HortScience 40(3):830–835. 2005.

Dissolved Organic Carbon in Soil from Compost-amended Bermudagrass Turf

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Additional index words. dissolved organic carbon, dissolved organic matter, compost, bermudagrass turf

Abstract. **Application of organic amendments can increase dissolved organic C (DOC) concentrations, which may influence movement of nutrients and heavy metals in soils. The objectives of this study were to investigate the influence of compost sources and application rates on concentrations of soil DOC, NO_3-N, and extractable P over 29 months after a one-time application of compost to bermudagrass [*Cynodon dactylon* (L.) Pers.] turf. Few differences were evident between compost sources for soil total organic C (TOC), DOC, and NO_3-N. However, the initial P content of compost sources significantly influenced soil extractable P. Increasing the rate of compost application increased soil TOC initially, but levels remained fairly stable over time. In contrast, DOC continued to increase from 3 to 29 months after application, suggesting that compost mineralization and growth of bermudagrass contributed to DOC dynamics in soil. Dissolved organic C was 98%, 128%, 145%, 175%, and 179% greater 29 months after application of 0, 40, 80, 120, and 160 Mg compost/ha, respectively, than before application. Rate of compost application had less effect on DOC than TOC, as DOC concentrations appeared controlled in part by bermudagrass growth patterns. Soil NO_3-N was generally unaffected by compost application rate, as NO_3-N decreased similarly for unamended soil and all compost treatments. Soil extractable P initially increased after compost application, but increasing the application rate generally did not increase P from 3 to 29 months. Seasonal or cyclical patterns of TOC, DOC, and extractable P were observed, as significantly lower levels of these parameters were observed in dormant stages of bermudagrass growth during cooler months.**

Reduction of the volume of urban landscape wastes is a current problem because landfill disposal options are limited. Increasing importance is being placed on the utilization of cropland and turfgrass for disposal of composted organic materials. Considerable research has been conducted on the fate of nutrients in compost-amended agricultural soils, but limited information is available on the use of composts for turfgrass production and subsequent effects on dissolved organic matter (DOM).

Many factors influence DOM dynamics in soil, such as pH, metal concentrations and availability, vegetation, and management factors such as tillage and organic amendment additions (McDowell, 2003). Dissolved organic matter generally accounts for only a small proportion of the total soil C, but is involved in many soil processes such as soil biological activity and transport of metals and organic pollutants (Chantigny, 2003). Dissolved organic matter may be refractory (Qualls and Haines, 1992), but is generally mobile in soil (Dunnivant et al., 1992). Therefore, the fate of DOC in compost-amended soils is important, as off-site movement of DOM has potential to impact adjacent terrestrial or aquatic ecosystems (Jacinthe et al., 2004).

Application of composts and organic amendments can potentially influence soil organic matter (SOM) levels, DOM, and soil nutrient status (Chang et al., 1991; Eghball, 2002). Compost application tends to increase the risk of leaching of heavy metals (Ashworth and Alloway, 2004), as metal ions complexed with DOM can readily move through soil (Kaschl et al., 2002; McBride et al., 1999). The N and P contents of composts, and related DOM concentrations, can modify the amount and composition of DOC in soils (Chantigny, 2003). Organic amendments may also desorb indigenous DOM (Bol et al., 1999). Baziramakenga and Simard (1998) reported that both the quantity and quality of DOC changed after compost application. Effects of organic amendments may improve soil properties for several years after application ceases (Ginting et al., 2003), as only a fraction of the organic material may be initially degraded or become available to plants and soil microorganisms (Hadas et al., 1996).

Significant increases in DOC have been observed after manure and compost additions (Chantigny et al., 2002; Gigliotti et al., 1997; Gregorich et al., 1998). The immediate increase in DOC is attributable to the presence of soluble materials in compost. High waste application rates may induce increases in DOC from several weeks to years (Chantigny et al., 2002; Chantigny, 2003). If wastes are rapidly decomposed in soil, DOC may quickly return to background levels (Franchini et al., 2001; Jensen et al., 1997). Dissolved organic C is often degraded too rapidly to reach lower soil depths, but biodegradability is often dependent on compost composition (Marschner and Kalbitz, 2003).

Seasonal variation of DOC is common and may be related to growth stages of plants and decomposition of soil organic matter. Depletion of degradable portions of DOM occurs at warmer temperatures in spring and summer, while DOM may accumulate during winter (Marschner and Kalbitz, 2003). However, other studies indicate that DOC concentrations are generally highest in summer (Hongve, 1999; Kalbitz et al., 2000) due to release of root exudates from plants and microbial metabolites (Marschner and Kalbitz, 2003).

Bermudagrass turf is often intensively managed and capable of sequestering large amounts of nutrients into soil and plant biomass, thus decreasing potential for runoff or leaching (Gross et al., 1990; Vietor et al., 2002). Furthermore, removal of turfgrass and sequestered nutrients is ultimately achieved when the top several cm of soil and turf are harvested as sod and removed from the site. In fact, 46% to 77% of manure-applied P was removed with a single sod harvest (Vietor et al., 2002). Thus, turfgrass sod has potential to absorb applications of organic materials while minimizing potential problems associated with leaching and runoff of nutrients.

