Biosolids as a source of soil conditioning and fertility for turfgrass

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ACADEMIC ABSTRACT

Wastewater treatment plants are shifting towards producing exceptional quality (EQ) biosolids to increase recycling rates to land, especially urban areas. Other methods of improving the environmental impact of wastewater treatment includes additions of iron (Fe) to reduce phosphorus (P) concentrations in outgoing treated water and precipitate the P into the biosolids. Proper management of biosolids to rehabilitate anthropogenically disturbed urban soils for improved plant growth and effects on the cycling of nutrients requires further study. Our objectives were: 1) to determine whether various EQ biosolids could be managed to improve degraded soil properties and turfgrass quality while minimizing risk of P loss in a field study; and 2) to use spectral reflectance data to compare relationships of vegetation indices to soil and turfgrass parameters. We found that after an initial lag-time of one year, biosolids amendments increased turfgrass clipping biomass and aesthetic quality greater than did synthetic fertilizer. Repeated topdressing applications of biosolids reduced soil bulk density and increased soil organic carbon (OC) and nitrogen (N) stocks. Biosolids applied at the agronomic N rate did not increase water-soluble P (15 and 18 mg P kg^{-1} of soil) compared to biosolids applied at the agronomic P rate (9.6 mg P kg^{-1} of soil) and synthetic fertilizer (13 mg P kg^{-1} of soil) after five years. We further demonstrated at this field site that collecting continuous data improves spectral reflectance vegetation indices relationships to turfgrass quality, clipping biomass, and tissue N accumulation. Soil volumetric water content was best correlated to the water band index (r = 0.60) and the green-to-red ratio index (r = 0.54) vegetation indices. Differences in soil and

turfgrass measured parameters were best detected when there was drought-stressed versus irrigated turfgrass.

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GENERAL AUDIENCE ABSTRACT

Biosolids are the sanitized and nutrient-rich organic solids and semi-solids resulting from treatment of wastewater. The nutrient-rich organic solids provide plant-essential elements (e.g., nitrogen) and can improve soil physical parameters such as soil compaction. Wastewater treatment plants are adopting processes that produce cleaner, exceptional quality (EQ) biosolids to increase biosolids recycling rates to land, especially to urban areas to improve urban soil quality. Adding iron to treated wastewater further improves the quality of biosolids and effluent released to surface water by removing phosphorus from wastewater and concentrating this essential plant nutrient within biosolids. Our research objectives were to quantify the potential benefits of EQ biosolids for improving degraded urban soils, providing sufficient plant available nitrogen to improve turfgrass quality, avoiding increasing soil phosphorus to levels that could result in pollution, and increasing the long-term storage of soil carbon to mitigate climate change. We learned that biosolids were the best long-term solution for providing a high quality turfgrass stand and improve soil properties. Repeated applications of EQ biosolids reduced soil bulk density and increased soil organic carbon and nitrogen stocks. The increased iron in the biosolids reduced water-soluble phosphorus and may reduce phosphorus loss to surface waters.

DEDICATION

No one is self-made, to all my teachers, especially my first:

Janet and John Badzmierowski

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TABLE OF CONTENTS

List of Abbreviations

ADB	anaerobically digested biosolids
ARE	Alexandria Renew Enterprises
Al	aluminum
BBN	blended biosolids–sand–sawdust applied annually at an agronomic nitrogen rate
BBP	blended biosolids–sand–sawdust applied annually at an agronomic phosphorus rate plus supplemental fertilizer nitrogen
Ca	calcium
C	carbon
CBN	composted biosolids applied annually at an agronomic nitrogen rate
cc	Crop Circle ACS-430 calculated indices
DBN	dewatered biosolids applied annually at an agronomic nitrogen rate
ET	evapotranspiration
EQ	exceptional quality
Fe	iron
FER	annually-applied synthetic N, P, K fertilizer
GRI	green-to-red ratio index
K	potassium
KCl	potassium chloride
MI	Mehlich I
Mg	magnesium
Mn	manganese
N	nitrogen
NDVI	normalized difference vegetation index

NIR	near-infrared
OC	organic carbon
OM	organic matter
P	phosphorus
PAN	plant available nitrogen
PRFPs	processes to further reduce pathogens
PSR	phosphorus saturation ratio
R	visible red
RE	red edge
RVI	simple ratio vegetation index
SOM	soil organic matter
TDR	time-domain reflectometry
TKN	total Kjeldahl nitrogen
VI	vegetation index
VWC	volumetric water content
WBI	water band index
WWTP	wastewater treatment plant
Zn	zinc

1. Introduction

1.1 Background

The conversion of forests and grasslands to intensive agriculture and urban areas has reduced approximately half of the organic matter (OM) content previously present in North American soils (Baumhardt et al., 2015). Biosolids, the semi-solid, nutrient-rich, organic end-product of wastewater treatment plants (WWTP), can increase OM content of soils, improve soil physical and chemical characteristics, and reduce fertilizer needs and water usage (Khaleel et al., 1981; Hargreaves et al., 2008; Annabi et al., 2011). Biosolids are produced in significant quantities (10×10^7 Mg yr^{-1}) at a global scale (Thangarajan et al., 2013) and might provide a significant source of organic matter and nutrients for restoring the function of degraded soils. A 2004 assessment estimated United States annual total for biosolids production was approximately 6,505,625 dry metric tons of which 49% went to land application (NEBRA, 2007).

Wastewater treatment plants have aimed to increase biosolids land-application recycling rates through the production of Exceptional Quality (EQ) Class A biosolids that have no application restrictions except for the amount of plant available nitrogen (N) and, in some cases, phosphorus (P) when applied from bulk sources. Such biosolids are treated by processes to further reduce pathogens (PRFPs) and have reduced vector attraction and low pollutant concentrations (USEPA, 1994). The term “exceptional quality” indicates that the biosolids have met the Code of Federal Regulations Title 40 Part 503 pollutant concentration limits in addition to meeting processes to further reduce pathogens (USEPA, 1994).

The improved quality of EQ biosolids has increased potential uses in urban landscapes, thereby decreasing transportation costs to distant agricultural fields. The urban area of the conterminous United States is approximately 3% and expanding. Anthropogenic development often results in exposing a low-nutrient, compacted subsoil as a result of mechanical topsoil removal (Lorenz and Lal, 2009). Amending anthropogenically disturbed urban soils with biosolids can provide local opportunities to improve degraded soil physical and chemical properties, improve plant growth, and increase organic matter (OM) and carbon (C) storage rates.

The most common plant choice of disturbed urban soils is turfgrass (Beard, 1973). Turfgrass is estimated to occupy 1.9% of the continental United States surface area (Milesi et al., 2005). Soil compaction and low-nutrient content can impede root development and result in poor turfgrass establishment and long-term density (Harris, 1991; Beniston and Lal, 2012). Soil compaction and low OM and nutrient content (e.g., N and P) of disturbed urban soils can be alleviated through the addition of increased inputs (e.g., fertilization and irrigation) to perennial plant cover (i.e., turfgrass) (Post and Kwon, 2000; Post et al., 2004; Milesi et al., 2005). Increased fertilizer and irrigation can come at the cost of deleterious environmental effects, including nutrient losses to surface waters and reduction in valuable water resources.

As the most irrigated crop in the United States, turfgrass has received scrutiny for its water demands, especially in urban environments where water availability can come at a premium. However, maintaining acceptable quality turfgrass often requires sufficient irrigation, especially in transition zone climates. Irrigation strategies that reduce water inputs and maintains turfgrass quality are needed for landowners and turfgrass managers.

Radiometers have been utilized to measure reflected energy and quantify physiological attributes based on plant tissue changes in spectral reflectance in the visible red (R), red edge (RE), and near-infrared (NIR) regions. Water stress in turfgrass may be best evaluated using spectral reflectance measurements (McCall et al., 2017; Roberson, 2018). Turfgrass research utilizing spectral reflectance to determine the onset of water stress remains largely un-explored at the field-scale. Determining soil-water-plant relationships can be an effective management tool to effectively use our water resources.

Turfgrass fertilization is often done to meet N needs as it is generally the most limiting nutrient for growth (Carrow et al., 2001). Successive applications of biosolids, which have low N:P ratios, can result in the overapplication of P as turfgrasses require lower quantities of P than N (Cogger et al., 2006). Concerns of P loss to surface waters has resulted in P-based regulations limiting the mass of biosolids applied to soil to avoid excessive soil P buildup (Jesiek and Wolfe, 2005). Despite observed reductions of dissolved reactive P in runoff and leachate from areas amended with biosolids treated with aluminum (Al) or iron (Fe) salts at WWTPs (Elliot et al., 2002, 2005; Penn and Sims, 2002) regulations often do not discriminate between the use of organic amendments based on P solubility and environmental loss risk. It is critical to develop fertilization strategies that provide sufficient plant available N (PAN) while avoiding environmentally deleterious P for the rehabilitation of disturbed urban soils.

1.2. Objectives

The goal of our research was to investigate biosolids at the field-scale and their potential for rehabilitating anthropogenically disturbed urban soils, effects on turfgrass growth and quality, determining best strategies for reducing water use and environmentally deleterious impacts including P loss. The specific objectives were:

1) To determine whether EQ biosolids products of varying organic matter, N, and P concentrations could be managed to enhance anthropogenically disturbed urban soil properties and provide sufficient PAN to improve turfgrass establishment, quality, and growth. [Chapter 2]
2) To compare two irrigation strategies and the use of a conventional synthetic fertilizer program to EQ biosolids products of varying OM, N, and P concentrations to improve an anthropogenically disturbed urban-turfgrass system without increasing soil P to excessive concentrations. [Chapter 3]
3) To compare the relationships of various vegetation indices using a traditional broadband, multispectral radiometer and a narrowband hyperspectral radiometer to soil volumetric water content (VWC), N fertility source, turfgrass quality, and leaf tissue analyses. [Chapter 4]

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2. Biosolids-based amendments improve tall fescue establishment and urban soils

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Abbreviations: exceptional quality (EQ); evapotranspiration (ET); normalized difference vegetation index (NDVI); plant available nitrogen (PAN)

2.1 Abstract

Turfgrass establishment and persistence in urban environments can be limited by topsoil removal and subsoil compaction. A three-year study (Sep 2013-Jun 2016) where tall fescue (*Festuca arundinacea* Schreb.) was grown to compare with and without irrigation during summer stress months and biosolids-based amendments with synthetic fertilizer on (i) quality and clipping biomass of tall fescue and (ii) soil properties of an anthropogenically disturbed urban soil. The experimental design was a split-plot with irrigation as the main factor and fertility treatments as the subplot factor. Fertility treatments were applied to meet the agronomic N rate of 224 kg plant available nitrogen ha^{-1} yr^{-1} for tall fescue during Sep. 2013 to June 2015. Fertility treatments were: 1) synthetic fertilizer; 2) anaerobically digested biosolids (ADB); 3) ADB blended with sand and sawdust; 4) ADB blended with sand and sawdust applied at the agronomic P rate of 64 kg P ha^{-1} yr^{-1} for tall fescue and supplemented with synthetic N; and 5) composted ADB biosolids. No fertility treatments were applied from June 2015 to May 2016 to measure residual effects. Greater turfgrass clipping biomass and quality, higher soil C and macro- and micro-nutrient concentrations, and reduced soil bulk density were observed for biosolids-blended products compared to synthetic fertilizer. Applying biosolids at the agronomic P rate did not yield desirable turfgrass quality; however applying biosolids products at the agronomic N rate continuously may lead to potential P loss if rates are not reduced.

2.2 Introduction

Turfgrass is the predominant vegetation in urban soils. Milesi et al. (2005) estimated that turfgrass covers 1.9% of the continental United States. Tall fescue (*Festuca arundinacea* Schreb.) is one of the most common grasses planted in the transition climate zone. Deep rooting, cold and drought tolerance, and relatively low irrigation, pesticide, and fertility requirements make tall fescue a popular choice of turfgrass managers (Beard, 1973; Christians, 2004; Zhang et al., 2012). Reductions in turfgrass quality can lead to soil erosion and diminished groundwater recharge and pollutant filtration (Beard, 1994).

Inputs of nutrients and irrigation are often needed for establishment and maintenance of high-quality tall fescue lawns. Studies relating irrigation needs to turfgrass evapotranspiration (ET) range from 0.60 to 0.85 for tall fescue (Ervin and Koski, 1998; Meyer and Gibeault, 1997). Irrigating to replace 80% of reference ET has been widely accepted for maintaining acceptable quality of a turfgrass stand (Kopec et al., 1988; Carrow, 1995; Ervin and Koski, 1998). However, irrigation of large land areas in turfgrass can be costly and energy intensive. Water prices are expected to increase four times present levels over the coming decades (Baird, 2010). Landowners and managers need to develop strategies that reduce irrigation inputs, while maintaining turfgrass quality (Ervin and Koski, 1998).

Urban lands account for 3.0% of the land surface area within the United States (U.S. Census Bureau, 2010). From 1963 to 2000, developed area increased by 33% in the contiguous United States and is continuing to accelerate in conversion rate over time (Sleeter et al., 2013). During land development, vegetation and topsoil are removed or buried, and the remaining subsoil is often compacted by heavy equipment (Cogger, 2005). Soil compaction results in the destruction of aggregates, reduced pore size and water infiltration, and increased bulk density

(Kozlowski, 1999; Hamza and Anderson, 2005). The removal or burial of topsoil in urban soils results in the loss of soil organic matter (SOM). This results in degraded soil structure and depletion of nutrients. Soil organic matter may contribute as much as 95% of soil nitrogen (N) and 25 to 50% of soil phosphorus (P) (Allison, 1973). The limitations posed by excavated and compacted urban soils pose substantial challenges to turfgrass establishment and maintenance.

The destruction of large, noncapillary pores, reduction in water infiltration, and lower oxygen levels in compacted soils can limit root growth of turfgrass (O'Neil and Carrow, 1982; Harivandi, 2002; Matthieu et al., 2011). These property changes may indirectly affect root growth as it can confine roots to a shallow top layer of the soil, causing nutrient and water deficiencies (Harivandi, 2002; Matthieu et al., 2011). The reduced root growth can cause any fertilization program to be inefficient if nutrients and water are not taken up by the turfgrass (Carrow et al., 2001).

Organic amendments, including biosolids and biosolids compost, can reduce soil bulk density and increase soil porosity, aggregation, and water-holding capacity more effectively than inorganic fertilizers (Khaleel et al., 1981; Zebarth et al., 1999; Foley and Cooperband, 2002; Rawls et al., 2003; Krull et al., 2004; García-Orenes et al., 2005; Price and Voroney, 2007). Biosolids are nutrient-rich organic materials resulting from the treatment of wastewater residuals (Water Environment Federation, 1991). Class A biosolids have been treated by processes to further reduce pathogens (PFRP), which result in byproducts meeting strict requirements for pathogen content and vector attraction reduction (USEPA, 1994). The term "exceptional quality" (EQ) indicates that the biosolids have met the Code of Federal Regulations Title 40 (40 CFR) Part 503 pollutant concentration limits in addition to meeting PFRP (USEPA, 1994). Exceptional quality biosolids being produced by wastewater treatment facilities have more potential uses in urban landscapes if they can be treated to improve handling and application. These products present a locally sourced, organic fertilizer that can be used to amend urban soils to enhance turfgrass establishment and growth via their beneficial effects on soil properties and nutrient availability (Pound and Street, 1991).

Class A EQ biosolids are generated via processes such as advanced aerobic and anaerobic digestion, thermal drying, alkali stabilization, and composting. After digestion, dewatering of the biosolids is performed to improve handling and disposal. This process reduces the cost of utilization whether via land application or disposal via landfilling or incineration. High carbon (C) to N ratio materials (e.g., sawdust, mulch, and paper products) can be added to further reduce moisture content and improve aggregation, while the addition of sand can improve ease of handling (Evanylo, 2009; Beecher and Goldstein, 2010). Materials with a high C:N also limit NO_3-N leaching potentials of biosolids through decreased N mineralization rates (Daniels et al., 2001). Banegas et al. (2007) and Hay et al. (1988) found that the mixing of sawdust and biosolids additionally destroyed pathogenic microorganisms. Based on previous greenhouse research by Yu et al. (2013), a blend of biosolids:sand:sawdust at a ratio of 2:1:1 (by dry mass) was developed. The lowered moisture content enabled homogenous field application and had a C:N ratio (~15:1) that provided net mineralizable N for adequate turfgrass growth.

Increasing concerns of phosphorus (P) loss to surface waters has resulted in phosphorus-based regulations, limiting the mass of organic amendments applied to soil to avoid excessive soil P buildup (Jesiek and Wolfe, 2005). Such regulations have reduced or eliminated biosolids applications to urban soils in Maryland (Boudeman et al., 2016). As regulations become more stringent, it is critical to develop organic byproduct land application strategies that provide ample plant available N without excessive amounts of environmentally deleterious P for the rehabilitation of disturbed urban soils.

A few studies have reported the beneficial uses of incorporating composted biosolids in turfgrass establishment in disturbed urban soils (Landschoot and McNitt, 1994; Loschinkohl and Boehm, 2001; Linde and Hepner, 2005). Loschinkohl and Boehm (2001) measured improved turfgrass percent cover and clipping biomass by the incorporation of a 1.3-cm layer of biosolids compost than non-biosolids amended soils. Linde and Hepner (2005) found that biosolids compost caused a 2 to 3-week delay in seed and sod establishment due to high salinity and excessive ammonium N. Fertilized plots had increased turfgrass cover compared to biosolids compost during the initial weeks. However, biosolids compost applied at a 5 to 7.5 cm layer was a better long-term strategy for turfgrass establishment based on sustained vegetative cover (Linde and Hepner, 2005). Landschoot and McNitt (1994) observed that composted biosolids applied at both 2.5 and 5 cm depths gave faster establishment rates than other composted materials such as yard trimmings, chicken manure, brewery byproducts, and paper mill byproducts.

The purpose of our research was to compare the effects of various EQ biosolids products and synthetic fertilizer on establishment and maintenance of turfgrass in a disturbed urban soil with and without irrigation. Our objectives were to determine whether EQ biosolids of varying OM, N, and P concentrations could be managed to (1) improve tall fesuce quality in a reduced irrigation strategy, (2) enhance properties of disturbed urban soil, (3) provide sufficient plant available N without increasing soil P to excessive concentrations, and (4) improve turfgrass establishment, quality, and growth. We hypothesized that the varying amounts of SOM from the biosolids-based amendments would improve tall fescue quality and clipping biomass during summer drought stress due to greater plant available water and improve soil physical and chemical properties to improve turfgrass establishment and maintenance.

2.3 Materials and Methods

2.3.1. Study Site Establishment

This study was conducted at the Virginia Tech Turfgrass Research Center in Blacksburg, VA (37°12'54.31"N, 80°24'42.14"W) and located in cold hardiness zone 6b (Daly et al., 2012). Mean monthly temperature and precipitation was reported using a nearby weather station for 2013 – 2016 (NOAA, 2016).

