Effects of Biosolids on Tall Fescue-Kentucky Bluegrass Sod Production and Soil Chemical and Physical Properties

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Abstract

Composted biosolids have been shown to enhance turfgrass establishment and growth more than fertilizer alone, but few studies have investigated the production of turfgrass using uncomposted biosolids. Increasingly employed treatment methods that generate pathogen-free, low pollutant-containing biosolids are creating alternative products for use in urban settings. Understanding the effects of these uncomposted and alternative biosolids products on turfgrass culture and soil chemical and physical properties is essential to understanding the benefits these products may provide in sod production systems. The objectives of this study were to compare processing methods, application and N mineralization rates of two biosolids products and an inorganic fertilizer control for sod fertilization on 1) agronomic parameters related to turfgrass quality, 2) the amount of soil, C and P exported at harvest, and 3) chemical and physical properties of the soil following sod harvest as an indicator of the benefits of biosolids use. The study was conducted on a sod farm in Remington, Virginia on a silt loam Ashburn-Dulles complex from 2009 to 2012. The biosolids products were applied at estimated plant available nitrogen (PAN) rates of 98 kg N ha^{-1} (0.5X), 196 kg N ha^{-1} (1.0X) and 294 kg N ha^{-1} (1.5X) for a tall fescue (*Festuca arundinacea* Schreb. 'Rebel Exeda' 'Rebel IV' and 'Justice')/ Kentucky bluegrass (*Poa pratensis* L. 'Midnight') mixture. One biosolids product was an anaerobically digested dewatered cake applied at 15, 30.5 and 46 wet Mg ha^{-1}. The second biosolids product was the same cake blended with wood fines applied at 17, 34 and 51 wet Mg ha^{-1}. The biosolids treatments were compared to an inorganic fertilizer control that supplied 196 kg N ha^{-1} through three applications over the production cycle. There were no differences in establishment between the cake biosolids treatments and the inorganic fertilizer control, but all of the blended biosolids were slower to establish. Only the 1.0X and 1.5X PAN rates from the cake biosolids matched the inorganic fertilizer control in producing an acceptable quality sod in ten months. Lower nitrogen uptake between the blended biosolids treatments compared to the inorganic fertilizer control and lower although acceptable sod quality ratings at harvest of the 1.0X cake biosolids indicate our PAN estimates of 30% organic nitrogen mineralization overestimated the PAN for both materials. There were no differences in sod tensile strength between the 1.5X cake biosolids and inorganic fertilizer control. There were no differences in transplant rooting strength among all treatments. After repeat applications of biosolids, the 0.5X rates did not increase soil extractable phosphorus, while the 1.0X rates steadily increased soil extractable phosphorus at. The 1.0X and 1.5X biosolids rates increased soil organic matter content, but only the 1.5X rate of cake biosolids reduced soil bulk density and mineral matter export at harvest. Overall results indicate that the cake biosolids are an acceptable fertility alternative to inorganic fertilizer, and applications of biosolids for sod production can improve soil quality. Sod growers should consider using biosolids in a rotational system to offset rising production costs and improve production field soil quality.

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Attributions

Chapter 3: Evaluation of a Biosolids-based Tall Fescue-Kentucky Bluegrass Sod Production System in Virginia

Erik H. Ervin, PhD (Crop and Soil Environmental Sciences, Virginia Tech): Dr. Ervin was a co-author for the manuscript and a principal investigator for the grant supporting the research.

Gregory K. Evanylo, PhD (Crop and Soil Environmental Sciences, Virginia Tech): Dr. Evanylo was a co-author for the manuscript and a principal investigator for the grant supporting the research.

Chapter 4: The Effects of Land Applying Biosolids for Sod Production on Soil Chemical and Physical Properties and Soil Loss at Harvest

Gregory K. Evanylo, PhD (Crop and Soil Environmental Sciences, Virginia Tech): Dr. Evanylo was a co-author for the manuscript and a principal investigator for the grant supporting the research.

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Chapter 4: The Effects of Land Applying Biosolids for Sod Production on Soil Chemical and Physical Properties and Soil Loss at Harvest

1. Introduction

1.1. Background

As urban sprawl continues to expand into formerly rural land, disturbed soils created by construction are typically stabilized with turfgrass. Turfgrass increases water infiltration as well as reducing runoff and erosion (Beard, 1973). Although seeding is the least expensive turfgrass establishment method, sodding is widely practiced in the United States. There were >1,800 sod farms covering 165,000 hectares which generated $1.3 billion in total sales in 2007 (USDA, 2007). The demand for sod is expected to grow as metropolitan area population increases.

Population growth entails increasing wastewater treatment (Bastian, 1997) with resulting sewage sludge waste by-product. Sewage sludge must either be disposed of or recycled into a beneficial product. The United States Environmental Protection Agency (USEPA, 1993) promulgated the Standards for the Use and Disposal of Sewage Sludge (Title 40, CFR, Part 503), commonly referred to as The 503 Rule, in order to address disposal and beneficial use options. In the 1990's the wastewater treatment industry introduced "biosolids" as the term for treated sewage sludge that can be used beneficially, most typically via land application as a soil amendment and fertilizer source. The USEPA reported that 6.5 million dry Mg of biosolids were produced in the U.S. as recently as 2004 (NEBRA, USDA, 2007).

The perishable nature of sod and the transportation costs to deliver sod to the install site are the biggest limitations to sod production. These limitations cause sod to be produced near the metropolitan areas they serve. Sod production has not typically benefited from biosolids application, but sod farms could possibly benefit from using biosolids products as both nutrient and organic matter replacement.

The amount of nitrogen that becomes available from land applying biosolids for crop production is a concern. If mineralization of organic N is too low crop yields can be affected; if mineralization is too high NO_3^- can accumulate in soil and potentially leach. Different biosolids processing methods can influence nutrient availability (especially nitrogen and phosphorus) (Maguire et al., 2001; Gilmour et al., 2003; Cogger et al., 2004).

Biosolids have been successfully employed to establish and maintain quality turfgrass in previous studies (Landschoot and McNitt, 1994; Linde and Hepner, 2005; Loschinkohl and Boehm, 2001; Schnell et al., 2009; Tesfamariam et al., 2009; Johnson et al., 2006; Norrie and Gosselin, 1996). Researchers determined that incorporating biosolids enhanced establishment and long-term turfgrass quality more than inorganic fertilizer alone (Linde and Hepner, 2005). Loschinkohl and Boehm (2001) determined that biosolids acted like a slow release fertilizer; a quicker greening response and greater turfgrass density was seen after turfgrass germination using inorganic fertilizer, but biosolids amended soil maintained turfgrass with above acceptable color and density longer than inorganic fertilizer. There have only been a few studies that have used biosolids for sod production (Schnell et al., 2009; Tesfamariam et al., 2009). In these studies the goal of the research was to produce acceptable quality sod, but utilize as much biosolids as possible to export nutrients from production fields to install sites. The results of these studies left gaps in the knowledge about the effects of lower rates of biosolids for sod production, especially on cool-season grass species. Further research is needed to determine the effects of N based biosolids rates for tall fescue-Kentucky bluegrass sod production on turfgrass establishment, growth and quality.

There are only a few studies that have quantified the amount of soil export that occurs at harvest during sod production (Sheard and Van Patter, 1978; Skogley and Hesseltine, 1978; Carr, 1996; Charbonneau, 2003; Millar et al., 2010). Results have been contradictory on whether or not soil export is occurring. In a recent study on sod farms in Rhode Island that investigated soil loss in sod production fields with varying years of production, it was found that significant soil export of 74 to 114 Mg ha^{-1} occurred each year (Millar et al., 2010). Biosolids application could reduce soil export at harvest. Tesfamariam et al. (2009) investigated the effects of excessive biosolids application rates on sod production and found that rates above 8 dry Mg ha^{-1} reduced soil export. Another study that applied and incorporated composted biosolids reported a reduction in sod dry weight at harvest and concluded that less native soil was exported using biosolids compared to treatments without (Schnell et al., 2009). Further research is needed to investigate the effects of N based biosolids rates for sod production on the amount of mineral matter export that occurs with sod harvest.

Soil quality is defined as "the ability of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1997). Soil quality is assessed by measuring indicators, some of which are organic matter, bulk density and water infiltration (Karlen et al., 1997). The application of biosolids has been shown to improve soil quality by increasing organic matter and water retention and decreasing bulk density (Lindsay and Logan, 1998; Epstein, 1975; Kelling et al., 1977; Kladivko and Nelson, 1979; Mays et al., 1973; Aggelides et al., 2000). Research using biosolids in turfgrass settings has found similar soil quality improvements (Johnson et al., 2006; Norrie and Gosselin, 1996). Although the effects of biosolids on turf establishment and sod properties has been researched (Landschoot and McNitt, 1994; Linde and Hepner, 2005; Loschinkohl and Boehm, 2001; Schnell et al., 2009; Tesfamariam et al., 2009), there are no studies using biosolids that measured soil properties after sod harvest. Further research is needed to investigate the effects of N based biosolids applications on C cycling and organic matter accumulation.

Because of the unbalanced nature of biosolids in terms of plant nutrition, application of biosolids at N based rates can result in the over application of phosphorus (Ott and Forster, 1978). Also, research has shown that repeated applications of biosolids increases soil phosphorus (Chang et al., 1983; Kelling et al., 1977; Maguire et al., 2000). Previous research using biosolids for sod production report that there is significant phosphorus and nitrogen export with each sod harvest (Vietor et al., 2002; Schnell et al., 2009; Tesfamariam, et al., 2009). Schnell et al. (2009) determined that more nutrients were exported when biosolids were topdressed compared to when incorporated. The effects of biosolids application on soil phosphorus after sod harvest was only reported once (Tesfamariam et al., 2009). The surface soil phosphorus was determined not to increase with topdressed biosolids application rates less than 67 dry Mg ha^{-1}. Further research is needed to investigate the effects of incorporated N based biosolids application rates on P cycling in sod production soil.

The evaluation of N based biosolids applications for sod establishment, quality, soil export at harvest, soil quality and production field phosphorus accumulation is needed. Additionally the mineralization rates of biosolids products with new processing methods need to be evaluated in field settings.

1.2. Objectives

The overall goal of this research was to evaluate the effects of biosolids on tall fescue-Kentucky bluegrass sod production. The specific objectives were to compare processing methods, application and N mineralization rates of two biosolids products and an inorganic fertilizer control for sod fertilization on: 1) agronomic parameters related to turfgrass quality, 2) the amount of soil, C and P exported at harvest, and 3) chemical and physical properties of the soil following sod harvest as an indicator of the benefits of biosolids use.

1.3. References

Aggelides, S.M., and P.A. Londra. 2000. Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. Bioresource Technology. 71:253-259

Bastian, R. 1997. The biosolids (sludge) treatment, beneficial use, and disposal situation in the USA. European Water Pollution Control Journal. 7:62-79.

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice-Hall, Englewood Cliffs, NJ.

Carr, M.Y. 1996. Metal levels in Rhode Island municipal sewage sludges and their resulting appropriateness for agricultural use by sod farms. Honors thesis. Brown Univ., Providence, RI.

Chang, A.C., A.L. Page, F.H. Sutherland, and E. Grgurevic. 1983. Fractionation of phosphorus in sludge-affected soils. J. Environ. Qual. 12:286–290.

Charbonneau, P. 2003. Soil loss during sod production. Available at www.omafra.gov.on.ca/english/crops/facts/info_sodprod.htm#loss (verified 1 Mar. 2013). Ontario Ministry of Agriculture, Food and Rural Affairs, Ottawa.

Cogger, C.G., A.I. Bary, D.M. Sullivan, and E.A. Myhre. 2004. Biosolids processing effects on first- and second-year available nitrogen. Soil Sci. Soc. Am. J. 68:162–167.

Epstein, E. 1975. Effect of sewage sludge on some soil physical properties. J. Environ. Qual. 4:139-142.

Evanylo, G. K. 1999. Agricultural land application of biosolids in Virginia: production and characteristics of biosolids. Virginia Cooperative Extension. Pub. 452-304.

Gilmour, J.T., C.G. Cogger, L.W. Jacobs, G.K. Evanylo, and D.M. Sullivan. 2003.

Decomposition and plant-available nitrogen in biosolids: Laboratory studies, field studies, and computer simulation. J. Environ. Qual. 32:1498–1507.

Johnson, G.A., J.G. Davis, Y.L. Quian, and K.C. Doesken. 2006. Topdressing turf with composted manure improves soil quality and protects water quality. Soil Sci. Soc. Am. J. 70:2114–2121.

Karlen, D. L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4-10.

Kelling, K.A., A.E. Peterson, and L.M. Walsh. 1977. Effect of wastewater sludge on soil moisture relationships and surface runoff. J. WPCF. 49:1698-1703.

Kelling, K.A., L.M. Walsh, D.R. Keeney, J.A. Ryan, and A.E. Peterson. 1977. A field study of the agricultural use of sewage sludge: II. Effect on soil N and P. J. Environ. Qual. 6:345–352.

Kladivko, E.J., and D.W. Nelson. 1979. Changes in soil properties from application of anaerobic sludge. J. WPCF. 51:325-332.

Landschoot, P., and A. McNitt. 1994. Improving turf with compost. BioCycle. 35:54-57.

Linde , D.T., and L.D. Hepner. 2005. Turfgrass seed and sod establishment on soil amended with biosolids compost. Horttechnology. 15:577-583.

Lindsay, B. J., and T.J. Logan. 1998 Field response of soil physical properties to sewage sludge. J. Environ. Qual. 27:534–542.

Loschinkohl, C., and M.J. Boehm. 2001. Composted biosolids incorporation improves turfgrass establishment on disturbed urban soils and reduces rust severity. Hort. Sci. 36(4):790-794.

Maguire, R.O., J.T. Sims, and F.J. Coale. 2000. Phosphorus solubility in biosolids-amended soils in the Mid-Atlantic region of the USA. J. Environ. Qual. 29:1225–1233.

Maguire, R. O., J.T. Sims, S.K. Dentel, F.J. Coale, and J.T. Mah. 2001. Relationships between biosolids treatment process and soil phosphorus availability. J. Environ. Qual. 30:1023-1033.

Mays, D.A, G.L. Terman, and J.C. Duggan. 1973. Municipal compost: Effect on crop yield and soil properties. J. Environ. Qual. 2:89-91.

Millar, D., M. Stolt, and J.A. Amador. 2010. Quantification and implications of soil losses from commercial sod production. Soil Sci. Soc. Am. J. 74:892-897.

NEBRA (North East Biosolids and Residuals Association). 2007. A national biosolids regulation, quality, end use and disposal survey-preliminary report. North East Biosolids and Residuals Association. http://www.nebiosolids.org/uploads/pdf/NtlBiosolidsReport-20July07.pdf.

Norrie, J., and A. Gosselin. 1996. Paper sludge amendments for turfgrass. Hort. Science. 31:957-960.

Schnell, R.W., D.M. Vietor, R.H. White, T.L. Provin, and C.L. Munster. 2009 Effects of composted biosolids and nitrogen on turfgrass establishment, sod properties, and nutrient export at harvest. Hort. Sci. 44(6):1746-1750.

Sheard, R.W., and M. Van Patter. 1978. Soil modification during nursery sod production. Dep. of Land Resource Science, Univ. of Guelph, Guelph, ON, Canada.

Skogley, C.R., and B.B. Hesseltine. 1978. Soil loss and organic matter return in sod production. Univ. of Rhode Island, Kingston.

Tesfamariam, E.H., J.G. Annadale, and J.M. Steyn. 2009. Exporting large volumes of municipal sewage sludge through turfgrass sod production. J. Environ. Qual. 38:1320-1328.

USDA 2007. Census of Agriculture. USDA/AC/07/A-51. United States Department of Agriculture, Washington D.C.

USEPA 1983. Process design manual for land application of municipal sludge. USEPA-625/1-83-016. Washington, DC., U.S. Environmental Protection Agency.

USEPA 1998. Biosolids generation, use and disposal in the United States. US EPA/530/r-99/009. United States Environmental Protection Agency Office of Solid Waste, Washington D.C.

USEPA 1993. 40 CFR part 503 Standards for the use and disposal of sewage sludge subpart B Land Application. 503.10 to 503.18. Print., U. S. G. Washington, D.C.

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.