For the long-term use of turfgrass for disposal of composted organic materials to be effective, management options should minimize negative environmental effects, such as runoff and leaching of organic and inorganic nutrients. The stability or decomposability of added composts to bermudagrass turf should be assessed by measuring changes in DOC, N, and P over time. A multi-year study was initiated to determine the influences of sources and rates of compost application on the temporal variability of TOC, DOC, NO_3-N, and extractable P in bermudagrass turf.

Materials and Methods

Site description. A field study was established at the Texas A&M University Turfgrass Field Laboratory at College Station, in June 2001. The soil at the site is a Boonville fine sandy loam (fine, smectitic, thermic Chromic Vertic Albaqualfs) with pH 7.3, and was previously under pasture before seeding of common bermudagrass [*Cynodon dactylon* (L.) Pers]. Average annual rainfall at the site is 980 mm and temperature is 20 °C.

A completely randomized experimental design was used with four replicated field plots measuring 20 m^2 each. Soil was chiseled to a depth of 35 cm, and then roto-tilled to a depth of 15 cm before compost application and seeding of bermudagrass. Treatments included three compost sources (DilloDirt, Bryan Compost, and Nature's Way) applied at rates of 0, 40, 80, 120, and 160 $Mg \cdot ha^{-1}$, which was equivalent to 0, 1.25, 2.5, 3.75, and 5.0 cm depths of compost application, respectively. DilloDirt and Bryan Compost are co-composted landscape wastes and municipal biosolids, while Nature's Way consists of composted landscape wastes containing small amounts of manure. Composts

Received for publication 30 Sept. 2004. Accepted for publication 30 Nov. 2004.

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Table 1. Characterization of Boonville soil and three compost sources.

Parameter	Units	Soil	DilloDirt	Bryan compost	Nature's Way compost
Total organic C	g C/kg	8.1	232	246	164
Total N	g N/kg	0.7	19.0	15.5	7.9
C/N Ratio		11.6	12.2	15.9	20.8
Extractable P	mg P/kg	42.7	13.2	6.4	1.4

were incorporated into the top 15 cm of soil by extensive roto-tilling in June 2001. Common bermudagrass was seeded into the prepared seedbed at a rate of 4.88 $g \cdot m^{-2}$ on June 29. Bermudagrass received N fertilizer at rates of 72 $kg \cdot ha^{-1}$ in 2001 and 49 $kg \cdot ha^{-1}$ in 2002, while no N was applied in 2003. Bermudagrass plots were periodically mowed to maintain a canopy height of 3.5 cm, with clippings being returned to the plots. To minimize moisture stress, supplemental irrigation was provided at 12 $mm \cdot d^{-1}$ for 60 d after seeding, followed by 12 mm every 3 d until November 2001. Thereafter, 6 mm of water was applied every 3 d during the growing season upon onset of symptoms of drought stress.

Fifteen soil cores (15-cm-diameter) were taken from each plot to a depth of 15 cm and composited. Samples were taken in June 2001 before compost application, and in October 2001, March 2002, June 2002, November 2002, June 2003, and December 2003, corresponding to 3, 8, 11, 16, 23, and 29 months after application of compost and seeding of bermudagrass. Soil was dried at 65 °C and passed through a 2-mm sieve. Readily identifiable plant materials were removed from soil before analysis.

Soil analysis. Soil TOC was measured by automated dry combustion using an Elementar VarioMax CN analyzer (Elementar Americas, Inc., Mt. Laurel, N.J.). For DOC determination, 7 g soil were shaken with 28 mL distilled water for 1 hour, followed by centrifugation and filtration through 0.45-µm filters. Extracts were analyzed for DOC by persulfate oxidation using a TOC analyzer (model 700; O.I. Analytical, College Station, Texas). Nitrate and extractable P were analyzed by the Texas Cooperative Extension Soil, Water, and Forage Testing Laboratory. Nitrate was extracted and analyzed by the cadmium-reduction method (Dorich and Nelson, 1984). Plant-available P was extracted using acidified NH_4OAc-EDTA and analyzed by ICP (Hons et al., 1990). Characterization data for Boonville soil and the three compost sources are presented in Table 1.

Statistical analysis. Data were analyzed using CoStat (CoStat Statistical Software, 2003). Analysis of variance (ANOVA) was performed to determine overall differences between compost sources, rates, and sampling times. Moreover, ANOVA was used for determination of differences between individual treatments for each sampling time after compost application. For TOC, DOC, and NO_3-N, ANOVA showed no differences between compost sources, so data from the three sources were combined for analysis and presentation in figures. Separation of means was accomplished using LSD, and Pearson's correlation coefficients were determined at $P < 0.05$.

Results and Discussion

All compost additions significantly increased TOC at 3 months. The rate of compost application significantly influenced TOC, as each rate increase produced greater TOC than the preceding lower rate. These effects of application rate were observed at all sampling times from 3 to 29 months after compost addition.