The experimental area was graded for an airport runway in the early 1940s. The runway was never used, and the site was converted to a tall fescue stand. After several decades of growth, a topsoil layer developed to a depth of 7.5 cm. In August 2013, the area was sprayed in two sequential applications, made two weeks apart, with a mixture of glyphosate (*N*-(phosphonomethyl) glycine) at 8.3 kg ae ha^{-1}) and diquat (diquat dibromide at 2.1 kg ai ha^{-1}) for complete vegetation kill. The topsoil that had accumulated since the 1940s was removed, exposing the clayey subsoil horizons. In-ground irrigation pipes with pop-up heads were installed following topsoil removal and the soil was subsequently roto-tilled to 10 cm to smooth and level the study site for plot layout, amendment application, and planting.

2.3.2. Experimental Design

The experimental design was a split-plot arrangement of a randomized complete block design replicated four times. Main plots were two irrigation treatments during summer, and subplots were five soil amendments. The irrigation treatments were (1) no water applied during critical summer months, unless necessary to keep vegetation alive, and (2) water applied to replenish 80% of evapotranspiration (ET) during drought-prone, high ET summer months. The five subplot treatments were synthetic fertilizer and four EQ biosolids byproducts applied to annually provide an estimated plant available N (PAN) rate of 224 kg PAN ha^{-1}. Dimensions of the experimental area were 22.7 m × 35.5 m (806 m^2). Subplots were 3.66 m × 3.66 m and had 0.61 m buffer strips between experimental units.

2.3.3. Soil Benchmark Sampling and Analysis

Soil sampling and characterization were performed immediately following site preparation in August 2013. Six subsamples from each of the 40 subplots were collected to a depth of 10 cm using a 2-cm diameter probe and composited by treatment plot. Samples were dried at 60°C for 48 h and ground to pass a 2-mm sieve. A routine soil test analysis for pH and Mehlich I (MI) extractable P, potassium (K), calcium (Ca), and magnesium (Mg) was conducted by the Virginia Tech Soil Testing Laboratory (Maguire and Heckendorn, 2011). Particle size analysis was performed using the pipette method (Day, 1965).

2.3.4. Amendment Treatments, Biosolids Analysis, and Soil Fertility

The five amendment treatments were four EQ biosolids byproducts and a synthetic fertilizer. Anaerobically digested, dewatered, Class A biosolids were obtained from Alexandria Renew Enterprises (ARE), an advanced wastewater treatment facility and biosolids generator located in Alexandria, VA. The ARE product was employed to provide two products: dewatered biosolids alone and dewatered biosolids blended with sand and sawdust. The blended byproduct was processed by Luck Stone Corporation (a quarrying company headquartered in Richmond, VA) by mixing biosolids with Caroline County (VA)-mined quartz sand (100% passing through 4.7 mm sieve size fraction) and sawdust at a 2:1:1 ratio (by dry mass), respectively. The dry sawdust was added to the blend to decrease biosolids moisture content and increase the C:N ratio and stabilize the N in the biosolids. The sand was added to disperse biosolids aggregates and increase granulation to improve ease of application spreading. A composted biosolids 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, creating an EQ biosolids compost.

Samples of each organic amendment used in the experiment were collected prior to application and analyzed by A&L Eastern Laboratories (Richmond, VA). Analyses included: total Kjeldahl N (SM-4500-NH3C-TKN) (APHA, 1992); total and volatile solids (SM-2540G) (APHA, 1992); organic N (calculated as the difference between TKN and NH_4-N); ammonia + ammonium-N (SM-4500-NH3C) (APHA, 1992); nitrate + nitrite-N (SM-4500NO3F) (APHA, 1992); P and potassium (K) (SW-6010C) (USEPA, 2000) (Table 2.1).

Four biosolids treatments were developed from the ARE and Spotsylvania byproducts. These were: (1) ARE dewatered biosolids to supply an annual PAN rate of 224 kg ha^{-1} (DBN), (2) ARE biosolids blended with sand and sawdust to supply an annual PAN rate of 224 kg ha^{-1} (BBN), (3) ARE biosolids blended with sand and sawdust to supply an annual P rate as recommended by Virginia Tech Soil Testing Laboratory soil test analysis plus supplemental sulfur coated urea fertilizer to also provide 224 kg PAN ha^{-1} annually for the entire treatment (BBP), and (4) Spotsylvania compost to supply an annual PAN rate of 224 kg ha^{-1} (CBN). The fifth amendment treatment was synthetic fertilizer N (as sulfur coated urea) to supply an annual PAN rate of 224 kg ha^{-1} (FER). Based on typical ranges for the establishment and maintenance of tall fescue in the transition zone and soil test recommendations (146 – 244 kg N ha^{-1}), the agronomic N rate was 224 kg N ha^{-1} and the agronomic P rate was 64 kg P ha^{-1} (Christians, 2004; VA DCR, 2014).

Application rates of biosolids byproducts were based on estimates of the organic N that would be mineralized during the first year after application per Virginia Department of Conservation and Recreation Nutrient Management Standards and Criteria (VA DCR, 2014). These N mineralization rates are estimated to be 30% for anaerobically digested biosolids and 15% for composted biosolids. For the biosolids, sand, and sawdust blends, the N mineralization rate of 20% was based on previous greenhouse studies (Yu et al., 2013). The biosolids blended byproduct applied at the rate to supply the recommended rate of P by the Virginia Tech Soil Test Laboratory (BBP) provided 31 kg PAN ha^{-1} and was supplemented by two split rates of urea (urea, 46-0-0, Potash Corporation, Saskatchewan, CA) totaling 193 kg N ha^{-1}. See Table 1 for application rates and dates.

The synthetic fertilizer (FER) was split-applied during the first growing season, receiving 124 kg N ha^{-1} of urea (urea, 46-0-0, Potash Corporation, Saskatchewan, CA) on 12 September 2013. The second application of FER of 100 kg N ha^{-1} (Pro-Mate 25-5-11, Helena Chemical, Collierville, TN) was surface-applied with a Gandy drop spreader (Gandy, Owatonna, MN) on 30 October 2013. See Table 1 for application rates and dates.

Triple superphosphate (0-46-0) and muriate of potash (0-0-60) were applied to the synthetic fertilizer treatment plots and to the biosolids treatment plots, as needed, based on the pre-treatment soil test results. Dolomitic 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.

Irrigation was withheld from all reps of the non-irrigated main plot starting 31 May 2014. Persistent, crop-threatening drought conditions necessitated irrigation of all main plot irrigation treatments to 80% of ET starting 5 July 2014 and continuing throughout the remainder of the growing season. It was our intention to impose split irrigation in 2015, however rainy conditions minimized water stress and differences between main plot treatments. Therefore, irrigation was applied at 80% of ET for the remainder of the study period.

Table 2.1. Application schedule for each fertility treatment during the trial period.†

	Sept. 2013‡	**Oct. 2013§**	**Aug. 2014**	**April 2015**	**June 2015¶**
			kg ha^{-1}		
Synthetic (FER)	270 (Urea#)	400 (Pro-Mate††)	162 (Urea)	162 (Urea)	162 (Urea)
Dewatered biosolids (DBN)	8,320	-	2,770	2,770	2,770
Biosolids-sand-sawdust N rate (BBN)	71,300	-	23,800	23,800	23,800
Biosolids-sand-sawdust P rate (BBP)	10,200 (BBP) + 210 (Urea)	210 (Urea)	10,200 (BBP) + 140 (Urea)	140 (Urea)	140 (Urea)
Composted biosolids (CBN)	42,600	-	14,200	14,200	14,200

† Application schedule is based on original soil test and biosolids composition analyses so that all treatments supply 224 kg PAN ha^{-1} yr^{-1}. Actual loading rates of biosolids were based on annual biosolids analyses.

‡ All treatments were incorporated to a depth of 10 cm in September 2013.

§ All treatments from October 2013 and forward were surface applied.

¶ No amendments were applied from June 2015 to June 2016.

Sulfur coated urea, 46-0-0, Potash Corporation, Saskatchewan, CA.

†† Pro-Mate 25-5-11, Helena Chemical, Collierville, TN.

2.3.5. Soil and Plant Establishment Management

Following tillage to incorporate the fertility amendments in September 2013, the area was seeded 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 used to lightly depress the seeded subplots to ensure adequate seed to soil contact for establishment. Daily irrigation cycles to promote seed germination over the entire research area commenced on 13 September 2014.

2.3.6. Irrigation Installation and Application

The irrigation system was designed to irrigate eight, equal main plots measuring 20.7 m × 3.7 m. Each main plot was designated (pre-establishment) as without irrigation or 80% ET irrigation replacement. Each valve was individually wired to an irrigation controller (Toro Model TMC-212, Minneapolis, MN) to allow for individual main plot operation. 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 were 570Z MPRs with matching MPR Plus nozzles (brown-3.7 m) (Toro Company, Bloomington, MN).

An audit of each irrigation main plot was performed using the catch cup method (IA, 2009). Each of the eight main plots were operated for 10 minutes and precipitation was collected. The audit indicated that the irrigation system had a distribution uniformity of 98% efficiency and precipitation rate was estimated at 3.8 cm hr^{-1}. Distribution uniformity is a measure of how evenly irrigation is applied to a given area.

Evapotranspiration was estimated using two modified ceramic atmometers from the ETgage Company (Loveland, CO) and installed approximately 40 m apart on two sides of the trial. The atmometers were mounted to a wooden post at a height of 1 m aboveground following manufacturer recommendations. They 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 ET readings. Every three days throughout the growing season, water loss from the atmometers were manually assessed and irrigation was calculated to replenish the water loss to 80% of ET to designated main plots (Boyd, 2016).

2.3.7. Sampling and Analysis

2.3.7.1. Turfgrass Clipping Yield

Turfgrass clipping yield was collected every other week throughout the growing season by mowing a single pass down the center of each plot. During weeks (April 2014 to October 2015) when yields were not collected, clippings were bagged and removed to ensure equal treatment across the trial. Beginning April 2016, all plots were mulched, and clippings left in place except for every other week mower swath. 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. Clippings were collected using a Honda HRX217VKA gasoline powered walk behind rotary mower (America Honda Power Equipment Division, Alpharetta, GA). 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.

2.3.7.2. Nitrogen Accumulation in Leaf Tissue

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). Processed clippings were subjected to a high heat combustion chamber at 1200°C for the determination of tall fescue leaf total N concentration. Clipping N accumulation was calculated as the product of biomass and N concentration.

2.3.7.3. Turfgrass Quality

A quick test to determine the quality of a turfgrass stand is by a visual quality rating assessment. The turfgrass visual assessment is determined by visually integrating the turfgrass color, density, uniformity, and leaf texture (Morris, 2000). Quality ratings were assigned by visual assessment on a scale of one to nine, where nine indicates an ideal turfgrass stand, six is the minimum acceptable quality, and one indicates the turfgrass is dormant or dead. Each plot was rated every other week from spring to fall.

2.3.7.4. Normalized Difference Vegetation Index

Normalized Difference Vegetation Index (NDVI) spectral analysis, calculated as [near infrared (NIR) – Red)] / [NIR + Red] of each plot turfgrass canopy was taken every other week throughout the growing season (Bremer et al., 2011). A handheld multispectral radiometer (Holland Scientific, Model ACS-430 Crop Circle) was mounted to a Bag Boy Quad Plus push cart (Bag Boy Company, Richmond, VA) to measure NDVI. The sensor simultaneously measures crop and soil reflectance at 670 nm (red), 730 nm (far-red), and 780 nm (near-infrared, NIR). Red reflectance is most affected by chlorophyll absorption, whereas NIR reflectance is mostly affected by the light scattering from various leaf cell structures such as the nuclei, protoplasts, stomata, and cell walls (Gausman, 1977). The device was mounted at a stationary height of 46 cm above the turf canopy. Radiometer measurements commenced at the edge of each plot and took an average of 100 readings per 3.7 m of linear travel through the center of each plot.

2.3.7.5. Soil Chemical and Physical Measurements

Following turfgrass establishment, six soil samples from each experimental unit were collected and combined using a 2-cm diameter probe to a depth of 10 cm in fall 2014 and 2015. Soil samples from September 2015 were analyzed for pH and MI extractable P, K, Ca, Mg, zinc (Zn), and manganese (Mn) by the Virginia Tech Soil Testing Laboratory. At the conclusion of the study period (1 June 2016), soil was sampled to a depth of 30 cm, which was subdivided into depths of 0 to 10, 10 to 20, and 20 to 30 cm.

Total soil carbon and nitrogen concentrations were analyzed using a Vario Max CNS macro elementar analyzer (Elementar Analysensysteme, Hanau, Germany), which employs a combustion chamber at 1200°C. Soil ammonium and nitrate concentrations in 3 g soil samples were extracted in 30 mL of 2 M potassium chloride (KCl). The solution was shaken mechanically for 30 minutes and then filtered through 0.45-micron filter paper. The filtrate was run through a Lachat QuikChem 8500 Series 2 Flow Injection Analyzer (Hach, Loveland, CO). QuikChem Method 12-107-06-2-A (Hofer, 2003) was used to determine ammonia concentration at absorbance 660 nm by heating with salicylate and hypochlorite in an alkaline phosphate buffer. QuikChem Method 12-107-04-1-B (Knepel, 2003) was used to analyze soil nitrate + nitrite absorbance at 520 nm by reducing nitrate to nitrite via a copperized cadmium reduction column.

Bulk density was determined using method 3B6a by Soil Survey Staff (2009). Each core was collected to a depth of 5 cm and dried in an oven at 110ºC until weight was constant. Two samples per subplot was taken on 31 May 2016.

2.3.7.6. Statistical Analysis

Data were statistically analyzed using JMP Pro software by SAS version 12.1 (Cary, NC). Non-normal data were transformed using a Box-Cox transformation. Main factors (with and without irrigation), interactions between the sub-factors (amendment types), and the blocking factor were analyzed using a mixed model to determine significance of differences ($P < 0.05$). Repeated measurements were subjected to a first-order auto-regressive, which estimated the correlation between two measurements that are one unit of time apart. Sampling dates were compared within, but not among years. Means were separated using a standard least squares model and using a Tukey's post hoc test.

2.4. Results and Discussion

2.4.1. EQ Biosolids Chemical Composition

Organic N was the largest N fraction for all biosolids products (Table 2.2). The dewatered biosolids (DBN) had the largest fractions of organic and total N (35 and 56 g kg^{-1}, respectively). The additions of sand and sawdust to the BBN and BBP and woody fines to the CBN diluted N concentrations in those products (Table 2.2). The dewatered biosolids (DBN) and CBN had nearly the same total C at 362 and 365 g kg^{-1}, respectively. The sand and sawdust biosolids blends (BBN + BBP) had the lowest C fraction at 119 g kg^{-1}. Phosphorus concentrations were highest in DBN as the product was not diluted by mineral or organic supplements (Table 2.2). The less than 2:1 N:P ratio in the biosolids products, if consistently applied at the agronomic N rate of turfgrass, will result in over-application of P (Table 2.2). Potassium in all products were negligible, i.e., ≤ 5 g kg^{-1}. The low potassium content of biosolids often requires supplemental K fertilization, whose costs can reduce the value of the products. Even the CBN that was amended with wood chips had relatively low K for turfgrass needs.

Table 2.2. Chemical composition† of the biosolids products used in this study.

Treatment	Total Solids	TKN‡	NH_4-N	NO_3-N	Org.-N	C	C:N	P	K
	g kg^{-1}								
DBN§	265	56	20	0.005	35	362	7	40	1
BBN/BBP¶	596	8.2	2.9	0.007	5.2	119	15	6.2	0.6
CBN#	712	27	1.8	<0.001	25	364	13	15	5

† All analysis was performed by A&L Eastern Labs, Richmond, VA.

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

§ Anaerobically digested biosolids. (Alexandria, VA)

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

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

2.4.2. Weather

During the trial period (Aug 2013 – Jun 2016), the research site experienced monthly average temperatures similar to the 30-year means (Figure 2.1). Temperatures were below normal winter means and above spring means. Precipitation was variable, but the 3-year means were similar to the 30-year average (Figure 2.2). In the summer of 2015, above average precipitation limited the ability to impose a drought cycle on the tall fescue.

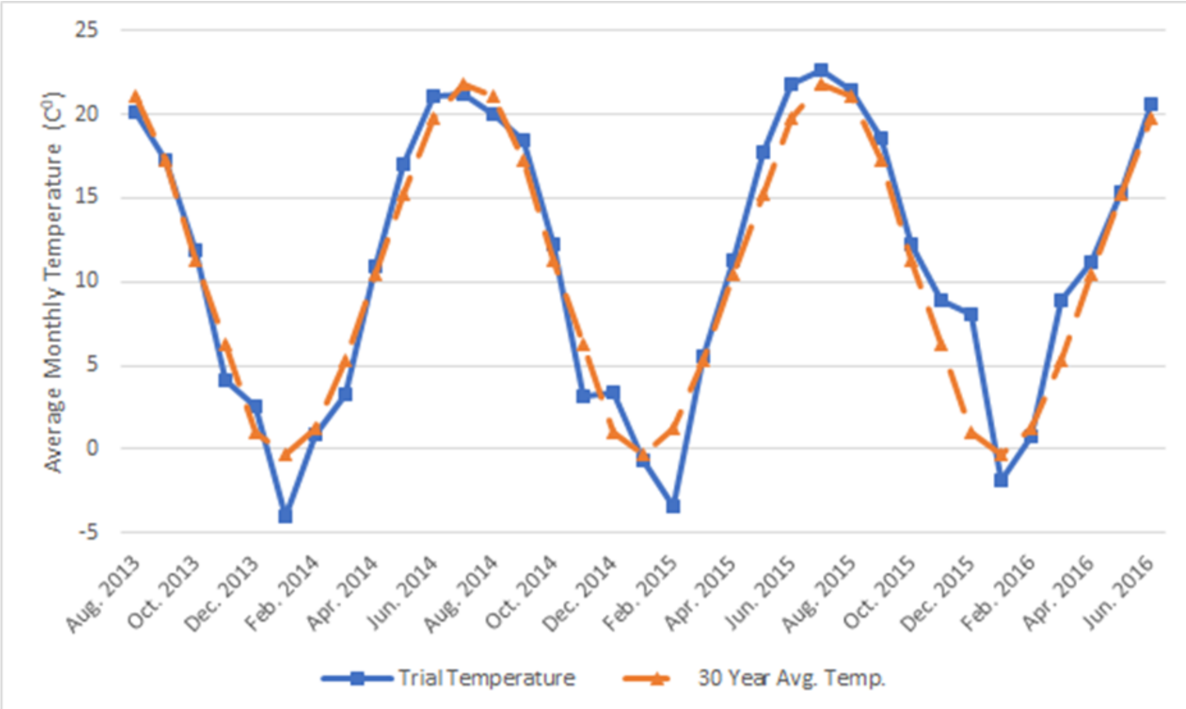

Figure 2.1. Air temperatures at the trial location (August 2013 to June 2016) vs the 30-year mean (1984-2014) for Blacksburg, VA.

