Drought Resistance Response of Tall Fescue Established in Disturbed Urban Soils Using Biosolids

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Abstract

Urban soils are typically degraded due to land disturbance. The poor quality physical and chemical properties of the soil can benefit from application of organic amendments. Local sources of such amendments are biosolids, which are treated domestic wastewater sludges. The objective of this experiment was to compare effects of various high quality biosolids-based soil amendments with synthetic fertilizer on the growth and quality of tall fescue (*Schedonorus arundinaceus)* under two different soil moisture regimes. The research site was a disturbed soil at the Virginia Tech Turfgrass Research Center in Blacksburg, Virginia. The experimental design was a split plot with irrigation regime as the main factor and soil amendments as the split factor. All treatments were arranged in four randomized complete blocks. The study was established in late summer 2013. Soil amendment treatments, applied prior to seeding in September 2013, were: 1) inorganic N, P, K applied according to soil test laboratory recommendations; 2) anaerobically digested, dewatered biosolids to supply agronomic N rate; 3) anaerobically digested, dewatered biosolids blended with sand and sawdust to supply agronomic N rate; 4) anaerobically digested, dewatered biosolids blended with sand and sawdust to supply agronomic P rate; and 5) composted biosolids to supply agronomic N rate. The agronomic N rate for the turfgrass was 224 kg of estimated plant available nitrogen (PAN) ha^{-1}. Inorganic fertilizer was applied to supply annual P and K requirements prior to seeding in late summer, and the N was split into three application timings (September 2013, April 2014, and

June 2014). Supplemental fertilizer N to achieve full agronomic N rate was applied to the treatment plots that received the agronomic P rate of blended biosolids-sand-sawdust. The area was seeded on September 13, 2013 with a tall fescue blend at a rate of 488 kg ha^{-1}. Following full tall fescue establishment, in June 2014, two irrigation regimes, consisting of 0% and 80% evapotranspiration replacement every three days, were initiated. The study had three phases denoted as the pre-drought, drought, and recovery phases which started in April and concluded in August of 2014. Turfgrass color and quality, volumetric soil moisture percentage to a 5 cm depth, normalized difference vegetative index (NDVI), clipping yield, and turfgrass N uptake were measured bi-weekly throughout the growing season. During the first May through July 2014 irrigation season, results were that the fertilizer control consistently provided improved responses relative to the biosolids amended treatments. Clipping yield, quality, and NDVI were all significantly greater in the inorganic fertilizer treatment, but volumetric soil moisture percentages were slightly greater in the biosolids treatments. Turfgrass responses appeared to have been associated with plant available nitrogen, which was lower in the biosolids treatments than in the fertilizer treatment. Calculated PAN for the biosolids products was too low to achieve ideal turfgrass growth and quality. Improving the estimated PAN and/or splitting the organic amendment application times should improve the growth and quality of the turfgrass.

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Table of Contents

List of Figures

List of Tables

1. LITERATURE REVIEW

1.1 Introduction and Background

New home construction practices have long been associated with post-construction landscaping challenges. Once a site is selected, the existing vegetation and topsoil are often removed exposing the lower soil horizons. These subsoils generally have a greater bulk density, organic matter levels that are very low to non-existent, and are more suitable for building foundations than lawns (Loschinkohl and Boehm, 2001; Dunifon et al., 2011). Unfortunately, the topsoil that is removed is rarely returned following completion.

Tall fescue (*Schedonorus arundinaceus* Schreb.) is one of the most common grasses planted on transition zone home lawns. It is very drought tolerant due to its deep rooting capability (Beard, 1973; Christians, 2004; Zhang et al., 2012). Tall fescue is also very hardy and resists most diseases with the exception of brown patch *(Rhizoctonia solani* Kuhn). Low maintenance requirements, such as reduced irrigation needs, reduced fertility needs, and reduced pesticide usage, for tall fescue when compared to Kentucky bluegrass make it a favorable choice for homeowners in the transition zone.

Following construction, contractors often hydroseed or sod new lawns with little remediation of the disturbed soil or restoration of topsoil (Christians, 2004). Construction-related compaction often results in poor turfgrass establishment. Returning the topsoil would be the simplest step in addressing this problem, but this practice is often not adopted due to time and/or expense. If the topsoil is not protected following removal, it may become contaminated with construction debris, trash, or other compactable fill material. It is also common for the topsoil to be stripped from the site and hauled away to be sold (Loschinkohl and Boehm, 2001). If topsoil is not returned, a good practice is to amend the soil with some form of organic residual which is incorporated via tillage prior to establishment (Pound and Street, 1991).

There are many forms of organic matter that may be used as soil amendments, but the availability of certain organic products is limited by location (Larney and Janzen, 1996). The most common forms available to urban areas are composted yard, manure and food wastes, thermally treated animal manure and sewage sludge (biosolids) (Loschinkohl and Boehm, 2001).

Biosolids have been widely used as a soil conditioner for decades in the U.S. and parts of Europe. Biosolids offers an increasingly growing choice as a soil amendment in urban areas due to an increasing amount of sewage sludge being processed into biosolids at wastewater treatment plants (Bastian, 1997). Biosolids composting facilities are increasing due to the public acceptance and agronomic value of the product (Loschinkohl and Boehm, 2001).

1.2 Disturbed Urban Soils

Urban development is a leading cause of soil degradation in the world today. As populations rise, development extends further from cities and encroaches into surrounding rural areas (Cogger, 2005). As homes, commercial properties, and roads are being built, the native vegetation and topsoils are stripped away. Once removed, the underlying subsoil is exposed, which the contractor then excavates and grades to their specific site needs (Loschinkohl and Boehm, 2001). The remaining subsoil lacks organic matter and nutrients, often has high clay content, and has a greater bulk density (Dunifon et al., 2011). These attributes are ideal for building foundations but are not suitable for healthy lawns and landscapes.

The process of removing large quantities of topsoil for the purpose of construction leaves the soil compacted, which may lead to an increase in runoff potential and an overall decrease in plant growth (Partsch et al., 1993). Kozlowski et al. (1999) determined that compaction associated with construction results in increased runoff and soil erosion, restricted root growth, increased soil bulk density, and decreased soil aeration, infiltration, and macroporosity. Continuous traffic over the building site with heavy equipment is the main cause of these problems.

Once construction is completed, the ideal practice to reverse the damage is to loosen the compacted soil with a tillage implement and return the removed topsoil to its original location prior to preparing the surface for turfgrass establishment (Christians, 2004). Recommendations for sites where topsoil has been removed, suggest that 10 cm to 20 cm of topsoil should be replaced before any establishment procedures take place. Unfortunately, this option can be cost prohibitive and is not often available. Even when topsoil is stockpiled, there are concerns with protecting its quality.

Many building contractors do not fully understand the consequences their actions may cause to the soil on the long term quality and performance of a lawn following completion of the building. The main goal is to complete the project within a set time as efficiently and quickly as possible, while also producing the best quality product. Soils that are mismanaged during construction will not always cause a problem immediately, but challenges may eventually show up years later as problem areas in a mature turfgrass stand. The final step, due to ease of application and low cost, is generally seeding.

If appropriate steps to remediate the damaged soil are not taken following final grading, inadequate turfgrass establishment and lack of long-term persistence of a dense stand are generally the ultimate result (Cogger, 2005). Addressing these issues before establishing turfgrass offers the most options of soil remediation to the contractor. Once turfgrass has been seeded or sodded, the available options are significantly limited. If uncontaminated topsoil is not available, a good practice is to amend the soil with a quality organic residual which is incorporated via tiller prior to establishment (Christians, 2007).

1.3 Organic Matter and Amendments

There are many sources of organic residuals that can be used for amending degraded soils. Composted or otherwise treated animal manures, biosolids, papermill sludges, food residuals, and yard trimmings are a few examples of organic soil amendments (Khaleel et al., 1981). Animal manures and other agricultural wastes are often used in soil rehabilitation on farmland (Larney and Janzen, 1996). Advocates of organic farming have long believed that animal manures are superior to commercial fertilizers because of their ability to provide nutrients, while also raising the organic matter content of the soil, aiding in microbial and biological diversity, and increasing soil water holding capacity (Sims, 1990). These materials are in high supply in rural farming communities, but due to transportation cost, manures are less likely to be available in urban areas. Examples of materials that may be available in urban settings generally include composted food and/or yard wastes, biosolids, and composted biosolids (Loschinkohl and Boehm, 2001).

1.4 Biosolids Source and Properties

Increasing urbanization results in increasing amounts of domestic wastewater, whose treatment produces “biosolids” (US EPA, 2014). The US Environmental Protection Agency (EPA) defines biosolids as “the nutrient rich organic materials resulting from the treatment of sewage sludge” (EPA, 2011). Biosolids (previously termed sewage sludge) have been widely used as a soil conditioner for decades in the U.S. and parts of Europe (Logan et al., 1997). During this time, there were very few regulations on sewage sludge, and it was not recognized as an amendment totally without hazards.

In 1993, the US Environmental Protection Agency promulgated “The Standards for the Use or Disposal of Sewage Sludge” (EPA, 1994). These regulations included the 40 CFR Part 503 Biosolids rule, or “503 Rule,” which addressed requirements for biosolids land application, including limits on heavy metal concentrations and reduction of pathogens and vector attraction (EPA, 1994). This rule established quality requirements specifically for biosolids and addressed loading and nutrient limits used for land application.

1.4.1. Pathogen Content Reduction

The 503 Rule defines the acceptable level of pathogens that are allowed in the biosolids finished product. Pathogens in raw sewage sludge such as viruses, protozoa, bacteria, and helminths have been implicated as potential disease-causing organisms (Hay, 1996). In order to reduce these pathogens, two class levels of pathogen reduction treatments were implemented by the 503 Rule.

Two classes of treated biosolids with respect to pathogen and vector attraction reduction are Class A and Class B. If the intended application area is public land such as home lawns, athletic fields, and gardens, only Class A products are permitted for use. Class A biosolids are treated by Processes to Further Reduce Pathogens to reduce pathogen density to below detectable levels and to preclude vector attraction. Vectors can be defined as any organism that has the ability to spread pathogens through contact with the biosolids such as birds, rodents, mosquitoes, flies, etc. (Evanylo, 2009). By reducing the odiferous characteristics of the materials, vector attraction is also reduced (Hay, 1996). There is no re-entry interval associated with this product due to the low pathogen risk.

Class B biosolids are also treated to reduce pathogen content, but still have a low detectable level of pathogens present following treatment. Biosolids that are designated as Class B are predominantly used for agricultural and reclaimed mined lands. Due to the greater pathogen content in Class B biosolids, there are re-entry intervals following application for public access, animal grazing and crop removal.

1.4.2. Pollutants

The US EPA has determined that certain pollutants may be cause for concern and must be regulated during land application of treated biosolids. There are nine trace elements that, if applied in high enough concentrations, could lead to health risks for animals, humans, and plants (EPA, 2006). These include arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), and zinc (Zn) (Evanylo, 2009). The pollutant ceiling concentration limit (CCL) for these elements (as defined by the 503 Rule) cannot be exceeded if the biosolids are to be permitted for land application. If any of the pollutant exceeds the CCL, the biosolids are deemed unusable and must be disposed using methods such as landfilling or incineration.

1.4.3. Exceptional Quality Biosolids

Class A biosolids that meet certain strict guidelines including reduced vector attraction, reduced pathogen content, and a lower pollutant limit (termed pollutant concentration limit, or PCL) can be designated as Exceptional Quality (EQ) biosolids (EPA, 2006). They are processed to an extremely high level and carry very few restrictions for application as long as agricultural loading rates and regulations are met. For this study EQ biosolids were used in all amendment treatments.

1.4.4. Dewatered Biosolids

Dewatering of the biosolids involves pressure applied to the material through belt presses, centrifuges, or filters which significantly reduces water weight (Evanylo, 2006). Dewatered biosolids typically contain 20-30% solids. The reduction in moisture allows for reduced transportation costs of biosolids to application sites.

In order to further reduce the moisture content of dewatered biosolids, Evanylo (2013) and Cataldi (2013) had biosolids blended with low moisture carbon sources such as wood shavings, sawdust, and sand to aid in handling and spreading. Such blending with woody residuals increases the the C:N analysis of the resulting product, making estimation of PAN mineralization rates more difficult.

1.4.5. Composted Biosolids

Composting biosolids is a common means of treatment to generate a marketable by-product. Composting creates a Class A biosolids product that is safe and suitable to use by the general public. The end product of the composting process may resemble topsoil or humus and can be used as a fertilizer for home lawns, gardens, and landscaping. The public perception of biosolids compost as an extremely safe product allows it to contend with other organic products that are sold bagged, or in bulk, such as animal manures, bone meal, or processed poultry litter.

1.5 Benefits of Biosolids Land Application

Biosolids provide benefits that make them excellent soil amendments. Biosolids are very high in organic matter which enables them to improve soil tilth by improving physical properties (Cogger, 2005). Research has shown that organic matter plays a large role in soil stabilization and the reconstituting of soil aggregates (Tisdall and Oades, 1982).

Since soil structure is ameliorated and enhanced, improvements in cation exchange capacity (Aggelides and Londra, 1999), pore space, water holding capacity (Darmody et al., 1983; Hornick and Parr, 1987), and bulk density result (Krause, 1988). Additional research has highlighted soil organic C increases that were also attributed to the application of biosolids (Krause, 1988; Lindsay and Logan, 1998; Kirchmann and Gerzabek, 2002).