Dissolved organic C increased up to 11 months after compost application, and then declined at 16 months, corresponding to a similar decrease in TOC (Fig. 1). The increases occurred at all application rates as well as for the unamended soil. Dissolved organic C often increases as the rate of sludge application increases (Antoniadis and Alloway, 2002). Dissolved organic C again increased from 16 to 23 months for all treatments, but did not exhibit the decrease that occurred for TOC at 29 months. In contrast to the relative stability of TOC for the unamended soil over time, DOC was significantly greater at successive sampling times with the exception of the 16 month sampling time. Since no compost was added to the unamended soil, increases in DOC

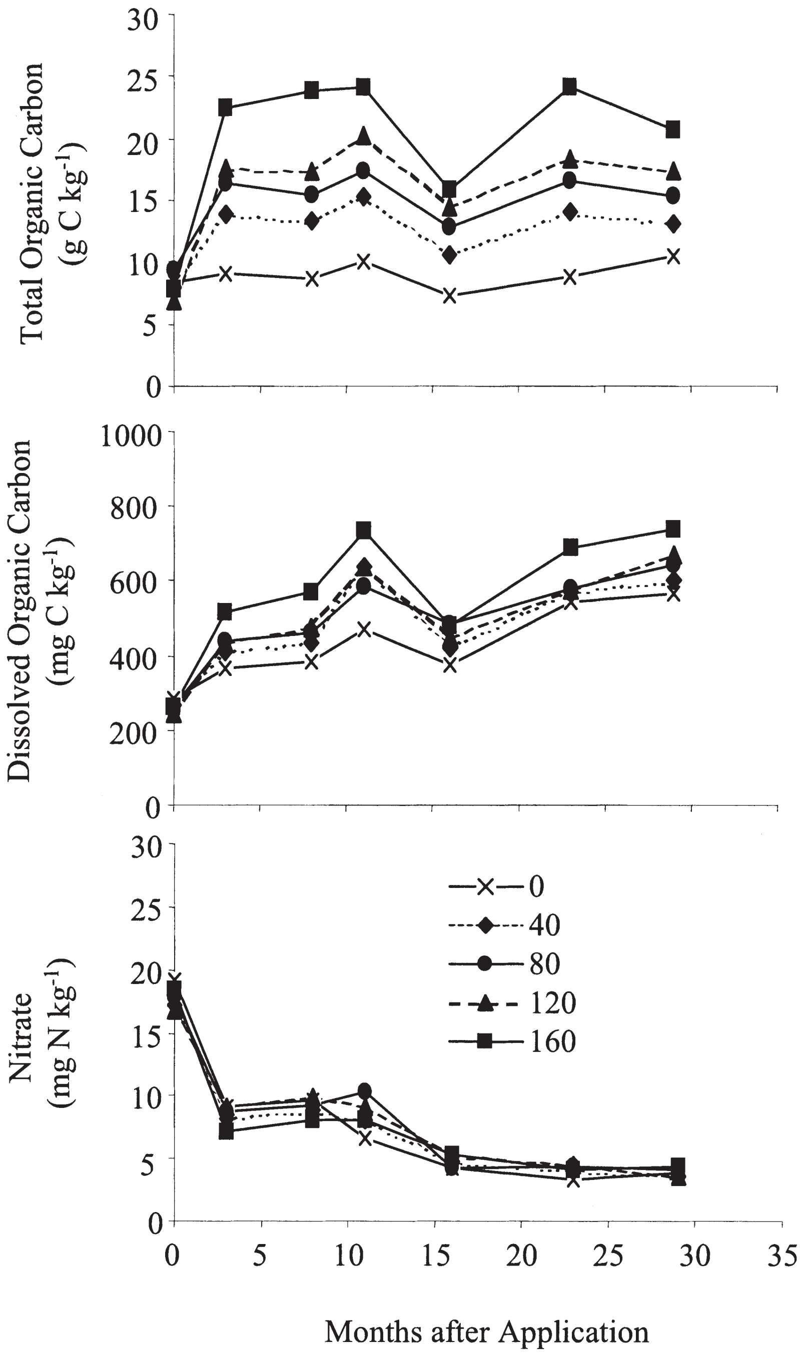

Fig. 1. Total organic C, dissolved organic C, and nitrate concentrations in compost-amended bermudagrass turf up to 29 months after compost application. Compost application rates ranged from 0 to 160 $Mg \cdot ha^{-1}$. No differences between compost sources were observed, so data from the three sources were averaged for analysis and presentation.

over time were attributed to C contribution from bermudagrass. Rate of compost application had less effect on DOC than TOC. Composts added at 160 Mg·ha^{-1} produced 58% greater TOC at 29 months than compost added at 40 Mg·ha^{-1}. However, DOC was only 22% greater for 160 than 40 Mg·ha^{-1} at 29 months.

The highest DOC for all sampling times after compost application was observed for bermudagrass receiving 160 Mg·ha^{-1}, while the unamended soil had the lowest DOC. No differences in DOC were observed between treatments receiving 40 to 120 Mg·ha^{-1}. These rates produced significantly lower DOC than treatments receiving 160 Mg·ha^{-1}, yet provided higher DOC than unamended soil. Dissolved organic C and TOC were significantly correlated (Fig. 2).