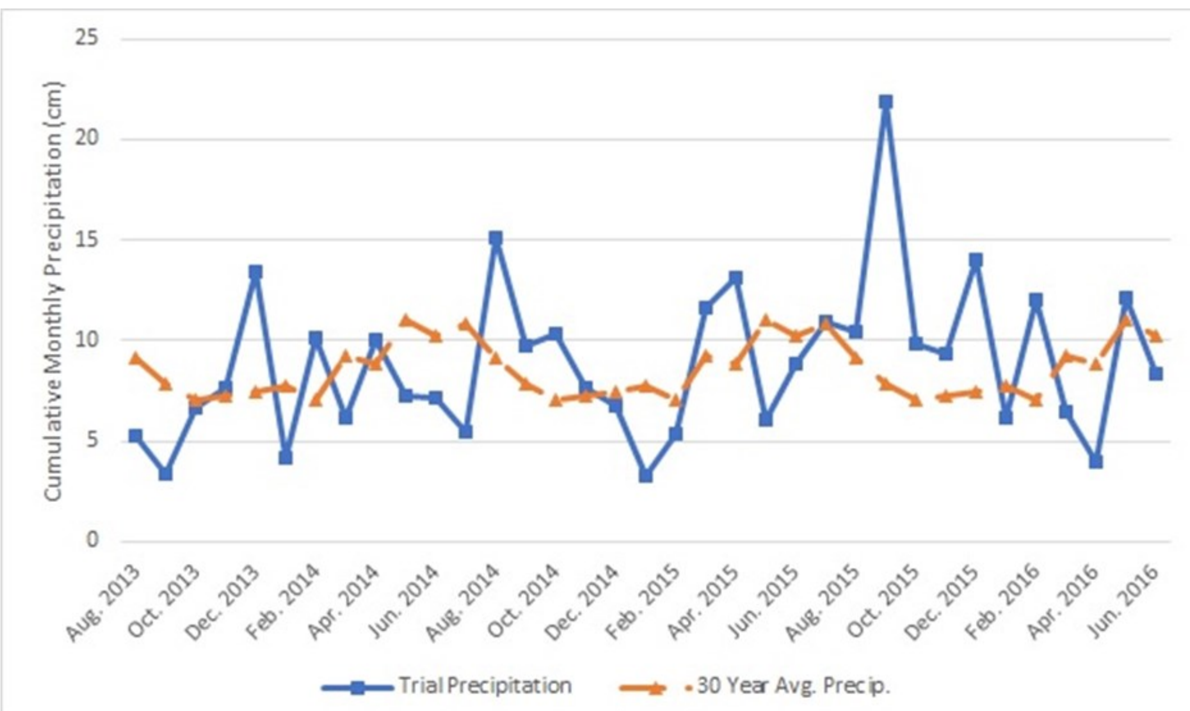

Figure 2.2. Cumulative monthly precipitation at the trial location (August 2013 to June 2016) vs the 30-year mean (1984-2014) for Blacksburg, VA.

2.4.3. Overall Study Statistical Trends

The study exhibited no irrigation x amendment interaction. We expected that the varying amounts of soil organic carbon would have impacted plant-available water, especially during the summer months. Beneficial effects of soil organic carbon on turfgrass quality and persistence did not occur due to the short duration of the drought cycle imposed throughout the trial (5 weeks in 2014). We decided to statistically analyze the results as an 8 replication RCBD design due to the lack of interaction between irrigation and amendment treatments on any variable. A full factorial of treatment, block, and date (when applicable for measurements over time) were analyzed for significance ($P < 0.05$). Means were separated using a standard least squares model and using a Tukey's post hoc test.

2.4.4. Soil Responses

<u>2.4.4.1 Soil Benchmark Data</u>

Routine soil test analysis of the original soil indicated that it had a pH of 5.1, 11 mg MI-P kg^{-1}, 61 mg MI-K kg^{-1}, 504 mg MI-Ca kg^{-1}, 218 mg MI-Mg kg^{-1}, and 3.0 g soil organic matter kg^{-1}. Particle size analysis determined the soil was in the textural class of clay (398 g sand kg^{-1}, 200 g silt kg^{-1}, 403 g clay kg^{-1}).

<u>2.4.4.2. Soil Fertility Variables</u>

Concentrations of Mehlich I P, Ca, Mg, Zn, and Mn in soil sampled in September 2015 were greater for the CBN and BBN than for the other soil amendments ($P < 0.05$) (Table 2.3). Mehlich I P concentrations in all biosolids treatments were adequate for tall fescue growth while never exceeding environmentally concerning P concentrations. Based on P management strategies in Virginia, the Virginia Department of Conservation and Recreation allows organic nutrient sources to be applied at N-based biosolids rates when soil MI-P concentrations are less than 55 mg kg^{-1}. Additionally, organic nutrient sources must be applied at P removal rates when soil MI-P concentrations are 55 to 162 mg kg^{-1} in the Ridge and Valley physiographic province of Virginia (VA DCR, 2014). The CBN and BBN treatments surpassed 55 mg MI-P kg^{-1}, which would recommend biosolids to be applied at the P removal rate of tall fescue clippings in a growing season (Table 2.3). Applying at the agronomic P rate for the BBP treatment resulted in a soil MI-P concentration of 12 mg kg^{-1} in 2015. This value is rated as medium availability by the Virginia Tech Soil Testing Laboratory. Implementing this P management strategy, while protective of water quality, resulted in reduced turfgrass quality. Higher rates could likely be applied in the short term to improve turfgrass growth and quality without increasing water impairment risk.

Table 2.3. September 2015 routine soil test analysis of pH and Mehlich I (MI) extractable P, K, Ca, Mg, Zn, and Mn†.

Treatment	pH‡	P	K	Ca	Mg	Zn	Mn
		mg kg^{-1}					
FER§	5.8b	9.4c	73a	752d	351c	0.7c	9.3d
DBN	6.0b	29b	47b	900c	396ab	2b	15bc
BBN	6.3ab	67a	61ab	1140b	421a	6a	19ab
BBP	5.9b	12c	65a	808cd	374bc	1c	12cd
CBN	6.7a	90a	77a	1420a	407ab	5a	24a

† All analysis was performed by the Virginia Tech Soil Testing Laboratory.

‡ Abbreviations: Mehlich I Extractable Phosphorus (P), Mehlich I Extractable Potassium (K), Mehlich I Extractable Calcium (Ca), Mehlich I Extractable Magnesium (Mg), Mehlich I Extractable Zinc (Zn), and Mehlich I Extractable Manganese (Mn).

§ Abbreviations: (1) annually-applied synthetic N, P, K fertilizer (FER), (2) biosolids applied annually at agronomic N rate (DBN), (3) blended biosolids-sand-sawdust applied annually at agronomic N rate (BBN), (4) blended biosolids-sand-sawdust applied annually at agronomic P rate plus supplemental fertilizer N (BBP), and (5) composted biosolids applied annually at agronomic N rate (CBN).

2.4.4.3. Soil Chemical Variables

Soil total N and total organic C responded similarly to fertility treatments (Table 2.4). The value of CBN and BBN can be seen throughout the trial period as they had greater total soil N and organic C of all treatments in 2016. This was expected due to the higher application rates in terms of total mass from CBN and BBN compared to DBN and BBP. The mineralized and nitrified N (NH_4^+ and NO_3^-) tested at the end of the sampling season in 2015 and 2016 was greater in the biosolids-based amendments applied at the agronomic N rate than the readily soluble, short-lived FER treatment (Table 2.4). Soil sampling in 2016 to depths of 10 to 20 cm and 20 to 30 cm showed no vertical movement of C or N (data not shown).

Table 2.4. Biosolids-based amendments effects on total soil nitrogen (N), total soil organic carbon (OC) and 2M KCl extractable soil nitrate (NO_3^-) and ammonium (NH_4^+) to a depth of 10 cm.†

Treatment	2014	2015	2016
	Total soil N 0 – 10 cm		
	-----------------g N kg^{-1}----------------		
FER‡	0.92c	0.85c	0.81b
DBN	0.98bc	1.2b	0.96b
BBN	1.2ab	1.4b	1.2a
BBP	0.97bc	0.98c	0.89b
CBN	1.4a	1.9a	1.7a
	Total OC 0 – 10 cm		
	-----------------g C kg^{-1}----------------		
FER	8.8c	11d	9.6b
DBN	9.6bc	13c	10b
BBN	12ab	16b	14a
BBP	9.6bc	12cd	10b
CBN	13a	20a	18a
	Soil NO_3^- 0 – 10 cm		
	----------------mg kg^{-1}-----------------		
FER	-	2.3c	2.8d
DBN	-	7.6a	10ab
BBN	-	4.8b	9.9bc
BBP	-	3.1c	5.7cd
CBN	-	7.6a	18a
	Soil NH_4^+ 0 – 10 cm		

	----------------mg kg^{-1}----------------		
FER	-	6.5b	8.3b
DBN	-	11a	13a
BBN	-	12a	12ab
BBP	-	8.3b	9.9ab
CBN	-	12a	14a

† Means in the same column followed by the same lowercase letter are not significantly different at $P < 0.05$.

‡ Abbreviations: (1) annually-applied synthetic fertilizer N, P, K (FER), (2) biosolids applied annually at agronomic N rate (DBN), (3) blended biosolids-sand-sawdust applied annually at agronomic N rate (BBN), (4) blended biosolids-sand-sawdust applied annually at agronomic P rate plus supplemental fertilizer N (BBP), and (5) composted biosolids applied annually at agronomic N rate (CBN).

2.4.4.4. Soil Physical Parameters

Our results provide further evidence that organic C additions, such as biosolids, reduce soil bulk density (García-Orenes et al., 2005; Ouimet et al., 2015; Sloan et al., 2016). Soil bulk density of the FER and BBP treatments within the 0 to 5 cm depth were comparable at 1.13 g cm^{-3} and 1.10 g cm^{-3}, respectively. Soil bulk density was reduced to 1.03, 0.97, and 0.84 g cm^{-3} in response to the DBN, BBN, and CBN treatments, respectively. The larger rates of organic C supplied with N-based rates of biosolids contributed to the reduced bulk density compared to FER and BBP treatments. Such reduced bulk density in the upper 5 cm of the soil profile would be expected to promote improved rooting conditions and a denser turfgrass stand; thus, better turfgrass growth and quality with the highest C-amendment applications. Composts such as CBN require higher rates of application than other less stabilized biosolids to provide adequate plant available N due to reduced rates of mineralization in stabilized organic amendments. Landschoot and McNitt

(1994) found improvement in soil structure and water infiltration derived from composted biosolids application.

2.4.5. Plant Responses

2.4.5.1. Turfgrass Biomass and Leaf Nitrogen Accumulation

Fertility treatments significantly affected turfgrass biomass yield and leaf tissue N accumulation during all sampling periods (Fig. 2.3, Fig. 2.4, Table 2.5). During the 2014 establishment year, the greatest biomass yield and leaf tissue N accumulation occurred with FER (Table 2.5). This was most likely due to the readily available N provided in the urea. Lower than expected PAN from the biosolids-based products may have limited turfgrass establishment. This was indicated by the biosolids treatments having both lower turfgrass biomass and leaf tissue N accumulation in 2014. The poor N recovery from the biosolids-based treatments is likely attributed to slower N mineralization or inaccessibility of N for roots due to depth. Total soil N was lowest in FER but had the greatest leaf tissue N accumulation in 2014 (Table 2.4 and 2.5). This suggests that the applied N from the biosolids treatments took longer than expected to mineralize and remained in the soil organic pool.

Upon additional surface applications of treatment amendments in August 2014, higher biomass and leaf tissue N accumulation occurred in biosolids-based treatments applied at the agronomic N rate (DBN, BBN, and CBN) than in the synthetic fertilizer treatment throughout the remainder of the study (Table 2.5). The longer-term mineralization of the original incorporated biosolids in addition to surface applications in later years created a readily available pool of inorganic N to meet the tall fescue needs. This was seen in the 2M KCl soil extract data where inorganic N was greatest in biosolids-based amendments applied at the agronomic N rate in 2015 and 2016. This slow, constant release of inorganic N from the biosolids-based amendments applied at the agronomic N rate proved important for sufficient leaf tissue N accumulation during the residual year from June 2015 to June 2016 (Figure 2.4). This reserve allowed BBN, CBN, and DBN to maintain minimum acceptable quality throughout 2015 and 2016 (Table 2.5).

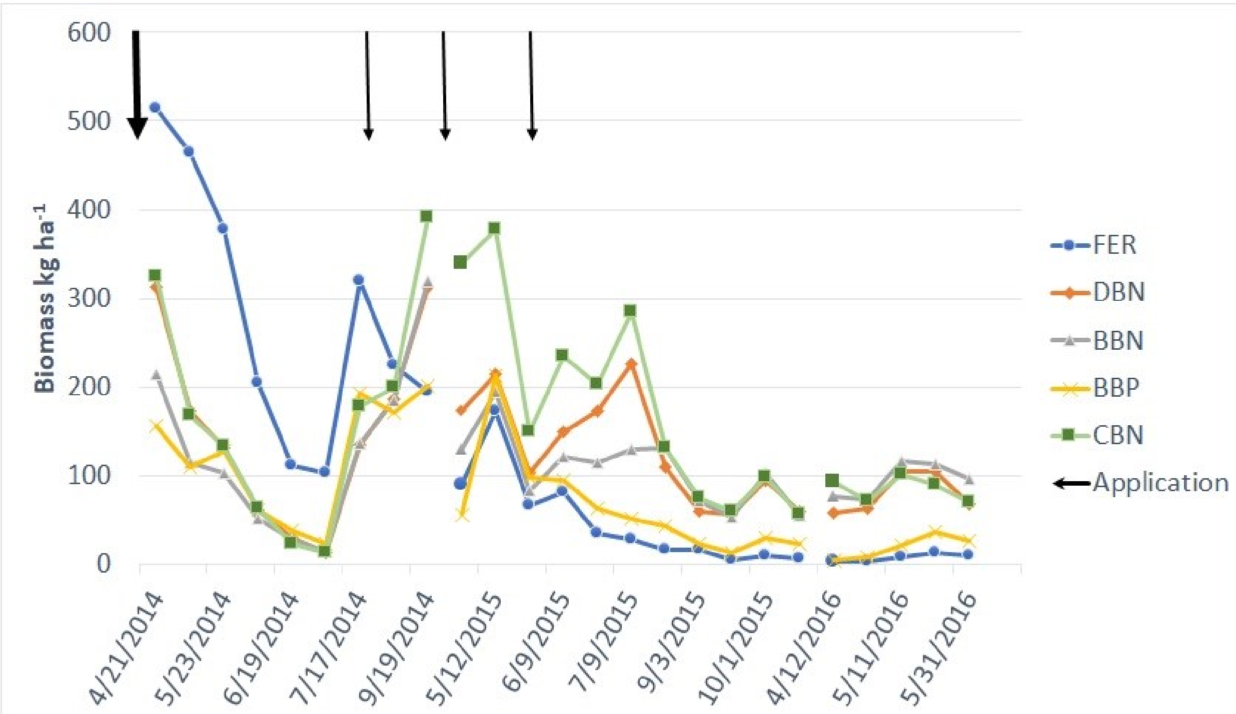

Figure 2.3. Biomass yield throughout trial period (April 2014 – May 2016) as influenced by fertility treatments. Black arrows indicate the application times and rates. The thick black arrow represents the full annual loading rate applied in fall 2013. The three thin black arrows indicate the three equally split surface applications of amendments in August 2014, April 2015, and June 2015. Fertility treatments were (1) annually-applied synthetic fertilizer N, P, K (FER), (2) biosolids applied annually at agronomic N rate (DBN), (3) blended biosolids-sand-sawdust applied annually at agronomic N rate (BBN), (4) blended biosolids-sand-sawdust applied annually at agronomic P rate plus supplemental fertilizer N (BBP), and (5) composted biosolids applied annually at agronomic N rate (CBN). Total number of dates were n = 25.

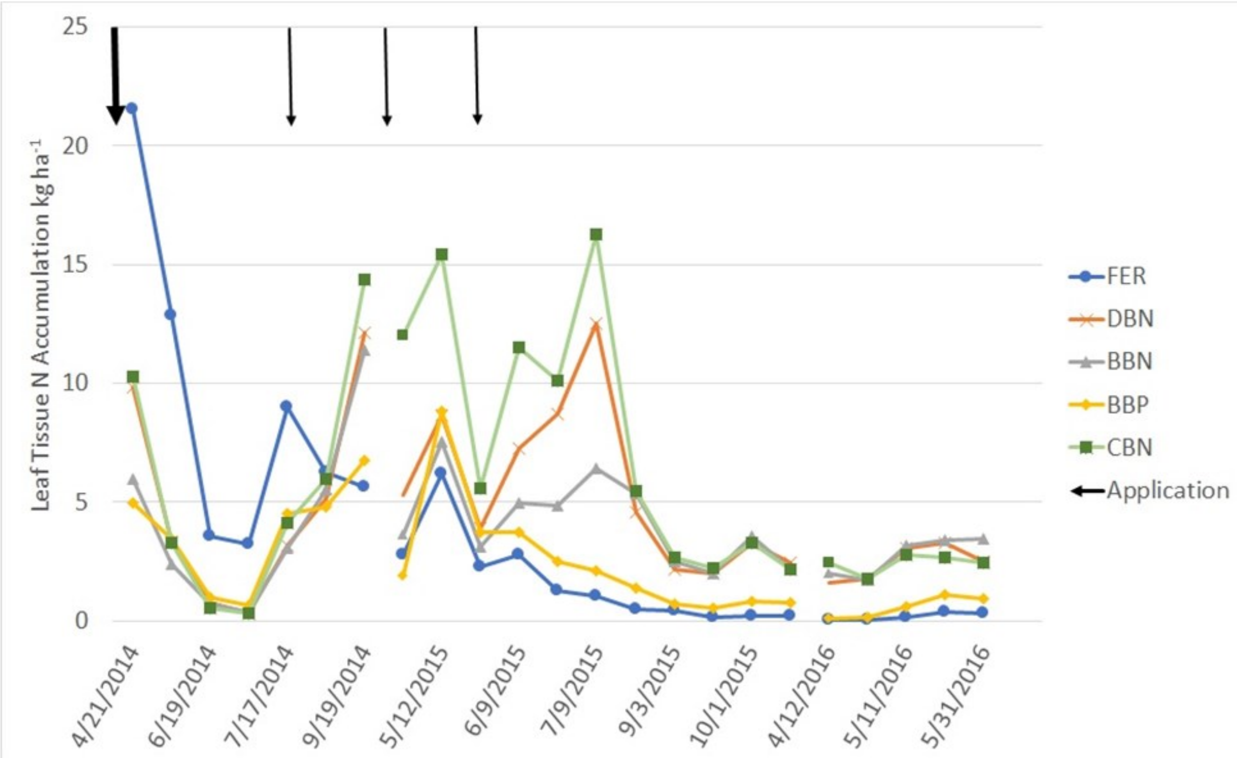

Figure 2.4. Tall fescue leaf N accumulation throughout trial period (April 2014 – May 2016) as influenced by fertility treatments. Black arrows indicate application times and rates. The thick black arrow represents the full annual loading rate applied in fall 2013. The three thin black arrows indicate the three equally split applications of amendments in August 2014, April 2015, and June 2015. Fertility treatments were (1) annually-applied synthetic fertilizer N, P, K (FER), (2) biosolids applied annually at agronomic N rate (DBN), (3) blended biosolids-sand-sawdust applied annually at agronomic N rate (BBN), (4) blended biosolids-sand-sawdust applied annually at agronomic P rate plus supplemental fertilizer N (BBP), and (5) composted biosolids applied annually at agronomic N rate (CBN). Total number of dates were n = 23.