2. Literature Review

2.1. Biosolids Applications

Land application of biosolids can supply crops with inexpensive plant essential nutrients. Biosolids have been found to be more cost effective source of nutrients, especially nitrogen, than inorganic fertilizers (Lagae et al., 2009; Lemainski and Silva, 2006; Faust and Oberst, 1996; Chen et al., 2012). The majority of nitrogen in biosolids must be mineralized before it becomes plant-available. Predicting the mineralization rates of organic-N in biosolids is the biggest concern with land application. If the mineralization rates estimated from biosolids are not accurate, either too little or too much N will be supplied to the crop. Such inaccuracies can result in poor plant growth (too little) or N impairment of the environment (too much). Accurately predicting the availability of nutrients in biosolids is difficult because it is dependent on the biosolids processing method, climate and soil type (Maguire et al., 2001; Gilmour et al., 2003; Cogger et al., 2004; Terry et al., 1979; Clark and Gilmour, 1983; Gilmour and Clark, 1988; Sukkariyah et al., 2007).

One processing method is anaerobic digestion. Anaerobic digestion is a biological treatment process that stabilizes biosolids (Evanylo, 1999). Organic matter decomposes into CO_2 and methane resulting in lower amounts of pathogens, odor and organic matter. The USEPA estimated that 20% of organic-N in anaerobically digested biosolids will be available the first year of application (USEPA, 1983). The EPA also encouraged states to develop their own mineralization estimates, suggesting that processing methods were a reliable indicator of biosolids mineralization rates (USEPA, 1995). Further research on processing methods reported that PAN in the first year of application did not correlate well to just processing method

(Gilmour and Skinner, 1999; Terry et al., 1979; Clark and Gilmour, 1983; Gilmour and Clark, 1988; Sukkariyah et al., 2007)

A study by Gilmour et al. (2003) used results from lab, field and computer modeling studies to determine the mineralization rate of organic-N from an anaerobically digested dewatered cake biosolids that was produced in Virginia (Alexandria Sanitation Authority, Alexandria, VA). The results from this study provide the basis for the mineralization rates for Virginia of 30 to 35%.

Biosolids generators are continually adopting new methods to process wastewater residuals into beneficial products. Some of these new processing methods are aimed at expanding the uses of biosolids by decreasing moisture content, ultimately making them easier to handle. As these new products are developed research investigating the current mineralization estimates with these new products is needed.

2.2. Effects of Using Organic Soil Amendments on Soil and Turfgrass Quality

Soil quality is defined as "the ability of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" and is assessed by measuring indicators like organic matter, water retention and bulk density (Karlen et al., 1997). Previous research has shown that using organic soil amendments, particularly biosolids, can improve soil quality by increasing organic matter and water retention and decreasing bulk density (Lindsay and Logan, 1998; Epstein, 1975; Kelling et al., 1977; Kladivko and Nelson, 1979; Mays et al., 1973). Similar soil improvement results have been reported with organic amendments in turfgrass settings as well. When paper sludge mixtures were used as amendment for turf establishment, there was an increase in soil organic matter (Norrie and Gosselin, 1996). Johnson et al. (2006) reported increased water retention and decreased bulk density when composted biosolids were used to topdress turfgrass. Dunifon et al. (2011) amended severely disturbed urban soils with compost applications and reported soil quality improvements that were related to an increase in soil organic matter and overall availability of soil nutrients.

The turfgrass industry has traditionally used inorganic fertilizers to establish and maintain quality turfgrass because of its relative ease of application and quick plant response. There have been several studies that have compared the effectiveness of inorganic fertilizer to organic fertilizer sources on turfgrass quality. Caceres et al., (2010), evaluated four cool season lawn fertility programs that included three inorganic and one organic program and found no significant differences in turfgrass quality and color between the programs. Carrow (1997) showed that organic N sources fell short in producing immediate and intermediate high quality turfgrass, but there were no differences over the long-term. Norrie and Gosselin (1996) evaluated establishment of plots amended with paper mill sludge mixtures and determined that supplemental nitrogen was needed to address the low nitrogen availability of the amendments. Similar results were reported by Gardner (2004) and Trenholmn and Unruh (2005) evaluating the nutrient value of composted tree mulch and vermicompost. They concluded that a reliable N source rather than estimated N rate was needed to maintain high quality turfgrass.

Biosolids have also been used to establish and maintain turfgrass. Establishment and growth of monocultures and mixed seedings of Kentucky bluegrass (*Poa pratensis* L. 'Cheri', 'Baron', and 'Washington') and perennial ryegrass (*Lolium perenne* L. 'Accent') were enhanced by biosolids more than inorganic fertilizer alone, likely due to more plant available N and P (Loschinkohl and Boehm, 2001). Landschoot and McNitt, (1994) reported similar establishment using composted biosolids compared to inorganic fertilizer in nutrient deficient subsoils. Linde and Hepner (2005) compared the effects of composted biosolids and inorganic fertilizer on seeded Kentucky bluegrass ('Touchdown') establishment. Fall establishment was faster with inorganic fertilizer, but there were no ground cover differences between the fertilizer and biosolids treatments the following spring. Composted biosolids were also shown to increase quality and growth of Kentucky bluegrass ('Nuglade') when topdressing applications were made after core aeration. All of these studies used biosolids in urban settings, investigating establishment and maintenance of turfgrass in its final destination, but establishment from seed is not the only way to establish turfgrass in urban areas, sodding is also commonly used.

Sodding is a more expensive but commonly used establishment practice in the United States. Several studies have evaluated biosolids applications for sod establishment. Schnell et al. (2009) found that Tifway bermudagrass (*Cynodon dactylon* L. Pers. var. dactylon x *C. transvaalensis* Burtt-Davey) coverage eight weeks after sprigging was 64% greater in soils with incorporated than unincorporated composted biosolids. The increase in coverage was attributed to greater sprig survival due to greater soil water retention and nitrogen availability. Tesfamariam et al. (2009) reported good establishment of warm season grass with application rates of heat-dried, anaerobically digested biosolids >8 dry Mg ha^{-1}. The establishment success was attributed to higher plant available nutrients with increasing rates of biosolids. Biosolids are also commonly used as the fertilizer source for cool season sod produced in Rhode Island (Millar et al., 2010). Application rates of 7 dry Mg ha^{-1} are typically used to achieve good turfgrass establishment.

Soil phosphorus increases with repeated applications of biosolids to land, (Chang et al., 1983; Kelling et al., 1977; Maguire et al., 2000). This is due to the high ratio of P to N in biosolids and a resulting over application of P when supplying crop N needs (Ott and Forster, 1978). Soil P accumulation could be reduced with sod harvesting that removes considerable amounts of P; thus, biosolids may be used more frequently in sod culture than other types of turfgrass production.

Vietor et al. (2002) found that 77% of total P and 47% of N was exported at sod harvest after topdressing organic amendments. Schnell et al. (2009) determined that topdressing composted biosolids resulted in more nutrient export compared to when it was incorporated. Tesfaramiam et al. (2009) reported that when anaerobically digested biosolids were applied at ≤67 dry Mg ha^{-1}, there was no accumulation of P in the top 15 cm of soil, concluding that there is significant nutrient removal with each sod harvest. These studies investigated the effects of biosolids on nutrient export and P accumulation using application rates higher than crop nutrient needs. The excessive rates were used to provide sod with essential nutrients to successfully establish once it is transplanted and to export nutrients from areas of high concentrations back to urban areas that traditionally have nutrient deficient soils (Vietor et al., 2010, Richards et al., 2008). There is still more information needed on what will happen to P accumulation when biosolids are incorporated using lower application rates that match crop needs.

Soil export associated with sod harvest has been investigated in several studies, estimating soil export to be in the range of 64-105 Mg ha^{-1} (Skogley and Hesseltine, 1978) and 74-114 Mg ha^{-1} (Millar et al., 2010) for sod harvest at a 1.25 cm depth. There are also several studies that have found soil export to be insignificant, concluding that the residual root biomass from the harvested sod that is left behind actually contributes up to 9 Mg ha^{-1} of soil back to production fields (Sheard and Van Patter, 1978; Skogley and Hesseltine, 1978). Millar et al. (2010) concluded that significant soil export is occurring with sod harvest based on results indicating fields that had been in production the longest had shallower surface soil profiles.

Biosolids for sod production could reduce soil export. Schnell et al. (2009) reported lower dry sod weight when using biosolids compared to inorganic fertilizer and concluded that the less dense biosolids had diluted the surface soil enough to reduce native soil export. Tesfamariam et al. (2009) reported that soil export was eliminated when 100 dry Mg ha^{-1} of biosolids were used and lower rates reduced soil export proportionate to the biosolids application rate. Again these studies used excessive rates of biosolids compared to plant nutritional needs. Biosolids were incorporated in one (Schnell et al., 2009) but not the other (Tesfamariam et al., 2009) study. Research on the effects of biosolids on soil export when lower rates are used and incorporated is still needed.

Overall, research has shown that organic amendments and biosolids can establish and maintain quality turfgrass. Also, the mineralization estimates of biosolids are dependent on many factors including processing method, climate and soil type and Virginia has developed mineralization estimates that work well for common biosolids sources in the state. Research has also shown that land application of biosolids can improve soil quality in agricultural and turfgrass settings. Biosolids can also be used for sod production and because of the soil export at harvest significant nutrients are exported from production fields each year. There is still a need to assess the nutrient availability of new biosolids products as they are developed to see if current mineralization estimates will continue to work. Also, more information is needed on the effects of incorporated applications of N based biosolids rates on soil quality improvements, soil P accumulation and soil export during sod production.

2.4. References

Caceres, V.A., C.A. Bigelow, and D.S Richmond. 2010. Aesthetic and economic impacts associated with four different cool-season lawn fertility and pesticide programs. Horttechnology. 20:418-426.

Carr, M.Y. 1996. Metal levels in Rhode Island municipal sewage sludges and their resulting appropriateness for agricultural use by sod farms. Honors thesis. Brown Univ., Providence, RI.

Carrow, R.N. 1997. Turfgrass response to slow-release nitrogen fertilizers. Agron. J. 89:491-496.

Chang, A.C., A.L. Page, F.H. Sutherland, and E. Grgurevic. 1983. Fractionation of phosphorus in sludge-affected soils. J. Environ. Qual. 12:286–290.

Charbonneau, P. 2003. Soil loss during sod production. Available at www.omafra. gov.on.ca/english/crops/facts/info_sodprod.htm#loss (verified 1 Mar. 2013). Ontario Ministry of Agriculture, Food and Rural Affairs, Ottawa.

Chen, H., S.H. Yan, Z.L. Ye, H.J. Meng, and Y.G. Zhu. 2012. Utilization of urban sewage sludge: Chinese perspectives. Environmental Science and Pollution Research. 19:1454-1463.

Clark, M.D., and J.T. Gilmour. 1983. The effect of temperature on decomposition at optimum and saturated soil water contents. Soil Sci. Soc. Am. J. 47:927–929.

Cogger, C.G., A.I. Bary, D.M. Sullivan, and E.A Myhre. 2004. Biosolids processing effects on first- and second-year available nitrogen. Soil Sci. Soc. Am. J. 68:162–167.

Dunifon, S.N., G.K. Evanylo, R.O. Maguire, and J.M. Goatley, Jr. 2011. Soil nutrient and fescue (Festuca spp.) responses to compost and hydroseed on a disturbed roadside. Compost Science and Utilization. 19:147-151.

Epstein, E. 1975. Effect of sewage sludge on some soil physical properties. J. Environ. Qual. 4:139-142.

Evanylo, G. K. 1999. Agricultural land application of biosolids in Virginia: production and characteristics of biosolids. Virginia Cooperative Extension. Pub. 452-304.

Faust, T.G., and R.L Oberst. 1996. Economic value of biosolids to farmers. Biocycle. 37:67-69.

Gardner, D.S. 2004. Use of vermicomposted waste materials as a turfgrass fertilizer. Hort. Technology. 14:372-375.

Gilmour, J.T., and M.D. Clark. 1988. Nitrogen release from wastewater sludge: A site-specific approach. J. Water Pollut. Control Fed. 60:494–498.

Gilmour, J.T., C.G. Cogger, L.W. Jacobs, G.K., Evanylo, and D.M. Sullivan. 2003. Decomposition and plant-available nitrogen in biosolids: Laboratory studies, field studies, and computer simulation. J. Environ. Qual. 32:1498–1507.

Johnson, G.A., Y.L. Qian, and J.G. Davis. 2009. Topdressing Kentucky bluegrass with compost increases soil water content and improves turf quality during drought. Compost Science and Utilization. 17:95-102.

Karlen, D. L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4-10.

Kelling, K.A., A.E. Peterson, and L.M. Walsh. 1977. Effect of wastewater sludge on soil moisture relationships and surface runoff. J. WPCF. 49:1698-1703.

Kelling, K.A., L.M. Walsh, D.R. Keeney, J.A. Ryan, and A.E. Peterson. 1977. A field study of the agricultural use of sewage sludge: II. Effect on soil N and P. J. Environ. Qual. 6:345–352.

Kladivko, E.J., and D.W. Nelson. 1979. Changes in soil properties from application of anaerobic sludge. J. WPCF. 51:325-332.

Lagae, H.J., M. Langemeier, D. Lybecker, and K. Barbarick. 2009. Economic value of biosolids in a semiarid agroecosystem. Agron. J. 101:933-939.

Landschoot, P., and A. McNitt. 1994. Improving turf with compost. BioCycle. 35:54-57.

Linde , D.T., and L.D. Hepner. 2005. Turfgrass seed and sod establishment on soil amended with biosolids compost. Horttechnology. 15:577-583.

Lindsay, B. J., and T.J. Logan. 1998 Field response of soil physical properties to sewage sludge. J. Environ. Qual. 27:534–542.

Lemainski, J., and J.E. da Silva. 2006. Agronomic and economic evaluation of biosolids application on soybean production. Pesquisa Agropeauaria Brasileira. 41:1477-1484.

Loschinkohl, C., and M.J. Boehm. 2001. Composted biosolids incorporation improves turfgrass establishment on disturbed urban soils and reduces rust severity. Hort. Sci. 36(4):790-794.

Maguire, R.O., J.T. Sims, and F.J. Coale. 2000. Phosphorus solubility in biosolids-amended soils in the Mid-Atlantic region of the USA. J. Environ. Qual. 29:1225–1233.

Maguire, R. O., J.T. Sims, S.K. Dentel, F.J. Coale, and J.T. Mah. 2001. Relationships between biosolids treatment process and soil phosphorus availability. J. Environ. Qual. 30: 1023-1033.

Mays, D.A, G.L. Terman, and J.C. Duggan. 1973. Municipal compost: Effect on crop yield and soil properties. J. Environ. Qual. 2:89-91

Millar, D., M. Stolt, and J.A. Amador. 2010. Quantification and implications of soil losses from commercial sod production. Soil Sci. Soc. Am. J. 74:892-897.

Norrie, J., and A. Gosselin. 1996. Paper sludge amendments for turfgrass. Hort. Science. 31:957-960.

Richards, C.E., C.L. Munster, D.M. Vietor, J.G. Arnold, and R. White. 2008. Assessment of a turfgrass sod best management practice on water quality in a suburban watershed. J. Environ. Management. 86:229-245.

Schnell, R.W., D.M. Vietor R.H. White, T.L. Provin, and C.L. Munster. 2009 Effects of composted biosolids and nitrogen on turfgrass establishment, sod properties, and nutrient export at harvest. Hort. Sci. 44(6):1746-1750.

Sheard, R.W., and M. Van Patter. 1978. Soil modification during nursery sod production. Dep. of Land Resource Science, Univ. of Guelph, Guelph, ON, Canada.

Sukkariyah, B., G. Evanylo, and L. Zelazny. 2007. Distribution of copper, zinc, and phosphorus in coastal plain soils receiving repeated liquid biosolids applications. J. Environ. Qual. 36: 1618-1626.

Terry, R.E., D.W Nelson, and L.E. Sommers. 1979. Decomposition of anaerobically digested sewage sludge as affected by soil environmental conditions. J. Environ. Qual. 8:342–347.

Tesfamariam, E.H., J.G. Annadale, and J.M. Steyn. 2009. Exporting large volumes of municipal sewage sludge through turfgrass sod production. J. Environ. Qual. 38:1320-1328.

Trenholm, L. E., and J.B. Unruh. 2005. Warm-season turfgrass response to fertilizer rates and sources. J. Plant Nutrition. 28:991-999.

USEPA 1983. Process design manual for land application of municipal sludge. USEPA-625/1-83-016. Washington, DC., U.S. Environmental Protection Agency.

USEPA 1995. Process design manual: Land application of sewage sludge and domestic septage. USEPA Rep. 625/R-95/001. USEPA. Washington, D.C., U.S. Gov. Print.

Office.

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.

Vietor, D.M., R.W. Schnell, C.L. Munster, T.L. Provin, and R.H. White. 2010. Biosolid and alum effects on runoff losses during turfgrass establishment. Bioresource Technology. 101:3246-3252.