The use of biosolids not only affects soil composition and structure, but can supplement nutrients and reduce or eliminate the need for inorganic fertilizers (Akrivos et al., 2000; Bugbee, 2002; Cataldi, 2013; Chen et al., 2012; Darmody et al., 1983; Faust and Oberst, 1996; Gilmour et al., 2003; Hornick et al., 1979; Lagae et al., 2009; Lemainski and Silva, 2006; O'Keefe et al., 1986; Parr et al., 1978; Pascual et al., 1997; Sikora and Yakovchenko, 1996; Tester, 1989). Due to their high organic matter contents, nitrogen and other nutrients are released slowly over long periods without the burn potential that is associated with some commercial fertilizer products (Blume et al., 2009). Studies have shown that slow releases of nutrients are more beneficial to plant productivity and persistence versus water soluble commercial fertilizers that release quickly (Obreza and Ozores-Hampton, 2000). Quick release of nutrients can be beneficial if the crop is able to take up large quantities quickly, but leaching loss can potentially be much greater. For these reasons, recommendations are being made to apply biosolids as a primary N source on leaching-prone sandy soils (Obreza and Ozores-Hampton, 2000).

Studies on turfgrasses using biosolids during establishment and using composted biosolids as topdressing have also shown positive results. Amendments including organic compost have been shown to enhance turfgrass quality and establishment when compared to other nutrient fertilizer sources (Angle et al., 1981; Cisar and Snyder, 1992; Garling and Boehm, 2001; Norrie and Gosselin, 1996). Research performed by Loschinkohl and Boehm (2001) demonstrated that perennial ryegrass (*Lolium perenne* L.) amended with composted biosolids at establishment had an accelerated germination and growth rate, as well as increased clipping yields over non-amended treatments. Sikora et al. (1980) reported similar findings on tall fescue. Landschoot and McNitt, (1994) also showed positive results when adding a composted biosolids to exposed subsoil and establishing Kentucky bluegrass. Dunifon et al. (2011) used composts to improve a disturbed urban soil roadside established with tall fescue, and reported increases in overall soil quality improvements.

There have also been several turfgrass studies that compared inorganic fertilizer to various organic amendments. Carrow (1997) showed that long term differences in turfgrass quality were not significantly affected by inorganic and organic amendments use, but organic sources did not produce the rapid flush of growth that inorganic fertilizer sources provide. Research by Caceres et al. (2010) found no significant differences on turfgrass color or quality between inorganic and organic fertility programs for cool season grasses.

Establishment rates and total groundcover percentage have also been researched. Linde and Hepner (2005) reported that there were no significant differences in spring ground cover establishment between fall-applied compost and inorganic fertilizer despite an initial lag in the compost-amended soils. Research by Tesfamariam et al. (2009) showed that the establishment rate of warm season grasses was higher using heat-dried, anaerobically digested biosolids at increasing rates above 8 dry Mg ha^{-1}. A study by Millar et al. (2010) reported that application rates of biosolids at 7 dry Mg ha^{-1} yielded the best turfgrass establishment results for cool season sod production. Turfgrass production in Virginia uses mineralization estimates for PAN established by the Virginia Department of Conservation and Recreation for composted and anaerobically digested biosolids products. However, newly developed alternative biosolids products, which have been developed for use in urban areas, often have PAN mineralization rates which are unknown.

Findings by Trenholm and Unruh (2005) highlight one big concern with organic amendments, i.e. accurate estimations of nitrogen that will become available over time following soil incorporation of variously-processed biosolids is crucial if these residuals are to function as synthetic fertilizer substitutes for adequate year-one plant growth and development. Since biosolids are organic fertilizers, mineralization of the organic N fraction relies on microbial activity which is driven by several environmental factors. These factors, including moisture, air and soil temperature, soil structure, soil pH, and soil type, all play a significant role in mineralization rates. The method used to process the biosolids material can also impact the mineralization rate, since nutrient availability of different materials is variable (Maguire et al., 2001; Gilmour et al., 2003; Cogger et al., 2004; Gilmour and Clark, 1988). Processes such as dewatering and composting function to lower the amount of plant available nitrogen, while also affecting the spreadability of the material (Evanylo, 2009).

Little previous research has been reported on the effects of dewatered biosolids cake on turfgrass growth or establishment. In a study by Cataldi (2013), two different forms of biosolids (cake and blend) were applied during establishment for sod production of a polystand of Kentucky bluegrass (*Poa pratensis* L.) and tall fescue in the transition zone. Cataldi blended dewatered biosolids with wood fines at a ratio of 1:0.65 to reduce the moisture percentage of the biosolids to aid in spreadability of the biosolids cake. The resulting blend yielded a C:N ratio of 15:1 as compared to the C:N ratio of the cake at 7:1. The products used by Cataldi have similar C:N ratios to the products we evaluated in our study.

Cataldi reported that using blended biosolids resulted in slower establishment when compared to the inorganic fertilizer control, but no differences in establishment were reported for the biosolids cake and inorganic treatments. Cataldi also reported that PAN estimations for the biosolids cake were closer to the inorganic fertilizer PAN than the blended biosolids. These differences in establishment rate were attributed to lower plant available nitrogen due to higher than expected C:N ratios of the blended biosolids material (Cataldi, 2013).

Cataldi’s findings suggest that a dewatered biosolids cake is an acceptable substitute for inorganic fertilizer during turfgrass establishment, and can improve overall soil quality. The biosolids estimation rates of N mineralization used in his study showed that current N mineralization estimates (30-35%) over predicted year-one N availability for the blended material. He recommended that turfgrass established with similar biosolids materials receive supplemental nitrogen applications during the spring (Cataldi, 2013).

1.6 Tall Fescue

Tall fescue is a cool-season, deeply rooted, turfgrass species with a coarse textured, bunch-type growth habit. Tall fescue forms a deep and extensive root system that allows it to withstand longer periods of drought than other cool season turfgrass species (Beard, 1973). Tall fescue is extremely adaptable to many different climates and performs well when grown in the transition zone of the United States ranging from the temperate to semitropical regions (Christians, 2004). If grown too far north, it is more susceptible to injury from low temperatures.

Tall fescue is also widely adapted to many soil types making it a viable candidate for various uses (Kim and Beard, 1988; Turgeon, 1987). Tall fescue is able to tolerate poor quality soils with low fertility, but grows best in fertile soils which are high in organic matter (Beard, 1973). Christians (2004) reported that tall fescue was better suited to drought and high temperatures than other cool season turfgrass species, due in part to a deep root system and other physiological characteristics. Common areas of use include parks, home lawns, sports fields, pastures, and low maintenance sites (i.e. highway medians and rights of way) (Meyer and Funk, 1989).

Tall fescue is propagated by seed and has a quick germination rate making it a very useful turfgrass for new lawn establishments (Beard, 1973). In certain circumstances such as athletic fields or golf courses, polystands of different turfgrass species are not acceptable, due to aesthetic differences and playability concerns. In these situations, blends of two to four different tall fescue cultivars are recommended in order to provide genetic variability in the turfgrass stand. This precaution is taken to reduce the risks of different environmental stresses such as disease pressure, insect damage, and drought stress from causing a total loss of turfgrass should damage occur.

There are several different measures researchers use to evaluate turfgrass quality, including subjective visual ratings of turfgrass color and quality and objective ratings using a Normalized Difference Vegetative Index (NDVI) (Bell et al., 2002; Keskin et al., 2008) or digital imaging analysis (Karcher and Richardson, 2003). NDVI is a common vegetation index which measures spectral reflectance and radiative differences between the red and near infrared (NIR) wavelengths (Bremer et al., 2011). Since red reflectance is part of the visible light spectrum and is mostly affected by chlorophyll absorption, the red reflectance is likely a large component of subjective visual ratings and NDVI (Gausman, 1977). This gives an objective measurement which correlates closely to the chlorophyll content of the plant material being analyzed (Bell et al., 2004; Carter and Spiering, 2002; Bremer et al., 2011; Stiegler et al., 2005).

The use of NDVI also allows for NIR reflectance to be measured. NIR reflectance is mostly affected by the scattering of light bouncing off of various structures in the leaf cell such as the nuclei, protoplasts, stomata, and cell walls (Gausman, 1977). NIR reflectance is not visible and is unable to be measured using subjective visual ratings. Any environmental stresses such as disease, water stress, shoot density, or shoot injury can affect the scattering of light causing the NIR reflectance reading to change along with the overall NDVI measurement (Penuelas et al. 1993). Using NDVI allows for detection of these stress related variations, which may or may not be detectable using subjective visual ratings of color and quality. Goodin and Henebry (1998) also reported that NDVI measurements may respond differently in plants under water stress.

Research by Bremer et al. (2011) has shown that NDVI readings very closely match the subjective visual quality ratings of turfgrass species. The correlations of NDVI to turfgrass visual quality ratings in studies performed by Trenholm et al. (1999); Bell et al. (2002); Lee et al. (2011); Fitz-Rodriguez and Choi (2002); and Jiang and Carrow (2005, 2007), all confirm that the objective NDVI readings and the subjective quality ratings are very similar. Research performed by Karcher and Richardson (2003) also highlighted significant similarities between subjective visual color and quality ratings when compared to NDVI and digital photography.

1.6.1. Fertilization Requirements

Cool season turfgrass species grown in the transition zone share a common fertilization schedule. Each species has varying needs based on location, usage, and residual fertility, but fertilization timing is similar. As with most cool season grasses, the peaks of growth for tall fescue shoots and roots are generally observed in the spring and fall of the year, with periods of slower growth and dormancy occurring during the summer months (Nutter et al., 1969).

There are many nitrogen fertilizer sources for turfgrass. Two forms of N in fertilizer are expressed as water soluble nitrogen (WSN) and water insoluble nitrogen (WIN). These terms describe the plant availability (or solubility) of the nitrogen source. Commercial fertilizers often use a mixture of both of these forms of nitrogen, which offers a quick green up with the quick release WSN, and a long lasting green color from the slow release WIN (Havlin et al. 2005). WSN largely consists of readily plant available inorganic N, and WIN is mostly organic N, which requires mineralization to transform the N to the available inorganic form.

Typical responses to higher nitrogen fertilizer rates are increased clipping yield, increased overall turfgrass quality, darker green color, and increased tiller density. Research has indicated that increased N rates result in greater tiller density when compared to lower annual rates, but often sacrifice root mass (Beard, 1973; Turner and Hummel, 1992).

A typical fertilization program for tall fescue located in the transition zone is based on annual fertility rates ranging from 195 to 244 kg N ha^{-1}. Primary applications of 49 kg N ha^{-1}

during the months of September, October, and November and 24 to 37 kg N ha^{-1} applied in March and April are ideally recommended for tall fescue home lawns (Beard, 1973; Christians, 2007; Fribourg et al., 2009). Depending on use demands on the turfgrass, rates may be adjusted up or down. The rate of 224 kg N ha^{-1} for our study falls within the recommended rate range of N fertilizer for tall fescue and was chosen based on the success of past research.

1.6.2. Drought Resistance

Tall fescue has been designated as a drought resistant cool season grass (Carrow, 1996). Drought can be defined as a period of prolonged stress brought on by lack of soil water availability and can affect plant species in different ways (Beard, 1973). Tall fescue shows signs of drought stress first during the stages of wilting, where leaves fold or roll on themselves, and have a blue green appearance (Carrow, 1996). If periods of drought stress continue past the wilting stage, slowed growth and chlorosis of the leaf tissue occurs, limiting the ability of the turfgrass to photosynthesize (Naylor, 1972). Continuing chlorosis results in dormancy and eventual death if water is not available (Beard, 1973).

Drought resistance of tall fescue can be very difficult to measure due to differences in environmental conditions and responses to soil moisture limitation (Levitt, 1980). Beard (1988) defined drought resistance as the combination of avoidance, tolerance, and escape. In simpler terms, drought resistance includes all mechanisms of the turfgrass plant which allow it to survive during prolonged periods of low soil moisture availability.

One physiological mechanism of drought avoidance described by Beard (1973) is the ability of tall fescue to roll its leaves as soil moisture becomes limiting, affectively decreasing leaf surface area for transpirational loss. The characteristics of tall fescue promoting deep rooting and dormancy allow it to avoid physical damage during drought stress and can be described as drought avoidance (Carrow, 1996a, 1996b; Huang and Fry, 1998; Huang and Gao, 2000; Kim and Beard, 1988).

1.6.3. Irrigation Requirements

Drought continues to plague the United States each year, affecting crop production and turfgrass health. In some areas, water restrictions limit the amount or frequency of supplemental irrigation that can be applied. These restrictions show the importance of a properly designed and water use efficient irrigation system. Choosing a drought tolerant turfgrass species, such as tall fescue, is also another option to combat drought for a homeowner.

Similar to the fertilization rates of cool season species, tall fescue irrigation needs also follow a common pattern. An average tall fescue turfgrass stand in the transition zone requires 2.5 to 4 cm of water per week to maintain normal growth in the summer (Turgeon et al., 1996). This water may be supplied solely by rainfall, supplemental irrigation, or a balanced mixture of the two. Depending on the microclimates associated with the location of the turfgrass, more or less water may be needed.