Table 2.5. Biosolids-based amendments effect on turfgrass biomass, leaf tissue nitrogen accumulation, normalized difference vegetation index (NDVI), and visual quality of tall fescue. Means reported are the average among the sampling dates for each year. Sampling was conducted between April – October for 2014 and 2015 and April – May for 2016.[†]

Treatment	2014	2015	2016
		Biomass	
		----------------------kg ha^{-1}----------------------	
FER[‡]	279a	48.4c	7.70c
DBN	151bc	129ab	79.6a
BBN	130c	108b	95.6a
BBP	121c	64.8c	19.7b
CBN	166b	183a	85.4a
		N Accumulation	
		---------------------kg N ha^{-1}---------------------	
FER	8.9a	1.6d	0.19c
DBN	5.0b	5.5ab	2.5a
BBN	4.2b	4.2b	2.8a
BBP	3.7b	2.5c	0.57b
CBN	5.6b	7.9a	2.4a
		NDVI[§]	
FER	0.79a	0.64c	0.54c
DBN	0.74b	0.78a	0.73a
BBN	0.73b	0.79a	0.73a
BBP	0.75b	0.72b	0.69b
CBN	0.75b	0.79a	0.71ab
		Quality[¶]	
FER	7.0a	5.5b	4.0d
DBN	6.2b	6.7a	6.1b
BBN	5.7bc	6.7a	6.5a
BBP	5.5c	6.0b	4.8c
CBN	6.1b	7.2a	6.6a

† Means in the same column followed by the same lowercase letter are not significantly different at $P < 0.05$.

‡ Abbreviations: (1) annually-applied synthetic N, P, K fertilizer (FER), (2) biosolids applied annually at agronomic N rate (DBN), (3) blended biosolids-sand-sawdust applied annually at agronomic N rate (BBN), (4) blended biosolids-sand-sawdust applied annually at agronomic P rate plus supplemental fertilizer N (BBP), and (5) composted biosolids applied annually at agronomic N rate (CBN).

§ No vegetation = 0; highest possible density of green leaves = 1.

¶ Visual quality ratings are rated on a scale of 1 to 9, where 9 indicates an ideal turfgrass stand, 6 is the minimum acceptable quality, and 1 indicates the turfgrass is dormant or dead.

The novel biosolids-sand-sawdust product applied at the agronomic P rate supplemented with synthetic N (BBP) resulted in poor turfgrass quality throughout the study (Figure 2.5). The goal of the sand and sawdust was to improve the ease of application and spreading, while also reducing the moisture content and stabilize the N. However, BBP resulted in lower total soil N across all time periods measured compared to biosolids-based amendments applied at the agronomic N rate (Table 2.4). The lower leaf tissue N accumulation by BBP than FER in 2014 provided supporting evidence of lower PAN (Table 2.5). This is an interesting finding since the supplemental synthetic N applied with the BBP did not provide sufficient available N as did the FER during the tall fescue establishment. This most likely resulted from N immobilization/lower N mineralization than expected due to the presence of incompletely stable sawdust C (despite the relatively low C:N ratio of 15:1). It is possible that reducing the amount of sawdust in this product would have led to a more desirable release of the synthetic fertilizer. Optimization of this organo-mineral fertilizer approach is important. It has the potential to be a highly-desired strategy for P mitigation, while receiving the immediate N benefits from the urea and the slow-release N of the biosolids. Turfgrass establishment has been improved using a fertilizer and biosolids compost combination (Sikora et al., 1980; Garling and Boehm, 2001; Loschinkohl and Boehm, 2001). However, two of these studies used biosolids as a supplement to inorganic fertilizer (Sikora et al., 1980; Garling and Boehm, 2001).

2.4.5.2. Turfgrass Quality and NDVI

Turfgrass quality and NDVI appeared to be associated with N fertility. The fertility treatments yielded similar trends in turfgrass quality and NDVI as observed in tissue N accumulation (Figure 2.5, Table 2.4). Turfgrass quality was sustained above the minimum acceptable value of 6 for the FER treatment only during 2014. Beginning in 2015, biosolids-based amendments applied at the agronomic N rate had higher quality ratings to begin the growing season. The quality of turfgrass grown in plots amended with biosolids applied at the agronomic N rate maintained minimum acceptable quality from July 2014 through the remainder of the trial period. The one exception was the first sampling day of 2016 (April 12) which was a result of the turfgrass beginning to break winter dormancy (Figure 2.5).

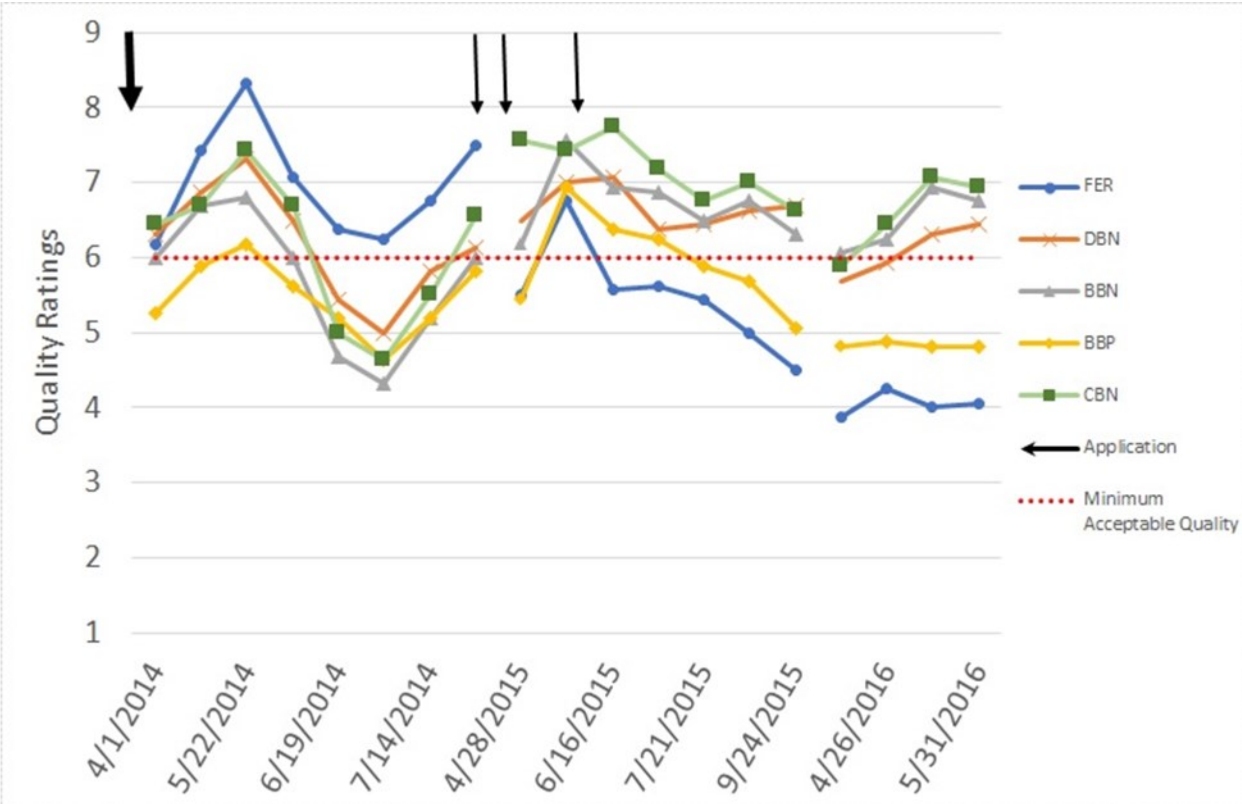

Figure 2.5. Turfgrass quality ratings throughout trial period (April 2014 – May 2016) as influenced by fertility treatments. Data are for mean turfgrass quality ratings by sampling date. The dotted red line represents the value for minimum acceptable quality rating. Black arrows indicate application times and rates. The thick black arrow represents the full annual loading rate applied in fall 2013. The three thin black arrows indicate the three equally split applications of amendments in August 2014, April 2015, and June 2015. Fertility treatments are (1) annually-applied synthetic fertilizer N, P, K (FER), (2) biosolids applied annually at agronomic N rate (DBN), (3) blended biosolids-sand-sawdust applied annually at agronomic N rate (BBN), (4) blended biosolids-sand-sawdust applied annually at agronomic P rate plus supplemental fertilizer N (BBP), and (5) composted biosolids applied annually at agronomic N rate (CBN). Total number of dates were n = 19.

Both visual quality ratings and spectral NDVI values had similar rankings across time as both measurements are closely aligned with leaf tissue N accumulation (Table 2.5). This matches the reports of other studies that have found strong correlations between NDVI and visual quality in turfgrasses (Trenholm et al., 1999; Bell et al., 2002; Jiang and Carrow, 2007; Lee et al., 2011). Quality of turfgrass, as measured by qualitative and quantitative measurements, suggest that PAN was likely a main limiting factor. Higher visual quality of turfgrass was associated with greater size of the inorganic N pool (Table 2.4). Since the estimated N rate and soil type were constant, we suspect that differences in turfgrass responses were due to variable N transformations of amendments such as mineralization rates, denitrification, and leaching. In 2014, turfgrass responded positively to FER due to the rapid availability of N, whereas the addition of biosolids-borne soil organic N in 2014 and 2015 created a reserve of slow-release PAN. The NDVI of the turfgrass receiving the synthetic fertilizer decreased from the highest among all treatments in 2014 to the lowest in 2015 and 2016 (Table 2.5).

2.4.5.3. Nitrogen Availability

The poor N recovery by tall fescue in biosolids-based treatments during 2014 was a clear indication that the biosolids did not mineralize as quickly as we anticipated (Table 2.5). This may have resulted due to soil environmental factors. Our PAN estimates were based on data from a greenhouse bioassay study using coarse-textured soil media (Alvarez et al., 2018). It is possible that in our soil system, the low C-containing clayey soil provided increased adsorption sites for organic C resulting in stabilized mineral associated organic matter. Causarano et al. (2008) found that increasing soil clay content lowered organic C decomposition rates. Additionally, the mineralization and humification of biosolids has been demonstrated to be strongly influenced by soil type (Garau et al., 1986; Strong et al., 1999; Corrêa et al., 2012). Garau et al. (1986) and Strong et al. (1999) considered soil type one of the most important and fundamental factors determining N mineralization. Matus and Maire (2000) found that mineralization rates were more related to the degree of C saturation in clay and silt particles. Adsorption of dissolved organic C is dependent on the available sites of the mineral surfaces (Matus and Maire, 2000). Such stabilized mineral associated organic matter could reduce accessibility to microbes and reduce mineralization rates. This may explain why despite CBN having the highest total soil N in 2014, the N may have been bound in the soil organic C pool (Table 2.4).

Carbon saturation theory is an explanation of the maximum C storage potential determined by the physicochemical properties of the soil (Six et al., 2002). As noted by Six et al. (2002), the protection of SOM is correlated to increased silt and clay content and the current C content of the soil. They suggest that new C inputs can be stabilized as mineral associated organic matter, but the soil matrix decreases in capacity to stabilize new organic matter inputs. The new C inputs that are not stabilized by these associations are susceptible to mineralization. This could help explain why the surface applications of biosolids in 2014 and 2015 had a more rapid effect on leaf tissue N accumulation (Figure 2.4). The original incorporation of biosolids materials had more access to adsorption sites in the soil and decreased the overall adsorption sites. Each subsequent surface application of biosolids increased the accessibility of C and N for microbial mineralization. Adjustments of in-field estimated mineralization rates for first-year applications of biosolids-based amendments should be made to account for reduced mineralization of mineral associated organic matter in fine-textured soils.

2.5. Conclusions

We hypothesized that the biosolids-based amendments would be able to provide the necessary plant essential nutrients and soil quality-restoring organic matter for establishing and maintaining turfgrass in a degraded, urban soil. Our results confirmed our hypothesis that the biosolids-based products applied at the agronomic N rate provided a better long-term solution than synthetic fertilizer for the maintenance of tall fescue. This was a result of the reduced bulk density and greater N availability, as indicated by leaf tissue N accumulation, and the increased macro- and micro- nutrient concentrations delivered by that the biosolids-based products. Reducing the initial lag time of biosolids N plant-availability observed early in 2014 should be prioritized. Our study demonstrated that the use of sand-sawdust as a bulking agent mixed with biosolids compares well with the industry standard, biosolids compost. All biosolids amendments applied at the agronomic N rate outperformed the use of synthetic fertilizer in producing an acceptable quality turfgrass stand in the long-term. The BBN and CBN resulted in greater total organic C and N in comparison to the non-blended DBN product by the end of the study. This may be attributed to the addition of high C:N materials such as sawdust in BBN and wood chips in CBN. Applying biosolids at the agronomic P rate did not yield desirable turfgrass quality. However, to reduce potential P loss, determining a rate between the agronomic P and N rate to produce a quality turfgrass stand and improve soil characteristics is desirable. Rainy conditions minimized water stress implementation. Continued research on the interaction between with and without irrigation and fertility treatment is needed to determine biosolids-based amendments impact on plant available water and turfgrass persistence during periods of drought.

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2.7. Conflict of Interest

The authors explicitly state that there are no conflicts of interest in the research conducted.

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3. Anthropogenically disturbed urban-turfgrass system improved with biosolids-based amendments

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Abbreviations: BBN, blended biosolids–sand–sawdust applied annually at an agronomic nitrogen rate; BBP, blended biosolids–sand–sawdust applied annually at an agronomic phosphorus rate plus supplemental fertilizer nitrogen; CBN, composted biosolids applied annually at an agronomic nitrogen rate; DBN, dewatered biosolids applied annually at an agronomic nitrogen rate; EQ, exceptional quality; ET, evapotranspiration; FER, synthetic fertilizer; PAN, plant available nitrogen; PSR, phosphorus saturation ratio.

3.1. Abstract

Rehabilitating anthropogenically disturbed soils is vital to restore soil functionality and improve plant growth. Biosolids can be used to improve such soils and increase soil carbon (C) stocks, but repeated applications of such organic byproducts may result in the overapplication of phosphorus (P). A five-year study (Sep 2013-Oct 2018) was conducted on an anthropogenic soil-tall fescue (*Festuca arundinacea* Schreb.) system to compare the effects of irrigation strategies (with and without irrigation during summer heat stress) and soil amendments (annual applications of biosolids products and a conventional synthetic fertilizer) for improving soil properties for tall fescue health and sustainability. Analysis of turfgrass parameters (i.e., tall fescue visual quality, clipping biomass, and leaf tissue N accumulation) on sampled dates during summer heat stress lacked irrigation × fertility amendment interaction ($P < 0.05$) and differences among non-irrigated fertility treatments with exception for 26 July 2017 tall fescue visual quality and 26 July 2016 leaf tissue N accumulation. For those two dates, the non-irrigated biosolids applied at the agronomic N rate had greater visual quality and leaf tissue N accumulation than non-irrigated, synthetic fertilizer. The repeated applications of biosolids-based amendments reduced soil bulk density and increase soil OC and N stocks. Repeated applications of biosolids containing high Fe concentrations (56 and 88 g Fe kg^{-1} of biosolids) applied at the agronomic N rate did not increase water-soluble P compared to biosolids applied at the agronomic P rate and synthetic fertilizer after five years. Biosolids applied at higher total solids loading rates increased soil N stocks that acted as a slow-release fertilizer and resulted in higher quality turfgrass than with synthetic fertilizer.

3.2. Introduction

The urban area of the conterminous United States is approximately 3% and expanding, resulting in extensive land-use and vegetative change from the formerly surrounding forestland, rangeland, or agricultural land (Imhoff, 1997). Anthropogenic development often results in mechanical topsoil removal, exposing a compacted subsoil or requires off-site fill as the new soil surface (Lorenz and Lal, 2009). Turfgrass is the most common landscape choice post-development, occupying an estimated 1.9% of the continental United States surface area (Beard, 1973; Milesi et al., 2005). The establishment of turfgrass can be difficult on anthropogenically disturbed soils due to low- soil OC and nutrient content and soil compaction impeding root development (Harris, 1991; Beniston and Lal, 2012). Perennial plant cover (e.g., turfgrass), organic amendments, fertilization, and irrigation, are restoration practices that can alleviate low soil OC and nutrient content (e.g., N and P), and reduce soil compaction (Post and Kwon, 2000; Lal, 2004; Post et al., 2004; Milesi et al., 2005).

Urban-turfgrass soil systems have gained interest for their potential to store soil C. Determining turfgrass' influence and management practices (e.g. irrigation and fertilization) that influence C storage rates has been the goal of recent research (Pouyat et al., 2002, 2006, Milesi et al., 2005; Zirkle et al. 2011). Pouyat et al. (2006) determined after a multi-city analysis of the United States that urban soils have the potential to store large quantities of OC, especially in residential areas due to minimal soil disturbance, fertilization, and irrigation. Golubiewski (2006) found that urban-turfgrass systems store more C, nearly double in some cases, than local native grasslands or agricultural fields on a per-area basis. The increased soil OC has been documented for offsetting greenhouse gas emissions (Golubiewski 2006; Townsend-Small and Czimczik 2010; Law and Patton, 2017).

Achieving the highest C-storage potential of turfgrass systems requires the input of irrigation and fertilization (Milesi et al. 2005; Selhourst and Lal 2013). Proper fertilization and irrigation increase turfgrass shoot and root growth and root exudates. The increased C biomass from turfgrass, especially root-derived C, increases the rate of soil OC storage due to interactions with the mineral fraction (Dignac et al., 2017). Improved plant growth results in higher quality turfgrass, improving the overall aesthetics, ecosystem functionality (e.g., decreased soil erosion, improved groundwater recharge and pollutant filtration), and stress tolerance (Beard and Green, 1994). Although additional inputs may be beneficial for urban-turfgrass systems to improve soil OC storage rates, information regarding appropriate fertilization and irrigation programs to determine the effects on N and P stocks are needed to minimize environmental effects associated with their potential nutrient losses and efficiently use water resources.

Nitrogen and P can be provided by synthetic and organic sources of fertilizer. Most fertilizer applied to turfgrass is synthetic and contains some variation of N, P, and potassium (K) (Soldat, 2008). Organic amendments, such as locally-produced biosolids, have received limited use for lawn fertilization. Wastewater treatment facilities have increasingly adopted the production of Exceptional Quality (EQ) Class A biosolids that have no application restrictions except for plant available N and P. Such biosolids are treated by processes to further reduce pathogens (PRFPs) and have reduced vector attraction and low pollutant concentrations (USEPA, 1994).

Biosolids normally have low N:P ratios (Cogger et al., 2006). Nitrogen is generally the most limiting nutrient for turfgrass growth and is used as the basis of fertility recommendations (Carrow et al., 2001). Successive applications of low N:P ratio fertilizer can result in the overapplication of P as plants require lower quantities of P than N. Concerns regarding P loss to surface waters has resulted in P-based regulations that limit the mass of organic amendments applied to soil to avoid excessive soil P buildup (Jesiek and Wolfe, 2005).