3. Evaluation of a Biosolids-based Tall Fescue-Kentucky Bluegrass Sod Production System in Virginia

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3.1. Abstract

Biosolids can be used to establish and maintain quality turfgrass, but the effectiveness of a N-based biosolids sod production system warrants further investigation. The objective of this study was to compare processing methods and application rates of anaerobically digested biosolids and an inorganic fertilizer control on agronomic parameters related to turfgrass sod production. The study was conducted on a sod farm in Remington, Virginia on a silt loam Ashburn-Dulles complex from 2009 to 2012. The biosolids products were applied at estimated plant available nitrogen (PAN) rates of 98 kg ha^{-1} (0.5X), 196 kg ha^{-1} (1.0X), 294 kg ha^{-1} (1.5X) for a tall fescue (*Festuca arundinacea* Schreb. 'Rebel Exeda', 'Rebel IV' and 'Justice')/ Kentucky bluegrass (*Poa pratensis* L. 'Midnight') mixture (85/15 % by weight) and plots were seeded at 236 kg ha^{-1}. One biosolids product was a dewatered cake applied at 15, 30.5 and 46 wet Mg ha^{-1}. The second biosolids product was the same dewatered cake blended with wood fines applied at 17, 34 and 51 wet Mg ha^{-1}. The biosolids treatments were compared to an inorganic fertilizer control that supplied 196 kg N ha^{-1} through three applications over the production cycle. There were no differences in establishment between the cake biosolids treatments and the inorganic fertilizer control, but all of the blended biosolids were slower to establish. Only the 1.0X and 1.5X PAN rates from the cake biosolids matched the inorganic fertilizer control in producing an acceptable quality sod in ten months. Lower nitrogen uptake between the blended biosolids treatments compared to the inorganic fertilizer control and lower although acceptable sod quality ratings at harvest of the 1.0X cake biosolids indicate our PAN estimates of 30% organic nitrogen mineralization overestimated the PAN for both materials. There were no differences in biomass yields between the 1.5X cake biosolids treatment and the inorganic fertilizer control. The rest of the biosolids treatments yielded less biomass than the

fertilizer control. There were no differences in sod tensile strength between the 1.5X cake biosolids and inorganic fertilizer control, but the other biosolids treatments gave lower tensile strength. There were no differences in transplant rooting strength among all treatments. A one-time application of anaerobically digested dewatered biosolids cake at the 1.5X rate was able to produce sod comparable to inorganic fertilizer. Supplemental nitrogen may be needed to improve the performance of the 1.0X cake biosolids rate, which is also the upper limit of biosolids application for sod production in Virginia.

3.2. Introduction

In recent years the cost of sod production has increased because of the rising prices of inorganic fertilizer and fuel (NASS, USDA, 2011). At the same time, wastewater treatment facilities have been dealing with the rising costs of sewage sludge disposal. Because organic sources of nutrients, including biosolids, can be used to successfully establish turfgrass (Dunifon et al., 2011, O'Brien and Barker, 1996; Richards et al., 2008; Wright, 2007), the beneficial use of these organic residuals could alleviate wastewater sludge disposal limitations while providing inexpensive alternative nutrient sources for sod growers.

Due to fewer land application restrictions and ease of handling, composted biosolids have been the predominant type of biosolids used in urban turfgrass settings. A comparison between the effects of composted biosolids and inorganic fertilizer on seeded Kentucky bluegrass (*Poa pratensis* L. 'Touchdown') establishment was studied by Linde and Hepner (2005). Fall establishment was faster with inorganic fertilizer, but there were no ground cover differences between the fertilizer and biosolids treatments the following spring. They concluded that biosolids provided long-term supply of nutrients. Establishment and growth of monoculture and mixed seedings of Kentucky bluegrass ('Cheri', 'Baron', and 'Washington') and perennial ryegrass (*Lolium perenne* L. 'Accent') were enhanced by biosolids more than inorganic fertilizer alone, likely due to more plant available N and P (Loschinkohl and Boehm, 2001). Schnell et al. (2009) found that bermudagrass (*Cynodon dactylon* L. Pers. var. dactylon x *C. transvaalensis* Burtt-Davey) coverage eight weeks after sprigging was 64% greater in soils that had incorporated composted biosolids than those without. The increase in coverage was attributed to greater sprig survival due to increased soil water retention and nitrogen availability.

Although biosolids use has been shown to successfully establish turfgrass, there has been little research on biosolids for sod production (Schnell et al., 2009; Tesfamariam et al., 2009). Sod is produced in rural areas, lending itself for the use of non-composted biosolids. The use of non-composted biosolids for sod production was studied by Tesfamariam et al. (2009). They found that when heat-dried anaerobically digested biosolids were applied at rates estimated to exceed turfgrass nutrient needs, there were no detrimental effects on growth or establishment. Rates above the South African upper limit of 8 dry Mg ha^{-1} enhanced turfgrass establishment. The use of biosolids for sod production also improves sod properties by increasing turfgrass quality and tensile strength at harvest (Schnell et al., 2009; Tesfamariam et al., 2009).

The application rates commonly recommended for sod production in Virginia are based on biosolids mineralization estimates for composted and anaerobically digested and dewatered biosolids (Virginia Department of Conservation and Recreation, 2005), but PAN is often unknown for alternative biosolids products that are constantly being developed for urban use. Such Exceptional Quality (EQ) products, (USEPA, 1993), can be used in public access settings due to their low pollutant concentrations and pathogen-free status.

The PAN of the anaerobically digested, dewatered cake biosolids from the Alexandria Sanitation Authority (Alexandria, VA) has been tested in previous lab and field studies (Gilmour et al., 2003). Based on those results the biosolids mineralization estimates for the state of Virginia are 30-35%. Although the Alexandria biosolids are de-watered, they have moisture contents ~700 g kg^{-1}. To further reduce this water content, enabling ease of handling in urban areas, and expanding the use of this EQ biosolids product, wood fines were blended with the cake. This lowered the moisture content to around 300 g kg^{-1} and increased the C:N ratio to

~15:1, which was expected to reduce nitrogen availability. Both the de-watered cake and blended product will be evaluated in our study.

Nitrogen availability and turfgrass-enhancing value of such newly developed EQ biosolids products warrant research because such uses are novel. Commonly used composts differ from non-composted products in N availability (Eghball, 2000; Flavel and Murphy, 2006), and few studies have evaluated EQ non-composted biosolids for turf production. The objective of this study was to compare processing method and application rates of two biosolids products and an inorganic fertilizer control on agronomic parameters related to turfgrass quality in sod production.

3.3. Materials and Methods

Site, experimental design, and treatment establishment

The study was conducted on a sod farm in Remington, VA (Lat. +38.51417, Long. -77.811717) on a silt-loam Ashburn-Dulles complex (*Fine-silty, mixed, active, mesic Oxyaquic Hapludalfs*). The study was conducted from the fall of 2009 until the summer of 2012. Mean monthly temperature and precipitation for the duration of the study were obtained from nearby weather stations (NOAA, 2013).

The study consisted of seven treatments, each replicated 4X and arranged in a randomized complete block design. The treatments included three rates (0.5X, 1.0X and 1.5X agronomic N rate) of each of two types of biosolids and a fertilizer control, according to Virginia Tech Soil Testing Laboratory recommendations (Donohue and Heckendorn, 1994). The 0.5X, 1.0X, and 1.5X treatments were designed to apply 98 kg ha^{-1}, 196 kg ha^{-1}, and 294 kg ha^{-1} of plant available nitrogen (PAN), respectively. Plot dimensions were 61 m by 11 m, which necessitated biosolids applications made using a commercial side-discharge manure spreader.

An EQ anaerobically digested, dewatered biosolids cake (Alexandria Sanitation Authority, Alexandria, VA) and the same material blended with wood fines (blended by Synagro, Inc., Champlain, VA) at a 1:0.65 by weight ratio of biosolids to wood fines were used. Biosolids were applied in the fall (Aug. 26, 2009, Sept. 8, 2010, and Oct. 12, 2011) of each year based on their estimated supply of plant available nitrogen assuming 30% of the organic nitrogen is mineralized in the first year (Virginia Department of Conservation and Recreation, 2005). Although the organic nitrogen content and application rate of the biosolids varied slightly from year to year the three-year mean biosolids rates were 15, 30.5 and 46 wet Mg ha^{-1} of cake biosolids, respectively, and 17, 34 and 51 wet Mg ha^{-1} of blended biosolids, respectively. The inorganic fertilizer control treatment supplied 196 kg N ha^{-1}, whose application was split to provide 74 kg N ha^{-1} (as urea and diammonium phosphate, DAP) at seeding, 74 kg N ha^{-1} (as calcium ammonium nitrate) in mid-October, and 48 kg N ha^{-1} (as calcium ammonium nitrate) in late-April. The DAP rate was calculated to meet the soil test recommended amount of phosphorus and incorporated to a depth of five cm.

Samples from each biosolids source were collected at application dates and sent to A&L Eastern Laboratories in Richmond, VA and analyzed for total solids (SM-2540G), total Kjeldahl N (SM-4500- TKN), ammonium-N (SM-4500-NH3) (Standard Methods for the Examination of Water and Wastewater, 1992), phosphorus (SW-846-6010C), potassium (SW-846-6010C) (U.S. Environmental Protection Agency, 1986), and other macro and micro nutrients. The cake biosolids was composed of 339 g kg^{-1} C, 5l.1 g kg^{-1} TKN, 35.6 g kg^{-1} P, 1.5 g kg^{-1} K and had a moisture content around 700 g kg^{-1}. The blended biosolids were composed of 230 g kg^{-1} C, 15.0 g kg^{-1} TKN, 9.7 g kg^{-1} P, 2.6 g kg^{-1} K and had a moisture content ~300 g kg^{-1}. The 0.5X, 1.0X and 1.5X cake biosolids rates applied 117, 235 and 352 kg of estimated PAN ha^{-1} respectively;

154, 308 and 462 kg P ha^{-1} respectively; and 1,525, 3,051, and 4,576 kg C ha^{-1} respectively. The 0.5X, 1.0X and 1.5X blended biosolids rates applied 90, 180 and 270 kg of estimated PAN ha^{-1} respectively; 105, 210 and 315 kg P ha^{-1} respectively; and 2,530, 5,060, and 7,820 kg C ha^{-1} respectively.

All plots were seeded with a Brillion Turfmaker (Brillion Farm Equipment, Brillion, WI) at 236 kg ha^{-1} with an 85% tall fescue (*Festuca arundinacea* Schreb. 'Rebel Exeda' 'Rebel IV' and 'Justice')/ 15% Kentucky bluegrass (*Poa pratensis* L. 'Midnight') mixture, by weight. Plots were seeded Sept. 2 in 2009; Sept. 14 in 2010; Oct. 12 in 2011. Plots were maintained at a 7.6 cm height throughout the growing season and clippings were returned.

Sampling and analysis

In the fall of 2009 soil cores with a 1.9 cm diameter were randomly collected from the 0-10 cm depth at the study site, air-dried, ground to pass through a 2 mm sieve and sent to Virginia Tech Soil Testing Laboratory for routine soil test analysis of Mehlich 1 extractable P, K, and pH and Walkley-Black soil organic matter content (Maguire and Heckendorn, 2011). Results indicated a pH of 6.1, extractable P and K of 12 mg kg^{-1} and 43 mg kg^{-1} respectively and soil organic matter content of 32 mg kg^{-1}. Fertilizer P recommendations for the inorganic fertilizer control plots and K recommendations for all treatments were made using soil testing results (Virginia Department of Conservation and Recreation, 2005). Establishment was tracked using digital image analysis (DIA) from three sample locations per plot every two weeks from seed germination to >95% cover. Sampling dates were Oct. 27, Nov. 10, Nov. 24 and Dec. 1 in 2009; Oct. 12, Oct. 26 and Nov. 8 in 2010; Nov. 17 in 2011 and Mar. 15, Apr. 12 and May 24 in 2012. The images were taken with a Canon Powershot 3.1 mega pixel digital camera (Melville, NY) and analyzed using SigmaScan® software (Systat Software Inc., San Jose, CA) with a macro developed specifically to analyze percent turfgrass cover (Richardson et al., 2001). The digital pictures were taken in a controlled environment created by using a light-box that simulates daylight wavelengths at high noon (standard method for DIA).

Turfgrass quality of the entire plot was visually rated every two weeks after >95% cover was reached. Rating dates were Mar. 23, Apr. 20, May 18 and Jun. 15 in 2010; Apr. 8, May 6, Jun. 3, and Jul. 1 in 2011; May 25, Jun. 22, Jul. 20 and Aug. 17 in 2012. Quality was rated on a 1-9 index scale with 1 being poorest turfgrass quality and 9 being perfect turfgrass; a commercially acceptable value was set at 6 (Morris, 2004).

Broadleaf weed pressure measurements were made Apr. 20 in 2010, Apr. 8 in 2011 and Apr. 13 in 2012 using the line intersect method (Laycock and Canaway, 1980). A 1.2 m^2 quadrat was randomly placed in five locations within each plot. The number of intersects where weed species were found was divided by the total number of intersects in the quadrant for a percentage of broadleaf weeds. One day after measurements, the broadleaf weeds were treated with 1.1 kg 2,4-D (2,4-dichlorophenoxyacetic acid) ha^{-1}.

Disease ratings were made Apr. 20, May 18 and Jun. 15 in 2010; May 6, Jun. 3, and Jul. 1 in 2011; May 25, Jun. 22, Jul. 20 and Aug. 17 in 2012. Disease damage was rated on a 1-9 scale with 1 being 100% damaged turf and 9 being no injury (Morris, 2004).

Turfgrass clippings for biomass yield were collected monthly when the slowest growing plot reached a height of 10 cm. Clipping yields for a seven day period were determined on a 1.8 m by 0.45 m area in each plot with a HRX217VKA Honda (America Honda Power Equipment Division, Alpharetta, GA) gasoline powered walk-behind rotary mower. The clippings were dried to a constant weight at 55°C, cleaned of any non-clipping debris and weighed. Sampling dates were May 18 and Jun. 15 in 2010; May 6, Jun. 3, and Jul. 1 in 2011; Jun. 22, Jul. 20 and Aug. 17 in 2012.

Sub-samples from each clipping sample date were analyzed for carbon and nitrogen by gas analysis using high heat combustion at 1200°C in a Vario Max CNS macro elementar analyzer (Elementar, GER). Nitrogen uptake for each sampling date was determined by multiplying N concentration (g N kg^{-1}) in the turfgrass tissue by the dry mass clipping yield (kg ha^{-1}) for each treatment.

Sod was harvested 10 months, or 40 weeks, after seeding using a Trebro Autostack automatic harvester (Trebro Mfg. Inc., Billings, MT) and transported to the Turfgrass Research Center at Virginia Tech for processing. Sod harvest depth in year one was 2.54 cm; harvest depth was 1.9 cm in years two and three. The tensile strength of three pieces of sod, 91 cm by 61 cm, randomly harvested from each plot, was measured using a sod stretcher (Goatley and Schmidt, 1991).

Transplant rooting strength was measured on three pieces of sod, 30.5 cm by 30.5 cm. Pieces were randomly selected from each plot and placed on rooting frames situated on bare mineral soil (Groseclose silt loam) to simulate new establishment (Schmidt et al., 1986). The sod pieces were hand-watered with 0.64 cm of water daily for one week and then as needed for three weeks. After a four week establishment period, hooks were attached to the corners of the rooting frames and the force required to free the pieces of sod from the ground was measured using a Chatillon hand held force gauge (Chatillon, Largo, FL).

Establishment, nitrogen uptake, turfgrass quality, clipping yields, sod tensile strength and transplant rooting strength data were subjected to analysis of variance using SAS Proc GLM (SAS Institute, 2008) to test the effects of treatments on agronomic parameters related to sod production. Means were separated using a Protected LSD at $P \leq 0.05$. There were significant year by treatment interactions for all parameters measured. Each year of turfgrass establishment, nitrogen uptake, quality, clipping yield, sod tensile strength and transplant rooting strength date are presented separately.

3.4. Results and Discussion

3.4.1 Temperature and precipitation

Average temperature and precipitation per month at the site is shown in Table 3.1. The 30 year average temperature for the site was 12.9 °C and the 30 year average rainfall was 105.5 cm. Average rainfall for each production cycle was 86.6 cm with a range of +/- 2.9. Weather conditions delayed seed germination in 2009. Plots were seeded the first week of September, but the study site did not receive adequate rainfall to promote germination until the end of the month. Weather conditions also delayed seeding in 2011. Plots were not seeded until mid-October because of rainfall on scheduled biosolids application dates postponed application. The delayed seeding in 2011 altered the inorganic fertilization schedule.