Most of the water loss that occurs from a plant occurs during the process of photosynthesis when the stomata open in order to fix carbon dioxide from the outside environment. When the stomata are open, transpiration occurs and the leaf temperature is regulated by means of evaporative cooling (Duble, 1995). In turfgrass, a dense canopy is generally formed protecting the soil surface from evaporation, meaning that most water loss is due to transpiration.

One very important factor that determines irrigation needs for any plant is evapotranspiration. Evapotranspiration (ET) can be defined as the combined water loss from plant tissue (transpiration) and the soil (evaporation) where the plant resides (McCann and Huang, 2008). ET is also affected by environmental factors such as relative humidity, wind, and temperature. When humidity is low, the dry air surrounding the plant creates an effective sink and causes a moisture gradient to occur (Turner, 1978). Moisture from within the plant is released via transpiration due to varying humidity levels between the plant and the environment.

The presence of wind also plays a large role in ET loss. As wind blows across the leaf surface, the microclimate surrounding each blade is disrupted signaling to the plant that transpiration is needed to regain this equilibrium of air and moisture (Levitt, 1980).

Temperature is another main cause of evapotranspiration. As temperatures rise, the plant senses that cooling is required and opens stomata (Levitt, 1980). This reaction starts the process of transpiration which allows water to leave the plant and effectively cool the turf canopy. If too high of a temperature is reached, the plant closes the stomata attempting to conserve water until the heat stress passes.

There are different methods of determining turfgrass water needs based on volumetric soil moisture, rainfall data, and atmospheric conditions. By collecting rainfall, monitoring volumetric soil moisture, and estimating ET values, a turfgrass manager or homeowner can accurately schedule their irrigation system to maximize water use efficiency.

Weather stations across the country generally use a form of the Kimberly-Penman equation to determine ET. The Kimberly-Penman method was researched in Kimberly, ID for eleven years and focused on meteorological variables including humidity, temperature, radiation and wind run (Ervin and Koski, 1995; Jensen et al. 1990). The Kimberly-Penman method focuses on the measured ET rates of alfalfa, but by using the proper crop coefficient (K_c) as a multiplier, the scheduling of irrigation can be accurately estimated. The standard K_c of 0.80 for cool-season turfgrasses has been widely accepted when ET estimates are utilized (Ervin and Koski, 1997).

In a previous study performed by Ervin (1995), different ranges of crop coefficients were tested to determine whether lower coefficients would provide acceptable quality on turf-type tall fescue and Kentucky bluegrass while reducing ET replacement needs. His findings suggest that adequate irrigation applied every third day at a range of 0.65 to 0.80 of ET provided acceptable quality of the cool-season turfgrass stand. He also suggested that use of the Kimberly-Penman equation was highly site specific and variations may occur in micro-environments.

One possible solution to help eliminate micro-environment variation from the Kimberly-Penman equation would be to use a weather station at the site of the crop. An inexpensive alternative would be to use several modified atmometers (Broner and Law, 1991; Ervin and Koski, 1997; Fontaine and Todd, 1993). Research performed by Ervin and Koski (1997), evaluated two different methods of ET estimation, when they compared the use of modified atmometers to the standard Kimberly-Penman weather station ET output estimates.

Their results indicated that the modified atmometers, measured approximately 75% of the actual ET when compared to the Kimberly-Penman equation estimates of ET. These measurements were repeated and turned out to be highly consistent from season to season in a semi-arid region. Since a recommended ET range of 65 to 80% was observed during the Ervin (1995) study, and this range coincides with the results of the Ervin and Koski (1997) study, it can be assumed that the 75% of ET measurements found by using the modified atmometers can be an accurate method for irrigation scheduling adjusting appropriately for differences in humidity levels.

1.7 Objectives

Previous research has shown that different types of biosolids offer beneficial effects to plants, e.g. increased soil moisture holding capacity, soil fertility, plant nutrition, and establishment and maintenance of quality turfgrass stands. There is little information on the use of newly developed Class A EQ biosolids products for improving disturbed urban soils and supplying essential plant nutrients for establishment and maintenance of tall fescue. Mineralization estimates of different organic residuals are based on research results adopted by Virginia Department of Conservation and Recreation, but there is a need to assess the estimated nutrient availability of newly developed biosolids products to determine if the current mineralization estimates still apply (Virginia Department of Conservation and Recreation, 2005). The goal of this research was to compare a variety of biosolids-based residuals with synthetic fertilizer on the persistence of tall fescue under optimally and inadequately irrigated conditions.

2. MATERIALS AND METHODS

2.1 Site, experimental design and treatment establishment

The research was conducted at the Virginia Tech Turfgrass Research Center in Blacksburg, VA. Blacksburg is located in Montgomery County at coordinates (37°12'54.31"N, 80°24'42.14"W) (see Figure 1) and is approximately 634 m above sea level. The soils that are native to the site are classified as Groseclose silt loams (a clayey, kaolinitic, mesic Typic Hapludults), but these were completely removed in the early 1940's and the site was graded for an airport runway that was never used. Subsequently, the site was planted in tall fescue and maintained as a temporary grass parking lot and staging area. Decades of tall fescue growth on this subsoil resulted in the development of a topsoil layer of approximately 7.5 cm in depth.

The site lies within USDA cold hardiness zone 6b and is classified as mountain temperate or humid continental with average annual rainfall of 104 cm. Mean monthly temperature and rainfall data for the trial period of August 2013 through December 2014 were obtained from a nearby weather station (NOAA, 2014) and are presented in Table 1.

An area measuring 22.7 m by 35.5 m was sprayed on 1 August 2013 with a mixture of glyphosate (*N*-(phosphonomethyl) glycine) at 23.4 L ha^{-1} and diquat (diquat dibromide) at 4.7L ha^{-1}, respectively) to kill vegetation. The treatment was applied again on 12 August 2013 to ensure complete removal of existing turf and weed species.

The experimental area was tilled to an approximate 7.5 cm depth using a tractor-mounted tiller (Rotadairon USA, Model RD 150, Anderson, SC). The loosened soil was excavated and removed using a Bobcat Model S-130 skid steer loader (Bobcat USA, Fargo, ND). Removal of the O, E, and A horizons left exposed B and C horizons across the experimental area. This simulated the removal of topsoil that occurs during construction. Following topsoil removal, the soil was tilled again to an approximate depth of 7.5 cm to prepare the soil for amendment applications.

2.1.1. Irrigation Installation

An in-ground irrigation system was installed following topsoil removal. The irrigation system was designed to irrigate eight equal zones measuring 20.7 m X 3.7 m. Each zone was designated (pre-establishment) as 0% or 80% ET. The control valves (Toro Model P-220 Series) measured 3.8 cm on the inflow and outflow of each valve. Each valve was individually wired to an irrigation controller (Toro Model TMC-212, Minneapolis, MN) to allow for individual zone operation. The lateral lines remained at 3.8 cm until being split into the two sides of each irrigation zone where they were reduced to 2.5 cm PVC. All irrigation lines were placed at a 60 cm depth to ensure they were installed below the frost line for the area. The irrigation heads are 570Z MPRs with matching MPR Plus nozzles (brown-3.7 m) from The Toro Company (Toro Company, Bloomington, MN). Each spray head was connected to its respective lateral line using 1.3 cm Toro Funny Pipe and 1.3 cm Toro Funny Pipe barbed adapters.

An audit of each irrigation zone was performed using the catch cup method. Each of the eight zones was operated for 10 minutes, during which time precipitation was collected. The audit indicated that the irrigation system had a distribution uniformity (DU) of 98% and precipitation rate was estimated at 3.8 cm hr^{-1}. DU is a measure of how evenly irrigation is applied to a given area.

Evapotranspiration loss was estimated using two modified ceramic atmometers from the ETgage Company (1931 S. County Rd. 19, Loveland, CO 80537) installed on the site. The two atmometers were mounted approximately 40 m from one another on either side of the trial in similar environmental conditions. The atmometers were mounted to wooden posts and leveled at a height of 1 m above the ground following recommendations given by the manufacturer. These atmometers were equipped with a green canvas (designated as Style No. 30) overlaying the ceramic cup which simulated water loss from the turf canopy. Distilled water was used to fill the atmometers and aided as a medium used for evapotranspiration readings. Simulated evapotranspiration readings were measured by looking through the glass sight tube on the side of the atmometers and recording the loss of distilled water. Readings were measured every three days throughout the growing season and an irrigation schedule was used to replenish the water loss to 80% of ET.

The experimental design was a two factor split-plot randomized complete block design (RCBD) with four replications. The main treatments were two levels of irrigation replacement every three days: 0% or 80% of ET. The sub treatments consisted of five soil amendments (see Figure 2, Table 2).

2.1.2. Amendment Characteristics

There were five amendment treatments used for this research. The synthetic fertilizer control (Control) treatment received an annual rate of 224 kg N ha^{-1} by means of split application. The first application of 124 kg N ha^{-1} (urea, 46-0-0, Potash Corporation, Saskatchewan, CAN) was applied on September 12, 2013. The secondary application of N was surface applied at 100 kg N ha^{-1} (Pro-Mate 25-5-11, Helena Chemical, Collierville, TN) with a Gandy drop spreader (Gandy, Owatonna, MN) on October 30, 2013.

Anaerobically digested, dewatered Class A biosolids (Alex-DB) were provided by Alexandria Renew Enterprises, an advanced wastewater treatment facility located in Alexandria, VA. The biosolids were applied at an estimated rate of 224 kg PAN ha^{-1}. The actual dry loading rate for Alex-DB was 8.1 Mg ha^{-1}. Rates were based on their estimates of PAN assuming that 30% of the organic nitrogen would be mineralized during the first year of growth per VA DCR recommendations.

The Alex-DB was also blended (by Luck Stone Corporation, Richmond, VA) with sand (Table 3) and sawdust at a 2:1:1 ratio by mass of biosolids:sand:sawdust. The addition of the sawdust to the biosolids increased the C:N ratio of the material from 7:1 to 15:1. This mixed biosolids material was used to supply different agronomic rates of PAN based on the agronomic N needs of tall fescue and the agronomic P needs as determined by soil testing. The agronomic N rate of biosolids mix (Alex-N) was applied at an estimated rate of 224 kg PAN ha^{-1}. The actual dry loading rate of Alex-N was 64.0 Mg ha^{-1}.

The mixed biosolids material applied at the agronomic P rate (Alex-P) provided 64 kg PAN ha^{-1} and was supplemented by two split rates of urea totaling 160 kg N ha^{-1}. The first supplemental application of 100 kg N ha^{-1} was applied and incorporated on September 12, 2013, and the second application of 60 kg N ha^{-1} was made on October 30, 2103. The actual dry loading rate of the Alex-P organic residual was 18.3 Mg ha^{-1}.

The biosolids compost (Spots) was obtained from the Spotsylvania County (VA) Livingston compost facility. This material was produced by composting anaerobically digested, dewatered, Class B biosolids with wood fines, resulting in a Class A biosolids compost. The actual dry weight of the Spots compost applied was 22.4 Mg ha^{-1}.

The compositions of the three organic amendments used in this trial are shown in Table 2. The digested biosolids-sand-sawdust mix had lower amounts of total Kjeldahl N (TKN), organic N, P, and K than the digested and composted biosolids products. The TKN of the digested biosolids was approximately 7x greater than the biosolids mix and 2x greater than the biosolids compost. The N:P ratio of the biosolids products was 1.3:1.0 for the mix, 1.4:1.0 for the digested biosolids, and 2:1 for the biosolids compost.

Samples of each organic amendment used in the experiment were taken prior to application and analyzed by A&L Eastern Laboratories (Richmond, VA) (Table 2). The methods used for each parameter were total Kjeldahl N (SM-4500-NH3C-TKN), total solids percentage (SM-2540G), organic N, ammonium-N (SM-4500-NH3C), nitrate + nitrite-N (SM-4500NO3F) (Standard Methods for the Examination of Waste and Wastewater, 1992), phosphorus (SW-6010C), and potassium (SW-6010C) (US EPA, 1986).

2.1.3. Soil Characteristics

Each of the 40 individual treatment plots in the experimental area were soil sampled using a 2 cm diameter probe to a depth of 10 cm. Six samples were collected and combined from each treatment, dried in a Blue M Stabil-Therm Constant Temperature oven for 48 hours at 60^{o}C, and ground to pass through a 2 mm sieve. Samples were analyzed by the Virginia Tech Soil Testing Laboratory for routine soil test analysis of Mehlich I extractable P, K, Ca, and Mg and pH (Maguire and Heckendorn, 2011).

The results indicated that the soil had a pH of 5.1, extractable P of 11.5 mg kg^{-1}, extractable K of 61 mg kg^{-1}, extractable Ca of 504 mg kg^{-1}, extractable Mg of 218 mg kg^{-1}, and soil organic matter concentration of 0.3%. Triple superphosphate (0-46-0) and muriate of potash

(0-0-60) were applied to the synthetic control plots based on the soil test results (Maguire and Heckendorn, 2011). Muriate of potash was also applied to the biosolids treatments based on the soil test results. Limestone was applied uniformly to all treatments based on recommendations from the Virginia Tech Soil Testing Laboratory with the goal of raising soil pH to 6.2.

2.1.4. Site Management

All synthetic and organic amendments were applied on September 12, 2013 and tilled into the soil at the same time. The digested biosolids, biosolids mix, and composted biosolids were applied based on estimated mineralization rates of 30%, 20% and 10% organic nitrogen during the first year. The digested and composted biosolids mineralization rates were based on recommendations in the VA DCR nutrient management handbook. Mixtures of biosolids, sand, and sawdust are not covered in the handbook so a scientific best estimate of 20% mineralization was used.