In maintained turfgrass systems, sediment loss is negligible, but runoff and leaching as a result of soluble P can vary based on fertilizer rate, source, and timing and soil type and P saturation (Soldat and Petrovic, 2008). One of the main determining factors of P loss is based on soil P saturation. The degree of P saturation is based on the maximum P sorption capacity of the soil. Methods used to define P saturation include the molar ratio of oxalate- or Mehlich3-extractable P: Fe + Al (Breeuwsma and Silva, 1992; Maguire and Sims, 2002; Lu et al., 2012). The upper few cm of soil in turfgrass systems should be sampled to obtain a representative soil P saturation to determine the risk of P surface runoff as fertilizer and organic amendments are surface applied (Soldat and Petrovic, 2007).

Some studies have demonstrated lower P loss risk with organic amendments than with conventional synthetic fertilizers (He et al., 2000; Maguire et al., 2001; Withers et al., 2001; Ajiboye et al., 2004; White et al., 2010). Biosolids treated with Al or Fe salts at wastewater facilities reduce concentrations of dissolved reactive P in runoff and leachate due to the formation of Fe-, Al-, and Ca-phosphates (Elliot et al., 2002, 2005; Penn and Sims, 2002). Land application of Fe- or Al- treated biosolids can increase the soil P storage capacity by providing additional sites for P adsorption or binding (Penn and Sims, 2002; Lu and O'Connor, 2001). Despite the reduction of P solubility in biosolids compared to other organic byproducts, regulations often do not discriminate between the use of organic amendments based on P solubility and environmental loss risk. It is critical to develop fertilization strategies that provide sufficient plant available N (PAN) while avoiding environmentally deleterious P for the rehabilitation of anthropogenic soils.

Tall fescue (*Festuca arundinacea* Schreb.) is the predominant choice for turfgrass and forage crop in the transition zone of the United States (Christians, 2004). Tall fescue has a deep root system and is considered a drought resistant cool season grass (Carrow, 1996). Tall fescue irrigation maintenance in the transition zone can require 2.5 to 4 cm of water per week during the summer (Turgeon et al., 1987). Water requirements is based on the evapotranspiration (ET), loss via transpiration and evaporation, of the turfgrass-soil system. Ervin and Koski (1997) determined that modified atmometers could be used to measure ET as a cheap on-site alternative to traditionally determined ET via the Kimberly-Penman equation that utilizes weather stations.

The addition of organic amendments and increasing OC has been suggested as a drought management strategy by increasing available water capacity and water retention (Rawls et al., 2003; Lal, 2004). Johnson et al. (2009) found that compost top-dressing had increased soil water content and improved Kentucky bluegrass (*Poa pratensis* L.) visual quality compared to the control during three 10-d dry down periods. A meta-analysis of 60 published studies and additional world databases conducted by Minasny and McBratney (2018) found that an increase of 1% OC by mass increased available water capacity by 1.16%, volumetrically. The increase of available water capacity is greatest in sandy soils and least in clays. Determining the effectiveness of organic amendments, such as biosolids-based amendments, on drought tolerance in urban-turfgrass systems is needed.

The goal of this study was to compare the change in soil chemical and physical properties and tall fescue quality grown on an anthropogenic soil rehabilitated with EQ biosolids products and synthetic fertilizer under varying irrigation regimes during summer stress. Our objectives were to compare two irrigation strategies and the use of a conventional synthetic fertilizer program to EQ biosolids products of varying C, N, and P concentrations (i) to enhance physical and chemical properties of an anthropogenically disturbed urban soil, (ii) determine the irrigation and fertility strategy that maximized C storage, (iii) to provide sufficient PAN without increasing soil P to excessive concentrations, and (iii) to improve tall fescue (*Festuca arundinacea* Schreb.) establishment, quality, and growth. Our hypothesis was that biosolids-based amendments would improve turfgrass quality, growth, drought resistance, and recovery of tall fescue compared to a conventional synthetic fertilizer program. The results reported here are longer term soil and turfgrass effects than first reported for turfgrass establishment for the period 2013-2016 (Badzmierowski et al., 2019).

3.3. Materials and Methods

3.3.1. Study Site Establishment

This study was conducted at the Virginia Tech Turfgrass Research Center in Blacksburg, VA (37°12'54.31"N, 80°24'42.14"W) and located in cold hardiness zone 6b (Daly et al., 2012). Detailed documentation of site description, field preparation, soil benchmark sampling and analysis, irrigation installation, application methods, and turfgrass establishment and management were previously reported by Badzmierowski et al. (2019).

3.3.2. Experimental Design

Experimental design was a split-plot arrangement of a randomized complete block design replicated four times. Main plots were two summer irrigation treatments, and subplots were five organic amendments, initially tilled into the soil, with subsequent applications surface applied. Irrigation treatments were (i) no water applied during critical summer months, unless necessary to keep turfgrass alive, and (ii) water applied every three days to replenish 80% of atmometer-estimated ET during high ET summer months. Split irrigation was performed in all years except 2015, when high rainfall supplied adequate plant-available soil moisture. Irrigation was withheld from all replications of the non-irrigated main plots starting 31 May 2014 to 5 July 2014, 12 July 2016 to 16 September 2016, 18 May 2017 to 26 July 2017, and 6 June 2018 to 12 July 2018. Persistent, crop-threatening drought conditions necessitated irrigation of all main plot irrigation treatments to 80% of ET at the end of each stress period. The dimensions of each main plot were 20.7 m × 3.7 m. Results for this manuscript will focus on drought stress in 2016 to 2018.

The five subplot treatments were synthetic fertilizer and four EQ biosolids products. Fertility amendments were applied annually (Sept. – Aug.) to provide an estimated plant available N (PAN) rate of 224 kg PAN ha^{-1} from September 2013 to June 2015 and resumed applications at an annual maintenance PAN rate of 171 kg ha^{-1} from June 2016 to the conclusion of the study in 2018. These application rates are consistent with recommended rates for the establishment and maintenance of tall fescue in the transition zone (Christians, 2004). The dimensions of each subplot were 3.66 m × 3.66 m, each of which was separated by a 0.61-m buffer strip.

3.3.3. Amendment Treatments, Biosolids Analysis, and Soil Fertility

Four EQ Class A anaerobically digested biosolids treatments were used in the study: (i) dewatered biosolids applied annually at rates to supply required plant available nitrogen (PAN) (DBN), (ii) dewatered biosolids blended with sand and sawdust annually applied at rates to supply required PAN (BBN), (iii) dewatered biosolids blended with sand and sawdust annually applied at rates to supply P recommended by Virginia Tech Soil Testing Laboratory plus supplemental S-coated urea fertilizer to provide equal annual PAN ha^{-1} (BBP), and (iv) biosolids compost annually applied at rates to supply required PAN (CBN). The fifth amendment treatment was synthetic fertilizer N (as S-coated urea) annually applied to supply required PAN (FER). Triple superphosphate (0–46–0 N–P–K) and muriate of potash (0–0–60 N–P–K) applications for 2016 to 2018 were adjusted for the synthetic fertilizer treatment plots and biosolids treatment plots, based on September 2015 soil test results (Badzmierowski et al., 2019). See Table 3.1 for application rates and dates.

Table 3.1. Application schedule for each fertility treatment on a wet weight basis during the trial period.†

Treatment	14 June 2016	22 Sept. 2016	29 Mar. 2017	20 Sept. 2017	18 Oct. 2017	3 Apr. 2018	Total Applied 2013 - 2018‡	Total C Applied	Total N Applied
			kg ha^{-1}						
Synthetic§ (FER)	159	159	53.0	159	159	53.0	1,500 (urea) 400 (Pro-mate)	0	788
Dewatered biosolids (DBN)	3,810¶	11,420¶	2,540	7,610	7,610	2,540	16,630 ARE 35,530 DC	15,791	2,175
Biosolids-sand-sawdust N rate (BBN)	12,600	12,600	4,220	12,600	12,600	4,220	142,700 ARE 58,840 DC	32,632	2,347
Biosolids-sand-sawdust P rate (BBP)	2,040 (BBP) + 146 (urea)	2,040 (BBP) + 146 (urea)	2,040 (BBP) + 122 (urea)	2,040 (BBP) + 146 (urea)	2,040 (BBP) + 146 (urea)	2,040 (BBP) + 122 (urea)	32,640 (BBP) + 1,668 (urea)	5,684	1,179
Composted biosolids (CBN)	8,350	8,350	2,790	8,350	8,350	2,790	124,180	45,981	3,469

† Application schedule shown is for June 2016 to April 2018 so that all treatments supply 171 kg plant available N ha^{-1} yr^{-1}. See Badzmierowski et al., 2019 for application schedule and loading rates for September 2013 to June 2016.

‡ All treatments were surface applied after the initial incorporation of amendments in September 2013. No amendments were applied from June 2015 to June 2016.

§ Sulfur coated urea (46–0–0 N–P–K) Potash Corporation, Saskatchewan, CA.

¶ In June 2016, DBN received only half of required application. In September 2016, DBN received the remaining half intended for June 2016 plus the September application rate.

Exceptional Quality unblended biosolids (DBN) used throughout the study were either processed by anaerobic digestion and pasteurization (Alexandria Renew Enterprises, ARE; see Badzmierowski et al., 2019) or by thermal hydrolysis and anaerobic digestion (DC Water Blue Plains Advanced Wastewater Treatment Plant, DC Water). The digested biosolids were dewatered and either applied "as is" or blended with sand and sawdust to create a low moisture, higher carbon-containing product. The ARE biosolids were applied from 2013 to 2015, and the DC Water Biosolids were applied from 2016-2018.

The DC Water biosolids were blended with sand and sawdust at a 1.5:1:1 ratio (dry weight basis), respectively. This recipe was developed by Yu (2013) to achieve a C:N ratio of 13:1 and a moisture content of approximately 50%, and later tested in a greenhouse bioassay by Alvarez-Campos et al. (2018). DC Water creates an EQ product through the CAMBI® thermal hydrolysis process and anaerobic digestion (Higgins et al., 2017). DC Water adds ferric chloride based on wastewater P concentrations for its complexation and removal from water. The CBN product obtained from the Spotsylvania County (VA) Livingston compost facility was used through the duration of the study. The biosolids used in the compost was originally from Massaponax WWTP.

Samples of each organic amendment used in the experiment were collected prior to application and analyzed by A&L Eastern Laboratories (Richmond, VA). Analyses included: total Kjeldahl N (SM-4500-NH3C-TKN; APHA, 1995), total and volatile solids (SM-2540G; APHA, 1995), organic N (calculated as the difference between total Kjeldahl N and NH_4–N), ammonia + ammonium N (SM-4500-NH3C; APHA, 1995), nitrate + nitrite-N (SM-4500NO3F; APHA, 1995), and P, K, Fe, and Al (SW-6010C; USEPA, 2000).

3.3.4. Sampling and Analysis

3.3.4.1. Soil Analyses

At the conclusion of the study period (1 October 2018), soil was sampled using a 2-cm diameter probe to a depth of 10 cm, which was subdivided into depths of 0 to 5 and 5 to 10 cm. Soil samples were air-dried and sieved through a 2-mm sieve.

Total soil C and N concentrations of the 0 to 5 and 5 to 10 cm were analyzed using a Vario Max CNS macro elementar analyzer (Elementar Analysensysteme), which uses a combustion chamber at 1200 °C. Soil C and N concentrations were converted to C and N mass per volume by multiplying bulk density to the fixed increment depths of 5 cm. Bulk density was determined using Method 3B6a by Soil Survey Staff (2009). Bulk density cores were collected to a depth of 10 cm subdivided to depths of 0 to 5 and 5 to 10 cm and dried in an oven at 110 °C until weight was constant. Four samples per subplot were collected in October 2018.

The soil surface, 0 to 5 cm, was analyzed for P using several methods. Water soluble P and Mehlich 3 P was extracted at a ratio of 2 g of soil to 20 mL deionized water and 20 mL of extraction solution containing 0.2N CH_3COOH, 0.25N H_4NO_3, 0.015N NH_4F, 0.015N HNO_3, and 0.001M EDTA, respectively (Mehlich, 1984; Kuo, 1996). Ammonium oxalate extractant was prepared using the method described in Pote et al. (1996) and mixed with soil at a ratio of 1 g of soil to 40 mL of ammonium oxalate solution. Ammonium oxalate extract was analyzed for P, Fe, and Al to determine the degree of P saturation. The P saturation is the molar ratio of the amount of P sorbed to a given depth to the maximum phosphate sorption capacity of the soil to that depth. The P saturation was calculated as the oxalate-extractable P (mmol kg^{-1}) divided by the oxalate-extractable Al and Fe (mmol kg^{-1}) content and multiplied by 100. This ratio was used to determine the P saturation ratio (PSR) to give an indication of potential P movement off-site

(Brandt et al., 2004). All extracts were analyzed by the Virginia Tech Soil Testing Laboratory using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES; CirOS VISION model, Spectro Analytical Instruments). Soil pH of the soil surface, 0 to 5 cm, was determined in both H_2O and 1M KCl using 10 g of air-dry soil and mixing with 10 mL of solution (Thomas, 1995).

3.3.4.2. Turfgrass Analyses

Turfgrass sampling protocol and analyses were the same as reported in Badzmierowski et al. (2019). Turfgrass clipping yield was collected every other week and processed clippings were subjected to a high-heat combustion chamber using a Vario Max CNS macro elementar analyzer (Elementar Analysensysteme) at 1200 °C for the determination of tall fescue leaf total N concentration. Clipping N accumulation was calculated as the product of biomass and N concentration.

Turfgrass quality was assessed using a visually by integrating the color, density, uniformity, and leaf texture on an ordinal scale of 1 to 9, where 9 indicates an ideal turfgrass stand, 6 is the minimum acceptable quality, and 1 indicates the turfgrass is dormant or dead (Morris, 2000). Each plot was rated every other week from spring to fall.

3.3.5. Weather Conditions

Mean monthly temperature and precipitation was reported using a nearby weather station (NOAA, 2018). During the trial period (August 2013– October 2018), the research site experienced monthly average temperatures similar to the 30-yr means (Fig. 3.1). Precipitation was variable and had increased rain during the late summers of 2015 to 2018 (Fig. 3.2). In summer 2015, above average precipitation limited the ability to impose a drought cycle. The lack of rain in late August to mid-September 2016, mid-May to late July 2017, and early-June to mid-July 2018, allowed for testing of no irrigation as indicated by the spilt-plot design.

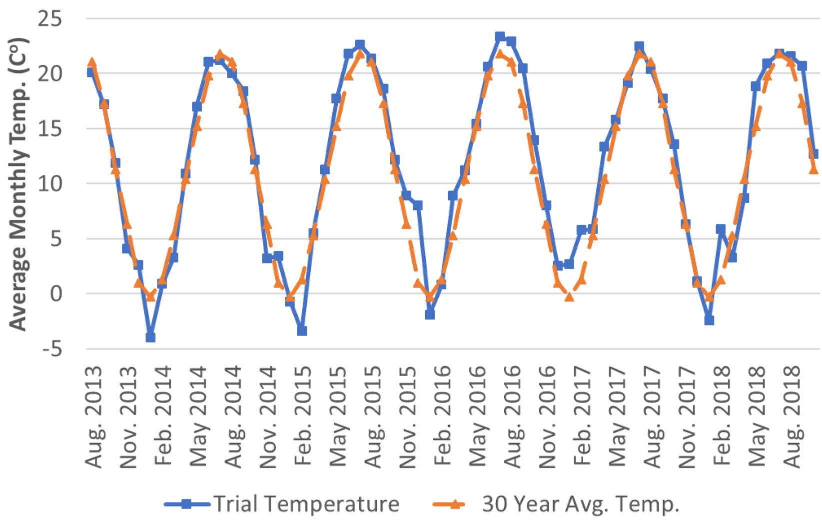


Figure 3.1. Air temperatures at the trial location (August 2013 to October 2018) vs. the 30-yr mean (1984–2014) for Blacksburg, VA.

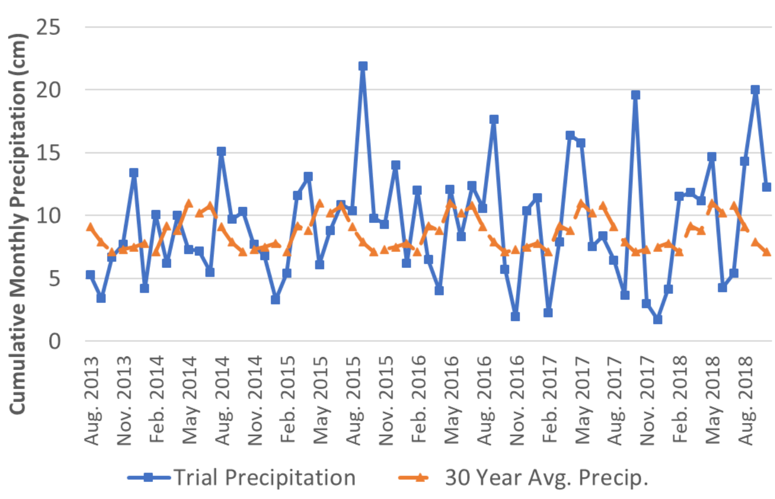


Figure 3.2. Cumulative monthly precipitation at the trial location (August 2013 to October 2018) vs. the 30-yr mean (1984–2014) for Blacksburg, VA.

3.3.6. Statistical Analysis

Data were statistically analyzed using JMP Pro software by SAS version 14.1 (Cary, NC). A first-order autoregressive repeated measures mixed model was used to reflect main factors (with and without irrigation during summer stress), subfactors (amendment types), blocking factor, and their interactions to determine significance of differences ($P < 0.05$). Sampling dates were compared within, but not among, years. Means were separated using a standard least squares model and using a Tukey's post hoc test for multiple comparisons and a Student's t test for separating irrigation means.

3.4. Results and Discussion

3.4.1. Exceptional Quality Biosolids Chemical Composition

Organic N was the largest N fraction within each biosolids product used from June 2016 to April 2018 (Table 3.2). The DBN was the most concentrated product as it was not diluted by other substrates. The DBN had larger fractions of organic and total N, total P, and total Fe (Table 3.2). The DC Water products (DBN, BBN, and BBP) had N/P ratios of approximately 1:1, and the CBN was approximately 3:1. Repeated applications of these biosolids could result in P accrual in topsoil with eventual potential for loss to surface waters. The elevated Fe and Al contents in the DC Water biosolids should promote P binding and reduce potential P loss (Table 3.2). Total C was highest in the CBN due to the addition of woody fines. All biosolids products have negligible K concentrations (i.e., <5 g kg^{-1}) and required broadcast application of potash for the site. Analyses of the biosolids used from September 2014 to June 2015 can be found in Badzmierowski et al. 2019.

Table 3.2. Chemical composition† of the biosolids products used from 2016 to 2018* this study.

