WEP compared with CB mixed in soil without Alum, but the CB limited detrimental Alum effects on soil pH and 'Tifway' coverage rate, clipping yield, and N and P uptake in sprigged treatments (Fig. 1; Table 1). Increases in soil organic carbon, which were the result of top-dressed or incorporated CB in this study, could have contributed to increased chelation of cations, including Al^{+3}, and buffering of soil pH changes (Tisdale et al., 1993).

Sediment loss. Mean runoff volume (12 $L·m^{-2}$ or 1.2-cm depth) for each of the three sampling intervals was similar ($P = 0.05$) among treatments. In contrast, mean sediment loss from transplanted sod treatments was less ($P = 0.01$) than loss from 'Tifway' sprigged in soil without CB during both rain events (Table 2). Sediment loss was
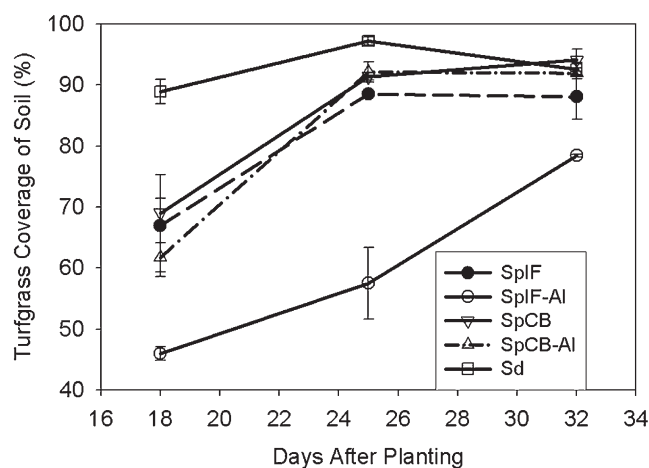

Fig. 1. Percent soil coverage of transplanted 'Tifway' bermudagrass sod (Sd) and Tifway sprigged (Sp) in soil amended with inorganic fertilizer (IF) or composted biosolids (CB) with and without Alum (Al). Error bars represent SE of means.

Table 2. Mean runoff loss of sediment, NO_3-N, and NH_4-N during application of simulated rain (10 $cm·hr^{-1}$) to box lysimeters over three 8-min sampling intervals at 20 d (Rain 1) and 37 d (Rain 2) after planting of 'Tifway' bermudagrass.[z]

Treatment	Sediment		NO_3-N		NH_4-N	
	Rain 1	Rain 2	Rain 1	Rain 2	Rain 1	Rain 2
	($g·m^{-2}$)		($mg·m^{-2}$)			
SpIF	670 a[y]	62 b	14.0 bc	4.9 b	6.2 bc	0.2 c
SpIF-Al	340 b	82 a	33.7 a	13.0 a	31.4 a	8.0 a
SpCB	20 c	1 c	17.6 bc	1.6 b	0.9 c	0.1 c
SpCB-Al	37 c	2 c	20.2 b	2.8 b	0.9 c	0.0 c
SdIF	1 c	0 c	9.2 d	5.2 b	1.0 c	1.8 bc
SdIF-Al	1 c	11 c	13.2 bcd	5.7 b	9.7 b	4.9 ab
SdCB	22 c	1 c	5.0 d	6.5 b	0.6 c	2.0 bc
SdCB-Al	1 c	0 c	10.0 cd	6.6 b	6.7 bc	4.8 b
P	0.001	0.01	0.01	0.02	0.001	0.01

[z]'Tifway' was sprigged (Sp) or transplanted as sod (Sd) with and without composted biosolid (CB) and Alum (Al).
[y]Numbers followed by the same letter within columns are not significantly different ($P = 0.05$).

greater ($P = 0.001$) during the first than third sampling interval for the first rain event, but losses for sprigged 'Tifway' without CB were consistently greater ($P = 0.01$) than the other six treatments for all three sampling intervals during each rain event. The greater sediment loss from sprigged 'Tifway' without CB at 20 d reflected differences in percent turfgrass cover among treatments 18 d after planting (Fig. 1; Table 2). From 20 to 37 d after planting, increasing turfgrass coverage could have contributed to reduced ($P = 0.001$) sediment loss for the sprigged 'Tifway' without CB. Yet, incorporation of the volume-based rate of CB before sprigging achieved greater reductions in runoff loss of sediment during the first rain event than the increases in turfgrass coverage between rain events (Table 2; Fig. 1). Previous field studies over eight natural rain events indicated sediment loss was comparable between 'Tifway' sprigged in soil mixed with 25% CB and sod transplanted from 'Tifway' top-dressed with a volume-based rate of CB (Hansen et al., 2007). Although sediment loss under the natural rain events was similar between sprigged and sodded 'Tifway' amended with CB, TDP concentration in runoff was greater for the CB-amended sod.