3.4.2. Biosolids composition and application

The properties of the two biosolids are shown in Table 3.2. The cake biosolids had more than three times the amount of TKN, NH_4^+-N, organic-N and total P than the blended biosolids. Although the amounts of N and P were three times greater in the cake biosolids, the ratio of N:P was similar for both products (1.5:1). The target and mean estimated actual PAN applied each year of the study are shown in Table 3.3, along with the applied total P and K. The target N rates were not exactly achieved with the two biosolids products. The application method was difficult to calibrate for the low amounts of product being applied at the 0.5X agronomic N rates and resulted in slightly over applying the estimated N in the cake biosolids treatments and slightly under applying the estimated N in the blended biosolids treatments.

3.4.3. Turfgrass establishment

In year one, germination was delayed because of lack of moisture (Table 3.4) despite the early season planting date. There were no differences in vegetative cover among the biosolids treatments and the inorganic fertilizer control until 11 weeks after seeding (WAS). From 11 through 13 WAS, there was less vegetative cover in the 0.5X cake, 0.5X and 1.0X blended biosolids treatments than in the inorganic fertilizer control. These dates correspond to the middle and end of November respectively.

In year two plots were seeded in the middle of September. Timely rainfall enabled the mid-September-seeded plots to establish rapidly. At four WAS, the 0.5X and 1.0X cake and blended biosolids treatments had lower vegetative cover compared to the inorganic fertilizer control, but those differences declined as establishment continued. The only treatment at 8 WAS that had lower vegetative cover than the inorganic fertilizer control was the 0.5X blended biosolids treatment.

Year three seeding (mid-October) was delayed because there was standing water on the study site the day biosolids were scheduled to be applied. This, combined with biosolids availability issues afterwards, further delayed application. In the two previous years all of the plots had reached greater than 75% vegetative cover by the end of November, after which no further establishment measurements were done. Because of the late seeding in year three, only one establishment measurement was performed in the fall, and additional measurements were made the following spring. At five WAS, there were no differences among treatments (Table 3.4). At 22 WAS, there were no differences among the 0.5X and 1.0X cake biosolids treatments and inorganic fertilizer control. At this time, there was lower vegetative cover for all of the blended biosolids treatments, and higher vegetative cover for the 1.5x cake biosolids treatment compared to the inorganic fertilizer control. After the second application of inorganic fertilizer (22 WAS), there were no differences in vegetative cover between the cake biosolids treatments and the inorganic fertilizer control. However, there was less vegetative cover in the blended biosolids treatments than in the inorganic fertilizer control. Adequate turfgrass coverage during the establishment period was limited by the late seeding date the most in the blended biosolids treatments.

The data indicate that lower application rates of the blended biosolids resulted in turfgrass establishment at a slower rate than the inorganic fertilizer control; however, there were no differences in establishment rates between the cake biosolids treatments and inorganic fertilizer. These results support the conclusion that we better estimated the PAN from the anaerobically digested, dewatered cake than from the blended biosolids, if the limitation in establishment was due to inadequate nitrogen.

There has been very little research on turfgrass establishment using non-composted biosolids. Linde and Hepner (2005) found that a one-time fertilizer application treatment at seeding resulted in a better establishment rate than composted biosolids alone. When composted biosolids treatments with a starter fertilizer were compared to treatments with just inorganic fertilizer, enhanced turfgrass establishment occurred with the composted biosolids treatments (Loschinkohl and Boehm, 2001, Schnell et al., 2009). The starter fertilizer was used to overcome the slowly available nitrogen in the composted organic materials (Flavel and Murphy, 2006). These results suggest that there is a PAN and turfgrass N need synchrony issue with composted biosolids and they are not as effective for turfgrass establishment when applied at a similar estimated PAN rate as inorganic fertilizer unless a starter fertilizer is used.

The results of our study are similar to Tesfamariam et al. (2009), who used oven-dried anaerobically-digested biosolids at varying application rates, at and above estimated turfgrass nutritional needs, and reported good turfgrass establishment with rates as low as 8 dry Mg ha^{-1}. Although application rates and biosolids moisture varied slightly, on average each year in our study we applied 4.5, 9 and 13.5 dry Mg ha^{-1} of cake biosolids and 11, 22 and 34 dry Mg ha^{-1} of blended biosolids with our 0.5X, 1.0X and 1.5X rates respectively. Tesfamariam et al. (2009) also reported an increased rate of establishment with higher biosolids rates and suggested that production time could be decreased when using higher application rates. Higher than plant estimated nutrient need biosolids rates were also tested in our study, but we did not see similar results, most likely because our highest rates were more than 65 dry Mg ha^{-1} less than the highest rate used in Tesfamariam et al. (2009). Our results support previous literature (Loschinkohl and Boehm, 2001; Schnell et al., 2009; Linde and Hepner, 2005; Tesfamariam et al., 2009) reporting that commercially acceptable turfgrass establishment is dependent on the biosolids source, particularly on how it has been processed after treatment.

3.4.4. Nitrogen uptake

Nitrogen uptake as kg N ha^{-1} was measured from turfgrass clipping yields collected in the spring of each year (Table 3.5). In year one, the inorganic fertilizer control N uptake was higher than all of the biosolids treatments at 36 WAS. By 40 WAS, there was no difference in N uptake between the 1.5X cake biosolids and the inorganic fertilizer control. All other biosolids treatments resulted in lower N uptake.

In year two, there were no differences among the 1.0X, 1.5X biosolids treatments and the inorganic fertilizer control across all sampling dates (32, 36 and 40 WAS). All other biosolids treatments had lower N uptake (Table 3.5).

In year three, the 1.5X biosolids treatment had higher nitrogen uptake than the inorganic control at 32 WAS. There were no differences in uptake among the other biosolids treatments and the inorganic fertilizer control. At 36 WAS, the 1.0X and 1.5X cake biosolids treatments had higher nitrogen uptake than the inorganic fertilizer control, and there were no uptake differences among the inorganic fertilizer control and the rest of the biosolids treatments. By 40 WAS, nitrogen uptake by the 1.5X cake biosolids treatment was higher than the inorganic fertilizer control, and there were no differences among the rest of the biosolids treatments and inorganic fertilizer control.

The nitrogen uptake results indicate that the low rates of cake and blended biosolids had lower nitrogen availability than the inorganic fertilizer control. This was expected since the low rates of biosolids were only estimated to supply about half of the PAN as the inorganic fertilizer control. The lower nitrogen uptake from the 1.0X and 1.5X blended biosolids than the inorganic fertilizer control was unexpected. We suspect that the estimated PAN in the blended biosolids product was lower due to greater N immobilization by the high carbon-containing, fine particle-sized, wood fines that were blended with the dewatered cake. The nitrogen uptake of the 1.0x and 1.5X cake biosolids was similar to the inorganic fertilizer control, indicating that these biosolids mineralized similar PAN as the inorganic fertilizer control and support our 30% mineralization PAN estimate for the anaerobically digested, dewatered cake biosolids. Also, our results show that, as temperature increased and with adequate rainfall (Table 3.1), there was a noticeable increase in turfgrass quality among all of the biosolids treatments. This increase was also shown with the inorganic fertilizer control and correlates to the spring application of fertilizer. This trend and the ability of the 1.0X and 1.5X cake biosolids rates to produce acceptable quality sod indicate that the N availability of the cake biosolids in Remington, VA matches the growth pattern of tall fescue-Kentucky bluegrass sod.

3.4.5 Turfgrass quality

The first turfgrass quality rating in year one was not taken until mid-March (28 WAS) because of the slow growth and suspected slower mineralization rates during the winter months (Table 3.6). The only treatment that had lower turfgrass quality than the inorganic fertilizer control was the 0.5X blended biosolids treatment. At 32 WAS and through sod harvest all of the biosolids treatments except the 1.5X cake biosolids treatment had lower turfgrass quality than the inorganic fertilizer control. And only the 1.0X and 1.5X cake biosolids treatments and inorganic fertilizer control had acceptable quality at harvest. These results, supported by the differences in our nitrogen uptake results, indicate that the amount of PAN that had mineralized from the blended biosolids and low cake biosolids treatments was not enough to produce an acceptable quality sod. We expected the quality ratings of the 1.0X and 1.5X biosolids treatments from each biosolids source to be similar to the inorganic fertilizer control because we calculated 1.0X biosolids rates to provide a similar amount of PAN as the inorganic fertilizer. The lower quality ratings with the blended biosolids treatments may not have occurred because of inadequate total PAN, but instead caused by poor synchrony between the spring and early summer tall fescue-Kentucky bluegrass N needs and PAN.

In year two, all biosolids treatments, except 1.5X cake, had lower quality ratings than the inorganic fertilizer at 28 WAS (early April) (Table 3.6). Following the final inorganic fertilizer application at 30 WAS, all of the blended biosolids and the 0.5X and 1.0X cake biosolids had lower quality ratings than the inorganic fertilizer control at 32 WAS and 36 WAS. Only the 1.0X and 1.5X cake biosolids treatments and the inorganic fertilizer control had acceptable turfgrass quality at harvest, and there were no differences in quality ratings among treatments. The results from year two continue to support the conclusions that there is a PAN and turfgrass N need synchrony issue with the blended biosolids and that the 0.5X biosolids treatments did not provided enough N to produce an acceptable quality sod.

In year three, a quality rating at 28 WAS (mid-May) was made due to delays in seeding and the inorganic fertilization. At 28 and 32 WAS, all biosolids treatments except the 1.5X cake had lower quality ratings than the inorganic fertilizer control (Table 3.6). After the second application of inorganic fertilizer (28 WAS), only the blended biosolids treatments had lower turfgrass quality ratings than the inorganic fertilizer control at 36 WAS. The quality ratings of the 0.5X and 1.0X cake biosolids treatments were not different than the inorganic fertilizer control, which were lower than the 1.5X cake. Following the final application of inorganic fertilizer (36 WAS), harvest quality ratings were not different between the 1.0X cake and the inorganic fertilizer control, which was lower than the 1.5X cake treatment. Only the 1.0X, 1.5X cake biosolids and the inorganic fertilizer control had acceptable quality ratings at harvest.

Similar to the previous year, the 1.0X cake biosolids treatment and inorganic fertilizer control had similar quality ratings at harvest. The inorganic ratings were barely acceptable, which was not the case in years one and two. The lower quality ratings can most likely be attributed to the altered fertilization schedule. The last fertilization did not occur until the first week of July and the turfgrass may have already been under heat stress and not able to efficiently use the available nitrogen. The lower nitrogen uptake of the inorganic fertilizer treatment at harvest in year three supports this conclusion. These results suggest there could be a non-nutritive benefit to using biosolids during times of plant stress as reported by Zhang et al. (2009). The results from year three still support the conclusion that there is a PAN and turfgrass N need synchrony issue with the blended biosolids treatments.

Quality ratings combine color, density and texture of a turfgrass stand into one rating. The below acceptable quality ratings measured in our study with the blended biosolids treatments and the 0.5X cake biosolids treatment are attributed to poor stand density. In year three, the lower quality ratings for the inorganic fertilizer control was attributed to poor color. Because of the altered fertilization schedule, the inorganic fertilizer plots were slightly yellow at harvest. The 1.0X cake biosolids quality ratings at harvest were acceptable each year, but usually lower than the inorganic fertilizer control. Although the color ratings were acceptable, the lower quality ratings with this treatment were attributed to lower density than the 1.5X cake biosolids and inorganic fertilizer control treatments.

Limited research has investigated turfgrass quality during the growing season using non-composted biosolids, but previous research on composted biosolids plus inorganic fertilizer demonstrate increased turfgrass quality compared to using inorganic fertilizer alone (Loschinkohl and Boehm, 2001; Schnell et al., 2009; Garling and Boehm, 2001). Tesfamariam et al. (2009) showed increased turfgrass quality with increasing rates of anaerobically digested biosolids. The biggest concern with using anaerobically digested biosolids to produce sod is matching the estimation of PAN to the actual mineralization rate throughout the growing season. Our quality results support the conclusion that the use of 30% organic nitrogen mineralization in the first year overestimated the PAN of the cake biosolids.

3.4.6. Weed and Disease Pressure

There were no differences in weed pressure among treatments all three years of the study (data not shown). Percent weed coverage was determined in mid-April each year and plots were treated with herbicide after measurements were made. Significant weed populations were not present at harvest each year. Previous research has shown that composted biosolids mulches can suppress weeds (Persyn et al., 2007; Roe et al., 1993; Stoffella et al., 2000), but when biosolids are incorporated the suppression effects diminish (Persyn et al., 2007). In turfgrass establishment settings on disturbed soils, Dunifon et al. (2011) saw that a one-time compost blanket did not suppress broadleaf weed coverage, but Linde and Hepner (2005) reported weed suppression when plots were amended with composted biosolids compared to plots that only received inorganic fertilizer. They attributed the suppression to the greater availability of N in biosolids amended plots allowing the turfgrass to out-compete weeds.

Disease ratings were taken every two weeks when active disease was noticed at the study site. The only disease that was rated during the study was brown patch (*Rhizoctonia solani* Kühn). There were no differences in disease pressure among treatments all three years of the study and disease symptoms were not evident at harvest (data not shown). Our results differed from previous studies that reported disease suppression effects when using organic amendments. Craft and Nelson (1996) reported Pythium root rot (*Pythium spp.*) suppression when seeding turfgrass into biosolids amended root zones. Topdressing with compost has been reported to suppress dollar spot (*Sclerotinia homoeocarpa* Bennett) (Boulter et al., 1999, Nelson and Craft, 1992), brown patch (Nelson and Craft, 1991a) and red thread (*Laetisaria fusiformis* McAlpine) (Nelson and Craft, 1991b). The mechanism of organic amendments suppressing disease is not well understood, and in some cases may just be the result of an increase in available nutrients promoting a healthier growing turfgrass that is more resistant to disease (Loschinkohl and Boehm, 2001).

3.4.7. Turfgrass Clipping Yield

Clipping weights were taken in the spring when the turfgrass was actively growing (Table 3.7). Each clipping yield represents one week of growth. Clipping yields were taken monthly until harvest. There were only two measurement dates for clipping yields in year one due to delayed germination from lack of fall moisture. At 36 and 40 WAS, there were no differences among the 1.5X cake and blended biosolids clipping yields compared to the inorganic fertilizer control. There were no differences among the 1.0X and 1.5X cake biosolids treatments and the inorganic fertilizer control at 32 WAS and 36 WAS in year two. At 40 WAS there were no differences among the 1.0X and 1.5X cake, the 1.5X blended and the inorganic fertilizer control. There were no differences among the 0.5X and 1.0X cake biosolids, the 0.5X and 1.5X blended biosolids, and the inorganic fertilizer control at 32 WAS in year three. The 1.5X cake biosolids treatment had higher yields and the 1.0X blended biosolids treatment had lower yields than the inorganic fertilizer control. There were no differences among the 0.5X and 1.0X cake biosolids, the blended biosolids, and the inorganic fertilizer control at 36 and 40 WAS. The 1.5X cake biosolids treatment had higher yields than the inorganic fertilizer control. The results in year three differed from previous years, likely because the delayed seeding altered the inorganic fertilization schedule. The fertilizer treatment should have received two applications in the fall and one in the spring, but there was only one fall application and two in the spring in year three. The last spring application was not efficiently utilized by the turfgrass as indicated by the nitrogen uptake, quality and clipping yield results (Table 3.5, Table 3.6, Table 3.7).

Similar clipping yields between the inorganic fertilizer control and the 1.5X cake biosolids treatment indicate that excessive growth would not occur. Overall, the results support our previous conclusions that the 1.5X cake biosolids treatment is providing enough PAN to support similar turfgrass growth compared to the inorganic fertilizer control. The results also indicate that the 1.0X cake biosolids clipping yields were lower than the inorganic fertilizer control, supporting the conclusion that 30% mineralization overestimates the amount of PAN of the cake biosolids material. Supplemental nitrogen could increase the yields of the treatment and allow for a quicker sod harvest cycle.

Previous research has attributed better turfgrass growth to improved soil conditions, such as decreased bulk density, more plant available nutrients and increased water holding capacity, from the application of composted biosolids (Cheng et al., 2007; Johnson et al., 2006; Landschoot and McNitt, 1994). Research has also shown, through increased clipping yields, that composted biosolids complemented inorganic fertilizer sources to produce faster establishment of turfgrass (Loschinkohl and Boehm, 2001; Garling and Boehm, 2001). We did not measure increased turfgrass growth from the use of anaerobically digested biosolids when compared to inorganic fertilizer.

3.4.8. Sod Tensile Strength

Without adequate tensile strength, sod cannot be lifted at harvest. Tensile strength in year one was determined on sod harvested at a 2.5 cm depth, deeper than the typical 1.2 to 1.9 cm harvest depth. We harvested the sod at this depth because of delayed fall germination and suspected handling issues at harvest. All biosolids treatments had lower tensile strength than the inorganic fertilizer control in year one (Table 3.8).