Treatment	pH	Total solids	TKN‡	NH_4–N	NO_3–N	Total organic N	C	C/N	P	N/P	K	Fe	Al
					g kg^{-1}								
DBN§	5.9	510	35	2.3	0.58	33	275	7.9	32	1.1	1.4	88	10
BBN/BBP¶	6.3	730	20	3.3	0.42	16	266	13	21	0.95	1.5	56	6.1
CBN#	7.3	816	30	6.6	0.82	23	384	13	11	2.7	4.3	19	14

† All analysis was performed by A&L Eastern Laboratories, Richmond, VA.

‡ TKN, total Kjeldahl N.

§ DBN, anaerobically digested biosolids (DC Water, DC).

¶ BBN/BBP, anaerobically digested biosolids blended with sand and sawdust (DC Water, DC).

CBN, anaerobically digested biosolids composted with wood fines (Spotsylvania, VA).

* Analyses shown are from subsamples taken in June 2016. Biosolids were analyzed yearly to adjust loading rates as necessary. Analyses of original biosolids used from 2013 to 2015 can be seen in Badzmierowski et al. 2019.

3.4.2. Overall Study Statistical Trends

Contrary to the first two years of the study, as reported in Badzmierowski et al. (2019), irrigation × amendment interactions were often detected (Tables 3.3 – 3.5). The final 2018 total soil OC and N, pH_{KCl}, pH_{H2O}, and water-soluble P had significant ($P < 0.05$) irrigation × fertility amendment interactions. However, the pH_{KCl}, pH_{H2O}, and water-soluble P had no differences detected among means separated by Tukey HSD of fertility treatments within each irrigation treatment. Due to the lack of interaction differences, we reported pH_{KCl}, pH_{H2O}, and water-soluble P based on fertility effects.

Irrigation × fertility amendment interaction was analyzed by date during summer stress periods in 2016, 2017, and 2018 for tall fescue clipping biomass, leaf N accumulation, and tall fescue visual quality. Significant differences ($P < 0.05$) were determined for several dates, however only 26 July 2017 visual quality and 26 July 2016 leaf N accumulation had significant differences in the 0% ET × fertility amendment. The 0% ET CBN visual quality (5.1) for 26 July 2016 was greater than all other 0% ET fertility treatments. The other two biosolids N rate (BBN, DBN) visual quality were greater (4.6 and 4.5, respectively) than FER (3.9). The BBP visual quality (4.4) was equal to BBN, DBN, and FER. The 0% ET BBN and CBN had greater leaf tissue N accumulation (3.7 and 3.5, respectively) than DBN, BBP, and FER (1.4, 1.0, and 0.36, respectively). We expected this outcome as the varying amounts of soil OC would have affected plant available water, especially during the summer months. There was also a lack of 0% ET × fertility amendment differences in the sampling dates post-summer stress. We expected to see biosolids-based fertility amendments to have quicker recovery. The lack of statistical differences of 0% ET × fertility amendment may be a consequence of infrequent, every other week, sampling. It is possible that differences may be observed with increased sampling frequency. Due to the lack of differences observed in the 0% ET fertility treatments, we aggregated the final year turfgrass parameters to give a perspective of five years of treatment effects. Block was significant in several parameters measured, but since it was consistently the same block causing the significance, it was left in the model.

Table 3.3. Mixed model effects *p*-values for 2018 tall fescue quality, biomass, leaf tissue N accumulation.

Source	Tall fescue quality	Tall fescue biomass	Tissue N accumulation
Irrigation (Irr.)	<0.0001	<0.0001	<0.0001
Fertility (Fert.)	<0.0001	<0.0001	<0.0001
Block	<0.0001	0.034	0.0003
Date	<0.0001	<0.0001	<0.0001
Irr. × Fert.	0.015	0.0058	<0.0001
Irr. × Block	<0.0001	---	---

Irr. × Date	0.0031	<0.0001	<0.0001
Irr. × Fert. × Block	0.020	---	0.016
Irr. × Fert. × Date	---	---	---
Irr. × Block × Date	---	---	---
Fert. × Block	0.0015	---	---
Fert. × Date	0.0031	0.0004	0.0003
Fert. × Block × Date	---	---	---
Block × Date	---	---	---
Irr. × Fert. × Block × Date	---	---	---

Table 3.4. Mixed model effects *p*-values for 2018 soil bulk density and OC and N soil stocks.

Source	Bulk density		Mg OC ha^{-1}		Mg N ha^{-1}	
	0-5cm[1]	5-10cm	0-5cm	5-10cm	0-5cm	5-10cm
Irrigation (Irr.)	0.073	0.034	0.0003	0.0011	0.0005	0.0029
Fertility (Fert.)	<0.0001	0.0006	0.063	0.0015	0.014	0.0007
Block	---	0.045	---	0.0081	---	0.018
Irr. × Fert.	---	---	0.074	0.0095	0.035	0.0044
Irr. × Block	---	---	---	---	---	---
Fert. × Block	---	---	---	---	---	---
Irr. × Fert. × Block	---	---	---	---	---	---

Table 3.5. Mixed model effects *p*-values for soil 0-5cm pH, water soluble P, Mehlich 3 extractable P, ammonium oxalate extractable P, Al, and Fe, and P saturation ratio.

Source			**Water**	**Mehlich 3**	**Am. oxalate extractable**			**P saturation**
	pH_{KCl}[1]	**pH_{H2O}**	**soluble P**	**extract. P**	**P**	**Al**	**Fe**	**ratio**
Irrigation (Irr.)	---	---	---	0.0034	0.032	---	---	0.014
Fertility (Fert.)	<0.0001	0.0020	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Block	0.026	---	---	---	0.050	---	0.048	---
Irr. × Fert.	0.014	0.029	0.050	---	---	---	---	---
Irr. × Block	---	---	---	---	---	---	---	---
Fert. × Block	0.0078	---	---	---	---	---	---	---
Irr. × Fert. × Block	---	---	---	---	---	---	---	---

3.4.3. Soil Responses

3.4.3.1. Soil Bulk Density

There was no interaction between the main factor (irrigation treatment) and subfactor (amendments) (Table 3.4). Both the main factor and subfactor did affect soil bulk density at 0-5 cm and the subfactor affected 5-10cm bulk density ($P < 0.05$). Greater bulk density occurred in the 0% ET than the 80% ET treatment at 0-5cm. The small differences in bulk density between the two irrigation treatments at both depths, (0% ET: 0.86 g cm^{-3}; 80% ET: 0.82 g cm^{-3}), most likely does not provide much biological significance.

Fertility amendments yielded greater contrast in measured bulk densities than irrigation strategy (Table 3.6). The trends observed for the 0-5 cm depth at the mid-point of this study in Badzmierowski et al. (2019) remained similar. A noticeable difference compared to the mid-point of the study was that the bulk density for the BBP was now lower than the FER treatment for the 0-5 cm depth (Badzmierowski et al. 2019). The bulk densities measured appear to be influenced by the overall C loading rates (Table 3.1). The largest C addition was with the CBN treatment, followed by BBN, DBN, and BBP and resulted in reduced surface bulk density in the same order (Table 3.6). Fertility amendments also affected bulk density at the 5-10 cm depth. The biosolids applied at the agronomic N rate gave lower bulk density than the FER treatment. Our results provide further evidence that surface-applied organic amendments reduce bulk density (García-Orenes et al., 2005; Rivenshield and Bassuk, 2007; Ouimet et al., 2015; Sloan et al., 2016). The reduced bulk density would be expected to promote improved rooting conditions and promote increased turfgrass biomass growth. This positive feedback could have complemented the biosolids treatments high C loading rates and contribute to the reduction in bulk density. However, determining the potential root contribution to reduced bulk density is not feasible with the design of this experiment and overall not well documented in the current literature (Unger and Kaspar, 1994).

Table 3.6. Biosolids-based amendment effects on bulk density at depths of 0-5 and 5-10 cm.

Treatment†	Bulk Density 0–5 cm	Bulk Density 5–10 cm
	— g cm^{-3} —	
FER	1.1a‡ (s§ = 0.051)	1.20a (s = 0.044)
DBN	0.79c (s = 0.036)	1.15ab (s = 0.036)
BBN	0.71cd (s = 0.086)	1.13bc (s = 0.022)
BBP	0.99b (s = 0.020)	1.16ab (s = 0.052)
CBN	0.64d (s = 0.058)	1.10c (s = 0.042)

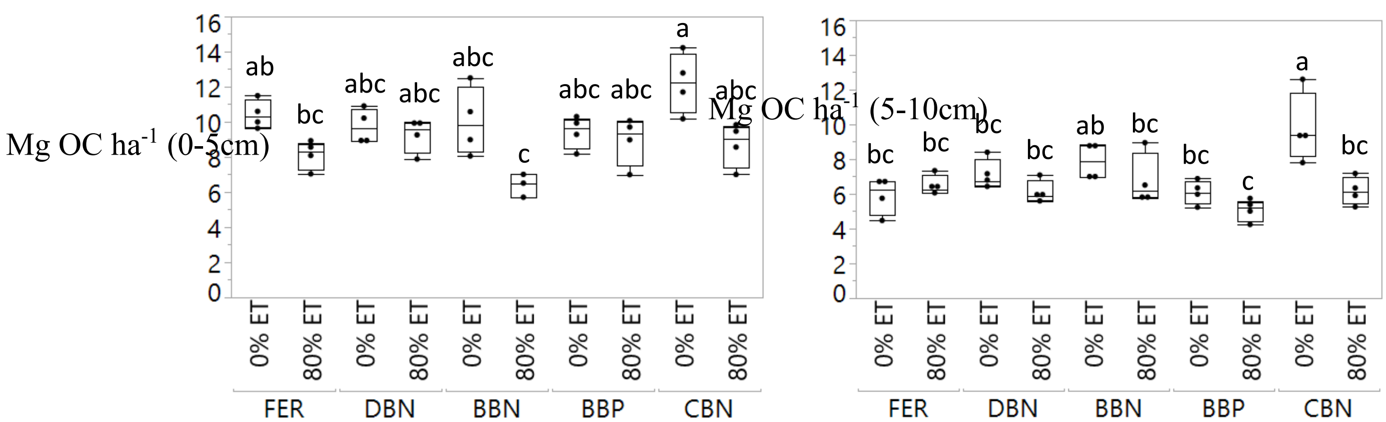
† FER, annually applied synthetic N–P–K fertilizer; DBN, biosolids applied annually at an agronomic N rate; BBN, blended biosolids–sand–sawdust applied annually at an agronomic N rate; BBP, blended biosolids–sand–sawdust applied annually at an agronomic P rate plus supplemental fertilizer N; CBN, composted biosolids applied annually at an agronomic N rate.

‡ Means in the same column followed by the same lowercase letter are not significantly different at $P < 0.05$.

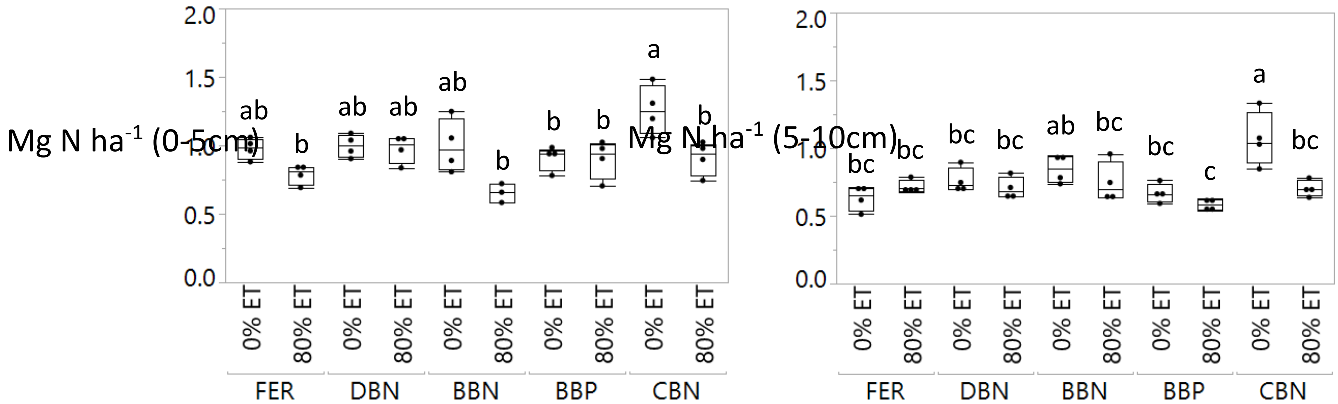
§ Standard deviation of mean. N = 8.

3.4.3.2. Soil Organic Carbon and Nitrogen Stocks

Effects of treatments on soil OC and N stocks were closely linked. Soil OC 5-10 cm and N stocks at both depths measured were affected by the interaction of irrigation × amendment ($P < 0.05$) (Table 3.4). Soil OC at the 0-5cm depth was significant at $P = 0.074$ and presented on an interaction basis (Fig. 3.3). Counter to our hypothesis, based on previous turfgrass studies (Milesi et al., 2005; Qian et al., 2010; Selhourst and Lal, 2013; Law and Patton, 2017), that increased inputs (e.g. irrigation and fertilizer) would increase soil OC and N, less irrigation gave greater soil OC and N for CBN (Fig. 3.3-3.6). The CBN 0% ET had the greatest soil OC and N compared to all other treatments (Fig. 3.4, 3.6). We cannot explain these effects and are unable to find other studies that can explain such responses.



Figures 3.3 & 3.4. Irrigation and fertility amendments effects on soil OC to a depth of 0-5 and 5-10 cm.



Figures 5 & 6. Irrigation and fertility amendments effects on soil N to a depth of 0-5 and 5-10 cm.

3.4.3.3. Soil Chemical Properties

The CBN maintained a higher soil pH than all other treatments (Table 3.7). This is most likely a result of the buffering capacity that was provided by the cumulative C loading from CBN in addition to the greater pH of the CBN material (Table 3.1, 3.2). Composts, such as CBN, and other manures contain carboxyl and phenolic groups that are able to consume protons when applied to soil and buffer the pH (Stevenson and Vance, 1989). To meet our original target of a pH of 6.5 (Badzmierowski et al., 2019) for optimal soil fertility, lime would need to be added to all treatments.

After applying the various fertility amendments for four of the five trial years, all P extraction methods and PSR were significantly affected (Table 3.5). The highest water-soluble P was in the CBN, a result most likely from the greatest total loading rate of material (Table 3.1). The soils treated with the biosolids having the highest Fe and Al concentrations (BBN/BBP, DBN) did not provide more water-soluble P than the synthetic fertilizer treatment (FER) after five years (Table 3.7). The increased Fe and Al concentration in the BBN and DBN products

(Table 3.2) likely reduced water-soluble P. The application of organic byproducts in Virginia are not permitted if soil PSR>65%, should not be greater than P crop removal if 65%<PSR>30%, and can be applied an agronomic N rate if PSR<30% (Virginia DCR, 2014). Virginia DCR regulations would limit all three treatments applied at the agronomic N rate to the P crop removal rate. For a turfgrass system where clippings are left in place, it would restrict further applications. Our results indicate that this regulation may not be appropriate for all biosolids materials, such as the DBN and BBN material treated with high concentrations of Fe salts. The Fe salts have reduced P solubility in the soil to that of synthetic fertilizer P applied according to soil test recommendations. Brandt et al. (2004) recommends consideration of the P source/treatment process and composition for biosolids P management. Management policies should reflect the decreased water-soluble as a result of Fe and Al salt treatment at certain wastewater treatment facilities.

Table 3.7. Biosolids-based amendments effects on soil pH and extractable P to a depth of 5 cm.

	pH_{KCl}	pH_{H2O}	Water soluble P	Mehlich 3 extract. P	Am. oxalate extractable P	Am. oxalate extractable Al	Am. oxalate extractable Fe	P saturation ratio
Treatment†			-----mg P kg^{-1}-----			-------mmol kg^{-1}-------		%
FER	4.9b (s = 0.20)	5.9b (s = 0.28)	13bc (s = 4.5)	18d (s = 8.8)	1.8c (s = 0.55)	26b (s = 2.0)	11c (s = 2.0)	5.0b (s = 1.7)
DBN	4.9b (s = 0.15)	5.8b (s = 0.23)	15bc (s = 3.1)	150c (s = 21)	47a (s = 8.5)	42a (s = 5.9)	65a (s = 18)	44a (s = 4.3)
BBN	4.9b (s = 0.10)	5.9b (s = 0.22)	18b (s = 5.2)	210b (s = 58)	38b (s = 6.3)	40a (s = 7.1)	49b (s = 11)	43a (s = 6.0)
BBP	5.0b (s = 0.23)	6.0b (s = 0.28)	9.6c (s = 2.9)	22d (s = 4.9)	4.4c (s = 1.2)	26b (s = 3.4)	18c (s = 6.6)	10b (s = 1.4)
CBN	5.3a (s = 0.14)	6.3a (s = 0.15)	30a (s = 9.0)	280a (s = 50)	39b (s = 7.1)	41a (s = 3.0)	44b (s = 4.6)	46a (s = 7.3)

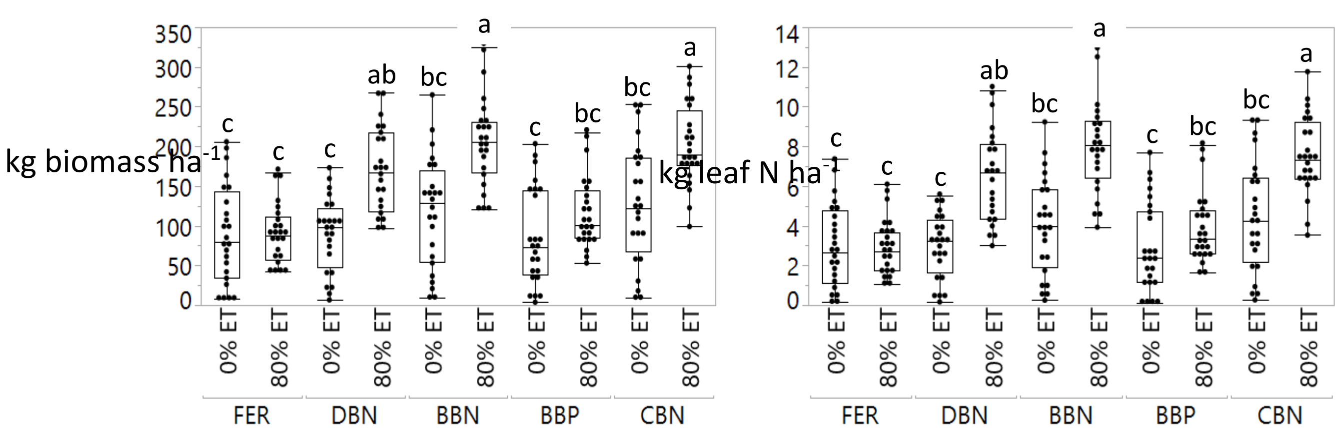
† FER, annually applied synthetic N–P–K fertilizer; DBN, biosolids applied annually at an agronomic N rate; BBN, blended biosolids–sand–sawdust applied annually at an agronomic N rate; BBP, blended biosolids–sand–sawdust applied annually at an agronomic P rate plus supplemental fertilizer N; CBN, composted biosolids applied annually at an agronomic N rate.