Cyclical patterns of TOC and DOC occurred after compost application, as evidenced by lower concentrations during the winter sampling at 16 and 29 months. Total organic C was significantly lower for all compost treatments and unamended soil at 16 months than at 11 and 23 months, which suggests that the transient decline in TOC was not compost related, but likely influenced by the reduced growth of bermudagrass during the onset of dormancy in winter. Bermudagrass growth is commonly more vigorous from late spring to summer, with a dormant period from late autumn to winter (Redmon, 2002; Stichler et al., 1998; Taylor and Gray, 1999). Bermudagrass often produces high levels of belowground biomass (Rouquette and Florence, 1986), which can increase soil C due to production of root exudates. Moreover, the decomposition byproducts of belowground plant materials and aboveground clippings may contribute to soil TOC and DOC. Bermudagrass was mowed to maintain a 3.5-cm height, and the clippings left on the turf may have contributed to soil TOC and DOC levels. Since bermudagrass production levels are lower in cooler than warmer months (Redmon, 2002; Stichler et al., 1998; Taylor and Gray, 1999), a lower contribution of bermudagrass to soil TOC and DOC would explain lower DOC at 16 (November 2002) and 29 months (December 2003).

Bermudagrass was irrigated during the growing season, which may have leached DOC from the soil surface (0 to 15 cm) at the 16 and 29 month sampling times. A similar decrease in TOC at 29 months compared to 23 months, although to a lesser extent, was also observed from compost-amended but not unamended soil. Studies have indicated that DOM added with compost to a sandy soil was leached from the root zone within a year (Kaschl et al., 2002). Thus, changes in TOC and DOC in our study over time may have been due not only to decomposition of compost materials, but also to decomposition of native SOM and production of DOC from bermudagrass residues. This supports the hypothesis of seasonal patterns of TOC and DOC dynamics related to bermudagrass growth.

Dissolved organic C was a greater contributor to TOC for unamended than for compost-amended soil (Fig. 3). In fact, the greater the rate of compost application, the lower the percent contribution of DOC to TOC. As TOC increased, the percentage of TOC as DOC decreased. The percentage of TOC as DOC increased 59% from 0 to 29 months for unamended soil, and also increased over time for most treatments. These results were most likely due to the effects of bermudagrass growth rather than compost application, as the greatest effects were observed for unamended soil.

Soil NO_3-N averaged 18 mg N/kg before compost application, and levels rapidly declined after compost application and in unamended soil to about 4 mg N/kg by 16 months (Fig. 1). Soil NO_3-N levels are often depleted in compost-amended soils under crop or turf production due to plant uptake of N or immobilization of N during decomposition of organic matter (Debosz et al., 2002; Hadas et al., 1996), or from leaching of NO_3-N below the soil surface (Johnson et al., 1995). Few differences in NO_3-N were noted between compost sources and rates of application. Thus, composts did not appear to be major sources of NO_3-N to surface soils under bermudagrass turf. However, since the growth of bermudagrass generally requires large quantities of N (McAfee, 2003; Redmon, 2002; Stichler et al., 1998; Taylor and Gray, 1999), inorganic N produced from compost mineralization was likely rapidly assimilated by bermudagrass, which decreased NO_3-N levels in both compost-amended and unamended soil. These results tend to support the hypothesis that NO_3-N leaching potential may be decreased in bermudagrass turf due to its high N requirement and rapid uptake of inorganic N. However, leaching below the 0 to 15 cm sampling depth may also explain decreases in soil NO_3-N from the time of

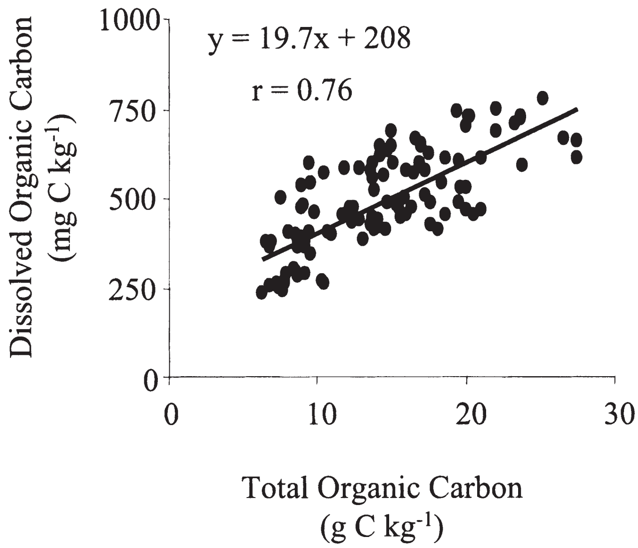

Fig. 2. The relationship between dissolved organic C and total organic C in compost-amended bermudagrass turf.