Soluble reactive phosphorus loss. Similar to observations under natural rainfall (Hansen et al., 2007), mean runoff loss of SRP over three sampling intervals was greater ($P = 0.01$) for CB-amended sod than all other establishment treatments during each simulated rain event (Fig. 2). As reported for manure top-dressed on sprigged versus sodded 'Tifway', CB rates could have been reduced to limit runoff loss of soluble P forms (Vietor et al., 2004). An upper limit of total manure P equal to 190 kg·ha⁻¹ constrained TDP loss in runoff to amounts comparable to sod grown with recommended rates of inorganic P. Although CB rates could similarly be reduced to limit SRP runoff loss after sod is transplanted, the P-based rate would not provide sufficient organic matter to benefit sod physical properties, quality, and establishment (Johnson et al., 2006b; Schnell et al., 2009).

In the present study, the surface spray of Alum effectively prevented runoff loss of SRP during both rain events after sod was transplanted from 'Tifway' top-dressed with CB (Fig. 2). During the second rain event, the Alum spray reduced ($P = 0.001$) SRP runoff loss for sod transplanted from 'Tifway' grown with inorganic fertilizer (Fig. 2). The Alum effect on SRP loss from fertilizer-grown sod indicated the rate applied in the surface spray was sufficient to react with P leached from plant residues (Roberson et al., 2007) as well as soil P sources. These results for transplanted sod indicate a surface spray of Alum will prevent SRP runoff loss from soil, CB, and plant sources of P in transplanted sod and established turf of 'Tifway' bermudagrass.

For sprigged 'Tifway', incorporation of Alum with inorganic fertilizer or with the volume-based CB rate in soil reduced ($P = 0.01$) mean mass loss of SRP in runoff over

sampling intervals of the first simulated rain event (Fig. 2). Although the Alum effect was less pronounced for 'Tifway' sprigged in soil mixed with P fertilizer during the second rain event, Alum did reduce ($P = 0.001$) SRP loss from CB incorporated in soil during the second event. Alum was typically incorporated with manure, CB, or soil in previous efforts to limit SRP runoff loss. Similar to the present study, incorporation of Alum with compost before application to soil reduced soluble P concentrations in runoff as much as 84% (DeLaune et al., 2006). In addition, Alum incorporation with annual poultry litter applications reduced soil WEP compared with litter applied without Alum on tall fescue (*Festuca arundinaceae* Schreb.) (Moore and Edwards, 2007). In the present study, Alum incorporated with CB or sprayed on transplanted sod with or without CB similarly reduced soil WEP concentration within the 0- to 5-cm depth after the second rain event (Table 1).

Although the surface spray of Alum reduced ($P = 0.001$) Mehlich-3 P of soil within

the 0- to 5-cm depth of sod amended with CB, surface sprays or incorporated Alum did not affect soil-test P of other treatments. Over 7 years of application on tall fescue, Alum incorporation with poultry litter reduced soil WEP compared with litter applied without Alum but did not reduce Mehlich-3 P (Moore and Edwards, 2007). Similarly, Alum incorporated (1.4 Mg Alum/ha) to mitigate high soil-test P concentrations in a fine sandy loam did not reduce either WEP or Bray-1 P concentrations at a field site near College Station, TX (Brauer et al., 2005). In the present study, Alum effectively reduced runoff loss of SRP from CB at the rates that were incorporated before sprigging or sprayed after transplanting of 'Tifway' sod.