The harvest depth for years two and three was 1.9 cm, and although slightly deeper than typical, it was necessary to ensure that the sod held together during harvest. In year two, there were no differences among the 0.5X and 1.0X cake biosolids, the 0.5X and 1.5X blended biosolids, and the inorganic fertilizer control. The 1.5X cake biosolids had higher tensile strength and the 1.0X blended biosolids treatment had lower tensile strength than the inorganic fertilizer control. There were no differences in tensile strength among the 0.5X and 1.5X cake biosolids treatments and the inorganic fertilizer control in year three. The trend of our tensile strength measurements was similar to our establishment, quality ratings and clipping yields results. Tensile strength increased with biosolids rate (Table 3.8). The higher tensile strength results in year two suggest that application timing, longer production cycle and increased density has a larger effect on tensile strength than increased harvest depth.

Tesfamariam et al. (2009) evaluated sod integrity as a percentage of harvestable sod. Sod integrity is similar to sod tensile strength, but instead of measuring the actual force required to break a piece of sod apart they measured how much of the sod in each plot could be handled without breaking. They found that as biosolids rates increased from 0 to 100 Mg ha^{-1}, sod integrity increased up to the 33 Mg ha^{-1} rate and then declined as the rates continued to increase. They attributed the decline in sod integrity to increased amounts of biosolids in the soil decreasing the sod mass at harvest. At the 33 Mg ha^{-1} rate, the ratio of biosolids to soil increased sod integrity, but as the ratio of biosolids to soil increased the turfgrass root system could not bind as well to the soil/biosolids mixture. Flanagan et al. (1993) using the heavy fraction of municipal solid waste, measured an increase in sod tensile strength as rates of heavy fraction increased. They attributed the increase to improved media aeration. We measured a similar response as Flanagan et al. (1993), i.e. tensile strength increased with higher rates of biosolids; however, we attributed the increase to improved turfgrass density and root growth.

Previous research concluded that a minimum sod tensile strength of 196-215 Newtons was needed so sod would not fall apart at harvest (Goatley and Schmidt, 1991; Flanagan et al., 1993; Shearman et al., 2001). The minimum tensile strength seen in our study is lower than what has been reported in previous literature. Tensile strengths less than 100 Newtons resulted in sod that did not hold together well at harvest. Overall, the tensile strength results still support our conclusion that the 1.5X cake biosolids treatment provided enough PAN during the production cycle to produce an acceptable quality sod compared to the inorganic fertilizer control. The results also indicate that 30% mineralization overestimates the amount of PAN of the cake biosolids material and supplemental nitrogen is needed with the 1.0X cake biosolids treatment to increase tensile strength to levels similar to the inorganic fertilizer control when using the current estimates.

3.4.9. Transplant Rooting Strength

Transplant rooting strength indicates how well sod grows after it is harvested and transplanted. When sod effectively roots at its establishment site, there is a lower chance that the sod will die from stressful transplanting conditions like infrequent watering or poor fertilization.

In year one, there were no differences among the cake biosolids, the 1.5X blended biosolids and the inorganic fertilizer control (Table 3.9). The 0.5X and 1.0X blended biosolids had lower transplant rooting strengths than the inorganic fertilizer control. In years two and three, there were no differences among any of the treatments.

Although only the 1.0X and 1.5X cake biosolids and the inorganic fertilizer control produced an acceptable quality sod each year, all treatments had similar transplant rooting strength. The sod was watered with 0.64 cm of water daily for a week after planting. The warm soil temperatures in summer and the adequate water supply most likely allowed more nitrogen from the biosolids to become plant available and promote adequate transplant rooting. All sod pieces that were transplanted and grown for a month had above acceptable turfgrass quality (data not shown).

The overall higher transplant rooting strengths measured in year one than in year two and three are most likely due to the deeper harvest depth. It is possible that the additional initial root mass and available nutrients in the sod pieces that were transplanted in year one promoted the increase in rooting strength. Similar transplant rooting strength results that were seen in our study were also seen by Flanagan et al. (1993) where there were no differences among treatments that had heavy fraction applied and treatments with just topsoil. The inorganic fertilizer control rooting strengths we measured are higher than previous studies that looked at transplant rooting strength of Kentucky bluegrass (‘Georgtown’, ‘Plush’) and tall fescue (‘Rebel Jr.’) sod on the same soil type at the Turfgrass Research Center in Blacksburg, VA (Goatley and Schmidt, 1991; Zhang et al., 2003a; Zhang et al., 2003b). The higher rooting strengths may have occurred because of higher rates of N used to establish and maintain the sod in our study (196 kg ha^{-1} compared to 100 kg ha^{-1}) than in earlier studies. Our results indicate that the use of EQ biosolids can result in the production of sod that transplants similar to inorganic fertilizer grown sod.

3.5. Conclusions

We determined that the EQ cake biosolids evaluated in this study, at the 1.0X and 1.5X rates, can produce an acceptable quality sod comparable to sod grown with inorganic fertilizer. The biosolids mineralization estimates used to recommend application rates underestimated the PAN for both biosolids products as indicated by the lower nitrogen uptake throughout the growing season and inadequate sod quality at harvest of the blended biosolids and the lower although acceptable sod quality ratings at harvest of the cake biosolids compared to the inorganic fertilizer control. We determined that there are no application uniformity issues when using the cake or blended biosolids products, which is a concern during sod production due to the aesthetic expectations of the crop. Also, biosolids use did not increase or suppress weed or disease pressure, and as shown by the reduced N uptake in the inorganic fertilizer control in year three, there may be non-nutritive benefits to using biosolids during times of plant stress. Sod growers could use these alternative nutrient sources to reduce production costs without decreasing sod quality. Sod production may provide another avenue for the beneficial use of biosolids.

3.6. Acknowledgements

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3.7 References

Boulter, J.I., G.J. Boland, and J.T. Trevors. 1999. Evaluation of compost for biological control of dollar spot (*Sclerotinia homoeocarpa*) on creeping bentgrass (*Agrostis palustris)*. Phytopathology 89:S8.

Cheng, H., W. Xu, J. Liu, Q. Zhao, Y. He, and G. Chen. 2007. Application of composted sewage sludge (CSS) as a soil amendment for turfgrass growth. Eco. Engineering. 29:96-104.

Craft, C.M., and E.B. Nelson. 1996. Microbial properties of composts that suppress damping off and root rot of creeping bentgrass caused by *Pythium graminicola*. Appl. Environ. Microbiol.62:1550–1557.

Donohue, S.J., and S.E., Heckendorn. 1994. Soil test recommendations for Virginia. Blacksburg, VA., Virginia Cooperative Extension Service Publication. 834.

Dunifon, S.N., G.K. Evanylo, R.O. Maguire, and J.M., Jr. Goatley. 2011. Soil nutrient and fescue (Festuca spp.) responses to compost and hydroseed on a disturbed roadside. Compost Science and Utilization. 19:147-151.

Eghball, B. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure or compost. Soil Sci. Soc. Am. J. 64:2024-2030.

Flanagan, M.S., R.E. Schmidt, and R.B., Jr. Reneau. 1993. Municipal solid waste heavy fraction for production of turfgrass sod. Hort. Science. 28:914-916.

Flavel, T.C., and D.V. Murphy. 2006. Carbon and nitrogen mineralization rates after application of organic amendments to soil. J. Environ. Qual. 35:183-193.

Goatley, J.M., Jr., and R.E. Schmidt. 1991. Biostimulator enhancement of Kentucky bluegrass sod. Hort. Sci. 26: 254-255.

Johnson, G.A., J.G. Davis, Y.L. Quian, and K.C. Doesken. 2006. Topdressing turf with composted manure improves soil quality and protects water quality. Soil Sci. Soc. Am. J. 70:2114–2121.

King, J.W., J.B. Beard, and P.E. Rieke. 1982. Factors affecting survival of Kentucky bluegrass sod under simulated shipping conditions. J. Amer. Soc. Hort. Sci. 107:634-637.

Landschoot, P., and A. McNitt. 1994. Improving turf with compost. BioCycle. 35:54-57.

Laycock, R.W., and P.M., Canaway. 1980. A new optical point quadrat frame for the estimation of cover in close mown turf. Journal of the Sports Turf Research Institute. 56:91-92.

Linde , D.T., and L.D. Hepner. 2005. Turfgrass seed and sod establishment on soil amended with biosolids compost. Horttechnology. 15:577-583.

Loschinkohl, C., and M.J. Boehm. 2001. Composted biosolids incorporation improves turfgrass establishment on disturbed urban soils and reduces rust severity. Hort. Sci. 36(4):790-794.

Morris, K. 2004. A guide to NTEP turfgrass ratings. 12 May 2013. http://www.ntep.org/reports/ratings.htm#quality.

NASS, USDA. 2011. Farm production expenditures 2011 summary. Natl. Agric. Statistics, Serv., Washington, DC.

NOAA. 2013. Unique Climatic Data. Sterling, VA. National Weather Service Forecast Office.

Nelson, E.B., and C.M. Craft. 1991a. Suppression of brown patch with top-dressings amended with composts and organic fertilizers. Biol. Cult. Tests Control Plant Dis. 6:90.

Nelson, E.B., and C.M. Craft. 1991b. Suppression of red thread with top-dressings amended with composts and organic fertilizers. Biol. Cult. Tests Control Plant Dis. 6:101.

Nelson, E.B., and C.M. Craft. 1992. Suppression of dollar spot on creeping bentgrass and annual bluegrass turf with compost-amended topdressings. Plant Dis. 76:954-958.

O'Brien, T.A., and A.V. Barker. 1996. Evaluation of ammonium and soluble salts on grass sod production in compost. II. Delaying seeding after compost application. Communications in Soil Science and Plant Analysis: 27:77-85.

Persyn, R.A., T.L. Richardson, T.D. Glanville, J.M. Laflen, and D.M. Dixon. 2007. Evaluation of revegetation from blanket applied composts on a highway construction site. Applied Eng. in Agric. 23:631-63.

Richards, C.E., C.L. Munster, D.M. Vietor, J.G. Arnold, and R. White. 2008. Assessment of a turfgrass sod best management practice on water quality in a suburban watershed. J. Environ. Management. 86:229-245.

Richardson, M. D., D.E. Karcher, and L.C. Purcell. 2001. Quantifying turfgrass cover using digital image analysis. Crop Sci. 41:1884-1888.

Roe, N.E., P.J. Stofella and H.H. Bryan. 1993. Municipal solid waste compost suppresses weeds in vegetable crop alleys. Hort. Sci. 28:1171-1172.

SAS Institute Inc. 2008. SAS 9.2. Cary, N.C.

Schmidt, R.E., R.H. White, and S.W. Bingham. 1986. Technique to measure rooting of sods grown in small containers. Agron. J. 78:212-216.

Schnell, R.W., D.M. Vietor, R.H. White, T.L. Provin, and C.L. Munster. 2009 Effects of composted biosolids and nitrogen on turfgrass establishment, sod properties, and nutrient export at harvest. Hort. Sci. 44(6):1746-1750.

Shearman, R.C., T.R. Turner, K.N. Morris, R.E. Gaussoin, M.R. Vaitkus, and L.A. Wit. 2001. Sod strength and lateral spread of *Poa pratensis* cultivars and experimental lines. International Turfgrass Society Research Journal. 9:928-933.

Standard Methods for the Examination of Water and Wastewater 1992. SM-4500.

Washington , DC, American Public Health Association.

Stoffella, P.J., M. Ozores-Hampton and D.T. Patterson. 2000. Potential of municipal solid waste compost as a biological weed control. ISHS Acta Hort. 533:211-213.

Tesfamariam, E.H., J.G. Annadale, and J.M. Steyn. 2009. Exporting large volumes of municipal sewage sludge through turfgrass sod production. J. Environ. Qual. 38:1320-1328.

Trenholm, L. E., and J.B. Unruh. 2005. Warm-season turfgrass response to fertilizer rates and sources. J. Plant Nutrition. 28:991-999.

U.S. EPA. 1986. EPA/SW-846. Test Methods for Evaluating Solid Waste. Washington, D.C., U.S. Environmental Protection Agency.

U.S. EPA. 1993. 40 CFR part 503 Standards for the use and disposal of sewage sludge subpart B Land Application. 503.10 to 503.18. Print., U. S. G. Washington, D.C.

Virginia Department of Conservation and Recreation. 2005. Virginia Nutrient Management Standards and Criteria. Virginia Department of Conservation and Recreation. Richmond, VA.

Wright, A.L. 2007. Nutrient accumulation and availability in compost-amended turfgrass soil. Hort. Science. 42:1473-1477.

Zhang, X., E.H. Ervin and R.E. Schmidt. 2003a. Plant growth regulators can enhance the recovery of Kentucky bluegrass sod from heat injury. Crop Sci. 43:952-956.

Zhang, X., E.H. Ervin and R.E. Schmidt. 2003b. Seaweed extract, humic acid, and propiconazole improve tall fescue sod heat tolerance and posttransplant quality. Hort. Sci. 38:440-443.

Zhang, X., E.H. Ervin, G.K. Evanylo, and K.C. Haering. 2009. Impact of biosolids on hormone metabolism in drought-stressed tall fescue. Crop Sci. 49:1893-1901.

Table 3.1 Average monthly temperature and precipitation for Remington, VA from August 2009 to August 2012

2009	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature (°C)	--	--	--	--	--	--	--	25.8	20.2	13.6	9.9	1.8
Precipitation (cm)	--	--	--	--	--	--	--	7.0	4.6	14.5	9.4	15.2

2010	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature (°C)	0.8	-0.6	9.7	15.2	19.4	24.9	26.4	25.0	21.8	14.4	7.9	-0.6
Precipitation (cm)	5.1	11.8	8.5	3.3	13.8	3.3	10.6	11.2	15.6	6.0	6.4	3.7

2011	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature (°C)	-1.1	3.4	6.8	14.1	19.1	23.8	27.2	24.6	20.6	12.8	9.5	5.3
Precipitation (cm)	4.7	5.6	12.9	13.2	8.3	3.6	6.6	9.5	20.1	15.9	5.5	11.3

2012	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature (°C)	3.2	5.0	12.4	12.3	20.3	22.2	27.0	25.1	--	--	--	--
Precipitation (cm)	4.7	5.7	3.9	4.6	13.7	4.5	6.2	7.7	--	--	--	--

30 yr. Avg. Temp.§	0.6	2.3	6.8	12.4	17.3	22.4	24.8	24.1	19.9	13.3	8.0	2.6
30 yr. Avg. Precip.§	7.4	6.9	8.6	8.9	11.7	10.2	9.4	8.9	9.9	8.4	8.6	7.6

§30 yr. average for the region (1982-2012)

Table 3.2. Chemical and physical composition of the biosolids products

Treatment	C:N	C§	TKN	NH_4-N	NO_3-N	Organic-N	Total P	K
	g kg^{-1}							
Blended†	15	230	15.0	5.3	0.004	9.7	9.5	2.6
Cake††	7	339	51.1	15.5	0.006	35.6	34.2	1.5

† Anaerobically digested dewatered biosolids blended with wood fines.
†† Anaerobically digested dewatered biosolids cake.
§ All analysis was done by A&L Eastern Labs, Richmond, VA.

Table 3.3. Target and Mean Actual Estimated First Year Plant Available Nitrogen (PAN) Applied from Biosolids

Treatment	Target PAN to Applied	Actual Estimated PAN Applied
	kg N ha^{-1}	
Fert. Control	196	196
Cake 0.5X†	98	117§
Cake 1.0X	196	235
Cake 1.5X	294	352
Blended 0.5X††	98	90
Blended 1.0X	196	180
Blended 1.5X	294	270

† Anaerobically digested dewatered biosolids cake.
†† Anaerobically digested dewatered biosolids blended with wood fines.
§PAN based on 100% availability of NH_4^+-N and 30% availability of organic-N applied.