Following tillage, the area was seeded on September 13, 2013 with a tall fescue blend (32.75% ‘Legitimate’, 32.64% ‘Chipper’, and 32.61% ‘Aristotle’) at a rate of 488 kg ha^{-1} pure live seed using a Gandy 91 cm variable rate push spreader (Gandy, Owatonna, MN). A Toro Sand Pro 5040 fitted with knobby pneumatic tires was then used to lightly depress the seeded treatments to ensure adequate seed to soil contact for establishment. Daily irrigation cycles to promote seed germination over the entire research area commenced on September 13, 2014.

2.1.5. Turfgrass establishment, pre-drought, drought, and recovery phases

The treatment and assessment of the turfgrass occurred during four study phases, identified as establishment, pre-drought, drought, and recovery. The time periods during which each phase occurred are shown in Table 4. The study was established on September 12, 2013. The entire study irrigated equally from the establishment date until May 30, 2014.

Initiation of spring mowing on April 14 signaled the beginning of data collection and the first day of the "pre-drought phase." At the beginning of this phase individual experimental units were at varying stages of development. Effects of amendments under equal irrigation were measured during this crop maturation phase. The only plant effects were due to amendment. Prior to initiation of differential irrigation treatments, our target was for all treatment plots to have achieved 95-100% tall fescue cover and a rating of 6 on the 1 to 9 subjective turfgrass quality scale for uniformity, density, and color. A quality rating of 6 is a standard in turfgrass research indicating minimal commercial acceptability. All plots were rated as 6 or higher by 30 May, therefore, allowing initiation of differential irrigation treatments for the drought phase.

The drought phase began on 1 June 2014, with plots being split and irrigated at 0% or 80% of ET. Clipping yield, NDVI, color, quality, VSM, and leaf nitrogen uptake were measured to differentiate tall fescue responses to inputs of irrigation and amendments. The drought phase continued from 1 June 2014 until 4 July 2014. On 4 July 2014, some of the treatment quality ratings reached an unacceptable rating of 2 out of 9, as well as VSM measurements of 5-8%. These measurements indicated that turfgrass death was imminent if access to irrigation or rainfall did not occur. This marked the end of the drought phase and beginning of the recovery phase for 2014.

The recovery phase of the trial began on 4 July 2014. This phase continued from 4 July 2014 until 21 August 2014 when the second year maintenance amendment applications were applied to the study. During the recovery phase, equal irrigation was reinstated across the entire trial to allow for adequate tall fescue recovery. The treatments were previously designated as 0 and 80% ET during the drought phase to differentiate the tall fescue responses of two different levels of irrigation. In order to show how the tall fescue recovered following drought, all experimental units retained the previous labels of differentiation.

2.2 Sampling and Analysis

2.2.1. Turfgrass Clipping Yield

Turfgrass clipping yield was collected biweekly throughout the growing season by mowing a single pass down the center of each treatment. One mower swath measuring 0.5 m x 3.7 m (1.9 m^2) was mowed at a constant 7.6 cm height on a seven day interval and clippings were collected using a Honda HRX217VKA gasoline powered walk behind rotary mower (America Honda Power Equipment Division, Alpharetta, GA). During weeks when yields were not collected, clippings were bagged and removed to ensure equal treatment across the trial. All clippings were dried for 48 hours at 60°C in a Blue M Stabil-Therm Constant Temperature oven. Any non-turfgrass debris (deciduous tree leaves, twigs, etc.) were removed and the dry clipping biomass recorded.

2.2.2. Nitrogen Leaf Uptake

After each sample was weighed, the biomass was ground using a Thomas Wiley mini-mill (Arthur H. Thomas Co., Swedesboro, NJ) to pass a sieve of 0.5 mm. Once ground, 300 mg sub samples of each were analyzed using a Vario Max CNS macro elementar analyzer (Elementar Analysensysteme, Hanau, Germany). Clippings were subjected to a high heat combustion chamber at 1200°C and analysis resulted in percent total carbon and nitrogen leaf content. To estimate nitrogen uptake of the sample, the nitrogen concentration percentage was multiplied by the total clipping yield dry mass.

2.2.3. Normalized Difference Vegetation Index

Normalized Difference Vegetation Index (NDVI) spectral analysis of the turfgrass canopy of each treatment was taken biweekly throughout the growing season using a handheld multispectral radiometer (Holland Scientific, Model ACS-430 Crop Circle) that was retrofitted to mount to a Bag Boy Quad Plus push cart (Bag Boy Company, Richmond, VA). The device was mounted at a stationary height of 46 cm above the turf canopy. The radiometer measurements commenced at the edge of each plot and took an average of 90 readings per 3.7 m of linear travel through the center of each plot. NDVI measurements were taken at approximately 1300 hrs eastern standard time on days with no cloud cover to minimize variances in reflectance.

2.2.4. Turfgrass Color

Turfgrass color ratings of each individual treatment were made as a visual estimate of canopy greenness as a subjective measure of the overall health of each treatment. Each treatment was visually rated biweekly starting in spring of 2014. Color was rated on a scale of 1-9, where 1 = a straw brown turfgrass canopy and 9 = a dark green turfgrass canopy with each unit between 1 and 9 indicating a perceived green color increase of 10 to 15 percent (Morris, 2006).

2.2.5. Turfgrass Quality

Turfgrass quality was visually rated using a scale of 1-9, where 1 = dead or very poor quality and 9 is perfect quality. Turfgrass quality is an overall combination of color, density, uniformity, and leaf texture. Each individual treatment was visually rated biweekly from spring to fall of 2014 (Morris, 2006). A rating of 6 on the scale index is categorized as minimally acceptable turfgrass quality for a home lawn.

2.2.6. Tiller Density

Plugs measuring 91.6 cm^2 were taken from each treatment before the onset of summer stress (May 15, 2014) and then again after summer stress ended (September 15, 2014). The tillers were manually counted and used to calculate density per square centimeter.

2.2.7. Root Mass

Root mass was quantified by taking four 5.0 cm plugs from each treatment and drying them in a 60°C Blue M Stabil-Therm Constant Temperature oven for 24 hours. All above ground shoots were removed and the samples were then weighed to determine total weight of each plug. After weighing each sample, the plugs were moved to a Blue M Ultra-Temp, forced air muffle furnace (SPX Thermal Products Solutions, White Deer, PA) and subjected to 500°C for 12 hours. Following incineration, the samples were weighed and the difference taken from pre ignition to post ignition to determine overall root mass. The mean of the four sub-samples was used to represent root mass for each experimental unit.

2.2.8. Statistical Analysis

Turfgrass clipping yield, leaf nitrogen uptake, NDVI, volumetric soil moisture percentage, turfgrass color, and turfgrass quality were all subjected to split-plot repeated measures analysis by using SAS JMP Multivariate ANOVA (MANOVA) (SAS Institute, Cary, NC. 2014) and Minitab GLM (Minitab Inc., State College, PA. 2015) to test the effects of various amendments and irrigation regimes on agronomic measures pertaining to the drought resistance of tall fescue. In this analysis, the dates of each rating and collection were treated as time. SAS JMP MANOVA and Minitab GLM both use Mauchley's sphericity test, which states that the repeated measures model consist of only independent variables. If the test data shows a violation of sphericity indicated by $P<0.05$, then an adjustment is made in the output and the F test value for the Univariate H-F Epsilon (Huynh and Feldt, 1976) should be chosen. Broadleaf weed pressure, disease pressure, tiller density and root mass were all subjected to analysis of variance using Minitab GLM. Means were separated using Fisher's protected LSD at $P \leq 0.05$.

3. RESULTS AND DISCUSSION

The average monthly precipitation and temperature for the research location in Blacksburg, VA is shown in Table 1. The 30-year average temperature for the site is 10.9°C and the 30 year average rainfall is 104 cm. During the 2014 season, the average temperature was 10.6°C and rainfall for the year totaled 100 cm. The treatments were seeded September 13, 2013, and during the months of September, October, and November rainfall totals were 3.4 cm, 6.7 cm, and 7.7 cm, respectively. In order to ensure that all treatments received equal treatment during establishment, supplemental irrigation was scheduled on an as needed basis.

During establishment (fall 2013 to spring 2014), temperatures were below average leading up to initiation of the pre-drought phase in April (Table 1, Table 4). The temperature differences between the 30-year average and the actual for the months of November 2013 through March 2014 were -2.2°C, -0.6°C, -3.7°C, -0.4°C, and -2.0°C.

3.1 Pre-drought Phase

3.1.1. Volumetric Soil Moisture

Analysis of variance of volumetric soil moisture (VSM) percentage showed no statistical differences across all treatments (mean = 45.4% ± 2.9) during pre-drought (Appendix A). Despite varying water-holding organic matter applied in the amendments, VSM was not different among any treatment due to the basal irrigation applied between April 14 and May 30 (Table 4).

3.1.2. Turfgrass Clipping Yield

Analysis of variance showed that amendment and time caused differences in mean clipping yields (Tables 5 and 6). The highest mean clipping yield was achieved with the fertilizer control (Table 5). The Alex-DB and Spots had similar yields, which were approximately 50% of the fertilizer. The biosolids mixes, Alex-N and Alex-P, had similar yields, which were approximately 33% of the fertilizer control.

Time of sampling also affected clipping yield (Table 6). Clipping yield was highest on the first date of collection (21 April) and declined thereafter.

3.1.3. Leaf Nitrogen Uptake

Analysis of variance indicated that there was a significant time x amendment interaction ($P \leq 0.10$) for leaf nitrogen uptake during the pre-drought phase (Appendix C and Table 7). Fertilizer control N uptake was higher than all biosolids amendments, which were not different on the initial collection date of 21 April (32 WAS). By 23 May (36 WAS), N uptake by fertilizer and biosolids mixes, but not digested or composted biosolids, declined. The fertilizer continued to elicit the highest N uptake.

3.1.4. NDVI

Analysis of variance results indicated there was a significant effect of amendment on NDVI (Appendix D and Table 8). The NDVI was highest in the fertilizer treatment and lowest in the biosolids mix applied at agronomic N rate during the entire pre-drought phase.

3.1.5. Turfgrass Color

Analysis of variance indicated that the time x amendment interaction was significant during the pre-drought phase (Appendix E and Table 9). At the beginning of the pre-drought phase, there were no differences in color ratings among treatments, which were all <6 on the 1-9 scale. By 34 WAS, the fertilizer treatment had higher color ratings than all biosolids amendments. All ratings were >6. By 36 WAS, the fertilizer-induced color ratings were the highest, with no difference among biosolids treatments. All treatments achieved ratings of ~7.

3.1.6. Turfgrass Quality

Analysis of variance indicated that the main effects of time and amendment were both significant for turfgrass quality during the pre-drought phase (Appendix F and Tables 10 and 11). Turfgrass quality was lowest on April 21 and increased throughout the pre-drought phase. This increase in turfgrass quality correlated to the increase in temperature and day length for the period shown in Table 1.

Quality ratings were highest with fertilizer and lowest with the biosolids mix applied at agronomic P rate plus supplemental fertilizer. All of the amendments except for Alex-P had mean quality ratings above the acceptable limit of 6 for the entire pre-drought phase. The drought phase was initiated on 30 May, when the Alex-P attained a quality rating of 6.

3.1.7. Discussion

The results of the pre-drought phase indicate that the fertilizer treatment attained higher clipping yield, leaf nitrogen uptake, visual color and quality ratings, and NDVI readings than the biosolids amendments. Even though the organically amended treatments had lower ratings than the fertilizer for all parameters measured, all of the treatments reached above average (>6) quality and color ratings during the pre-drought phase. The organic treatments were applied based on an estimated nitrogen mineralization rate equivalent to the plant available nitrogen provided by the fertilizer control. Since irrigation was non-limiting across all plots throughout the pre-drought phase, differences between the measured parameters were associated with the N availability of each amendment.

The results of clipping yield, NDVI, and nitrogen leaf uptake indicate that all of the organic amendments had lower nitrogen availability than the fertilizer control. A study by Cataldi (2013) also reported that treatments of a biosolids blend estimated to supply equal amounts of PAN to a fertilizer control were deficient. Cataldi stated that these results suggested there was a synchrony issue between the PAN and actual turfgrass N needed for adequate turfgrass establishment and growth.

Research has reported that crops fertilized by biosolids had higher yields than crops fertilized by synthetic fertilizers, when both nutrient sources were applied at equal rates of plant available nitrogen (Akrivos et al., 2000; Bugbee, 2002). Further research by Loschinkohl and Boehm (2001), Schnell et al. (2009), and Flavel and Murphy (2006) also reported similar results of increased turfgrass establishment and growth by incorporating or topdressing composted biosolids into a disturbed urban soil. Our results of significantly less clipping yields, NDVI readings, and leaf nitrogen uptake for the biosolids amendments contradicted the findings of this previous research, most likely due to the poor conformity between the tall fescue N need and the PAN provided by the organic amendments during the pre-drought phase. These previous trials also utilized additional starter fertilizers, which helped aid in establishment.