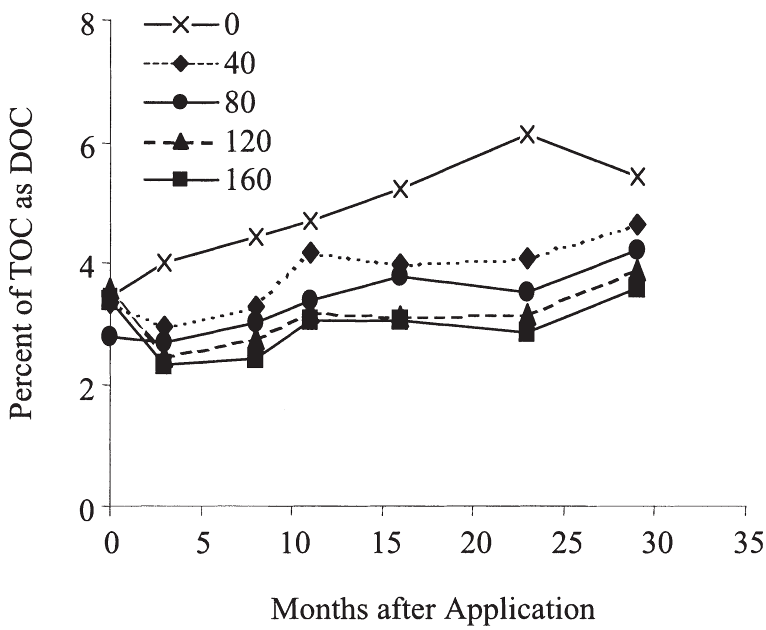

Fig. 3. The percentage of total organic C (TOC) as dissolved organic C (DOC) in compost-amended bermudagrass turf up to 29 months after compost application. Compost application rates ranged from 0 to 160 Mg·ha^{-1}.

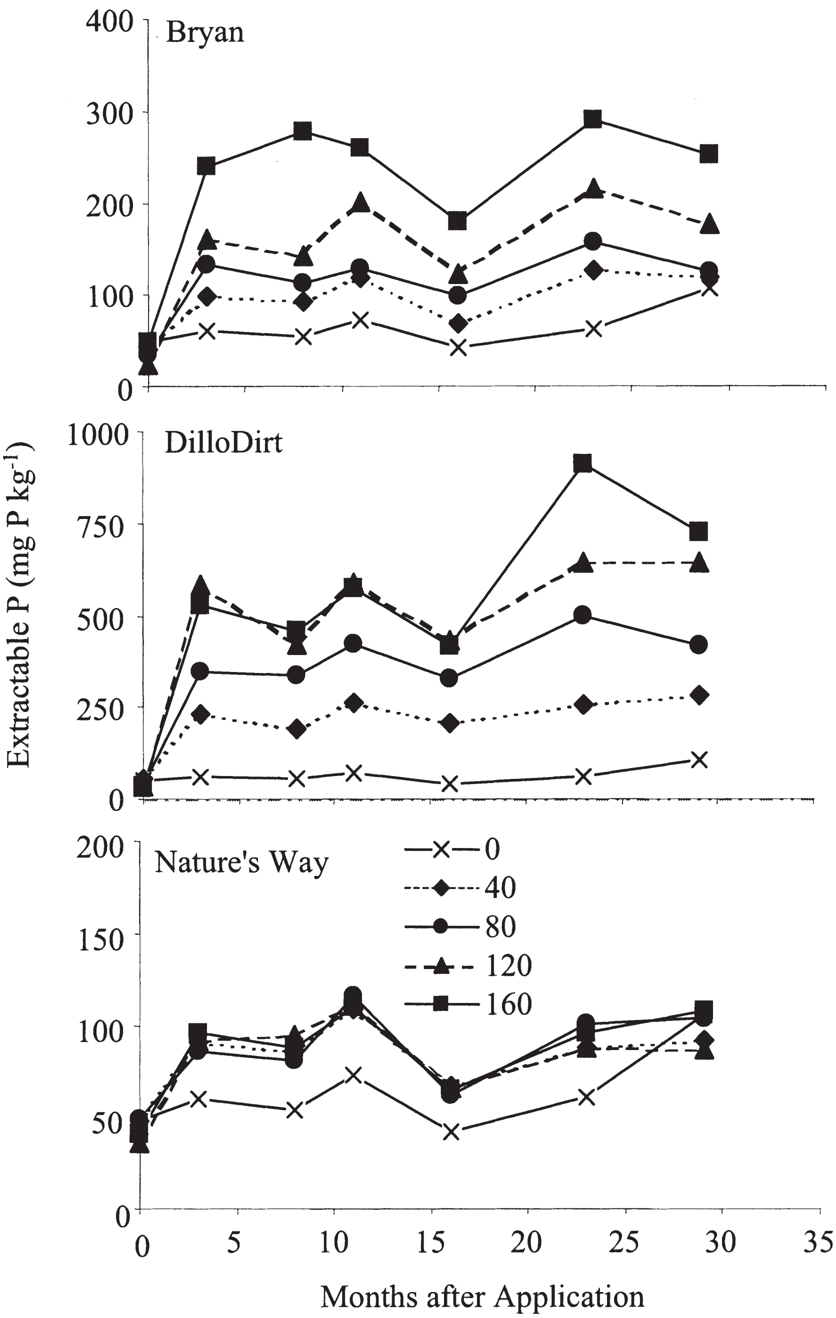

Fig. 4. Extractable P concentrations in compost-amended bermudagrass turf up to 29 months after compost application. Compost application rates ranged from 0 to 160 Mg·ha^{-1}.

compost application to 29 months. Dissolved organic C and NO_3-N showed inverse relationships over time ($r = -0.62$), suggesting that as DOC increased, NO_3-N was being assimilated by soil microorganisms for decomposition of DOC (Hadas et al. 1996). Soil NO_3-N was also negatively related to TOC ($r = -0.38$) and percent TOC as DOC ($r = -0.29$).