‡ Means in the same column followed by the same lowercase letter are not significantly different at $P < 0.05$.

3.4.4. Plant Responses

3.4.4.1. Tall Fescue Clipping Biomass, Leaf Nitrogen Accumulation, and Quality

During the final year of the study, tall fescue clipping biomass and leaf N accumulation had irrigation × amendment interactions (Table 3.3). Tall fescue clipping biomass and N accumulation was increased in BBN, CBN, and DBN at the 80% ET irrigation rate, while BBP and FER gave no differences between irrigation strategies (Fig. 3.8, 3.9). The 80% ET irrigation treatment improved turfgrass visual quality (rating = 7.2) as expected compared to the 0% ET irrigation (rating = 5.8).



Figures 3.8 & 3.9. Irrigation and fertility amendments interaction effects on tall fescue aboveground biomass and leaf tissue N accumulation from all sampling dates during the final sampling year (April – August 2018).

Our hypothesis was that biosolids-based amendments would improve turfgrass quality and growth compared to a conventional synthetic fertilizer program. This was an important hypothesis to test as the adoption of using biosolids-based amendments in turfgrass systems would prove most successful if it yielded improved aesthetic quality. The mean tall fescue clipping biomass and quality of each sampling date during the five years is shown in Figures

3.10 and 3.11. As discussed in Badzmierowski et al. (2019), the first year resulted in rapid growth in the FER treatment as a result of greater available N. After the first year of growth through the end of the study in 2018, biosolids applied at the agronomic N rate (BBN, CBN, DBN) resulted in increased biomass, N accumulation and visual quality than BBP and FER. The higher loading rates from BBN, CBN, and DBN increased soil organic N stocks that acted as a slow-release fertilizer to meet the tall fescue needs. This resulted in mean acceptable quality ratings (>6) during almost all measured dates during the final four years for BBN, CBN, and DBN (Fig. 3.11; Badzmierowski et al., 2019). The FER was the only fertility treatment that ended the trial with a mean visual quality (rating = 5.7) lower than the acceptable minimum quality rating of 6.

The novel BBP resulted in an acceptable mean visual quality (rating = 6.2) in the last year of the study. Turfgrass managers and low maintenance turfgrass areas that can accept slower rates to reach acceptable quality (e.g., highway roadsides, parks, industrial lawns, etc.) could find this option useful and reduce potential P loss. For situations that require a quicker timeline to reach an acceptable turfgrass stand (e.g., higher maintenance lawns and golf courses), optimizing the immediate source of N (synthetic), slow-release of N (biosolids), and mitigating P loss is highly desired. Testing the application of a different biosolids product that does not include sawdust at the agronomic P rate and supplementing it with N fertilizer may yield more desirable results. It is possible that N was immobilized by the presence of incompletely stable sawdust C (despite the relatively low C/N ratio of 15:1).

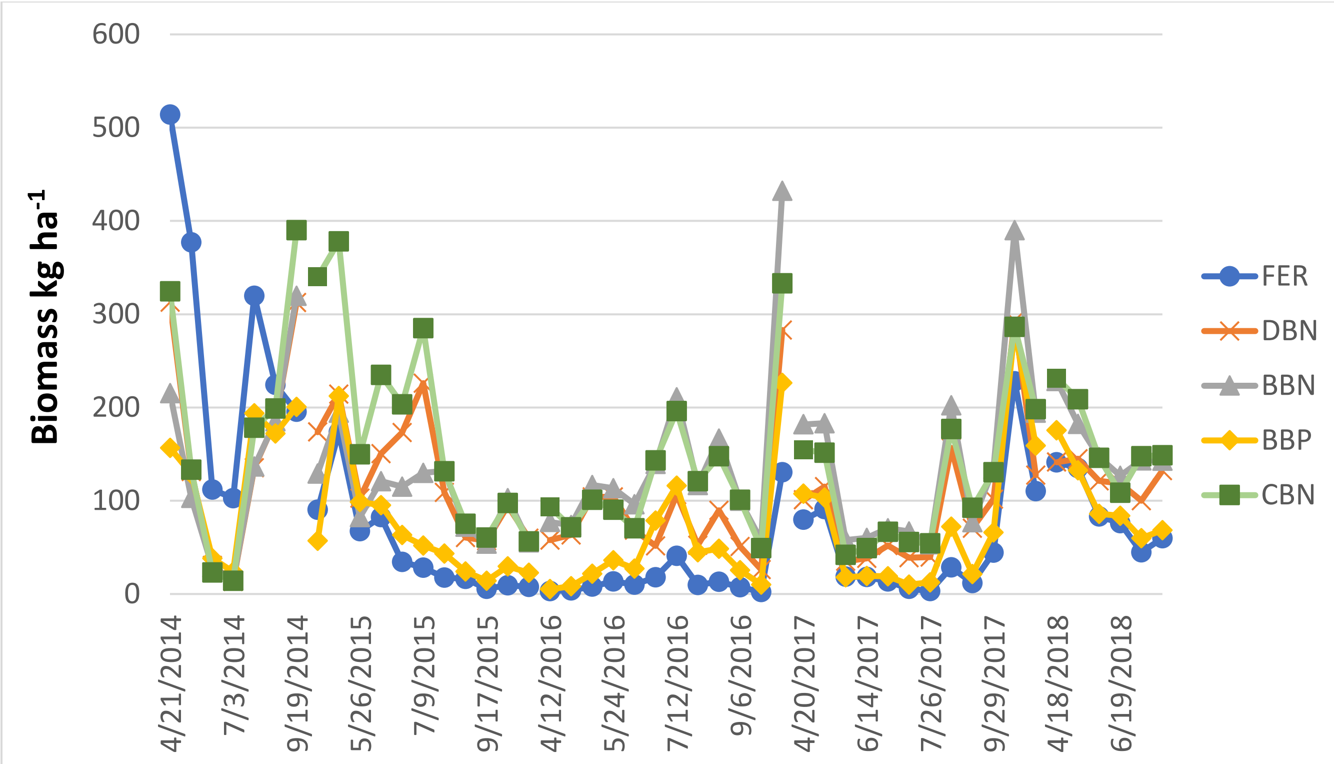


Figure 3.10. Biosolids-based amendments effect on turfgrass biomass throughout the duration of the sampling period (April 2014 – August 2018).

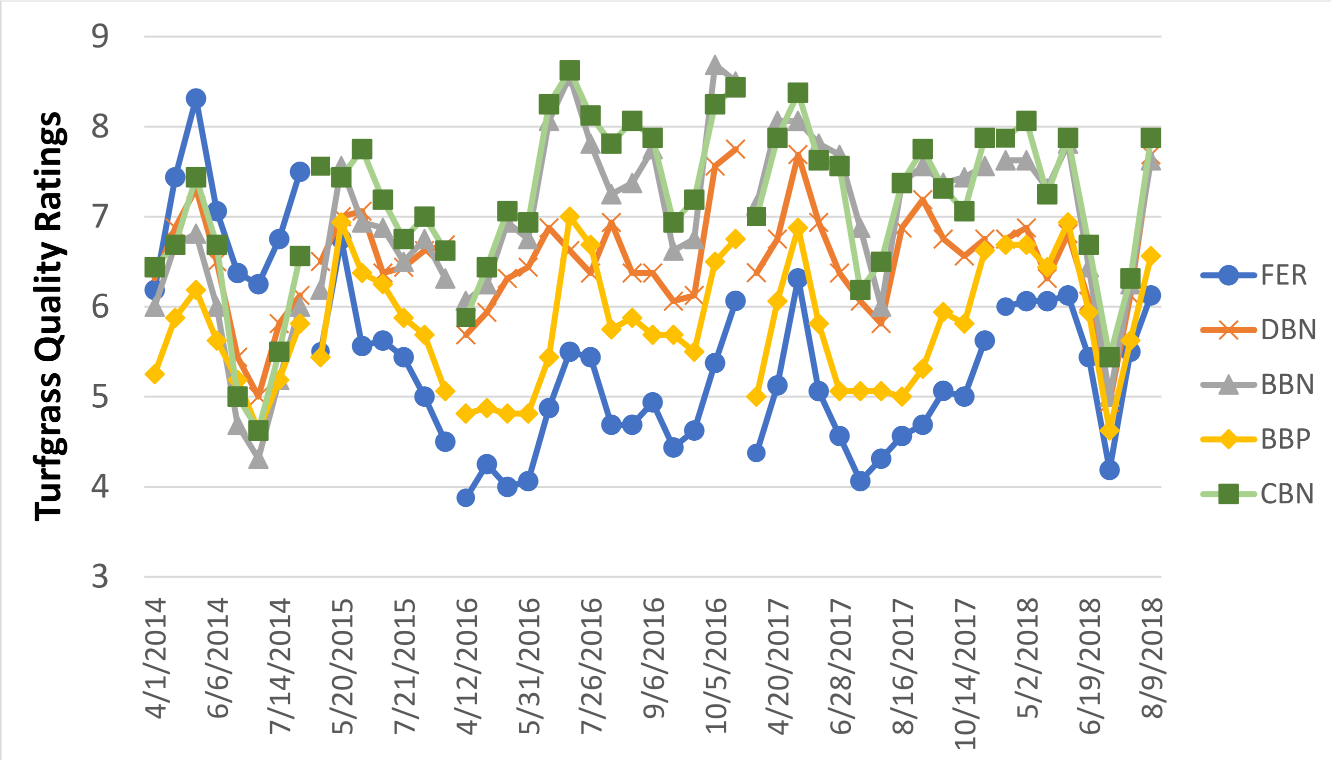


Figure 3.11. Biosolids-based amendments effect on turfgrass quality throughout the duration of the sampling period (April 2014 – August 2018).

3.5. Conclusions

Research on the use of EQ biosolids for turfgrass grown in anthropogenically-impacted soils has not been well documented. Our results found that the biosolids-based products applied at agronomic N rate improved visual quality and tall fescue growth compared to synthetic fertilizer during a 5-year year period of establishment and equilibration. The repeated applications of biosolids-based amendments reduced soil bulk density and increased soil OC and N stocks with minimal environmental P risk. Biosolids with high Fe concentrations applied at the agronomic N rate did not increase the risk of P loss as assessed by water-soluble soil P. The soil PSR did indicate that all biosolids applied at the agronomic N rate would be limited to P crop removal rates. This indicates that the soil PSR is overestimating P runoff risk from biosolids with high Fe concentrations. Regulations should support the differences in biosolids processing methods to reflect their P loss risk. Biosolids applied at the agronomic P rate with supplemental synthetic N resulted in acceptable turfgrass quality by the end of the study. Biosolids applied at the agronomic P rate can be used in low maintenance turfgrass areas and should be further researched to improve timing to acceptable turfgrass status.

3.6. Acknowledgments

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3.7. Conflict of Interest

The authors explicitly state that there are no conflicts of interest in the research conducted.

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4. Using Hyperspectral and Multispectral Indices to Detect Water Stress for an Urban Turfgrass System

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Keywords: tall fescue; turfgrass management; vegetation index; NDVI; drought stress; soil volumetric water content; nitrogen availability

4.1 Abstract

Spectral reflectance measurements collected from hyperspectral and multispectral radiometers have the potential to be a management tool for detecting water and nutrient stress in turfgrass. Hyperspectral radiometers collect hundreds of narrowband reflectance data compared to multispectral radiometers that collect three to ten broadband reflectance data for a cheaper cost. Spectral reflectance data have been used to create vegetation indices such as the normalized difference vegetation index (NDVI) and the simple ratio vegetation index (RVI) to assess crop growth, density, and fertility. Other indices such as the water band index (WBI) (narrowband index) and green-to-red ratio index (GRI) (both broadband and narrowband index) have been proposed to predict soil moisture status in turfgrass systems. The objective of this study was to compare the value of multispectral and hyperspectral radiometers to assess soil volumetric water content (VWC) and tall fescue (*Festuca arundinacea* Schreb.) responses. The multispectral radiometer VI had the strongest relationships to turfgrass quality, biomass, and tissue N accumulation during the trial period (April 2017–August 2018). Soil VWC had the strongest relationship to WBI (r = 0.60), followed by GRI and NDVI (both r = 0.54) for the 0% evapotranspiration (ET). Nonlinear regression showed strong relationships at high water stress periods in each year for WBI (r = 0.69–0.79), GRI (r = 0.64–0.75), and NDVI (r = 0.58–0.79). Broadband index data collected using a mobile multispectral sensor is a cheaper alternative to hyperspectral radiometry and can provide better spatial coverage.

4.2. Introduction

Turfgrass covers approximately 2% of the continental United States [1]. This makes turfgrass the largest irrigated crop in the United States. Sufficient irrigation is necessary to maintain acceptable quality turfgrass stands. As water prices increase and availability declines due to climate change and increased human demand, water conservation is critical for successful turfgrass management. Irrigation strategies that reduce water inputs and maintains turfgrass quality are needed for landowners and turfgrass managers.

Turfgrass managers implement various strategies to optimize the efficiency of irrigation inputs. Evapotranspiration (ET)-based irrigation is designed to return less water than actual ET without compromising turfgrass quality [2]. Irrigating at 80% ET for cool-season turfgrasses has been widely accepted [3,4]. Feldhake et al. [5] and Ervin [6] suggest that ET-based irrigation does not provide adequate spatial resolution for the heterogeneity of ET that occurs at a local scale. The use of on-site atmometers is a reliable means to predict ET while overcoming the limitation of spatial resolution [2,7,8].

Hand-held moisture meters have been employed to assess soil moisture and irrigation needs at a fine-scale resolution [9,10]. Time-domain reflectometry (TDR) has been used for smaller landscape areas to directly measure soil volumetric water content (VWC) [11–14]. Time-domain reflectometers are hand-held devices that consist of metal rods that emit high-frequency electromagnetic pulses through the soil. The velocity of the pulses between the rods can be used to calculate the soil VWC [14,15]. Soil VWC measurements by TDR is limited by the time needed to collect data over large areas [4]. Carrow et al. [16] proposed using TDR and spectral reflectance mapping as a precision turfgrass management strategy to improve irrigation efficiency on a site-specific scale. Spectral reflectance data acquisition of turfgrass, via satellite or mobile devices, can contribute greatly to quantifying crop water needs, especially if integrated with soil and plant measurements [16,17].

Turfgrass managers have traditionally relied on visual evaluation to estimate turfgrass health status, irrigation or fertilizer needs, damage, or environmental stress [17]. Spectral reflectance data can overcome the subjectivity of visual assessments of turfgrass response to management practices [17,18]. Spectral reflectance data can be acquired via remote sensing radiometers on ground-based, aircraft, or satellite instruments [19]. Hyperspectral radiometers measure reflected energy in hundreds to thousands of continuous narrowbands across the electromagnetic spectrum. Multispectral radiometers are a less expensive option to measure reflected energy in three to ten broadbands [20]. These radiometers can be used in to quantify physiological attributes of healthy and stressed plant tissue due to changes in spectral reflectance in the visible red (R), red edge (RE), and near-infrared (NIR) regions [21]. Physiological differences have been detected prior to visual stress symptoms in various agronomic settings [22–25]. Spectral reflectance measurements have potential as a management tool for water and nutrient stress in turfgrass. McCall et al. [26] and Roberson [27] demonstrated at the greenhouse scale the detection of water stress using spectral reflectance. However, variations in fertility and irrigation strategies, as well as the comparison of multispectral and hyperspectral radiometers, are largely unexplored at the field-scale in turfgrass research.

Agricultural research and management have employed the use of vegetation indices (VI), typically, a ratio of two or more spectral bands, derived from spectral data to assess plant responses [28]. The most commonly used index for measuring plant performance or stress indicator is the normalized difference vegetation index (NDVI):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR}-\mathrm{R})}{(\mathrm{NIR}+\mathrm{R})}, \tag{1}$$

The normalized difference vegetation index has demonstrated correlation in turfgrass systems to soil moisture, N fertilization, tissue biomass, tissue chlorophyll concentration, and turfgrass quality parameters (e.g., color, density, and uniformity) [18,28–36]. Additional VI have shown useful in quantifying plant responses. The ratio vegetation index (RVI):

$$\mathrm{RVI} = \frac{\mathrm{NIR}}{\mathrm{R}}, \tag{2}$$

is sensitive to dense vegetation growth, but insensitive to sparse vegetation cover [28]. In contrast, NDVI is more sensitive to sparse vegetation and less sensitive to dense growth. Despite the ability of the NDVI and RVI to quantify plant response to fertility or to stress (e.g., soil moisture), it is unable to differentiate and determine the cause of the plant response [16].

Water indices utilizing narrowband spectral reflectance have been used to assess plant water status and drought effects [26,37,38]. Water indices have potential for early water stress detection independent of other stressors. Water absorption bands exist in the NIR region beyond the photosynthetically active radiation, reducing the confounding effect from other abiotic stresses. McCall et al. [26] determined that soil VWC had the strongest correlation to the water band index (WBI) ($r \geq 0.80$), followed by the green-to-red ratio index (GRI) ($r \geq 0.50$) in a greenhouse study assessing creeping bentgrass grown in a sand-based media:

$$\mathrm{WBI} = \frac{\mathrm{R}_{900}}{\mathrm{R}_{970}}, \tag{3}$$

and

$$\mathrm{GRI} = \frac{\mathrm{R}_{550}}{\mathrm{R}_{670}}, \tag{4}$$

where *R* refers to reflectance and the subscripts refer to a specific spectral band. In this same study, NDVI did not correlate with soil VWC. Roberson [27] found similar results in various soil textures that WBI and GRI were better at detecting moisture stress in comparison to NDVI. It is important to gather more information at field-scale regarding WBI and GRI detection of moisture stress, as GRI can be used in both hyperspectral and multispectral radiometers.

Determining the most suitable VI can provide site-specific management strategies regarding water stress and N fertility when combined with geographic information systems applications. With the advent of unmanned automated systems (drones), the use of spectral reflectance can be a cost-effective management strategy to rapidly collect large data sets and assess target vegetation stresses in real-time. Our research was to test the scalability of previous research conducted by McCall et al. [26] and Roberson [27] relating spectral reflectance data to soil VWC and N fertility in a tall fescue (*Festuca arundinacea* Schreb.) urban turfgrass system. The objectives of our study were to (1) compare the relationships of various vegetation indices using a traditional broadband, multispectral radiometer and a narrowband hyperspectral radiometer to soil VWC, turfgrass quality, and leaf tissue analyses; (2) define the relationship of vegetation indices to irrigation strategy; and (3) compare the relationship of different vegetation indices to different sources of N fertility including organic sources (exceptional quality biosolids-based amendments), a synthetic source (urea), and a blend of the two (exceptional quality biosolids-based amendments + urea).

4.3. Materials and Methods

4.3.1. Study Site Establishment

This study was conducted from April 2017 to August 2018 at the Virginia Tech Turfgrass Research Center in Blacksburg, VA, USA (37°12′54.31″ N, 80°24′42.14″ W) located in Cold Hardiness Zone 6b [39]. Mean monthly temperature and precipitation was reported using a nearby weather station for 2017 to 2018 [40]. The results presented are part of an ongoing research study assessing tall fescue growth and maintenance in an anthropogenically disturbed, clayey urban soil that began in August 2013. Initial site description, field preparation, soil benchmark sampling and analysis, irrigation installation, fertility applications, and plant establishment management were reported by Badzmierowski et al. [41].