Contradictory studies on dry matter production of grasses have shown equivalent yields only when organic sewage sludge rates were applied at 2 to 10 times the inorganic N rates (King and Morris, 1972; Boswell, 1975). In a sod study, Tesfamariam et al. (2009) reported exceptional turfgrass growth using oven dried anaerobically digested biosolids which were applied at or above the nutritional turfgrass needs. Similar results were also reported by Cataldi (2013) by using anaerobically digested biosolids applied at 1.5X the suggested agronomic N-rate. Kiemnec et al. (1987) also reported over a three year study that increasingly high rates of sewage sludge were needed to supply equal PAN amounts when compared to ammonium nitrate.

In a greenhouse study performed by Tester et al. (1982), the effects of sewage sludge compost applied at varying rates to tall fescue was evaluated. Two different soil types were used to evaluate variations in N mineralization rates. Their results reported large variations in net mineralization rate based on soil type alone. These variations were the result of higher N immobilization based on differences in C:N ratio. Similar to our study, this previous research reported the highest clipping yields and N uptake results occurred at the initial clipping date.

A study performed by Cataldi (2013) compared three N rates of two biosolids products with a synthetic fertilizer control for establishment of Kentucky bluegrass/tall fescue sod. Cataldi used a biosolids blend of dewatered biosolids cake and wood fines that is similar to our biosolids mix. His results showed reduced quality, leaf nitrogen uptake, and clipping yields for the treatments receiving the biosolids blend at agronomic N rates of 0.5X, 1.0X, and 1.5X when compared to the biosolids cake and synthetic fertilizer. A study by Linde and Hepner (2005) similarly found that a one-time application of fertilizer at establishment resulted in a denser stand of turfgrass when compared to applications of composted biosolids. The results of reduced quality, clipping yield and leaf nitrogen uptake for the Alex-N, Alex-P, Alex-DB, and Spots amendments in our study support the previous research performed by Cataldi (2013) and Linde and Hepner (2005).

Cataldi (2013) also reported that as temperatures increased from winter into early summer, turfgrass quality increased across all treatments. A similar trend was seen in our results shown in Tables 9 and 10 as temperatures increased (Table 1). These data are consistent with research of Er et al. (2011), who identified three primary factors that determine rate of N mineralization: application rate, C:N ratio of the material, and temperature. Plant available N increases with application rate, reduced C:N ratio, and increased soil temperature. Wang et al. (2003) also found that mineralization rates of N were significantly greater at 20°C than 10°C. Mean air temperatures in the early stages of our experiment were: November (4.1°C), December (-0.4°C), January (-4.0°C), February (0.9°C), and March (3.3°C). Such low temperatures following seeding in September were most likely a primary cause of reduced N mineralization from the organic residuals prior to the start of the pre-drought phase.

Although N mineralization was not directly measured in our study, we suspect that the estimated PAN of all of the organic amendments was lower than expected based on our nitrogen leaf uptake, NDVI readings and clipping yield results. It is also likely that the organic amendments had higher rates of N immobilization, especially in the biosolids mix material, associated with high C:N ratios and lower temperatures. These findings support previous research by Allison (1965), Sabey et al. (1975), and Tester et al. (1982) which reported lower nitrogen mineralization rates following the addition of woody materials into soil and sludge.

Overall, our results showed that using different forms of biosolids produced an acceptable tall fescue stand from establishment with similar turfgrass quality and density when compared to the synthetic fertilizer treatment. Even though mean clipping yields, NDVI readings, and color ratings were lower than the fertilizer treatments during the pre-drought phase, all of the plots reached above acceptable ratings (>6) of quality.

3.2 Drought Phase

The drought phase began on 1 June 2014, with plots being split and irrigated at 0% or 80% of ET. The average temperature (21.2°C) and precipitation (7.2 cm) for the month of June 2014 is shown in Table 1. When compared to the 30-year average, temperatures were 1.3°C higher than normal, and the precipitation was 3.0 cm below average.

3.2.1. Volumetric Soil Moisture

Analysis of variance for volumetric soil moisture percentage (Appendix G) indicated that there was a significant amendment x irrigation treatment interaction (Table 12) and time x irrigation interaction (Table 13) for the drought phase. Spots had significantly greater VSM % at 80% ET than other amendments except for Alex-N and Alex-DB (Table 12). Alex-N and Alex-P had the highest VSM% among the amendments at 0% ET.

The time x irrigation interaction for VSM percentage showed that the 80% ET regime had the highest level on 11 June when compared to all other dates during the drought phase (Table 13). VSM% was consistently higher for the treatments receiving 80% ET when compared to those treatments receiving 0% ET as expected. Rain events occurring on 9 June and 29 June and increases in VSM% for both irrigation regimes are reflected on Table 13.

3.2.2. Clipping Yield

Analysis of variance indicated that the amendment x irrigation interaction was significant for tall fescue mean clipping yield (Appendix H and Table 14). The fertilizer treatment receiving 80% ET had a significantly higher mean clipping yield than all other treatments receiving 0 or 80% ET for the drought phase. The fertilizer treatment receiving 0% ET interestingly had the second highest mean clipping yield for the drought phase when compared to all other treatments.

3.2.3. Leaf Nitrogen Uptake

Analysis of variance results indicated there was a significant amendment x irrigation interaction for tall fescue leaf nitrogen uptake during the drought phase (Appendix I and Table 15). The fertilizer treatment receiving 80% ET had significantly higher leaf nitrogen uptake when compared to all other treatments receiving 0 or 80% ET. The fertilizer treatment receiving 0% ET had the second highest leaf nitrogen uptake out of all the amendments and yielded approximately 42% of the fertilizer treatment receiving 80% ET.

3.2.4. NDVI

Analysis of variance indicated that the main effect of amendment (Table 16) as well as the time x irrigation interaction (Table 17) were significant for the drought phase (Appendix J). There was a large main effect of amendment on the NDVI measurements throughout the drought phase. The fertilizer treatment maintained the highest NDVI measurements. The Alex-P treatment, which received supplemental nitrogen, was significantly higher than the other organically amended plots of Alex-N, Alex-DW, and Spots.

Treatments receiving 80% ET maintained the highest NDVI readings throughout the entire drought phase and showed no significant differences for all three dates. Treatments receiving 0% ET had lower NDVI readings when compared to the treatments receiving 80% for all collection dates. Readings taken on 19 June 2014, for the plots receiving 0% ET had the lowest measured readings for the drought phase.

3.2.5. Color

Analysis of variance showed that there was a significant amendment x irrigation interaction (Table 18) and time x irrigation interaction (Table 19) for the drought phase

(Appendix K). Visual tall fescue color ratings showed that the fertilizer treatment receiving 80% ET had significantly higher color ratings than all other treatments receiving 0 or 80% ET (Table 18).

Visual color ratings associated with the interaction of time x irrigation showed that the treatments receiving 80% ET had the highest ratings at the beginning of the drought phase on 6 June. Table 19 shows that there was a reduction in color ratings starting 6 June (38 WAS) through 3 July 2014 (42 WAS) for both of the irrigation regimes.

3.2.6. Quality

Analysis of variance results showed that there was a significant amendment x irrigation interaction (Table 20) and time x irrigation interaction (Table 21) for tall fescue quality ratings during the drought phase (Appendix L). The amendment x irrigation interaction results show that the fertilizer treatment receiving 80% ET had significantly higher quality ratings than all other amendments at 0 or 80% ET during the drought phase.

The interaction of irrigation x time results showed that the treatments receiving 80% ET had the highest quality ratings on 6 June (38 WAS). The quality ratings for the treatments receiving 80% ET t decreased throughout the drought phase as seen in Table 21. The highest quality ratings for treatments receiving 0% ET followed the same pattern with the highest quality ratings on 6 June (38 WAS), and similar quality reductions on 19 June (40 WAS) and 3 July 2014 (42 WAS).

3.2.7. Discussion

The data indicated that even with adequate irrigation (Table 13), heat stress (Table 1) resulted in a loss of turfgrass quality throughout the drought phase for all treatments receiving

80% ET. This loss of quality, but to a greater extent, was also observed in all treatments receiving 0% ET. Turfgrass quality is an overall combination of color, density, uniformity, and leaf texture. All treatments receiving 80% ET had quality ratings above the acceptable value of 6 throughout the drought phase except for the Alex-N treatment, while all of the treatments receiving 0% ET had below acceptable ratings of quality. These quality ratings were attributed to reduced color and overall uniformity of the turfgrass stand. This loss of quality closely corresponded with the increased summer temperatures (Table 1) and occurred between 1 June and 4 July. Previous work by Fry and Butler (1989), reported that visual quality of turfgrass decreased as the intensity level of drought stress increased. Similar results were observed by Merewitz et al. (2010) where they compared different varieties of Kentucky bluegrass and reported similar decreases in turfgrass quality as summer temperatures increased under well-watered and drought conditions. Our results are consistent with this previous research.

Temporary stress conditions mainly caused by mechanical damage also followed each mowing event. Ratings of color and quality were taken shortly after each mowing event to ensure rating uniformity; however, the temporary stress injury associated with mowing, under high summer temperatures, slightly reduced the overall visual ratings of color and quality. It is common practice to reduce mowing frequency during the summer months on tall fescue and other cool season turfgrasses to allow the turfgrass to acclimate to summer stress (Christians, 2004). By inducing injury through a weekly mowing schedule, we effectively increased the summer stress level on the turfgrass, which may have resulted in lower color, quality and NDVI readings primarily on the treatments receiving 0% ET. Research by Sonmez et al. (2008) also reported a reduction of NDVI, quality, and color ratings following mowing of a drought stressed bermudagrass trial. Our results for reduced NDVI measurements, quality, and color ratings support this previous research.

Cool season turfgrasses, such as tall fescue, often experience summer stress during the months of June to August in Blacksburg and their photosynthetic efficiency decreases as summer stress increases (Beard, 1973). Significant differences in NDVI were not observed among treatments receiving 80% ET (Table 17); however, significant differences were observed in all of the plots receiving 0% ET. NDVI measures of reflectance are commonly used to determine concentrations of chlorophyll, nitrogen, green biomass, and water content of leaves (Penuelas et al. 1994). Since NDVI has been shown to be an effective means of measuring turfgrass quality objectively (Bremer et al., 2011; Goodin and Henebry, 1998; Penuelas et al., 1994; Trenholm et al., 1999; Bell et al., 2002; Lee et al., 2011), these readings offer a snapshot of the overall plant health of the turfgrass at each time point. Rainfall events occurred on 9 June and 29 June and subsequently resulted in small increases in NDVI readings (Table 17) and volumetric soil moisture percentage (Table 13) among the 0% ET treatments.

Tall fescue typically enters into a state of dormancy during extended periods of drought, where energy is conserved and upward growth decreases. This reduction in growth is reflected in our study by reduced clipping yields (Table 14) and reduced leaf nitrogen uptake (Table 15) in both irrigation treatments. This demonstrates that the plants were unable to assimilate nutrients due to the high temperatures and drought stress. The decrease of nutrient assimilation was also reflected in reduced turfgrass color (Tables 18 and 19), quality, and NDVI measurements. Greenhouse research by Zhang et al. (2005, 2009, 2012) reported a decrease in shoot growth under uniform drought conditions, as well as a reduction in turfgrass quality. They also reported that the biosolids amended treatments delayed leaf wilting during periods of moisture stress with respect to the inorganic fertilizer control. These data are similar to our research and support our findings.

As occurred in the pre-drought phase, clipping yields and leaf nitrogen uptake indicate a large discrepancy in N availability between the organic amendments and fertilizer treatments. Previous research has reported that crops fertilized with biosolids had higher yields than crops fertilized with synthetic fertilizers, when both are applied to supply equal amounts of nutrients (Akrivos et al., 2000; Bugbee, 2002). This biosolids-based yield increase is attributed to an increase in nitrogen availability while also positively affecting the biological, chemical, and physical properties of the soil. Our results of significantly less clipping yields and nitrogen leaf uptake for the biosolids amendments contradict findings of this previous research. Akrivos produced cotton in containers using lime stabilized biosolids, while Bugbee produced various forms of nursery plants in containers using in-vessel biosolids compost. Variations in crop type, as well as chemical and environmental differences most likely were the main reasons our results differed.

Limited research has investigated NDVI, turfgrass color and quality, clipping yield, and leaf nitrogen uptake during a period of drought stress using various forms of biosolids. In a study performed by Zhang et al. (2012), biosolids were used to compare the drought stress responses of tall fescue with a synthetic fertilizer control. They used similar irrigation regimes labeled "well-watered" and "drought stressed" to differentiate the parameters of irrigation and amendment. Unlike our field experiment, their research was performed in a greenhouse where more uniform temperatures were maintained, resulting in a more consistent release of PAN. Unlike our study, their estimations of PAN for the anaerobically digested biosolids and lime stabilized biosolids closely matched the release of the inorganic fertilizer. We suspect that the discrepancy in PAN release in our study was based primarily on N immobilization associated with the higher C:N ratios of our materials, as well as other PAN influencing factors. They reported that turfgrass quality gradually declined over time when the plots were subjected to moisture stress. These findings coincided with our results which showed a gradual decline of turfgrass color and quality, mean clipping yields, and leaf nitrogen uptake for the drought stressed irrigation regime.

Overall, our results indicated that using different forms of biosolids produced acceptable quality tall fescue under adequate irrigation conditions when compared to the fertilizer treatment. The biosolids treatments which received 0% ET, although unacceptable, showed comparable turfgrass quality, color, and NDVI measurements when compared to the fertilizer treatment. Further research of new organic residual blends is needed to determine the plant available nitrogen of these materials as well as appropriate loading rates needed for application.