Soluble unreactive phosphorus loss. During the initial rain event, mean SURP loss for the three sampling intervals was similar ($P = 0.05$) among establishment treatments and was unaffected by incorporation or surface sprays of Alum (Fig. 3). The SURP could have comprised organic P and soluble polyphosphates (Haygarth and Sharpley, 2000),
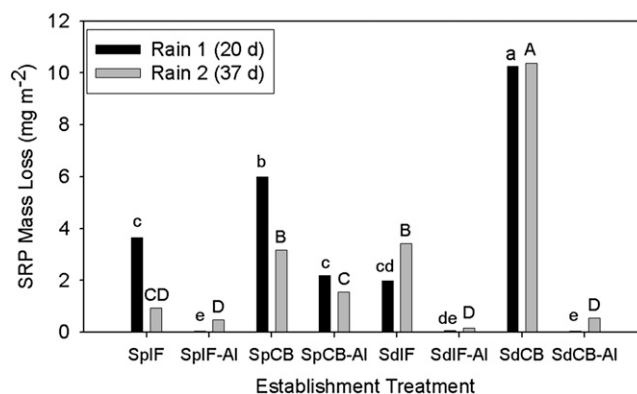

Fig. 2. Mean runoff loss of soluble reactive phosphorus (SRP) during establishment of 'Tifway' bermudagrass as sprigs (Sp) or transplanted sod (Sd). Runoff was sampled and analyzed during three consecutive 8-min intervals of simulated rain at 20 and 37 d after planting. Sprigs were planted in soil mixed with inorganic fertilizer (IF) or composted biosolids (CB) with or without Alum (Al). 'Tifway' sod grown with or without CB was established with and without a surface spray of Al solution. Bars labeled with the same lower case or capital letter were not different ($P = 0.05$) for the respective rain events.
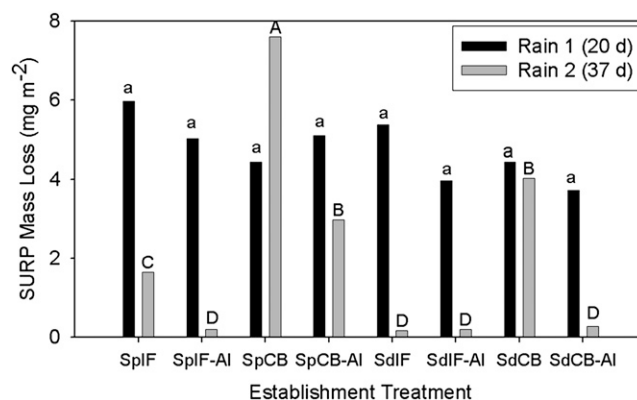

Fig. 3. Mean runoff loss of soluble unreactive phosphorus (SURP) during establishment of 'Tifway' bermudagrass as sprigs (Sp) or transplanted sod (Sd). Runoff was sampled and analyzed during three consecutive 8-min intervals of simulated rain at 20 and 37 d after planting. Sprigs were planted in soil mixed with inorganic fertilizer (IF) or composted biosolids (CB) with or without Alum (Al). 'Tifway' sod grown with or without CB was established with and without a surface spray of Al solution. Bars labeled with the same lower case or capital letter were not different ($P = 0.05$) for the respective rain events.

both of which were expected to be less reactive than SRP with products of Alum hydrolysis in soil (Tisdale et al., 1993). During the second rain event, SURP was greater ($P = 0.001$) for sprigged or sodded treatments with than without CB (Fig. 3). Low runoff loss of SURP for sod grown with inorganic fertilizer indicated 'Tifway' biomass was a negligible source during the second rain event. In contrast, both soil and CB could have been sources of SURP in runoff loss from sprigged 'Tifway' during the second rain event. In addition, Alum incorporation in CB and soil or the surface spray on CB-amended sod reduced SURP loss during rain Event 2 compared with respective treatments without Alum (Fig. 3). Variation of Alum effects on SURP between rain events was associated with the higher ($P = 0.001$) mean total soil P concentrations with (739 mg·kg⁻¹) than without (105 mg·kg⁻¹) CB. Mean Mehlich-3 P concentrations were similarly greater with than without CB. Although the chemical forms of SURP in runoff from CB-amended treatments was not characterized during the second rain event, reductions resulting from Alum treatment indicated the forms differed from that in runoff of the initial rain event (Fig. 3).