The three compost sources initially had varying amounts of extractable P, so data are presented for each compost source (Fig. 4). Soil extractable P increased at 3 months after compost addition for all sources and rates. However, after 3 months, few increases in extractable P were observed. DilloDirt applied at 160 Mg·ha^{-1}, however, showed greater extractable P at 23 and 29 months than at other sampling times. For Bryan compost, averaged across sampling dates, increasing the rate of application increased extractable P. Likewise, for DilloDirt, each application rate produced greater extractable P than the preceding lower rate, except for the two highest application rates that produced similar P levels. For Nature's Way, no effect of application rate was observed. Unamended soil had the lowest extractable P at all sampling times except at 29 months.

Similar to TOC and DOC, soil extractable P exhibited a seasonal effect, with significant decreases at 16 months compared to 11 and 23 months for all compost sources, application rates, and unamended soil. Furthermore, extractable P significantly decreased for Bryan and DilloDirt applied at rates above 80 Mg·ha^{-1} from 23 to 29 months. The decreases at 16 and 29 months were more pronounced at the highest compost application rates, but were also observed for unamended soil at 16 months. Lower extractable P at 16 and 29 months during winter may be due to lower mineralization of soil organic P compared to warmer months. For unamended soil, extractable P increased 159% from 16 to 29 months. This increase must have resulted from the mineralization of SOM or bermudagrass residues because no compost was applied to unamended soil. Turnover of SOM and increased extractable P may have been a result of enhanced phosphatase activity in warmer months as a result of more prolific growth of bermudagrass. Plant uptake and translocation of P from deeper depths and deposition of clippings to the soil surface may have also contributed to this effect. These results indicate the importance of the contribution of native SOM and effects of plants on P cycling in compost-amended turfgrass. Results showed that compost sources were major contributors to extractable P. Concentrations remained fairly constant over time perhaps because the assimilation of P by bermudagrass was balanced by mineralization of organic P from compost and bermudagrass residues. Extractable P was positively related to both TOC ($r = 0.55$) and DOC ($r = 0.40$).

Dissolved organic C/extractable P ratios were significantly greater for unamended than for compost-amended soil (Fig. 5). This was likely a result of composts serving as significant sources of extractable P to soil, which increased extractable P relative to DOC. In fact, composts were likely a greater source of extractable P than DOC, as addition of composts (Bryan and DilloDirt) rapidly decreased DOC/extractable P ratios. For the compost with the lowest initial P (Nature's Way), DOC/extractable P was fairly stable from 0 to 29 months, suggesting that little extractable P was released from this material, or that both DOC and extractable P were being produced at similar rates. For the two compost sources with higher initial P, increasing the rate of compost application decreased DOC/extractable P. For Nature's Way, application rate did not impact DOC/extractable P. Increasing DOC content in soil is an indication of decomposition of compost, SOM, or plant residues over time. Degradation of these materials also increases inorganic P liberated from organic matter. Thus, DOC was significantly related to extractable P ($r = 0.40$).

Since DOM is often mobile in soils, it is possible that compost additions increased DOC levels below the 0 to 15-cm sampling depth, which would have influenced NO_3-N and extractable P dynamics in soils. Compost application to sandy soils caused an initial large vertical flux of DOM, followed by a lower and more stable flux (Kaschl et al., 2002). These results may explain the initial large increases in DOC and extractable P observed in our study, followed by a slower increase in DOC and maintenance of extractable P levels from 3 to 29 months after compost application. Compost application possibly contributed to greater amounts of DOC and extractable P than were observed in surface soil, but these materials may have leached below the 0 to 15-cm sampling depth. In fact, organic