Table 3.4. Tall fescue-Kentucky bluegrass cover during the establishment season as influenced by inorganic fertilizer and various levels of de-watered cake or blended biosolids in Remington, VA from 2009-2012

	Year 1§				Year 2¶			Year 3¶¶			
Weeks after Seeding (WAS)	7	9	11	13	4	6	8	5	22	28	34
Treatment and Estimated PAN	% Vegetative Cover††										
Fert. Control (196 kg N ha^{-1})	11.3ab	42.3ab	82.2ab	87.1a	8.4a	65.8a	92.7abc	12.5a	66.0b	84.5ab	77.8ab
Cake 0.5X (98 kg N ha^{-1})	10.3ab	35.1b	63.7d	64.3c	3.6b	53.4ab	88.7bc	13.6a	59.6b	70.5b	74.5b
Cake 1.0X (196 kg N ha^{-1})	9.8ab	40.0ab	73.9bc	78.2ab	3.4b	60.2ab	95.9ab	14.2a	64.6b	76.3b	79.6ab
Cake 1.5X (294 kg N ha^{-1})	9.1b†	35.8b	76abc	78.4ab	5.0ab	64.2a	97.7a	15.3a	80.6a	93.6a	93.1a
Blended 0.5X (98 kg N ha^{-1})	10.7ab	40.3ab	69.6cd	71.1bc	4.4b	49.5b	85.1c	12.6a	33.0c	39.2d	40.5c
Blended 1.0X (196 kg N ha^{-1})	11.2ab	41.1ab	72.5cd	72.8bc	4.6b	57.0ab	89.9bc	13.9a	36.4c	49.8cd	47.8c
Blended 1.5X (294 kg N ha^{-1})	13.0a	48.2a	84.5a	86.4a	6.6ab	64.4a	94.7ab	13.7a	42.6c	55.1c	54.0c
LSD ($P \leq 0.05$)	3.6	8.5	9.5	9.6	3.6	13.6	7.7	3.9	13.0	14.5	15.6

†Means followed by the same letter are not significantly different at the $P \leq 0.05$.
††Establishment coverage was determined using digital image analysis (DIA).
§Actual rating dates in 2009 were Oct. 27, Nov. 10, Nov. 24 and Dec. 1.
¶Actual rating dates in 2010 were Oct. 12, Oct. 26 and Nov. 8.
¶¶ Actual rating dates in 2011 were Nov. 17 and in 2012 Mar. 15, Apr. 12 and May 24.

Table 3.5 Nitrogen uptake of tall fescue-Kentucky bluegrass sod during the growing season in Remington, VA from 2009-2012

	Year 1§		Year 2¶			Year 3¶¶		
Weeks After Seeding (WAS)	36	40††	32	36	40††	32	36	40††
Treatment and Estimated PAN	N Uptake† (kg N ha^{-1})							
Fert. Control (196 kg N ha^{-1})	24.9a	28.9a	9.2a	15.5a	13.9a	6.0b	5.4b	16.6bcd
Cake 0.5X (98 kg N ha^{-1})	3.7c#	7.0c	1.3bc	6.2bc	4.1bc	4.2b	3.9b	20.0bc
Cake 1.0X (196 kg N ha^{-1})	8.4bc	11.3bc	6.6ab	11.4ab	8.6abc	6.2b	13.4a	28.7ab
Cake 1.5X (294 kg N ha^{-1})	15.2b	21.6ab	10.5a	17.5a	12.0a	16.6a	19.5a	41.4a
Blended 0.5X (98 kg N ha^{-1})	1.4c	3.1c	0.3c	1.3c	2.6c	1.0b	0.7b	5.4d
Blended 1.0X (196 kg N ha^{-1})	2.1c	6.5c	0.3c	1.3c	2.5c	0.8b	0.7b	8.4cd
Blended 1.5X (294 kg N ha^{-1})	12.0b	13.3bc	1.8bc	4.0c	9.1ab	2.0b	0.8b	9.5cd
LSD (*P*< 0.05)	7.8	10.8	5.4	6.1	6.4	5.2	7.8	14.1

Means followed by the same letter are not significantly different at the P ≤ 0.05.
† Calculated by multiplying turfgrass tissue N concentration (g N kg^{-1}) by dry mass clipping yield (kg ha^{-1}) for each treatment.
††Sod was harvested at 40 WAS.
§ Actual sampling dates in 2010 were May 18 and Jun. 15.
¶ Actual sampling dates in 2011 were May 6, Jun. 3, and Jul. 1.
¶¶ Actual sampling dates in 2012 were Jun. 22, Jul. 20 and Aug. 17.

Table 3.6. Tall fescue-Kentucky bluegrass sod turfgrass quality during the growing season in Remington, VA from 2009-2012

	Year 1§				Year 2¶				Year 3¶¶			
Weeks After Seeding (WAS)	28	32	36	40††	28	32	36	40††	28	32	36	40††
Treatment and Estimated PAN	Quality Rating† (1-9)											
Fert. Control (196 kg N ha^{-1})	5.8ab	8.0a	8.4a	7.8a	3.8b	6.5a	7.8a	7.3ab	5.1a	6.1a	6.0bc	6.6b
Cake 0.5X (98 kg N ha^{-1})	5.0bc	5.9b	5.9c	5.5bc	2.9cd	4.8b	5.3bc	5.1c	4.3b	4.8bc	5.3c	5.3c
Cake 1.0X (196 kg N ha^{-1})	5.4bc	6.0b	6.1bc	6.0b	3.3c	4.9b	6.1b	6.5b	4.1b	4.9b	6.1b	6.4b
Cake 1.5X (294 kg N ha^{-1})	6.5a	7.8a	7.8a	7.3a	4.4a	6.5a	8.0a	8.0a	5.3a	6.9a	7.3a	7.6a
Blended 0.5X (98 kg N ha^{-1})	4.5c#	5.4b	5.4c	4.9c	2.5d	3.0d	4.0d	4.0d	3.5c	3.8d	4.4d	4.5d
Blended 1.0X (196 kg N ha^{-1})	5.1bc	6.1b	6.0bc	5.8bc	2.6d	3.4cd	4.5cd	4.5d	3.6c	4.0cd	4.3d	4.5d
Blended 1.5X (294 kg N ha^{-1})	5.4bc	6.4b	6.8b	5.8bc	3.1c	4.5bc	5.6b	5.4c	3.5c	3.9d	4.4d	4.8cd
LSD (P< 0.05)	0.9	1.3	0.8	0.9	0.4	1.1	0.9	0.7	0.4	0.8	0.7	0.7

Means followed by the same letter are not significantly different at the P ≤ 0.05.
†Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.
††Sod was harvested at 40 WAS.
§ Actual sampling dates in 2010 were Mar. 23, Apr. 20, May 18 and Jun. 15.
¶ Actual sampling dates in 2011 were Apr. 8, May 6, Jun. 3, and Jul. 1.
¶¶ Actual sampling dates in 2012 were May 25, Jun. 22, Jul. 20 and Aug. 17.

Table 3.7. Tall fescue-Kentucky bluegrass clipping yields during the growing season in Remington, VA from 2009-2012

	Year 1[§]		Year 2[¶]			Year 3[¶¶]		
Weeks After Seeding (WAS)	36	40[††]	32	36	40[††]	32	36	40[††]
Treatment and Estimated PAN	Clipping Yields[†] (kg ha^{-1})							
Fert. Control (196 kg N ha^{-1})	850.1a	1079.6a	324.7a	630.1a	445.5a	251.9bc	205.4bc	673.4bc
Cake 0.5X (98 kg N ha^{-1})	173.5cd[#]	340.0cd	60.9c	348.4bc	133.6bc	193.3cd	130.0c	694.7bc
Cake 1.0X (196 kg N ha^{-1})	387.1bc	590.7bcd	243.1ab	562.3ab	301.7ab	265.5b	389.9ab	900.2ab
Cake 1.5X (294 kg N ha^{-1})	626.4ab	950.9ab	365.5a	728.2a	381.4ab	607.2a	561.1a	1303.2a
Blended 0.5X (98 kg N ha^{-1})	75.0d	177.7d	20.2c	66.4d	88.4c	52.6cd	36.1c	196.9c
Blended 1.0X (196 kg N ha^{-1})	112.7cd	361.2cd	13.7c	71.4d	87.3c	39.4d	35.9c	330.9bc
Blended 1.5X (294 kg N ha^{-1})	561.4ab	687.4abc	86.1bc	192.6cd	309.5ab	96.9bcd	35.0c	318.7bc
LSD ($P < 0.05$)	305.8	453.1	159.9	262.3	209.5	205.3	216.4	461.2

Means followed by the same letter are not significantly different at the $P \leq 0.05$.
†Data was collected after one week of growth when the slowest growing plot reach a 10 cm height.
††Sod was harvested at 40 WAS.
§ Actual sampling dates in 2010 were May 18 and Jun. 15.
¶ Actual sampling dates in 2011 were May 6, Jun. 3, and Jul. 1.
¶¶ Actual sampling dates in 2012 were Jun. 22, Jul. 20 and Aug. 17.

Table 3.8. Tall Fescue-Kentucky bluegrass sod tensile strength at harvest in Remington, VA from 2010-2012

	Year 1[§]	Year 2[¶]	Year 3[¶¶]
Treatment and Estimated PAN		Newtons[†] (N)	
Fert. Control (196 kg N ha^{-1})	164.3a	187.6bc	118.9a
Cake 0.5X (98 kg N ha^{-1})	94.4cd[#]	182.7bcd	101.7a
Cake 1.0X (196 kg N ha^{-1})	98.1cd	196.1ab	78.5b
Cake 1.5X(294 kg N ha^{-1})	111.6bc	220.7a	105.4a
Blended 0.5X (98 kg N ha^{-1})	84.6d	165.5cd	68.6b
Blended 1.0X (196 kg N ha^{-1})	80.9d	154.5d	39.2c
Blended 1.5X (294 kg N ha^{-1})	127.5b	166.7bcd	78.5b
LSD (*P*< 0.05)	25.2	30.0	18.4

Means followed by the same letter are not significantly different at the $P \leq 0.05$.
†Tensile strength was measured on three 91cm x 61cm pieces on sod from each plot at harvest.
§ Harvest date was Jun. 15 in 2010.
¶ Harvest date was Jul. 1 in 2011.
¶¶ Harvest date was Aug. 17 in 2012.

Table 3.9. Tall fescue-Kentucky bluegrass sod transplant rooting strength four weeks after transplant from 2010-2012

	Year 1[§]	Year 2[¶]	Year 3[¶¶]
Treatment and Estimated PAN		Newtons[†] (N)	
Fert. Control (196 kg N ha^{-1})	750.2ab	360.4ab	453.3ab
Cake 0.5X (98 kg N ha^{-1})	610.5abc	517.8a	547.6a
Cake 1.0X (196 kg N ha^{-1})	693.8abc	384.9ab	411.0ab
Cake 1.5X (294 kg N ha^{-1})	890.0a	413.4ab	513.6a
Blended 0.5X (98 kg N ha^{-1})	414.3c	387.4ab	425.5ab
Blended 1.0X (196 kg N ha^{-1})	436.4c	476.6a	514.2a
Blended 1.5X (294 kg N ha^{-1})	475.6bc	266.3b	333.6b
LSD (*P*< 0.05)	291.1	160.0	152.6

Means followed by the same letter are not significantly different at the $P \leq 0.05$.
†Three pieces of 30 cm x 30 cm sod were placed on rooting frames and allowed to establish for four weeks after transplant
§ Transplant date was Jun. 15 in 2010.
¶ Transplant date was Jul. 1 in 2011.
¶¶ Transplant date was Aug. 17 in 2012.

4. The Effects of Land Applying Biosolids for Sod Production on Soil Chemical and Physical Properties and Soil Loss at Harvest

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4.1. Abstract

Regulated application rates of biosolids products for sod production are required to be based on crop N needs; however, the removal of nutrients (esp., N and P) and organic matter with sod may warrant higher than agronomic N rate applications. The objective of this study was to compare various application rates two types of biosolids products that may be suitable for sod production. Exceptional Quality (EQ) products derived from anaerobically digested biosolids were compared with an inorganic fertilizer control for sod fertilization on 1) the amount of soil, C and P exported at harvest and 2) chemical and physical properties of the soil following sod harvest as indicators of the benefits of biosolids use. The study was conducted on a sod farm in Remington, Virginia on a silt loam Ashburn-Dulles complex from 2009 to 2012. The biosolids products were applied at estimated plant available nitrogen (PAN) rates of 98 kg ha^{-1} (0.5X), 196 kg ha^{-1} (1.0X), 294 kg ha^{-1} (1.5X) for a tall fescue (*Festuca arundinacea* Schreb. 'Rebel Exeda', 'Rebel IV' and 'Justice') Kentucky bluegrass (*Poa pratensis* L. 'Midnight') mixture (85/15 % by weight) and plots were seeded at 236 kg ha^{-1}. One biosolids product was a dewatered cake applied at 15, 30.5 and 46 wet Mg ha^{-1}. The second biosolids product was the same dewatered cake blended with wood fines applied at 17, 34 and 51 wet Mg ha^{-1}. The biosolids treatments were compared to an inorganic fertilizer control that supplied 196 kg N ha^{-1} through three applications over the production cycle. After repeat applications of biosolids, the 0.5X rates did not increase soil extractable phosphorus, but the 1.0X rates steadily increased soil extractable phosphorus. The 1.0X and 1.5X biosolids rates increased soil organic matter content, and only the 1.5X rate of cake biosolids reduced soil bulk density and mineral matter export at harvest. Our results indicate biosolids used as fertility sources and soil amendments for sod production can maintain soil phosphorus at concentrations that preclude environmental impairment within

rotational sod production systems that rely on annual biosolids applications. Occasional substitution of inorganic fertilizer without phosphorus can ensure that environmentally harmful soil P concentrations do not accrue.

4.2. Introduction

The rising prices of fertilizer and fuel have increased the cost of sod production (NASS, USDA, 2011). Use of biosolids as a soil amendment and plant nutrient source may be a way to reduce costs. Previous research has found that production systems that used biosolids were more economically efficient due to reduced nutrient costs (Faust and Oberst, 1996; Soulsby et al., 2002).

Lower production costs associated with biosolids use are not the only benefits sod producers might incur. The use of biosolids could reduce the amount of soil and associated nutrients exported at harvest. Soil export is a serious environmental and agronomic consequence of sod production (Millar et al., 2010; Carr, 1996; Charbonneau, 2003). When biosolids were topdressed or incorporated at rates that greatly exceed turfgrass nutritional needs, soil export at harvest was reduced (Tesfariam et al., 2009; Schnell et al., 2009). Although heavy rates can reduce export, the effects of N based biosolids applications for sod production on soil export need to be evaluated.

Biosolids could also help replace organic matter. The addition of organic residuals has been shown to increase soil organic matter and available nutrients and reduce bulk density (Dai et al., 2009; Brown and Cotton, 2011; Dunifon et al., 2011; Hepperly et al., 2009; Norrie and Gosselin, 1996; Tambone et al., 2007; Evanylo et al., 2008; Bulluck III et al., 2002). Applications of biosolids for turfgrass production were reported to have similar results (Schnell et al., 2009; Johnson et al., 2006; Loschinkohl and Boehm, 2001). Long-term maintenance of turfgrass systems naturally result in soil organic matter deposition (Qian and Follet, 2002), but there have been conflicting reports on whether or not sod production increases or diminishes soil organic matter (Carr, 1996; Sheard and Van Patter, 1978; Charbonneau, 2003; Skogley and

Hesseltine, 1978; Millar et al., 2010). Although previous studies have reported that biosolids applications increased soil organic matter in turfgrass culture, more research is needed to determine if N-based rates will increase soil organic matter in a sod production system.

Because of the imbalance in biosolids N and P, the application of biosolids to supply crop nitrogen needs will result in the over application of phosphorus (Ott and Forster, 1978). The continual application of organic residuals can cause excessive soil phosphorus accumulation to impair surface water quality as P transport occurs (Richards et al., 2008; Whalen and Chang, 2001; Rostagno and Sosebee, 2001; Korboulewsky et al., 2002; Shober and Sims, 2003). Excessive soil phosphorus accumulation in production fields could be reduced by standard sod harvest as sod production exports nutrients through sod harvest (Vietor et al., 2004; Richards et al., 2008; Tesfariam et al., 2009; Schnell et al., 2009).

Alternative processing methods that produce EQ (USEPA, 1993) products are constantly being developed. These products can be used in urban settings because of their low pollutant concentrations and pathogen-free status. They are usually composted, have higher C:N ratios and lower moisture contents which make them easier to handle. The need for bulking agents during composting allows for beneficial use of lower value waste products (e.g., yard-waste or municipal solid waste) in these higher value EQ products (Beecher and Goldstein, 2010). Typically inorganic fertilizer is used in conjunction with these products because of their low amounts of PAN (Loschinkohl and Boehm, 2001). Previous research in turfgrass culture has shown that these products enhance turfgrass establishment and quality more than inorganic fertilizer alone and can increase surface soil organic matter as well (Schnell et al., 2009; Loschinkohl and Boehm, 2001; Linde and Hepner, 2005; Landschoot and McNitt, 1994). Understanding the value of such products (e.g., the effects on soil chemical and physical properties, nutrient availability) will enable their promotion for sod production. Nitrogen availability of digested, dewatered cake biosolids have been previously studied (Gilmour et al., 2003), but little is known about nitrogen availability of non-composted woody blended biosolids products.