NO₃-N and NH₄-N loss. Over the three sampling intervals of both simulated rain events, mean mass loss of NO₃-N in runoff was greater ($P = 0.02$) for 'Tifway' sprigged in soil amended with inorganic fertilizer and Alum than the other treatments (Table 2). During the initial rain event, mass loss of NO₃-N from sprigged 'Tifway' with or without CB and Alum was greater ($P = 0.01$) than sod transplanted from 'Tifway' grown with inorganic fertilizer or CB. Compared with other sprigged treatments, lower percent cover, yield, and N uptake of turfgrass on soil amended with fertilizer and Alum could have increased the proportions of NO₃-N lost in runoff (Fig. 1; Table 2). These observations for 'Tifway' are consistent with runoff losses reported for cool-season turfgrass. Over a 2-year period after seeding, runoff loss of NO₃-N from the cool-season turfgrass was reduced as shoot density increased (Easton and Petrovic, 2004). During the second rain event in the present study, both turfgrass coverage and runoff loss of NO₃-N were similar between transplanted sod and 'Tifway' sprigged in soil with CB or without Alum (Fig. 1; Table 2). The differences in NO₃-N runoff loss occurred despite similar NO₃-N concentrations within soil samples removed from the 0- to 5-cm depth after the second rain event (Table 1).

Variation of turfgrass coverage was associated with greater ($P = 0.001$) NH₄-N loss for 'Tifway' sprigged in soil amended with fertilizer and Alum than other treatments (Table 2), but other factors contributed to treatment differences (Easton and Petrovic, 2004). Alum reduced soil pH in sprigged or sodded 'Tifway' without CB compared with other treatments (Table 1). In addition to H⁺ released during Alum hydrolysis, Al⁺³ could have replaced H⁺ and other positively-

charged ions on soil colloids and contributed to greater NH₄⁺ loss in runoff (Tisdale et al., 1993). For both rain events, NH₄-N runoff loss from Tifway sprigged in soil amended with inorganic fertilizer and Alum was greater ($P = 0.01$) than the four treatments established without Alum (Table 2). During the first rain event, NH₄-N runoff loss from transplanted sod grown with inorganic fertilizer was greater ($P = 0.001$) with than without Alum and greater than sprigged or transplanted sod treatments with CB and no Alum. During the second event, NH₄-N runoff loss from transplanted sod amended with Alum, with or without CB, was greater ($P = 0.01$) than 'Tifway' sprigged in soil without Alum. Similar to the buffering effect of CB on Alum reductions in soil pH (Table 1), NH₄-N losses in runoff from CB-amended soil or sod were similar with and without Alum for both rain events.

Relationship between runoff and soil phosphorus concentrations. Variation of soil-test P is among the potential indicators of runoff concentrations and losses of dissolved P forms, including SRP (Pote et al., 1999). Variation of Mehlich-3 P within the 0- to 2-cm depth of a Captina silt loam accounted for 72% of the variation of runoff concentrations of SRP during simulated rain applications on grass plots. In the present study, Alum treatments reduced runoff mass loss of SRP and SURP during one or both simulated rain events without corresponding changes in Mehlich-3 P within the 0- to 5-cm sampling depth (Table 1; Fig. 2). Variation of Mehlich-3 P accounted for only 45% of variation of SRP concentration during rain Event 1 and 37% of the variation during Event 2. The Mehlich-3 method could have extracted and measured Ca-P and Al-P minerals of CB- and Alum-amended treatments, which could have confounded relationships with variation of SRP concentrations and losses in runoff among treatments (Sharpley et al., 2004). In addition, sampling to the

5-cm depth of lysimeters on which sod was transplanted could have misrepresented the imported sod layer and the effect of surface sprays of Alum on the soil depth interacting with simulated rain. Yet, a previous study indicated changing sampling depth generally did not improve regression relationships between soil-test P and dissolved P concentrations in runoff from bare soil and soil with turfgrass cover (Soldat et al., 2009). Evaluations of soil test procedures indicated WEP rather than Mehlich-3 P could improve predictions of runoff concentration of SRP (Pote et al., 1999). Alum treatments reduced both mean runoff loss of SRP and soil WEP on the dates sampled (Table 1; Fig. 2). Yet, a regression analysis relating runoff SRP to soil WEP concentrations accounted for less than 42% of variation among lysimeters comprising the three replications of eight treatments for the two simulated rain events.

Relationships between soil and runoff P concentrations were evaluated further through three changes in the regression analysis: 1) treatments amended with Alum were deleted; 2) Mehlich-3 *P* values from analyses of imported sod layers were substituted for those sampled from the 5-cm depth of sodded lysimeters; and 3) the sum of SRP and SURP (TDP) was substituted for SRP. The r^2 values for the linear regression relating variation of concentrations of Mehlich-3 P and runoff TDP were 0.713 ($P = 0.001$) and 0.839 ($P = 0.001$) for the respective rain events (Fig. 4). The direct relationship between Mehlich-3 P and TDP concentration in runoff illustrated the potential impact of CB amendments of soil and sod on water quality.