3.3. Recovery Phase

The recovery phase of the study commenced on 4 July and ended on 21 August 2014 when the second year maintenance topdressing of amendments occurred. On 4 July, supplementary irrigation was reinstated for all of the treatments to allow for adequate recovery from drought stress. Each of the treatments previously labeled as 0 or 80% ET replacement during the drought phase, maintained this designation in order to observe how the reintroduction of irrigation affected the individual treatments.

3.3.1. Volumetric Soil Moisture

Volumetric soil moisture percentage was found not to be statistically significant (Appendix M) across all treatments (mean = 44.7% ± 3.2). Since all treatments were receiving equal amounts of irrigation, this result was expected.

3.3.2. Clipping Yield

Analysis of variance indicated a significant time x amendment (Table 22) and time x irrigation interaction (Table 23) for clipping yield during the recovery phase (Appendix N). The interaction of time x amendment showed that the fertilizer treatment measured on 17 July (44 WAS) had the highest mean clipping yield when compared to all other amendments for the entire phase. Clipping yield, collected just before the end of the trial on 15 August (48 WAS), showed a significant reduction of the fertilizer control when compared to 17 July (44 WAS). On 15 August, all of the treatments had similar mean clipping yields and no significant differences were measured.

The interaction of time x irrigation also had an effect on the tall fescue mean clipping yield during the recovery phase (Table 23). The initial clipping for the recovery phase occurred on 17 July (44 WAS) and results showed that all treatments receiving 80% ET had significantly higher clipping yields than the treatments receiving 0% ET. Clippings collected on 15 August (48 WAS), showed no significant differences between treatments.

3.3.3. Nitrogen Uptake

Analysis of variance indicated there was a significant time x amendment interaction for nitrogen uptake during the recovery phase (Appendix O and Table 24). The fertilizer treatment had the highest leaf nitrogen uptake on 17 July when compared to all other amendments for the same date. A reduction of leaf nitrogen uptake was observed for the fertilizer treatment from 17 July to 13 August 2014. At 13 August, all treatments had similar leaf nitrogen uptake with no significant differences detected.

3.3.4. NDVI

Analysis of variance indicated that the time x irrigation interaction for NDVI was significant during the recovery phase (Appendix P and Table 25). During the recovery phase, irrigation was reinstated for all treatments to maintain the plots labeled as 80% ET while also allowing for drought stress damage recovery of the treatments labeled as 0% ET. Treatments receiving 80% ET had significantly higher NDVI readings than the treatments receiving 0% ET on 14 July (44 WAS). On 28 July (46 WAS), there were no significant differences measured among all treatments. On 15 Aug (48 WAS), the 0% ET treatments yielded significantly higher NDVI measurements than the 80% ET treatments.

3.3.5. Color

Analysis of variance showed that the time x irrigation interaction for tall fescue visual turfgrass color was significant (Appendix Q and Table 26). The treatments receiving 80% ET maintained color ratings >6.0 for the duration of the recovery phase. Treatments receiving 0% ET had significantly lower color ratings on 15 July (44 WAS), but ratings increased for the remainder of the recovery phase yielding mean color ratings of 6.7 and 6.8 respectively for 28 July and 15 August. Ratings taken on 15 August (48 WAS) yielded no significant differences among all treatments.

3.3.6. Quality

Analysis of variance of tall fescue visual quality ratings indicated that there was a time x irrigation interaction during the recovery phase (Appendix R and Table 27). Ratings started on 14 July (44 WAS) and continued through 15 August 2014 (48 WAS). Irrigation was reinstated on all of the treatments to allow for adequate recovery potential. Ratings taken on 14 July, show that the treatments receiving 80% ET had significantly higher mean quality ratings than the treatments previously receiving 0% ET. For 28 July and 15 August, quality ratings equalized across all treatments and similar mean quality ratings were measured.

3.3.7. Weed and Disease Pressure

During the season, there were no differences among treatments in weed pressure. The percent weed coverage data at the beginning of the establishment phase (32 WAS) measured 1.5% ± 1.2% and during the recovery phase weed coverage measured 4.4% ± 1.8%, respectively.

Analysis of variance for disease pressure indicated that the time x irrigation interaction was significant (Appendix S and Table 28). At 38 WAS, brown patch disease pressure was significantly greater for the treatments receiving 0% ET than for those receiving 80% ET. At 45 WAS, the disease pressure shifted and the treatments receiving 80% ET displayed greater brown patch disease damage.

3.3.8. Tiller Density

Analysis of variance output for tiller density did not indicate any significant treatment effects at initiation (19.6 ± 7.1) or recovery (18.9 ± 5.8).

3.3.9. Root Mass

Analysis of variance indicated that only the main effect of irrigation was significant for root mass at the end of the 2014 (Appendix T and Table 29). Treatments receiving 80% ET throughout the entire season had greater overall root mass across all treatments when compared to the treatments receiving 0% ET.

3.3.10. Discussion

Our results indicated that the fertilizer treatments had higher mean clipping yield, leaf nitrogen uptake, turfgrass color and quality, and NDVI measurements at the beginning of the recovery phase when compared to the organic amendments. This was a trend measured throughout the pre-drought and drought phases of the study as well. Once irrigation was reintroduced, a reduction of clipping yield and leaf nitrogen uptake was measured for the fertilizer treatments (Tables 22 and 24). Measurements taken at 13 August showed that mean clipping yield and leaf nitrogen uptake for all amendments were similar and showed no significant differences. NDVI, color, and quality ratings also showed these changes. These data indicated that overall plant health rapidly increased once supplemental irrigation was reinstated. This is consistent with previously reported results (Merewitz et al., 2010; Zhang et al., 2005, 2007, 2009, 2012).

This was the first time in the study that all treatments based on amendment or irrigation regime had similar mean clipping yields or leaf nitrogen uptake responses, and neared a point of equilibrium. These data indicated that the fertilizer treatment reached a point of exhausting plant available nitrogen in the soil, which decreased overall clipping yields near the end of the recovery phase.

The organically amended treatments maintained their clipping yields or increased them from 17 July to 13 August 2014. This is an indication that nitrogen continued to be mineralized and made plant available from the organic amendments even after one year of growth, while the nitrogen supplied via the synthetic fertilizer treatment had been utilized by the plants or lost from the system. This exhausting of PAN provided by synthetic fertilizer was also reported by Tester et al (1982) in a greenhouse study after 100 days. Tester et al (1982) also showed that even after 167 days (conclusion of the study), the biosolids amended plots continued to supply nitrogen to the pots of tall fescue. These results mirror our results of continued release of plant available nitrogen one year after the initial application.

Limited research has investigated NDVI, turfgrass color and quality, clipping yield, and leaf nitrogen uptake following a period of drought stress using various forms of biosolids. In a study performed by Zhang et al. (2012), biosolids were used to compare the drought stress of tall fescue with a synthetic fertilizer control. Similar to our study, they used irrigation regimes labeled "well-watered" and "drought stressed" to differentiate the parameters of irrigation and amendment. Their findings were that turfgrass quality rebounded for all treatments once supplemental irrigation was reinstated. These results correspond with our data and show a dramatic increase of clipping yield, leaf nitrogen uptake, NDVI measurements, and color and quality ratings once irrigation was reinstated for plots receiving 0% ET.

Further research by Merewitz et al. (2010) reported that the plant's ability to maintain a green turf canopy and regulate cell membrane stability under extreme drought conditions is important for rapid turfgrass recovery. Their study, involving various Kentucky bluegrass varieties, demonstrated that once water became available to the turfgrass following summer stress, recovery quickly ensued and turfgrass quality increased. Our results of increased leaf nitrogen uptake, increasing NDVI measurements and color and quality ratings support their findings. They also reported that the relative content of hormones such as abscisic acid and cytokinins increased the recuperative ability in some varieties. Turfgrass research by Fry and Huang (2004) has shown that recovery potential from drought stressed turfgrass is heavily dependent on the rooting characteristics and rhizome production of different turfgrass species. Huang (2001) also reported that differences in allocation of nutrients, as well as osmotic adjustment were also very important in drought survival and recuperative ability.

Additional research performed by Zhang et al (2005, 2009) also reported that the use of biosolids could potentially increase a plant's tolerance to drought stress by encouraging root growth. They have reported that biosolids naturally contain biologically active substances such as auxin and humic acids which aid in root initiation. Auxin and humic acids were not measured in our study, but overall root biomass showed slight differences among treatments receiving 0 and 80% ET (Table 29). No measured differences in root biomass were found based on amendment. The studies performed by Zhang et al. (2005, 2009, 2012) were all performed in a greenhouse where temperature and moisture were carefully controlled.

Overall, our results indicated that using different forms of biosolids produced acceptable quality tall fescue following drought conditions when compared to the fertilizer treatment. The biosolids treatments improved turfgrass quality, color, clipping yield, NDVI and leaf nitrogen uptake one year after initial application. Incorporation of biosolids at establishment can aid in recovery from periodic drought stress and may be an adequate substitute for inorganic fertilizers.

4. CONCLUSIONS

The use of organic amendments, such as anaerobically digested and dewatered biosolids, biosolids compost, and biosolids mixtures of sand and sawdust can be used with positive effects as amendments for improving disturbed urban soils via increased water holding capacity, enhanced plant nutrition, and improved establishment and maintenance. The incorporation of these amendments at establishment also has a beneficial effect on turfgrass quality, color, NDVI readings, clipping yield, and leaf nitrogen uptake. This thesis focused on incorporation at establishment of three different compositions of biosolids products and evaluated the effects each product has on drought resistance characteristics of tall fescue when compared to a synthetic fertilizer control.

In order to assess the drought resistance characteristics of the tall fescue treatments, an experiment was designed to incorporate two different irrigation regimes of 0 and 80% ET respectively, as well as five amendments including a Class A EQ dewatered biosolids cake, a mixture of the same Class A EQ dewatered biosolids cake blended with sand and sawdust, and a Class A EQ biosolids compost. To evaluate the effects of each of these amendments a 1-year field study in Blacksburg, VA began in August 2013.

Our results showed that the fertilizer control treatment generally had higher mean clipping yields, leaf nitrogen uptake, NDVI, visual turfgrass color and quality throughout the entire growing season when compared to all of the organic-based amendments. Plant available nitrogen release estimations, based on previous research, were used to determine appropriate loading rates for each of the organic amendments. The clipping yield data clearly shows a wide gap of leaf biomass between the fertilizer treatments and organically amended plots beginning at the first collection and continuing throughout the entire growing season. This suggests that there was poor synchrony between the PAN and tall fescue N needs of the organically amended treatments during the spring season of 2014. The data also suggests that supplemental nitrogen provided by inorganic fertilizers should be considered when using organic amendments to help alleviate this synchrony issue. Our results also showed that incorporating organic amendments into the soil at establishment helped the soil to retain higher amounts of soil moisture.

Future research should address the issues of varying mineralization rates for different biosolids residuals. More research is needed in order to determine what the appropriate “recipe” of a biosolids mix should be, focusing on ease of spreadability, repeatable mineralization results, and maximizing nitrogen content. If this study is repeated, earlier summer application of the biosolids amendments prior to establishment should be considered. The use of biosolids residuals as a topdressing for established turfgrass should also be researched since the majority of the contractors using these products would be applying them post emergence.

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Figure 1. Field study was located at the Virginia Tech Turfgrass Research Center, Blacksburg, VA (Coordinates: 37°12'54.31"N, 80°24'42.14"W). The red rectangle is the location of the trial. Dimension of the research trial is 22.7m x 35.5m

Figure 2. Field layout of two irrigation regimes on five different amendments

Rep 1	80% ET	4 Alexandria dewatered biosolids	3 Alexandria biosolids mix P rate	1 fertilizer control	5 Spotsylvania biosolids compost	2 Alexandria biosolids mix N rate
	0% ET	5 Spotsylvania biosolids compost	1 fertilizer control	4 Alexandria dewatered biosolids	2 Alexandria biosolids mix N rate	3 Alexandria biosolids mix P rate
Rep 2	0% ET	2 Alexandria biosolids mix N rate	4 Alexandria dewatered biosolids	5 Spotsylvania biosolids compost	3 Alexandria biosolids mix P rate	1 fertilizer control
	80% ET	3 Alexandria biosolids mix P rate	5 Spotsylvania biosolids compost	2 Alexandria biosolids mix N rate	1 fertilizer control	4 Alexandria dewatered biosolids
Rep 3	0% ET	5 Spotsylvania biosolids compost	3 Alexandria biosolids mix P rate	4 Alexandria dewatered biosolids	2 Alexandria biosolids mix N rate	1 fertilizer control
	80% ET	1 fertilizer control	2 Alexandria biosolids mix N rate	5 Spotsylvania biosolids compost	3 Alexandria biosolids mix P rate	4 Alexandria dewatered biosolids
Rep 4	80% ET	1 fertilizer control	5 Spotsylvania biosolids compost	2 Alexandria biosolids mix N rate	4 Alexandria dewatered biosolids	3 Alexandria biosolids mix P rate
	0% ET	3 Alexandria biosolids mix P rate	4 Alexandria dewatered biosolids	1 Fertilizer control	5 Spotsylvania biosolids compost	2 Alexandria biosolids mix N rate

Table 1. Average monthly temperature and precipitation for Blacksburg, VA from August 2013 to December 2014

2013	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature (°C)	--	--	--	--	--	--	--	20.2	17.2	11.9	4.1	-0.4
Precipitation (cm)	--	--	--	--	--	--	--	5.3	3.4	6.7	7.7	0.0
2014	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Temperature (°C)	-4.0	0.9	3.3	10.9	17.0	21.1	21.2	20	18.4	12.2	3.2	3.4
Precipitation (cm)	4.2	10.1	6.2	10	7.3	7.2	5.5	15.1	9.7	10.3	7.7	6.8
30 yr. Avg. Temp.§	-0.3	1.3	5.3	10.4	15.2	19.8	21.8	21.1	17.3	11.3	6.3	1.0
30 yr. Avg. Precip.§	7.8	7.1	9.2	8.8	11.0	10.2	10.8	9.1	7.9	7.1	7.3	7.5

§30 yr. average for the region (1984-2014)

Table 2. Chemical composition§ of the biosolids products used in this study

Treatment	C:N¥	C	TKN	NH_4-N	NO_3-N	Org.-N	P	K
				g kg^{-1}				
Blended†	15	795	8.2	5.3	0.004	9.7	6.2	0.6
Cake††	7	377	55.5	15.5	0.006	35.6	39.7	1.4
Compost†††	13	372	28.7	7.8	NA	15.3	14.5	4.5

† Anaerobically digested dewatered biosolids blended with sand and sawdust (Alexandria, VA)

†† Anaerobically digested dewatered biosolids cake. (Alexandria, VA)

††† Anaerobically digested dewatered biosolids composted with wood fines. (Spotsylvania, VA)

§ All analysis was done by A&L Eastern Labs, Richmond, VA.