The objective of this study was to compare processing methods and application rates of anaerobically digested biosolids products with an inorganic fertilizer control for sod fertilization on 1) the amount of soil, C and P exported at harvest and 2) chemical and physical properties of the soil following sod harvest as indicators of the benefits of biosolids use.

4.3. Materials and Methods

Site, experimental design, and treatment establishment

The study was conducted on a sod farm in Remington, VA (Lat. +38.51417, Long. -77.811717) on a silt-loam Ashburn-Dulles complex (*Fine-silty, mixed, active, mesic Oxyaquic Hapludalfs*). The study was conducted from the fall of 2009 until the summer of 2012. Mean monthly temperature and precipitation for the duration of the study were obtained from nearby weather stations (NOAA, 2013).

The study consisted of seven treatments, each replicated 4X and arranged in a randomized complete block design. The treatments included three rates (0.5X, 1.0X and 1.5X agronomic N rate) of each of two types of biosolids and a fertilizer control, according to Virginia Tech Soil Testing Laboratory recommendations (Donohue and Heckendorn, 1994). The 0.5X, 1.0X, and 1.5X treatments were designed to apply 98 kg ha^{-1}, 196 kg ha^{-1}, and 294 kg ha^{-1} of plant available nitrogen (PAN), respectively. Plot dimensions were 61 m by 11 m, which necessitated biosolids applications made using a commercial side-discharge manure spreader.

An EQ anaerobically digested, dewatered biosolids cake (Alexandria Sanitation Authority, Alexandria, VA) and the same material blended with wood fines (blended by Synagro, Inc., Champlain, VA) at a 1:0.65 by weight ratio of biosolids to wood fines were used. Biosolids were applied in the fall (Aug. 26, 2009, Sept. 8, 2010, and Oct. 12, 2011) of each year based on their estimated supply of plant available nitrogen assuming 30% of the organic nitrogen is mineralized in the first year (Virginia Department of Conservation and Recreation, 2005). Although the organic nitrogen content and application rate of the biosolids varied slightly from year to year the three-year mean biosolids rates were 15, 30.5 and 46 wet Mg ha^{-1} of cake biosolids, respectively, and 17, 34 and 51 wet Mg ha^{-1} of blended biosolids, respectively. The inorganic fertilizer control treatment supplied 196 kg N ha^{-1}, whose application was split to provide 74 kg N ha^{-1} (as urea and diammonium phosphate, DAP) at seeding, 74 kg N ha^{-1} (as calcium ammonium nitrate) in mid-October, and 48 kg N ha^{-1} (as calcium ammonium nitrate) in late-April. The DAP rate was calculated to meet the soil test recommended amount of phosphorus and incorporated to a depth of five cm.

Samples from each biosolids source were collected at application dates and sent to A&L Eastern Laboratories in Richmond, VA and analyzed for total solids (SM-2540G), total Kjeldahl N (SM-4500- TKN), ammonium-N (SM-4500-NH3) (Standard Methods for the Examination of Water and Wastewater, 1992), phosphorus (SW-846-6010C), potassium (SW-846-6010C) (U.S. Environmental Protection Agency, 1986), and other macro and micro nutrients. The cake biosolids was composed of 339 g kg^{-1} C, 5l.1 g kg^{-1} TKN, 35.6 g kg^{-1} P, 1.5 g kg^{-1} K and had a moisture content around 700 g kg^{-1}. The blended biosolids were composed of 230 g kg^{-1} C, 15.0 g kg^{-1} TKN, 9.7 g kg^{-1} P, 2.6 g kg^{-1} K and had a moisture content ~300 g kg^{-1}. The 0.5X, 1.0X and 1.5X cake biosolids rates applied 117, 235 and 352 kg of estimated PAN ha^{-1} respectively;

154, 308 and 462 kg P ha^{-1} respectively; and 1,525, 3,051, and 4,576 kg C ha^{-1} respectively. The 0.5X, 1.0X and 1.5X blended biosolids rates applied 90, 180 and 270 kg of estimated PAN ha^{-1} respectively; 105, 210 and 315 kg P ha^{-1} respectively; and 2,530, 5,060, and 7,820 kg C ha^{-1} respectively.

All plots were seeded with a Brillion Turfmaker (Brillion Farm Equipment, Brillion, WI) at 236 kg ha^{-1} with an 85% tall fescue (*Festuca arundinacea* Schreb. 'Rebel Exeda' 'Rebel IV' and 'Justice')/ 15% Kentucky bluegrass (*Poa pratensis* L. 'Midnight') mixture, by weight. Plots were seeded Sept. 2 in 2009; Sept. 14 in 2010; Oct. 12 in 2011. Plots were maintained at a 7.6 cm height throughout the growing season and clippings were returned.

Sampling and analysis

In the fall of 2009 soil cores with a 1.9 cm diameter were randomly collected from the 0-10 cm depth in the study site, air-dried, ground to pass through a 2 mm sieve and sent to Virginia Tech Soil Testing Laboratory for routine soil test analysis of Mehlich 1 extractable P, K, and pH and Walkley-Black soil organic matter content (Maguire and Heckendorn, 2011). Results indicated a pH of 6.1, extractable P and K of 12 mg kg^{-1} and 43 mg kg^{-1} respectively and soil organic matter content of 32 mg kg^{-1}. Fertilizer P recommendations for the inorganic fertilizer control plots and K recommendations for all treatments were made using soil testing results (Virginia Department of Conservation and Recreation, 2005).

Soil extractable phosphorus was measured in each plot before initial treatments and after each sod harvest. Soil cores with a 1.9 cm diameter were randomly collected from the 0-10 cm depth in each plot, air-dried, ground to pass through a 2 mm sieve and sent to Virginia Tech Soil Testing Laboratory for analysis of Mehlich 1 extractable P (Maguire and Heckendorn, 2011).

Organic matter to a depth of 10 cm was measured for each plot before initial treatments and after each sod harvest. Organic matter was determined using soil cores with a 1.9 cm diameter that were randomly collected from the 0-10 cm depth in each plot, air-dried, ground to pass through a 2 mm sieve and sent to Virginia Tech Soil Testing Laboratory for analysis of Walkley-Black soil organic matter content (Maguire and Heckendorn, 2011). Bulk density was measured by taking five 81 cm^2 plugs with a standard golf course cup cutter, saving the removed soil, lining the hole with plastic and recording volume of water required to fill the hole. The saved soil was dried to a constant weight at 60°C and weighed. The weight of soil in grams was divided by the volume of water required to fill the hole to give bulk density in g cm^{3-1} (Blake and Hartge, 1986).

The amount of mineral matter exported at harvest was quantified using physical plant-soil separation. Four sod pieces, 91 cm by 61 cm were randomly harvested from three locations in each plot. One 81 cm^2 plug was taken from each piece of sod using a standard golf course cup cutter. The plugs were dried at 60°C for several days before the plant tissue was removed. The plant tissue was removed by grinding the samples with a mortar and pestle to loosen the soil. Mineral matter export was determined by weighing the separated soil after it was ignited in a Blue M Ultra-Temp, forced-air drying oven (SPX Thermal Products Solutions, White Deer, PA) for 6 hours at 500°C.

Soil extractable phosphorus, organic matter, bulk density and mineral matter export data were subjected to analysis of variance using SAS Proc GLM (SAS Institute, 2008) to elucidate the effects of organic soil amendments on soil chemical and physical properties. Means were separated using a Protected LSD at $P \leq 0.05$.

4.4. Results and Discussion

There were significant year by treatment interactions for the extractable phosphorus and soil loss data, so each year is presented separately. There was no significant year by treatment interactions for the organic matter and bulk density data, so the averages over the three year study are presented.

4.4.1. Biosolids composition and application rates of N, P, K and C

Biosolids composition and application rates of N, P, K and C are shown in Tables 4.1 and 4.2. The amounts of C, TKN, NH_4^+-N, organic-N and P were lower in the blended biosolids than in the cake biosolids. The only nutrient that was higher in the blended biosolids was K. The additional processing the blended biosolids underwent caused a reduction in the amount of ammonia nitrogen and organic nitrogen resulting in a product with a C:N ratio of 15:1 as compared to 7:1 of the cake biosolids.

The amount of total P that was applied from each nutrient source is shown in Table 4.2. The 0.5X levels of cake and blended biosolids provided similar total P as the inorganic fertilizer control. Results from the 0.5X treatments can be used to demonstrate the effects of phosphorus-based biosolids rates on soil chemical and physical properties.

4.4.2. Soil extractable phosphorus accumulation

After harvest in year one, the 1.0X and 1.5X blended biosolids treatments resulted in greater soil extractable phosphorus than the inorganic fertilizer control (Table 4.3). After year two harvest, all of the biosolids treatments except the 0.5X cake treatment resulted in greater soil extractable phosphorus than the inorganic fertilizer control. After year three harvest, only the 0.5X cake and blended biosolids treatments did not have higher soil extractable phosphorus than the inorganic fertilizer control.

Previous research has shown that repeat applications of biosolids at N based rates and above can increase soil phosphorus (Kelling et al., 1977; Chang et al., 1983; Maguire et al., 2000). Sod production may counteract the accumulation of phosphorus in the soil from repeat biosolids applications. Previous research has reported that sod production can export nutrients and the amount exported is dependent on the amount of nutrients applied, incorporation method and harvest depth (Vietor et al., 2002; Schnell et al., 2009; Tesfariam et al., 2009). Vietor et al. (2002) and Schnell et al. (2009) reported that the amount of phosphorus exported at sod harvest increases when more phosphorus is applied, and concluded that more phosphorus is exported when organic amendments are topdressed instead of incorporated. When organic amendments were topdressed and harvested at a 2.5 cm depth, Vietor et al. (2002), reported that 77% of phosphorus applied was exported with the sod. Schnell et al. (2009) reported that all of the phosphorus from a 46 dry Mg biosolids ha^{-1} application that was incorporated to a 5 cm depth was removed from consecutive sod harvests of 2 and 2.7 cm depths. Tesfariam et al. (2009) did not measure an increase in surface soil phosphorus to a 15 cm depth until biosolids were topdressed at ≥33 dry Mg ha^{-1}.

Initial soil test phosphorus at the study site was 12 mg kg^{-1}. Based on soil test recommendations, we applied 86 kg ha^{-1} each year to our inorganic fertilizer treatment plots. The biosolids supplied 154, 308, and 462 kg P ha^{-1} with the 0.5X, 1.0X and 1.5X cake rates, respectively, and 105, 210, and 315 kg P ha^{-1} with the 0.5X, 1.0X, and 1.5X blended rates, respectively. Although the 1.0X and 1.5X biosolids rates supplied more than two and three times, respectively, more phosphorus than the soil test recommendations, the increases in soil extractable phosphorus after three years would not have prohibited further use of biosolids for sod production. For sod production in Virginia, phosphorus applications are recommended when

Mehlich I soil extractable phosphorus levels are below 55 mg kg^{-1} (Virginia Department of Conservation and Recreation, 2005). Our extractable phosphorus results indicate that N-based rates of biosolids can be used in consecutive years without excessive increases in soil extractable phosphorus. To implement a biosolids-based sod production system, growers would likely need to adopt a rotational system where biosolids would be used for several years at N-based rates before switching to an inorganic fertilizer system with no phosphorus inputs to deplete the accumulated soil phosphorus. This period of permissible biosolids application will be lower in sod production systems due to the removal of phosphorus with the sod.

4.4.3. Soil organic matter accumulation and soil bulk density

After applying the biosolids treatments for three years, the 1.0X and 1.5X cake and blended biosolids treatments increased organic matter compared to the inorganic fertilizer control (Table 4.4). The 1.5X blended biosolids treatment increased organic matter more than any other treatment. Only the 1.5X cake biosolids treatment decreased soil bulk density compared to the inorganic fertilizer control.

Long-term turfgrass systems increase soil organic matter because of the high root turn-over and low soil disturbance (Qian and Follet, 2002). Sheard and Van Patter (1978) and Skogley and Hesseltine (1978) reported sod production maintains and possibly increases soil organic matter. They concluded that organic matter depletion does not occur because of the dense root system that is left behind after sod harvest. Skogley and Hesseltine (1978) estimated that about 9 Mg ha^{-1} yr^{-1} of organic matter is added to soil in sod production.

In traditional agricultural crop production, organic matter increases with the addition of organic amendments has been reported (Khaleel et al., 1981). Johnson et al. (2006) reported that topdressing composted organic amendments increased soil organic matter during turfgrass establishment, but there has been no research on the effects of organic amendments on soil organic matter in sod production. Organic amendments are usually topdressed or surface applied in turfgrass settings, but in sod production the beneficial effects of the amendment on soil physical properties are not realized without incorporation below the sod harvest depth. Our results indicate that soil organic matter can be increased more than with inorganic fertilizer given that repeat applications of incorporated biosolids at N based rates are made.

Decreasing bulk density in sod production fields can improve turfgrass growth and quality (Dunifon et al., 2011; Gaudreau et al., 2002; Johnson et al., 2006) and reduce the weight of sod, which can reduce transport costs for producers. Khaleel et al. (1981) attributed the decrease in bulk density with organic amendments to the dilution of heavier mineral component of soil by the less dense organic matter. Both Schnell et al. (2009) and Tesfariam et al. (2009) attributed reduced sod weight when high rates of biosolids were applied to reduced surface soil bulk density. The effects of repeated N-based biosolids rates on bulk density in sod production soils are not well known. The use of approximately N-based rates by Tesfariam et al. (2009) did not reduce soil bulk density when biosolids were surface-applied. In our study, only the 1.5X cake biosolids rate decreased bulk density. It remains to be seen how longer term annual applications of agronomic N rates of biosolids would affect soil bulk density.

4.4.4. Mineral matter export

During the entire study, only the 1.5X cake biosolids had a positive effect on soil export, reducing mineral matter export during harvest in years 1 and 3 and eliciting no difference in year 2 (Table 4.5).

A number of studies to quantify the amount of soil export with each sod harvest have been completed since the late 1970's. There have been conflicting reports as to whether or not mineral soil export during sod production is actually occurring (Carr, 1996; Sheard and Van Patter, 1978; Charbonneau, 2003; Skogley and Hesseltine, 1978). Mineral soil export is difficult to quantify because harvested sod consists of roots, rhizomes, organic matter and mineral soil that are bound together in the sod pad. Overestimation of soil export occurs if the mineral fractions from the roots, rhizomes and organic matter are included in the calculations (Sheard and Van Patter, 1978; Skogley and Hesseltine, 1978).

Millar et al. (2010) reported that mineral soil export at harvest was between 74 and 114 Mg ha^{-1} each year, similar to the range of Skogley and Hesseltine (1978) at 61 to 105 Mg ha^{-1} at a 1.25 cm harvest depth. In our study we were forced to use two distinct harvest depths based on differences in crop development by ten months after seeding. In year one, to ensure that all of the treatments would hold together, sod was harvested at a 2.5 cm harvest depth. This was lowered to a 1.9 cm depth for years two and three. The inorganic fertilizer control in years two and three exported between 149 and 224 Mg of mineral matter ha^{-1}. We reported mineral matter removal to account for the added mineral fraction of the biosolids.

We expected the amount of mineral matter exported to decrease with increasing rates of biosolids. This did not always occur. A hypothesis that warrants further investigation as to why we did not measure the expected trend is that there was harvest depth variability. The cutting height was not changed from plot to plot, but the sod was not harvested as deep from plots that were drier compared to wetter plots (Cataldi, personal observation).

Both Tesfariam et al. (2009) and Schnell et al. (2009) cited sod mass differences to conclude that biosolids could reduce the export of soil during sod harvest by diluting the soil surface with the organic amendment. Significant soil export reduction did not occur unless biosolids rates of 33 to 100 dry Mg ha^{-1} were used (Tesfariam et al., 2009; Schnell et al., 2009).

The only treatment in our study that reduced mineral matter export at harvest compared to the inorganic fertilizer control was the 1.5X cake biosolids treatment. The range of mineral matter export for this treatment was 143-177 Mg ha^{-1}. The 1.5X cake rate applied 13.5 dry Mg biosolids ha^{-1}, which is less than the lowest rate reported to reduce soil export in Tesfariam et al. (2009). We concluded that the 1.5X biosolids rate diluted the surface soil with less dense organic material and also reduced mineral soil export. Although our 1.5X cake rate reduced mineral soil export, our results indicate that the state allowable biosolids rate for sod production (1.0X) did not reduce mineral soil export.