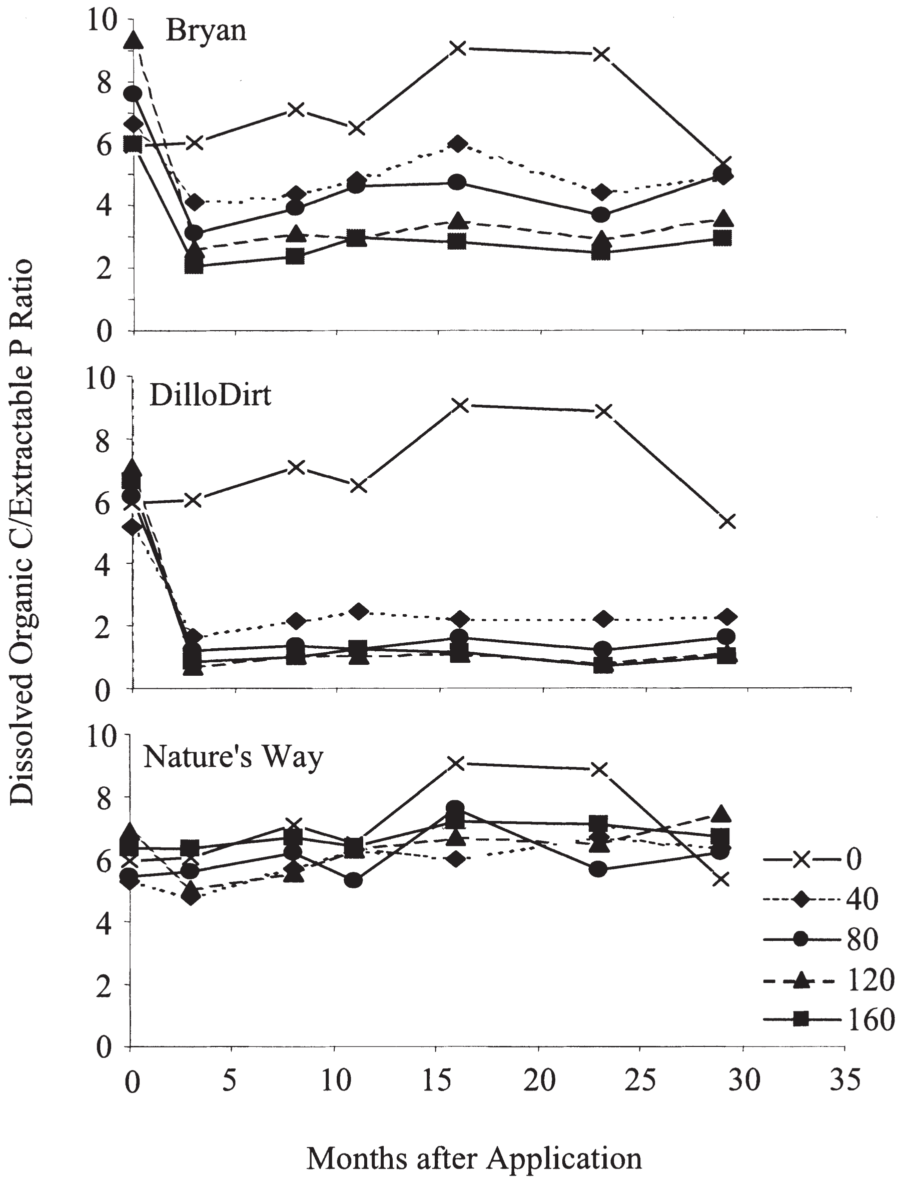

Fig. 5. Dissolved organic C/extractable P ratios of compost-amended bermudagrass turf up to 29 months after application. Compost application rates ranged from 0 to 160 Mg·ha^{-1}.

amendments applied to bermudagrass at high P rates caused P movement below 30 cm in sandy soils (Johnson et al., 2004).

In summary, compost application increased soil TOC, DOC and extractable P. After initial increases, TOC and extractable P did not increase over time, suggesting that maintenance of TOC and extractable P in surface soils was achievable. However, results of this study indicated that decomposition of compost or contributions from bermudagrass have the potential to increase DOC over time. Seasonal variation in all parameters indicated that dynamics of TOC, DOC, extractable P, and NO_3-N in soil were affected by growth stages of bermudagrass in addition to compost application.

Literature Cited

Antoniadis, V. and B.J. Alloway. 2002. The role of dissolved organic carbon in the mobility of Cd, Ni, and Zn in sewage sludge-amended soils. Environ. Pollut. 117:515–521.

Ashworth, D.J. and B.J. Alloway. 2004. Soil mobility of sewage sludge-derived dissolved organic matter, copper, nickel, and zinc. Environ. Pollut. 127:137–144.

Baziramakenga, R. and R.R. Simard. 1998. Low molecular weight aliphatic acid contents of composted manures. J. Environ. Qual. 27:557–561.

Bol, R., N.J. Ostle, C. Friedrich, W. Amelung, and I. Sanders. 1999. The influence of dung amendments on dissolved organic matter in grassland soil leachates—Preliminary results from a lysimeter study. Isot. Environ. Health Stud. 35:97–109.

Chang, C., T.G. Sommerfeldt, and T. Entz. 1991. Soil chemistry after eleven annual applications of cattle feedlot manure. J. Environ. Qual. 20:475–480.

Chantigny, M. 2003. Dissolved and water-extractable organic matter in soils: A review on the influence of use and management practices. Geoderma 113:357–380.

Chantigny, M.H., D.A. Angers, and P. Rochette. 2002. Fate of carbon and nitrogen from animal manure and crop residues in wet and cold soils. Soil Biol. Biochem. 34:509–517.

CoStat Statistical Software. 2003. CoHort v. 6.2, Monterey, Calif.

Debosz, K., S.O. Petersen, L.K. Kure, and P. Ambus. 2002. Evaluating effects of sewage sludge and household compost on soil physical, chemical, and microbiological properties. Appl. Soil Ecol. 19:237–248.

Dorich, R.A. and D.W. Nelson. 1984. Evaluation of manual cadmium reduction methods for determination of nitrate in potassium chloride extracts of soils. Soil Sci. Soc. Amer. J. 48:72–75.