Previous comparisons of natural rainfall runoff between 'Tifway' sprigged in CB-amended soil and sod transplanted from CB-amended 'Tifway' revealed direct linear relationships between Mehlich-3 P and runoff concentrations of TDP (Hansen et al., 2007; Vietor et al., 2004). The reasons for higher r^2 values in regressions between TDP
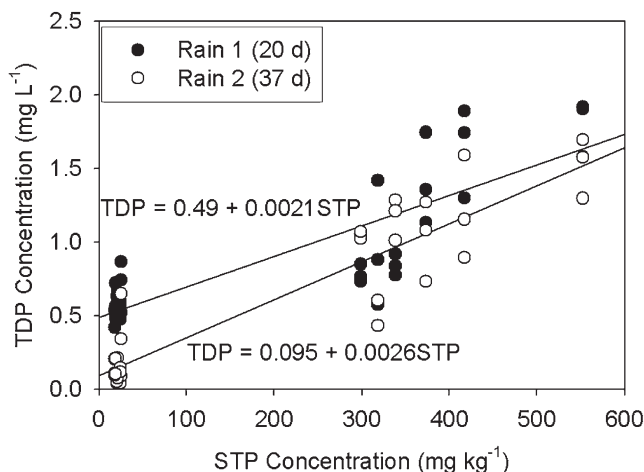
Fig. 4. Regression relationship between variation of runoff concentration of total dissolved phosphorus (TDP) and Mehlich-3 P (STP) of soil during establishment of 'Tifway' bermudagrass as sprigs or transplanted sod. Runoff from sprigged or sodded 'Tifway' with or without composted biosolids was sampled from lysimeters and analyzed during three consecutive 8-min intervals of simulated rain at 20 and 37 d after planting.

and Mehlich-3 P than between SRP and soil WEP or Mehlich-3 P were not clear. The soil P forms that reacted with hydrolysis products of Alum could have been extracted and detected through the Mehlich-3 method yet were retained in sediment during the filtering step before measurement of SRP and TDP concentrations in runoff. In addition, the SURP component of TDP in the present study could have included P forms that were extracted as Mehlich-3 P (Haygarth and Sharpley, 2000) but not detected in the colorimetric assay of SRP (Lopez and Vargas-Albores, 2003). Additional research is needed to relate variation of total P, Mehlich-3 P, or WEP concentration within the surface layer of soil or sod to variation of total P and SRP and SURP concentrations in runoff with and without CB and Alum treatments.

Conclusion

Observations of runoff from lysimeters under simulated rain verified previous reports of greater SRP loss from sod transplanted from 'Tifway' grown with top-dressed CB than from soil mixed with CB before sprigging. Although Alum amendments were not previously evaluated for turfgrass, the surface spray on transplanted 'Tifway' sod prevented runoff loss of dissolved P forms from CB and turfgrass sources as effectively as Alum incorporated with CB or soil before sprigging. In addition, the Alum rates required for the sprays per unit area of establishing turfgrass surface were more than 40% less than Alum rates per unit area incorporated with soil or CB. With or without CB, the Alum treatments reduced soil WEP and SRP loss in runoff for one or both simulated rain events. Loss of SRP was reduced, but negative Alum effects included acidulation of soil, reduced coverage rate and biomass of sprigged 'Tifway', and greater sediment loss from soil mixed with inorganic fertilizer than other treatments. Yet neither the Alum surface spray nor incorporated Alum was detrimental to turfgrass coverage and growth in sodded or sprigged turfgrass amended with CB. The CB buffered soil against pH reductions and minimized Alum-affected increases in runoff loss of NH_4-N. Variation of Mehlich-3 P of treatments without Alum accounted for a larger portion of the variation of the sum of SRP and SURP than variation of soil WEP. Although Alum reduced Mehlich-3 P of CB-amended sod only, incorporated or surface sprays of Alum were effective practices for preventing runoff loss of fertilizer, soil, turfgrass, and CB sources of dissolved P during turfgrass establishment. Additional research is needed to evaluate the Alum effects on runoff loss of P during turfgrass establishment on intact soil profiles under simulated and natural rainfall.

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