¥ Abbreviations: Carbon Nitrogen Ratio (C:N), Carbon (C), Total Kjeldahl Nitrogen (TKN), Ammonium Nitrogen (NH_4-N), Nitrate Nitrogen (NO_3-N), Total Organic Nitrogen (Org. N), Total Extractable Phosphorus (P), Total Extractable Potassium (K)

Table 3: Luck Stone masonry sand particle size analysis (PSA) from the Caroline County, VA quarry

Sieve Size (mm)	4.7	2.4	1.0	0.5	0.3	0.1	0.07
Specification (%)[#]	100-100	95-100	70-100	40-75	10-35	2-15	0-5
Target	100	97.5	85	57.5	22.5	8.5	2.5
Tolerance	0	2.5	15	17.5	12.5	6.5	2.5

# Indicates the sand specifications for particle size passing percentages

Table 4. Defining characteristics of the pre-drought, drought, and recovery phases used in this study – 2014

Phase	Time Period	Irrigation
Pre-drought	April 14 – May 30	Non-limiting
Drought	June 1 – July 4	0 or 80% ET
Recovery	July 4 – August 21	Non-limiting

Table 5. Effect of amendment on tall fescue clipping yield, averaged over time, during the 2014 pre-drought phase§.

Amendment	Clipping Yield† (kg ha^{-1})
Fertilizer	503.0a#
Alex-N¥	160.9c
Alex-P	146.7c
Alex-DB	228.9b
Spots	232.3b

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD.

†Data are based on 7 days of growth, post-mowing.

§ Pre-drought phase defined by actual sampling dates in 2014: April 21, May 9, and May 23.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 6. Tall fescue mean clipping yield as affected by the main effect of time during the pre-drought phase of the study in 2014

Sampling Date	Clipping Yields† (kg ha^{-1})
April 21	339.2a#
May 9	229.3b
May 23	194.5b

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD.

†Data are based on 7 days of growth, post-mowing.

§ Actual sampling dates in 2014 were April 21, May 9, and May 23.

Table 7. Leaf nitrogen uptake of tall fescue as affected by the interaction of time x amendment during the pre-drought phase§ – 2014

	Weeks After Seeding (WAS)	
	32§	36
Amendment	N Uptake† (kg N ha^{-1})	
Fertilizer	22.7a#	14.3b
Alex-N¥	5.1cd	2.6d
Alex-P	4.7cd	3.9d
Alex-DB	8.5c	3.7d
Spots	8.7c	3.7d

Means followed by the same letter are not significantly different at the $P \leq 0.10$ using Fisher's LSD. Means can be compared across rows and down columns.
†Calculated by multiplying turfgrass tissue N concentration (g N kg^{-1}) by dry mass clipping yield (kg ha^{-1}) for each treatment.
§ Actual sampling dates in 2014: April 21 and May 23.
¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 8. Tall fescue NDVI readings as affected by amendment during the pre-drought phase§ in 2014

Amendment	NDVI Measurements†
Fertilizer	0.82a#
Alex-N¥	0.74c
Alex-P	0.76b
Alex-DB	0.79b
Spots	0.77b

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD.
†Data was collected between 1300 hours and 1400 hours just before each clipping collection
§ Actual sampling dates in 2014: April 11 and April 21.
¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 9. Visual color ratings of tall fescue as affected by time x amendment during the pre-drought phase§ in 2014

	Weeks After Seeding (WAS)		
	32§	34	36
Amendment	Color Ratings† (1-9)		
Fertilizer	5.9e-h#	8.1a	8.3a
Alex-N¥	5.4h	6.2def	6.8bc
Alex-P	5.6gh	6.4cde	6.9b
Alex-DB	5.8fgh	6.7bcd	7.1b
Spots	5.8fgh	6.1efg	6.9b

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.

†Index scale is 1-9 where 1 equals completely brown grass, 6 equals minimal acceptable commercial quality, and 9 = dark green grass.

§ Actual sampling dates in 2014 were April 21, May 9, and May 23.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 10. Visual quality ratings of tall fescue as affected by time during the pre-drought phase§ in 2014

Rating Date	Turf Quality Ratings† (1-9)
April 21	6.0c#
May 9	6.7b
May 23	7.2a

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD.

†Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.

§ Actual sampling dates in 2014 were April 21, May 9, and May 23.

Table 11. Visual quality ratings of tall fescue as affected by amendment during the pre-drought phase§ in 2014

Amendment	Turf Quality Ratings† (1-9)
Fertilizer	7.3a#
Alex-N¥	6.5b
Alex-P	5.8c
Alex-DB	6.8b
Spots	6.9b

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD.

†Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.

§ Actual sampling dates in 2014 were April 21, May 9, and May 23.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 12. Mean volumetric soil moisture (VSM) percentage as affected by the interaction of amendment x irrigation during the drought phase§ of the study – 2014

Amendment	Irrigation Regime (%)	Mean VSM (%)
Fertilizer	80†	36.7b#
	0	19.3e
Alex-N¥	80	38.8ab
	0	23.1cd
Alex-P	80	36.3b
	0	25.3c
Alex-DB	80	38.5ab
	0	21.3de
Spots	80	40.4a
	0	21.4de

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD

† Irrigation replenishment calculated by estimating ET loss through the use of atmometers

§ Actual sampling dates in 2014 were June 2, June 11, June 19, and June 30.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 13. Mean volumetric soil moisture (VSM) percentage as affected by the interaction of irrigation x time during the drought phase§ of the study – 2014

	Weeks After Seeding (WAS)			
	38§	39	40	42
Irrigation Regime (%)	Volumetric Soil Moisture %†			
80†	34.1c#	44.6a	31.9c	42.0b
0	12.5f	25.0d	17.5e	33.4c

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.

† Irrigation replenishment calculated by estimating ET loss through the use of atmometers

§ Drought phase defined by actual sampling dates of June 2, June 11, June 19, and June 30.

Table 14. Tall fescue mean clipping yield as affected by the interaction of amendment x irrigation during the drought phase of the trial in 2014

Amendment	Irrigation Regime (%)	Mean Clipping Yield† (kg ha^{-1})
Fertilizer	80††	222.7a#
	0	88.3b
Alex-N¥	80	47.4c
	0	23.4c
Alex-P	80	53.2bc
	0	38.4c
Alex-DB	80	55.5bc
	0	23.0c
Spots	80	47.3c
	0	27.1c

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD.

†Data are based on 7 days of growth, post-mowing.

§ Actual sampling dates in 2014: July 17 and August 13.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 15. Leaf nitrogen uptake of tall fescue as affected by the interaction of amendment x irrigation during the drought phase¶ in 2014

Amendment	Irrigation††	N Uptake† (kg N ha^{-1})
Fertilizer	80% ET	5.3a#
	0 % ET	2.2b
Alex-N¥	80 % ET	0.8bc
	0% ET	0.4c
Alex-P	80% ET	1.0bc
	0% ET	0.8bc
Alex-DB	80% ET	1.0bc
	0% ET	0.2c
Spots	80% ET	0.7c
	0% ET	0.3c

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD.

†Calculated by multiplying turfgrass tissue N concentration (g N kg^{-1}) by dry mass clipping yield (kg ha^{-1}) for each treatment.

†† Irrigation replenishment calculated by estimating ET loss through the use of atmometers

¶ Actual sampling dates in 2014: June 19 and July 3.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 16. Tall fescue NDVI readings as affected by amendment during the drought phase[§] in 2014

Amendment	NDVI Measurements†
Fertilizer	0.81a
Alex-N[¥]	0.72c
Alex-P	0.77b
Alex-DB	0.73c
Spots	0.74bc

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD.

†Data was collected between 1300 hours and 1400 hours just before each clipping collection

§Actual sampling dates in 2014: June 19 and July 3.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 17. Tall fescue NDVI readings as affected by the interaction of time x irrigation during the drought phase[§] in 2014

	Weeks After Seeding (WAS)		
	38[§]	40	42
Irrigation Regime	NDVI Measurements†		
80%††	0.80a	0.81a	0.80a
0%	0.73b	0.68c	0.71b

Means followed by the same letter are not significantly different at the $P \leq 0.10$ using Fisher's LSD. Means can be compared across rows and down columns.

†Data was collected between 1300 hours and 1400 hours just before each clipping collection

†† Irrigation replenishment calculated by estimating ET loss through the use of atmometers.

§ Actual sampling dates in 2014: June 3, June 19, and July 3.

Table 18. Visual color ratings of tall fescue as affected by amendment x irrigation during the drought phase§ in 2014

Amendment	Irrigation††	Color Ratings† (1-9)
Fertilizer	80% ET	8.3a#
	0 % ET	5.3de
Alex-N¥	80 % ET	5.9cd
	0% ET	4.8e
Alex-P	80% ET	6.8b
	0% ET	4.8e
Alex-DB	80% ET	6.5bc
	0% ET	5.0e
Spots	80% ET	6.7c
	0% ET	4.9e

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD.
† Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.
††Irrigation replenishment calculated by estimating ET loss through the use of atmometers
§ Actual sampling dates were June 6, June 19, July 3, 2014.
¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 19. Visual color ratings of tall fescue as affected by time x irrigation during the drought phase§ - 2014

	Weeks After Seeding (WAS)		
	38§	40	42
Irrigation Regime	Color Ratings† (1-9)		
80%††	7.2a#	6.8ab	6.2c
0%	6.4bc	4.3d	4.3d

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.
† Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.
††Irrigation replenishment calculated by estimating ET loss through the use of atmometers
§ Actual sampling dates were June 6, June 19, July 3, 2014.

Table 20. Visual quality ratings of tall fescue as affected by amendment x irrigation during the drought phase§ in 2014

Amendment	Irrigation††	Turf Quality Ratings† (1-9)
Fertilizer	80% ET	8.2a#
	0 % ET	5.0de
Alex-N¥	80 % ET	5.6cd
	0% ET	4.4e
Alex-P	80% ET	6.0c
	0% ET	4.3e
Alex-DB	80% ET	6.8b
	0% ET	4.5e
Spots	80% ET	6.4bc
	0% ET	4.5e

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD.
† Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.
††Irrigation replenishment calculated by estimating ET loss through the use of atmometers
§ Actual sampling dates were June 6, June 19, July 3, 2014.
¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 21. Visual quality ratings of tall fescue as affected by irrigation x time during the drought phase§ – 2014

	Weeks After Seeding (WAS)		
	38§	40	42
Irrigation Regime	Turf Quality Ratings† (1-9)		
80%††	7.0a#	6.7ab	6.1bc
0%	5.8c	4.0d	3.9d

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.

† Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.

†† Irrigation replenishment calculated by estimating ET loss through the use of atmometers

§ Actual sampling dates were June 6, June 19, and July 3, 2014.

Table 22. Tall fescue mean clipping yields as affected by the interaction of time x amendment during the recovery phase§ in 2014

	Weeks After Seeding (WAS)	
	44§	48
Amendment	Clipping Yields† (kg ha^{-1})	
Fertilizer	355.9a#	249.9b
Alex-N¥	152.3c	206.3bc
Alex-P	215.6bc	191.8bc
Alex-DB	150.9c	206.8bc
Spots	198.5bc	221.5b

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.

†Data are based on 7 days of growth, post-mowing.

§ Actual sampling dates in 2014: July 17 and August 13.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 23. Tall fescue mean clipping yields as affected by the irrigation x time interaction during recovery phase§ in 2014

	Weeks After Seeding (WAS)	
	44§	48
Irrigation Regime	Clipping Yields† (kg ha^{-1})	
80%††	233.9a#	206.9ab
0%	195.3b	223.6ab

Means followed by the same letter are not significantly different at the P ≤ 0.10 using Fisher's LSD. Means can be compared across rows and down columns.