Dunnivant, F.M., P.M. Jardine, D.L. Taylor, and J.F. McCarthy. 1992. Transport of naturally occurring dissolved organic carbon in laboratory columns containing aquifer material. Soil Sci. Soc. Amer. J. 56:437–444.

Eghball, B. 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. Agron. J. 94:128–135.

Franchini, J.C., F.J. Gonzalez-Vila, F. Cabrera, M. Miyazawa, and M.A. Pavan. 2001. Rapid transformations of plant water-soluble organic compounds in relation to cation mobilization in an acid oxisol. Plant Soil 231:55–63.

Gigliotti, G., P.L. Giusquiani, D. Businelli, and A. Macchioni. 1997. Composition changes of dissolved organic matter in a soil amended with municipal waste compost. Soil Sci. 162:919–926.

Ginting, D., A. Kessavalou, B. Eghball, and J.W. Doran. 2003. Greenhouse gas emissions and soil indicators four years after manure and compost applications. J. Environ. Qual. 32:23–32.

Gregorich, E.G., P. Rochette, S. McGuire, B.C. Liang, and R. Lessard. 1998. Soluble organic carbon and carbon dioxide fluxes in maize fields receiving spring-applied manure. J. Environ. Qual. 27:209–214.

Gross, C.M., J.S. Angle, and M.S. Welterlen. 1990. Nutrient and sediment losses from turfgrass. J. Environ. Qual. 19:663–668.

Hadas, A., L. Kautsky, and R. Portney. 1996. Mineralization of composted manure and microbial dynamics in soil as affected by long-term nitrogen management. Soil Biol. Biochem. 28:733–738.

Hongve, D. 1999. Production of dissolved organic carbon in forested catchments. J. Hydrol. 224:91–99.

Hons, F.M., L.A. Larson-Vollmer, and M.A. Locke. 1990. NH_4OAc-EDTA-extractable phosphorus as a soil test procedure. Soil Sci. 149:249–256.

Jacinthe, P.A., R. Lal, L.B. Owens, and D.L. Hothem. 2004. Transport of labile carbon in runoff as affected by land use and rainfall characteristics. Soil Tillage Res. 77:111–123.

Jensen, L.S., T. Mueller, J. Magid, and N.E. Nielsen. 1997. Temporal variation of C and N mineralization, microbial biomass, and extractable organic pools in soil after oilseed rape straw incorporation in the field. Soil Biol. Biochem. 29:1043–1055.

Johnson, A.F., D.M. Vietor, F.M. Rouquette, V.A. Haby, and M.L. Wolfe. 1995. Estimating probabilities of nitrogen and phosphorus loss from animal waste application, p. 411–418. In: K. Steel (ed.). Animal waste and the land-water interface. Lewis Publ., Boca Raton, Fla.

Johnson, A.F., D.M. Vietor, F.M. Rouquette, and V.A. Haby. 2004. Fate of phosphorus in dairy wastewater and poultry litter applied on grassland. J. Environ. Qual. 33:735-739.

Kalbitz, K., S. Solinger, J.H. Park, and B. Michalzik, and E. Matzer. 2000. Controls on the dynamics of dissolved organic matter in soils: A review. Soil Sci. 165:277–304.

Kaschl, A., V. Romheld, and Y. Chen. 2002. The influence of soluble organic matter from municipal solid waste compost on trace metal leaching in

calcareous soils. Sci. Total Environ. 291:45–57.
McAfee, J.A. 2003. Turf tips. Texas Coop. Ext. vol. 3. no. 1.
Marschner, B. and K. Kalbitz. 2003. Controls of bioavailability and biodegradability of dissolved organic matter in soils. Geoderma 113:211–235.
McBride, M.B., B.K. Richards, T. Steenhuis, and G. Spiers. 1999. Long-term leaching of trace elements in a heavily sludge-amended silty clay loam soil. Soil Sci. 164:613–623.
McDowell, W.H. 2003. Dissolved organic matter in soils–future directions and unanswered questions. Geoderma 113:179–186.
Qualls, R.G. and B.L. Haines. 1992. Biodegradability of dissolved organic matter in forest throughfall, soil solution, and stream water. Soil Sci. Soc. Amer. J. 56:578–586.
Redmon, L.A. 2002. Forages for Texas. Texas Coop. Ext. SCS-2002-14.
Rouquette, F.M. and M.J. Florence. 1986. Influence of long-term grazing pressures on root-rhizome mass of common and coastal bermudagrass pastures. Texas Agr. Ext. Serv. PR-4347.
Stichler, C., E. Prostko, and S. Livingston. 1998. Managing warm-season improved pastures. Texas Agr. Ext. Serv. L-5218.
Taylor, G.R., and J. Gray. 1999. Maintaining bermudagrass lawns. Texas Coop. Ext. L-5339.
Vietor, D.M., E.N. Griffith, R.H. White, T.L. Provin, J.P. Muir, and J.C. Read. 2002. Export of manure phosphorus and nitrogen in turfgrass sod. J. Environ. Qual. 31:1731–1738.