4.5. Conclusions

We determined that the cake and blended biosolids improved soil quality by increasing soil organic matter. We also determined that repeat applications of low rates of biosolids did not reduce bulk density in a sod production system. Biosolids can be used to reduce soil bulk density by diluting the heavy native surface soil with less dense material. We determined that the lower biosolids rates were not supplying enough material below the sod harvest depth to measurably dilute the soil even though all treatments were incorporated to 5 cm. Mineral matter export at harvest was reduced using the highest cake biosolids rates, indicating again that there was not enough material being applied with the lower rates to dilute the surface soil and reduce the sod mass exported as was reported in previous studies. These results indicate that sod growers that use biosolids to produce sod not only get the benefit of reduced production costs, but will also see soil quality improvements and will be able to consecutively use biosolids to supply all of the crop N needs without increasing soil phosphorus above manageable levels.

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4.7. References

Beecher, N., and N., Goldstein. 2010. Biosolids composting in the United States-2010 update. Biocycle. 51:35-41.

Blake, G.R., and K.H, Hartge. 1986. Bulk density. In: Klute, A. (ed). Methods of soil analysis, part I, physical and mineralogical methods. ASA and SSSA, Madison, 363–375.

Brown, S., and M. Cotton. 2011. Changes in soil properties and carbon content following compost application: results of on-farm sampling. Compost Science and Utilization. 19:87-96.

Bulluck III, L.R., M. Brosius, G.K. Evanylo, and J.B. Ristaino. 2002 Organic and synthetic fertility amendments influence soil microbial, physical, and chemical properties on organic and conventional farms. Applied Soil Ecology. 19:147-160.

Carr, M.Y. 1996. Metal levels in Rhode Island municipal sewage sludges and their resulting appropriateness for agricultural use by sod farms. Honors thesis. Brown Univ., Providence, RI.

Chang, A.C., A.L. Page, F.H. Sutherland, and E. Grgurevic. 1983. Fractionation of phosphorus in sludge-affected soils. J. Environ. Qual. 12:286–290.

Charbonneau, P. 2003. Soil loss during sod production. Available at www.omafra. gov.on.ca/english/crops/facts/info_sodprod.htm#loss (verified 1 Mar. 2013). Ontario Ministry of Agriculture, Food and Rural Affairs, Ottawa.

Chen, H., S.H. Yan, Z.L. Ye, H.J. Meng, and Y.G. Zhu. 2012. Utilization of urban sewage sludge: Chinese perspectives. Environmental Science and Pollution Research. 19:1454-1463.

Dai, X., D.M. Vietor, F.M. Hons, T.L. Provin, R.H. White, T.W. Boutton, and C.L. Munster.

2009. Effects of composted biosolids on soil organic carbon storage during establishment of transplanted sod. Hort. Sci. 44(2):503-507.

Donohue, S.J., and S.E., Heckendorn. 1994. Soil test recommendations for Virginia. Blacksburg, VA., Virginia Cooperative Extension Service Publication. 834.

Dunifon, S.N., G.K. Evanylo, R.O. Maguire, and J.M. Goatley, Jr. 2011. Soil nutrient and fescue (festuca spp.) responses to compost and hydroseed on a disturbed roadside. Compost Science and Utilization. 19:147-151.

Evanylo, G.K., and W.L. Daniels. 1999. Papermill sludge composting and compost utilization. Compost Science and Utilization. 7:30-39.

Evanylo, G., C. Sherony, J. Spargo, D. Starner, M. Brosius, and K. Haering. 2008. Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. Agriculture, Ecosystems and Environment. 127:50-58.

Faust, T.G., and R.L. Oberst. 1996. Economic value of biosolids to farmers. Biocycle. 37:67-69.

Gilmour, J.T., C.G. Cogger, L.W. Jacobs, G.K. Evanylo, and D.M. Sullivan. 2003. Decomposition and plant-available nitrogen in biosolids: Laboratory studies, field studies, and computer simulation. J. Environ. Qual. 32:1498–1507.

Haynes, R.J., and R. Naidu. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and physical conditions. Nut. Cycling Agroeco. 51:123-137.

Hepperly, P., D. Lotter, C.Z. Ulsh, R. Seidel, and C. Reider. 2009. Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content. Compost Science Utilization. 17:117-126.

Johnson, G.A., J.G. Davis, Y.L. Qian, and K.C. Doesken. 2006. Topdressing turf with composted manure improves soil quality and protects water quality. Soil Sci. Soc. Am. J. 70:2114–2121.

Khaleel, R., K.R. Reddy, and M.R. Overcash. 1981. Changes in soil physical properties due to organic waste applications: A review. J Environ. Qual. 10:133-141

Kelling, K.A., L.M. Walsh, D.R. Keeney, J.A. Ryan, and A.E. Peterson. 1977. A field study of the agricultural use of sewage sludge: II. Effect on soil N and P. J. Environ. Qual. 6:345–352.

Korboulewsky, N., S. Dupouyet, and G. Bonin. 2002. Environmental risks of applying sewage sludge compost to vineyards: carbon, heavy metals, nitrogen, and phosphorus accumulation. J. Environ. Qual. 31:1522–1527.

Lagae, H.J., M. Langemeier, D. Lybecker, and K. Barbarick. 2009. Economic value of biosolids in a semiarid agroecosystem. Agron. J. 101:933-939.

Lemainski, J., and J.E. da Silva. 2006. Agronomic and economic evaluation of biosolids application on soybean production. Pesquisa Agropeauaria Brasileira. 41:1477-1484.

Landschoot, P., and A. McNitt. 1994. Improving turf with compost. BioCycle. 35:54-57.

Linde , D.T., and L.D. Hepner. 2005. Turfgrass seed and sod establishment on soil amended with biosolids compost. Horttechnology. 15:577-583.

Loschinkohl, C., and M.J. Boehm. 2001. Composted biosolids incorporation improves turfgrass establishment on disturbed urban soils and reduces rust severity. Hort. Sci. 36:790-794.

Maguire, R.O., J.T. Sims, and F.J. Coale. 2000. Phosphorus solubility in biosolids-amended soils in the Mid-Atlantic region of the USA. J. Environ. Qual. 29:1225–1233.

Millar, D., M. Stolt and J.A. Amador. 2010. Quantification and implications of soil losses from commercial sod production. Soil Sci. Soc. Am. J. 74:892-897.

NASS, USDA. 2011. Farm production expenditures 2011 summary. Natl. Agric. Statistics, Serv., Washington, DC.

NOAA. 2013. Unique Climatic Data. Sterling, VA. National Weather Service Forecast Office.

Norrie, J., and A. Gosselin. 1996. Paper sludge amendments for turfgrass. Hort. Science. 31:957-960.

Ott, S.L., and D.L. Forster. 1978. Landspreading: An alternative for sludge disposal. Am. J. Agric. Econ. 60:555-558.

Qian, Y., and R.F. Follett. 2002. Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agron. J. 94:930-935.

Richards, C.E., C.L. Munster, D.M. Vietor, J.G. Arnold, and R. White. 2008. Assessment of a turfgrass sod best management practice on water quality in a suburban watershed. J. Environ. Management. 86:229-245.

Rostagno, C.M., and R.E. Sosebee. 2001. Biosolids application in the Chihuahuan deserts. Effects of runoff water quality. J. Environ. Qual. 30:160–170.

Schnell, R.W., D.M. Vietor, R.H. White, T.L. Provin, and C.L. Munster. 2009. Effects of composted biosolids and nitrogen on turfgrass establishment, sod properties, and nutrient export at harvest. Hort. Sci. 44(6):1746-1750.

Sheard, R.W., and M. Van Patter. 1978. Soil modification during nursery sod production. Dep. of Land Resource Science, Univ. of Guelph, Guelph, ON, Canada.

Shober, A.L, and J.T. Sims. 2003. Phosphorus restrictions for land application of biosolids: Current status and future trends. J. Environ. Qual. 32:1955–1964.

Skogley, C.R., and B.B. Hesseltine. 1978. Soil loss and organic matter return in sod production. Univ. of Rhode Island, Kingston.

Soulsby, P.G., G.A.W. Hickman, and P.L. McMahon. 2002. Economics of recovering value from recycling treated biosolids to land. Water Environ. Manage. 16:18-24.

Tambone, F., P. Genevini, and F. Adani. 2007. The effects of short-term compost application on soil chemical properties and on nutritional status of maize plant. Compost Science and Utilization. 15:176-183.

Tesfamariam, E.H., J.G. Annadale, and J.M. Steyn. 2009. Exporting large volumes of municipal sewage sludge through turfgrass sod production. J. Environ. Qual. 38:1320-1328.

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.

Vietor, D.M., T.L. Provin, R.H. White, and C.L. Munster. 2004. Runoff losses of phosphorus and nitrogen imported in sod or composted manure for turf establishment. J. Environ. Qual. 33:358-366.

Virginia Department of Conservation and Recreation. 2005. Virginia Nutrient Management Standards and Criteria. Virginia Department of Conservation and Recreation. Richmond, VA.

Whalen, J.K., and C. Chang. 2001. Phosphorus accumulation in cultivated soils from long-term annual applications of cattle feedlot manure. J. Environ. Qual. 30:229-237.

Table 4.1. Chemical and physical composition of the biosolids products applied to the experiment (2009-2012)

Treatment	C:N	C§	TKN	NH_4-N	NO_3-N	Organic-N	Total P	K
	g kg^{-1}							
Blended†	15	230	15.0	5.3	0.004	9.7	9.5	2.6
Cake††	7	339	51.1	15.5	0.006	35.6	34.2	1.5

† Anaerobically digested dewatered biosolids blended with wood fines.
†† Anaerobically digested dewatered biosolids cake.
§ All analysis was done by A&L Eastern Labs, Richmond, VA.

Table 4.2. Annual application rates of biosolids on a dry weight basis and N,P,K and C to treatments in Remington, VA (2009-2011)

Treatment and Estimated PAN	Rate Mg ha^{-1}	N§	P	K	C
		kg ha^{-1}			
Fert Control (196 kg N ha^{-1})	--	196	86	140	--
Cake 0.5X (98 kg N ha^{-1})†	4.5	230	154	147	1525
Cake 1.0X (196 kg N ha^{-1})	9.0	460	308	154	3051
Cake 1.5X (294 kg N ha^{-1})	13.5	690	462	161	4576
Blended 0.5X (98 kg N ha^{-1})††	11.0	165	105	169	2530
Blended 1.0X (196 kg N ha^{-1})	22.0	330	210	198	5060
Blended 1.5X (294 kg N ha^{-1})	34.0	510	315	227	7820

† Anaerobically digested dewatered biosolids cake.
†† Anaerobically digested dewatered biosolids blended with wood fines.
§Based on TKN applied, plant available nitrogen rates are lower.

Table 4.3. Mehlich I soil extractable phosphorus of the surface soil to a 0-10 cm depth in Remington, VA (2010-2012)

Treatment and Estimated PAN	Year 1[§]	Year 2[¶]	Year 3[¶¶]
		mg kg^{-1}	
Fert. control (196 kg N ha^{-1})	11.5c[†]	9.5e	11.3c
Cake 0.5X (98 kg N ha^{-1})	10.5c	11.5de	15.5c
Cake 1.0X (196 kg N ha^{-1})	12.8c	14.8b	24.8b
Cake 1.5X (294 kg N ha^{-1})	13.0c	15.8bc	33.0a
Blended 0.5X (98 kg N ha^{-1})	11.8c	13.8cd	15.8c
Blended 1.0X (196 kg N ha^{-1})	17.8b[#]	17.8b	23.0b
Blended 1.5X (294 kg N ha^{-1})	25.3a	26.0a	33.0a
LSD (P< 0.05)	3.4	3.2	6.5

Means followed by the same letter are not significantly different at the P ≤ 0.05.
†Soil extractable phosphorus was sampled after each harvest.
§ Actual sample date was Jun. 15 in 2010.
¶ Actual sample date was Jul. 1 in 2011.
¶¶ Actual sample date was Aug. 17 in 2012.

Table 4.4. Soil organic matter and bulk density averaged over three production cycles (2009-2012)

Treatment and Estimated PAN	Organic Matter†	Bulk Density
	$g\ kg^{-1}$	$g\ cm^{-3}$
Fert. Control (196 kg N ha^{-1})	29.8d	1.51a
Cake 0.5X (98 kg N ha^{-1})	30.8cd	1.53a
Cake 1.0X (196 kg N ha^{-1})	31.7bc	1.52a
Cake 1.5X (294 kg N ha^{-1})	32.7b#	1.42b
Blended 0.5X (98 kg N ha^{-1})	30.7cd	1.54a
Blended 1.0X (196 kg N ha^{-1})	32.0bc	1.52a
Blended 1.5X (294 kg N ha^{-1})	34.9a	1.48ab
LSD ($P < 0.05$)	1.6	0.07

Means followed by the same letter are not significantly different at the $P \leq 0.05$.
†Organic matter and bulk density values are averaged across the three years of the study.

Table 4.5. Mineral matter export at harvest each year (2010-2012)

Treatment and Estimated PAN	Year 1†	Year 2¶	Year 3¶¶
	Mg ha^{-1}		
Fert. Control (196 kg N ha^{-1})	200a	149e	224a
Cake 0.5X (98 kg N ha^{-1})	169bc#	201ab	228a
Cake 1.0X (196 kg N ha^{-1})	191ab	181cd	220a
Cake 1.5X (294 kg N ha^{-1})	166c	143e	177b
Blended 0.5X (98 kg N ha^{-1})	205a	217a	220a
Blended 1.0X (196 kg N ha^{-1})	184abc	194bc	223a
Blended 1.5X (294 kg N ha^{-1})	190ab	161de	200ab
LSD (P< 0.05)	23	20	31

Means followed by the same letter are not significantly different at the P ≤ 0.05.
† Harvest depth was 2.54 cm. Harvest date was Jun. 15 in 2010.
¶ Harvest depth was 1.9 cm. Harvest date was Jul. 1 in 2011.
¶¶ Harvest date was Aug. 17 in 2012. Harvest depth was 1.9 cm.

5. Conclusions

Application of organic amendments, particularly biosolids, can be used to establish and maintain high quality stands of turfgrass. The application of organic amendments in turfgrass settings can also improve soil quality by increasing soil organic matter, water retention and decreasing bulk density. Biosolids have been used for sod production, but the focus of previous studies has been to export nutrients/biosolids from sod production fields to establishment sites. Because of this focus biosolids were applied at rates that exceeded crop nutritional needs. The effects of N-based biosolids applications for sod production are not well known. This thesis focused on the effects of N-based biosolids applications, from two EQ biosolids products, for sod production on turfgrass establishment and quality as well as soil chemical and physical properties. To accomplish this an experiment was designed to evaluate an EQ de-watered cake biosolids and the same material blended with wood fines, for sod production on the establishment, sod quality, sod tensile strength, sod transplant rooting strength, soil extractable phosphorus, soil organic matter content and mineral matter export at harvest of a tall fescue-Kentucky bluegrass sod.

To evaluate these effects we conducted a three-year field study in Remington, VA on a silt-loam Ashburn-Dulles complex from 2009-2012. Overall our results indicated that current N mineralization estimates of 30-35% worked well for the dewatered cake biosolids, but were too high for the blended biosolids product. Sod properties, such as tensile strength and quality at harvest were the same if not slightly higher with the 1.5X cake biosolids rate than the inorganic fertilizer control. The 1.0X cake biosolids was the only other biosolids rate to produce an acceptable quality sod, but slightly lower quality ratings and tensile strength seen in our study suggest that the treatment would benefit from a spring application of supplemental nitrogen.

We also saw that the 1.0X and 1.5X of both biosolids products increased organic matter after three years of applications, but only the highest rate of cake biosolids reduced bulk density. These results indicate that incorporation of N based biosolids rates can still apply enough organic matter to increase soil organic matter and slightly improve soil quality even after sod harvest. Even with our deeper harvest depths and lower application rates than previous studies, we saw an accumulation of P in the surface 10 cm of soil with biosolids rates higher than 0.5X. These results suggest and support other researcher's conclusions that nutrient export of incorporated biosolids is less than topdressed or unincorporated biosolids applications. Also, our results indicate that incorporated N based biosolids rates can reduce soil export at harvest, but only when using the 1.5X cake biosolids rate.

These results could provide background information for turfgrass establishment and sod production studies using alternative biosolids products in the state of Virginia. Future work using biosolids for sod production should look at using synthetic netting to increase the tensile strength of the sod and reduce the harvest depth. The shallower harvest depth will affect the amount of nutrients exported from the production field and could ultimately lead to faster increases in soil phosphorus, but it would more accurately reflect the sod production industry in the state. Also, a better quantification of soil export when using biosolids is needed. The future research will add to the knowledge base and further refine the recommendations made when using biosolids for sod production or in general turfgrass settings.