†Data are based on 7 days of growth, post-mowing.

†† Irrigation replenishment calculated by estimating ET loss through the use of atmometers.

§ Actual sampling dates in 2014: July 17 and August 13.

Table 24. Leaf nitrogen uptake of tall fescue as affected by amendment x time during the recovery phase –2014

	Weeks After Seeding (WAS)	
	44§	48
Amendment	Nitrogen Uptake† (kg N ha^{-1})	
Fertilizer	10.0a#	7.0b
Alex-N¥	3.4d	6.2bc
Alex-P	5.0bcd	5.3bcd
Alex-DB	3.5d	5.7bc
Spots	4.6cd	6.6bc

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.

†Data was collected after one week of growth.

§ Actual sampling dates in 2014: July 17 and August 13.

¥ Abbreviations: Alexandria biosolids mix - agronomic N-rate (Alex-N), Alexandria biosolids mix-agronomic P-rate (Alex-P), Alexandria dewatered biosolids cake (Alex-DB), Spotsylvania biosolids compost (Spots)

Table 25. Tall fescue NDVI readings as affected by the time x irrigation interaction during the recovery phase§ in 2014

	Weeks After Seeding (WAS)		
	44§	46	48
Irrigation Regime	NDVI Measurements†		
80%††	0.78a	0.74c	0.71d
0%	0.74c	0.75bc	0.77ab

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD. Means can be compared across rows and down columns.
†Data was collected between 1300 hours and 1400 hours just before each clipping collection

†† Irrigation replenishment calculated by estimating ET loss through the use of atmometers.

§ Actual sampling dates were July 14, July 28, and August 15, 2014.

Table 26. Visual color ratings of tall fescue as affected by time x irrigation during the recovery phase§ - 2014

	Weeks After Seeding (WAS)		
	44§	46	48
Irrigation Regime	Color Ratings† (1-9)		
80%††	6.2b#	6.1b	6.6a
0%	5.1c	6.7a	6.8a

Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD. Means can be compared across rows and down columns.
† Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.
††Irrigation replenishment calculated by estimating ET loss through the use of atmometers

§ Actual sampling dates were July 14, July 28, and August 15, 2014.

Table 27. Visual quality ratings of tall fescue as affected by irrigation during the recovery phase§ – 2014

	Weeks After Seeding (WAS)		
	44§	46	48
Irrigation Regime	Turf Quality Ratings† (1-9)		
80%††	6.1c#	6.2bc	6.5abc
0%	5.3d	6.6ab	6.7a

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.

† Index scale is 1-9. 1 being brown grass and 6 being the minimal acceptable commercial quality rating.

†† Irrigation replenishment calculated by estimating ET loss through the use of atmometers

§ Actual sampling dates were July 14, July 28, and August 13.

Table 28. Rhizoctonia brown patch incidence of tall fescue as affected by time x irrigation during the growing season – 2014

	Growing Season §	
	Weeks After Seeding (WAS)	
	38	45
Irrigation Regime	Disease Incidence Count	
80%†	1.5c#	6.3a
0%	4.7b	2.4c

Means followed by the same letter are not significantly different at the P ≤ 0.05 using Fisher's LSD. Means can be compared across rows and down columns.

† Irrigation replenishment calculated by estimating ET loss through the use of atmometers

§ Actual rating dates were June 6 and July 28, 2014.

Table 29. – Tall fescue root mass sample weights taken after one year of growth as affected by the main effect of irrigation.

	End of Season 1 §
Irrigation Regime	Root Mass† (g $196cm^{-3}$)
80%††	2.1a#
0%	1.9b

\# Means followed by the same letter are not significantly different at the $P \leq 0.05$ using Fisher's LSD.

†Data collected by taking a 10cm deep core sample and ashing the sample in a muffle furnace at 500°C for 24 hours (root mass (g) = pre ignition weight - post ignition weight)

†† Irrigation replenishment calculated by estimating ET loss through the use of Atmometers

§ Actual sampling date was September 12, 2014. Exactly one year after seeding.

Appendix

Analysis of variance table for the effect of amendment on tall fescue volumetric soil moisture percentage during the pre-drought phase (14 April to 30 May 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	44.07	11.017	1.40	0.254
Error	35	275.16	7.862		
Total	39	319.23			

Analysis of variance table for the interactive effect of amendment and time on tall fescue mean clipping yield during the pre-drought phase (14 April to 30 May 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Time	2	456299	228149	15.63	0.000
Amendment	4	1998713	499678	34.23	0.000
Time*Amendment	8	110768	13846	0.95	0.480
Error	105	1532886	14599		
Total	119	4098665			

Analysis of variance table for the interactive effect of amendment by time on tall fescue leaf nitrogen uptake during the pre-drought phase (14 April to 30 May 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	2367.3	591.82	36.50	0.000
Time	1	369.0	368.96	22.76	0.000
Amendment*Time	4	131.4	32.86	2.03	0.100
Error	70	1135.0	16.21		
Total	79	4002.7			

Analysis of variance table for the interactive effect of amendment and time on tall fescue NDVI measurements during the pre-drought phase (14 April to 30 May 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	0.057053	0.014263	16.29	0.000
Time	1	0.005458	0.005458	6.23	0.015
Amendment*Time	4	0.006934	0.001733	1.98	0.107
Error	70	0.061302	0.000876		
Total	79	0.130746			

Analysis of variance table for the interactive effect of amendment and time on tall fescue visual color ratings during the pre-drought phase (14 April to 30 May 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	23.904	5.9760	21.61	0.000
Time	2	47.863	23.9313	86.55	0.000
Amendment*Time	8	8.283	1.0354	3.74	0.001
Error	105	29.031	0.2765		
Total	119	109.081			

Analysis of variance table for the interactive effect of amendment and time on tall fescue visual quality ratings during the pre-drought phase (14 April to 30 May 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	31.429	7.8573	13.06	0.000
Time	2	27.817	13.9083	23.12	0.000
Amendment*Time	8	5.496	0.6870	1.14	0.342
Error	105	63.156	0.6015		
Total	119	127.898			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue volumetric soil moisture percentage for the drought phase (1 June to 4 July 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	202.6	50.7	3.14	0.017
Irrigation	1	10270.0	10270.0	637.04	0.000
Time	3	6195.7	2065.2	128.11	0.000
Amendment*Irrigation	4	297.0	74.2	4.61	0.002
Amendment*Time	12	161.8	13.5	0.84	0.613
Irrigation*Time	3	1007.4	335.8	20.83	0.000
Amendment*Irrigation*Time	12	58.2	4.9	0.30	0.988
Error	120	1934.6	16.1		
Total	159	20127.4			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue mean clipping yield during the drought phase (1 June to 4 July 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Time	2	80612	40306	20.88	0.000
Amendment	4	260159	65040	33.69	0.000
Irrigation	1	61200	61200	31.70	0.000
Time*Amendment	8	20664	2583	1.34	0.235
Time*Irrigation	2	13402	6701	3.47	0.035
Amendment*Irrigation	4	60768	15192	7.87	0.000
Time*Amendment*Irrigation	8	14345	1793	0.93	0.497
Error	90	173742	1930		
Total	119	684892			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue leaf nitrogen uptake during the drought phase (1 June to 4 July 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	126.612	31.6529	13.33	0.000
Irrigation	1	19.523	19.5229	8.22	0.006
Time	1	3.037	3.0371	1.28	0.263
Amendment*Irrigation	4	23.203	5.8007	2.44	0.056
Amendment*Time	4	0.120	0.0299	0.01	1.000
Irrigation*Time	1	6.943	6.9431	2.92	0.092
Amendment*Irrigation*Time	4	5.170	1.2925	0.54	0.704
Error	60	142.524	2.3754		
Total	79	327.131			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue NDVI measurements during the drought phase (1 June to 4 July 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	0.131781	0.032945	12.96	0.000
Time	2	0.010752	0.005376	2.11	0.127
Irrigation	1	0.286945	0.286945	112.89	0.000
Amendment*Time	8	0.004645	0.000581	0.23	0.985
Amendment*Irrigation	4	0.011886	0.002971	1.17	0.330
Time*Irrigation	2	0.014942	0.007471	2.94	0.058
Amendment*Time*Irrigation	8	0.001254	0.000157	0.06	1.000
Error	90	0.228760	0.002542		
Total	119	0.690964			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue visual color ratings during the drought phase (1 June to 4 July 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	28.833	7.2083	7.95	0.000
Irrigation	1	92.752	92.7521	102.35	0.000
Time	2	54.067	27.0333	29.83	0.000
Amendment*Irrigation	4	12.175	3.0437	3.36	0.013
Amendment*Time	8	4.267	0.5333	0.59	0.785
Irrigation*Time	2	14.867	7.4333	8.20	0.001
Amendment*Irrigation*Time	8	3.175	0.3969	0.44	0.895
Error	90	81.562	0.9062		
Total	119	291.698			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue visual quality ratings during the drought phase (1 June to 4 July 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	36.300	9.075	8.65	0.000
Irrigation	1	126.075	126.075	120.23	0.000
Time	2	42.829	21.415	20.42	0.000
Amendment*Irrigation	4	14.633	3.658	3.49	0.011
Amendment*Time	8	5.650	0.706	0.67	0.714
Irrigation*Time	2	10.612	5.306	5.06	0.008
Amendment*Irrigation*Time	8	2.617	0.327	0.31	0.960
Error	90	94.375	1.049		
Total	119	333.092			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue mean clipping yield during the recovery phase (4 July to 21 August 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Time	1	7	7.4	0.00	0.967
Amendment	4	167252	41813.1	9.78	0.000
Irrigation	1	2381	2381.3	0.56	0.458
Time*Amendment	4	73490	18372.5	4.30	0.004
Time*Irrigation	1	15335	15335.1	3.59	0.063
Amendment*Irrigation	4	1149	287.2	0.07	0.992
Time*Amendment*Irrigation	4	626	156.5	0.04	0.997
Error	60	256640	4277.3		
Total	79	516880			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue leaf nitrogen uptake during the recovery phase (4 July to 21 August 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	159.808	39.9520	9.38	0.000
Irrigation	1	0.002	0.0019	0.00	0.983
Time	1	14.251	14.2514	3.35	0.072
Amendment*Irrigation	4	0.873	0.2181	0.05	0.995
Amendment*Time	4	90.213	22.5532	5.30	0.001
Irrigation*Time	1	9.998	9.9978	2.35	0.131
Amendment*Irrigation*Time	4	1.811	0.4528	0.11	0.980
Error	60	255.528	4.2588		
Total	79	532.484			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue NDVI measurements during the recovery phase (4 July to 21 August 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	0.076190	0.019047	20.37	0.000
Time	2	0.011887	0.005944	6.36	0.003
Irrigation	1	0.002143	0.002143	2.29	0.134
Amendment*Time	8	0.006665	0.000833	0.89	0.528
Amendment*Irrigation	4	0.000923	0.000231	0.25	0.911
Time*Irrigation	2	0.043665	0.021832	23.35	0.000
Amendment*Time*Irrigation	8	0.006336	0.000792	0.85	0.564
Error	90	0.084153	0.000935		
Total	119	0.231960			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue visual color ratings during the recovery phase (4 July to 21 August 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	18.1542	4.5385	11.25	0.000
Irrigation	1	0.2521	0.2521	0.62	0.431
Time	2	25.0792	12.5396	31.08	0.000
Amendment*Irrigation	4	1.0292	0.2573	0.64	0.637
Amendment*Time	8	1.7958	0.2245	0.56	0.811
Irrigation*Time	2	14.3042	7.1521	17.73	0.000
Amendment*Irrigation*Time	8	1.0708	0.1339	0.33	0.952
Error	90	36.3125	0.4035		
Total	119	97.9979			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue visual quality ratings during the recovery phase (4 July to 21 August 2014).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	35.146	8.7865	20.18	0.000
Irrigation	1	0.352	0.3521	0.81	0.371
Time	2	18.404	9.2021	21.13	0.000
Amendment*Irrigation	4	2.929	0.7323	1.68	0.161
Amendment*Time	8	1.617	0.2021	0.46	0.878
Irrigation*Time	2	9.129	4.5646	10.48	0.000
Amendment*Irrigation*Time	8	2.183	0.2729	0.63	0.753
Error	90	39.187	0.4354		
Total	119	108.948			

Analysis of variance table for the effects of amendment, irrigation, and time on tall fescue rhizoctonia blight incidence during the growing season of 2014.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Amendment	4	100.825	25.206	4.73	0.002
Irrigation	1	2.450	2.450	0.46	0.500
Time	1	31.250	31.250	5.87	0.018
Amendment*Irrigation	4	7.675	1.919	0.36	0.836
Amendment*Time	4	16.625	4.156	0.78	0.542
Irrigation*Time	1	252.050	252.050	47.33	0.000
Amendment*Irrigation*Time	4	37.575	9.394	1.76	0.148
Error	60	319.500	5.325		
Total	79	767.950			

Analysis of variance table for the interactive effect of irrigation and amendment on tall fescue root mass weights after one full season.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Irrigation	1	0.61622	0.61622	4.92	0.034
Amendment	4	0.06306	0.01576	0.13	0.972
Irrigation*Amendment	4	0.30437	0.07609	0.61	0.660
Error	30	3.75402	0.12513		
Total	39	4.73767			