4.3.2. Experimental Design

The experimental design was a split-plot arrangement of a randomized complete block design replicated four times. Main plots were two summer irrigation treatments, and subplots were five soil fertility amendments. Irrigation treatments were (1) no water applied during critical summer months (0% ET), unless necessary to keep vegetation alive, and (2) water applied to replenish 80% of ET during drought-prone (80% ET), high-ET summer months. Irrigation was withheld from all replicates of the 0% ET main plot from 18 May–26 July 2017, and 6 June–12 July 2018. Irrigation of all main plots to 80% of ET was resumed at the end of each drought stress period. Each main plot was 20.7 × 3.7 m.

The five subplot treatments were synthetic fertilizer and four exceptional quality (EQ) biosolids products applied to provide an estimated annual plant-available nitrogen (PAN) rate of 171 kg PAN ha^{-1}. Dimensions of the experimental area were 22.7 × 35.5 m (806 m^2). Each subplot was 3.7 × 3.7 m and had 0.61-m buffer strips between subplots.

4.3.3. Amendment Treatments, Biosolids Analysis, and Soil Fertility

Three of the four EQ Class A biosolids treatments used in the study were processed at DC Water Blue Plains Advanced Wastewater Treatment Plant (DC Water) undergoing thermal hydrolysis and anaerobic digestion. The digested biosolids were dewatered and surface applied "as is" or blended with sand and sawdust to improve characteristics (i.e., lower moisture and increased carbon) for spreading in a turfgrass system. The three DC Water amendments are: (1) dewatered biosolids (DBN), (2) dewatered biosolids blended with sand and sawdust (BBN), and (3) dewatered biosolids blended with sand and sawdust to supply an annual P rate as recommended by Virginia Tech Soil Testing Laboratory soil test analysis plus supplemental S-coated urea fertilizer to provide equal annual PAN ha^{-1} (BBP). The fourth biosolids treatment was anaerobically digested, dewatered biosolids compost (CBN) produced at Spotsylvania County (Virginia, USA) Livingston.

The fifth amendment treatment was synthetic fertilizer N (as S-coated urea) (FER). Triple superphosphate (0–46–0 N–P–K) and muriate of potash (0–0–60 N–P–K) applications for 2017 to 2018 were adjusted for the synthetic fertilizer treatment plots and biosolids treatment plots, based on September 2015 soil test results [41].

Fertility amendments were applied on 29 March 2017 (24.4 kg PAN ha^{-1}), 20 September 2017 (73.1 kg PAN ha^{-1}), 18 October 2017 (73.1 kg PAN ha^{-1}), and 3 April 2018 (24.4 kg PAN ha^{-1}).

4.3.4. Sampling and Analysis

4.3.4.1. Spectral Reflectance Measurements

Spectral reflectance data were collected using two independent tools. The Spectral Evolution PSR-1100F is a handheld portable field radiometer (Spectral Evolution, Lawrence, MA, USA) fitted with a contact probe measuring a spot size of 2.5 cm directly from the canopy surface. A total of 512 unique spectra were sampled from 320 to 1100 nm at a 1.4-nm sampling bandwidth and a 3-nm spectral resolution. A $BaSO_4$ white panel was used to calibrate a reference by placing the probe directly on the panel surface prior to each replication. Four spot measurements were taken walking a linear path in the middle of each experimental unit.

A second handheld multispectral radiometer, the Crop Circle ACS-430 (Holland Scientific, Inc., Lincoln, NE, USA), was mounted to a Bag Boy Quad Plus pushcart (Bag Boy Company, Richmond, VA, USA) to measure broadband VI. The sensor simultaneously measures crop and soil reflectance fixed at broadbands red = 670 nm, red edge = 730 nm, and near infrared = 780 nm. The hyperspectral radiometer spectral indices NDVI, RVI, and GRI were calculated using the equivalent spectra to the Crop Circle ACS-430 filters (670, 730, and 780 nm) (Table 4.1), while maintaining the principles described in the literature and in Equations (1)–(4) [42–44]. The Crop Circle ACS-430 was mounted at a stationary height of 46 cm above the turf canopy and set to collect 10 samples per second. Radiometer measurements commenced at the edge of each plot and took an average of 100 readings per 3.7 m of linear travel through the center of each subplot. Spectral reflectance sampling was conducted prior to mowing and taken to coincide with other turfgrass and soil measurements.

Previous greenhouse turfgrass trials conducted by McCall et al. [26] and Roberson [27] were used as the basis for determining indices to assess soil moisture status and turfgrass parameters (Table 4.1). Both studies aimed to develop relationships of soil moisture status and health of turfgrass using various vegetation indices. Based on their findings, WBI and GRI were significantly related to soil VWC. The WBI and GRI were analyzed using the hyperspectral radiometer as the manufactured filter of the Crop Circle ACS-430 cannot measure the required wavelengths. Both the Crop Circle ACS-430 and the hyperspectral radiometer were used for turfgrass growth and quality relationships to compare the continuous data collection of the Crop Circle ACS-430 and the individual points measured by the handheld hyperspectral radiometer.

4.3.4.2. Turfgrass and Soil Sampling

Turfgrass clipping and N analysis of tissue content remained the same as reported in Badzmierowski et al. [41]. Turfgrass clipping yield was collected every other week throughout the growing season by mowing a single pass down the center of each plot. During weeks when yields were not collected, all plots were mulched, and clippings were left in place. All biomass clippings were dried for 48 h at 60 °C and the dry clipping biomass was recorded. The biomass was ground to pass through a 0.5 mm sieve and subjected to a high-heat combustion chamber at 1200 °C for the determination of tall fescue leaf total N concentration. Clipping tissue N accumulation was calculated as the product of biomass and N concentration.

Table 4.1. Listing of vegetation indices investigated for correlation to tall fescue quality, biomass, tissue N accumulation, and soil volumetric water content.

Acronym	Index Name [1]	Formula Used	Citation
NDVI	Normalized difference vegetation index	(NIR− R)/(NIR + R)	Rouse et al. 1974 [2]
RVI	Simple ratio vegetation index	NIR/R	Birth and McVey 1968
GRI	Green to red ratio index	R_{550}/R_{670}	Gamon and Surfus 1999
WBI	Water band index	R_{900}/R_{970}	Penuelas et al. 1993

[1] NDVI and RVI were collected using the Crop Circle ACS-430 and hyperspectral radiometer. The green-to-red ratio index (GRI) and water band index (WBI) was only measured using the hyperspectral radiometer as the ACS-430 model cannot measure the required wavelengths; [2] Formulas were modified to use spectra equivalent to filters used on the Crop Circle ACS-430 multispectral radiometer (red = 670 nm, red edge = 730 nm, and near infrared = 780 nm).

Turfgrass quality ratings were assigned by visual assessment based on guidelines established by the National Turfgrass Evaluation Program [45]. Visual assessment integrates turfgrass color, density, uniformity, and leaf texture and rates the turfgrass stand on a scale of 1 to 9, where 9 indicates an ideal turfgrass stand, 6 is the minimum acceptable quality, and 1 indicates the turfgrass is dormant or dead.

Soil VWC was collected from each subplot using a Field Scout TDR 300 (Spectrum Technologies, Inc., Plainfield, IL, USA) fitted with two 7.6 cm length, stainless steel turf rods. The average of four replicates for each subplot were recorded. Measurements were taken on turfgrass sampling dates.

4.3.5. Statistical Analysis

The spectral reflectance vegetation indices, visual turfgrass quality, tissue biomass, leaf tissue N accumulation, and soil VWC, were subjected to a mixed model. The model was partitioned to reflect main factors (with and without irrigation), subfactors (amendment types), blocking factor, year, and their interactions using an auto-regressive repeated measures mixed model in JMP Pro software (SAS Institute, v. 14.1, Cary, NC, USA). Pearson correlation coefficients were calculated to assess the relationships among response variables. Non-normal data were transformed using a box-cox transformation. Nonlinear regression was performed on an individual basis comparing various multispectral and hyperspectral relationships to selected turfgrass and soil variables using a four-parameter logistic model. Means were separated using a Student's *t*-test or a Tukey's post hoc test ($p \leq 0.05$) when appropriate.

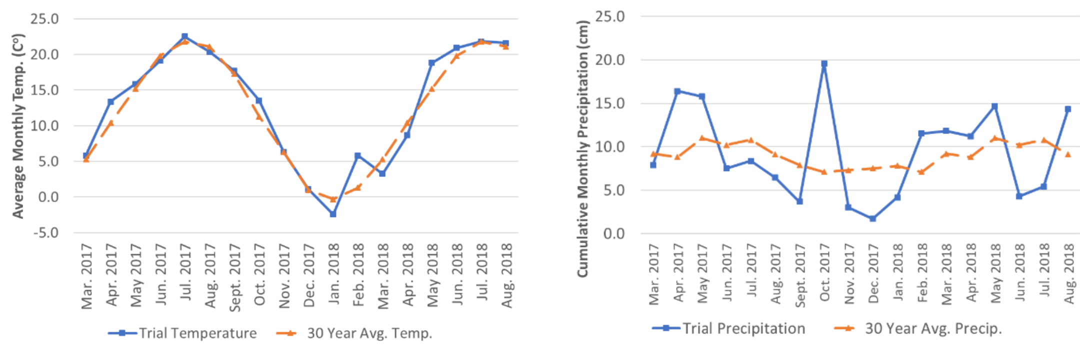
4.4. Results and Discussion

4.4.1. Weather

The research location experienced similar monthly average temperatures compared to the 30-year mean during the trial period (March 2017–August 2018) (Figure 4.1). Cumulative monthly precipitation was variable (Figure 4.1). The below average precipitation from in the summer of 2017 and 2018 provided the opportunity to impose two drought cycles on the tall fescue.

4.4.2. Overall Study Statistical Trends

Significant and strong relationships were observed in indices compared (Table 4.1) to each other from both radiometer instruments (data not shown). The NDVI and RVI from both instruments and the GRI and WBI measured from the hyperspectral instrument are discussed in this study. These indices were chosen due to their common use by plant scientists (NDVI), have been suggested to be more applicable to turfgrass systems (RVI), or exclude chlorophyll-related effects on water content estimation (WBI) [16,38,46,47].



(**a**) (**b**)

Figure 4.1. Monthly air temperature (**a**) and cumulative monthly precipitation (**b**) as measured by a local National Oceanic and Atmospheric Administration weather station (March 2017 to August 2018) vs. the 30-year mean for Blacksburg, VA, USA.

The only dependent variable for which treatment interaction occurred was tall fescue quality RVIcc, where "cc" represents VI data collected by the Crop Circle ACS-430 (Tables 4.2 and 4.3). The main factor (irrigation) elicited significant effects on all variables. Relationships were assessed separating the 0% ET and 80% ET main plots. The subfactor, fertility amendment, affected all turfgrass variables and soil VWC. Fertility amendments had no effect (p >0.05) on VI measured by the hyperspectral radiometer but did yield a response in VI measured by the Crop Circle ACS-430 multispectral radiometer. Crop Circle ACS-430 Vis, denoted with "cc", were additionally assessed by separating the fertility amendments.

Table 4.2. Mixed model effects p-values for tall fescue quality, biomass, leaf tissue N accumulation, and soil volumetric water content (VWC).

Source	Tall Fescue Quality	Tall Fescue Biomass	Tissue N Accumulation	Soil VWC
Irrigation (Irr.)	<0.0001	0.002	0.0002	<0.0001
Fertility (Fert.)	<0.0001	0.0003	0.0007	<0.0001
Block	0.025	---	---	<0.0001
Year	---	0.0002	---	---

Irr. × Fert.	---	---	---	---
Irr. × Block	---	---	---	---
Irr. × Year	0.002	---	---	---
Irr. × Fert. × Block	---	---	---	---
Irr. × Fert. × Year	---	---	---	---
Irr. × Block × Year	---	---	---	---
Fert. × Block	---	---	---	---
Fert. × Year	---	---	---	---
Fert. × Block × Year	---	---	---	---
Block × Year	---	---	---	---
Irr. × Fert. × Block × Year	---	---	---	---

Table 4.3. Mixed model effects *p*-values for spectral reflectance vegetation indices using a multispectral and hyperspectral radiometer for all dates of the trial.

Source	NDVI [1]	NDVI$_{CC}$	RVI	RVI$_{CC}$	GRI	WBI
Irrigation (Irr.)	<0.0001	<0.0001	<0.0001	<0.0001	0.0007	0.0006
Fertility (Fert.)	---	0.016	---	0.012	---	---
Block	---	---	---	---	---	---
Year	---	0.0004	---	<0.0001	---	---
Irr. × Fert.	---	---	---	---	---	---
Irr. × Block	---	---	---	---	---	---
Irr. × Year	---	---	---	---	---	---
Irr. × Fert. × Block	---	---	---	---	---	---
Irr. × Fert. × Year	---	---	---	---	---	---
Irr. × Block × Year	---	---	---	---	---	---
Fert. × Block	---	---	---	---	---	---
Fert. × Year	---	---	---	0.044	---	---
Fert. × Block × Year	---	---	---	---	---	---
Block × Year	---	---	---	---	---	---
Irr. × Fert. × Block × Year	---	---	---	---	---	---

[1] NDVI, normalized difference vegetation index; RVI, simple ratio vegetation index; GRI, green-to-red ratio index; WBI, water band index. Multispectral Crop Circle ACS-430 calculated indices

represented by “cc”. Indices not denoted with “cc” were calculated by the hyperspectral radiometer.

4.4.3. Irrigation Effects on Tall Fescue Responses, Soil Volumetric Water Content, and Spectral Indices

Irrigating throughout the year at 80% ET resulted in greater soil VWC and improved tall fescue biomass, tissue N accumulation, and visual quality compared to plots that experienced drought during summer months (0% ET) (Table 4.4). This was expected as water is a limiting factor for growth.

Table 4.4. Irrigation strategies effects on turfgrass biomass, leaf tissue N accumulation, and visual quality of tall fescue. Means reported are the average among the sampling dates for each year. Sampling was conducted between April and October for 2017 and between April and August of 2018.

	Tall Fescue Quality [1]		Biomass		Tissue N Accumulation [2]		Soil VWC [3]	
Treatment	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
			kg ha^{-1}		**kg ha^{-1}**		**%**	
0% ET [4]	6.1b [5]	5.8b	80.8b	102b	3.0b	3.5b	40b	39b
80% ET	6.6a	7.2a	114a	156a	4.8a	5.7a	49a	51a

[1] Visual quality ratings are rated on a scale of 1 to 9, where 9 indicates an ideal turfgrass stand, 6 is the minimum acceptable quality, and 1 indicates the turfgrass is dormant or dead; [2] Based on the product of tissue N% and biomass; [3] Soil volumetric water content (VWC) determined using time-domain reflectometry TDR; [4] 0% evapotranspiration (ET), no irrigation was applied during summer stress months unless crop death was imminent and 80% ET, irrigation was applied at 80% of measured evapotranspiration. [5] Means in the same column followed by the same lowercase letter are not significantly different at $p < 0.05$.

Pearson correlation coefficients were separated by main factor (irrigation) to examine the relationships between indices analyzed and instrument used (hyperspectral vs. multispectral) since all indices were significantly affected by irrigation treatment ($p < 0.001$, Table 4.3). All spectral indices for both instruments resulted in greater values in the 80% ET compared to the 0% ET treatment (Table 4.5). This correlates to the observed increase of turfgrass response and soil VWC in the 80% ET for 2017 and 2018 (Table 4.4).

4.4.4. Irrigation Effects on Measurement Correlations

Each index was significantly (p <0.0001) related to all tall fescue responses (Table 4.6). All indices were more associated to the corresponding tall fescue measurement for the 0% ET treatment (r = 0.39–0.83) than the 80% ET treatment (r = 0.32–0.81). The indices measured by the Crop Circle ACS-430 was best at estimating overall turfgrass quality (0% ET r = 0.77–0.81; 80% ET r = 0.54–0.63), where NDVI provided the best estimate for both irrigation treatments. The ability of the Crop Circle ACS-430 to obtain data faster and over a larger area provided a better representation of turfgrass quality compared to the isolated spot measurements using the hyperspectral radiometer (0% ET r = 0.65–0.75; 80% ET r = 0.24–0.38). The same trends were observed for biomass and tissue N accumulation. Increased correlation was observed for 0% ET vs. 80% ET and the Crop Circle ACS-430 was a better estimator of biomass and tissue N accumulation. The RVIcc was the most related index to biomass and tissue N accumulation (r = 0.76–0.83). This matches reports that RVI is a better index than NDVI for established turfgrass systems because of the near-complete canopy coverage [47].

Table 4.5. Irrigation strategies effects on spectral indexes. Means reported are the average among the sampling dates for each year. Sampling was conducted between April and October for 2017 and between April and August of 2018.

	NDVI [1]		NDVIcc		RVI		RVIcc		GRI		WBI	
Treatment	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
0% ET [2]	0.69b [3]	0.69b	0.70b	0.70b	7.5b	7.2b	6.5b	7.5b	1.8b	1.7b	1.02b	1.02b
80% ET	0.73a	0.77a	0.76a	0.83a	8.2a	9.2a	8.4a	11a	1.9a	1.9a	1.03a	1.03a

[1] NDVI, normalized difference vegetation index; RVI, simple ratio vegetation index; GRI, green-to-red ratio index; WBI, water band index. Multispectral Crop Circle ACS-430 calculated indices represented by "cc". Indices not denoted with "cc" were calculated by the hyperspectral radiometer; [2] 0% evapotranspiration (ET), no irrigation was applied during summer stress months unless crop death was imminent and 80% ET, irrigation was applied at 80% of measured evapotranspiration; [3] Means in the same column followed by the same lowercase letter are not significantly different at p <0.05.

Table 4.6. Pearson correlation coefficients (r) between turfgrass quality, tissue N content, tissue biomass, soil volumetric water content (VWC), and vegetation indices derived from spectral reflectance of tall fescue grown in Blacksburg, VA utilizing two irrigation strategies.

	Turfgrass Quality		Biomass		Tissue N Accumulation (kg ha^{-1})		Soil VWC	
Index	0% ET [1]	80% ET	0% ET	80% ET	0% ET	80% ET	0% ET	80% ET
NDVI [2]	0.75 *	0.38	0.64	0.49	0.62	0.48	0.54	NS
$NDVI_{CC}$	0.81	0.63	0.70	0.75	0.68	0.70	0.49	NS
RVI	0.65	0.32	0.64	0.44	0.64	0.46	0.49	NS
RVI_{CC}	0.77	0.54	0.83	0.81	0.78	0.76	0.42	NS
GRI	0.70	0.24	0.64	0.29	0.62	0.30	0.54	NS
WBI	0.71	0.24	0.66	0.30	0.65	0.32	0.60	0.17

[1] 0% evapotranspiration (ET), no irrigation was applied during summer stress months unless crop death was imminent; 80% ET, irrigation was applied at 80% of measured evapotranspiration; [2] NDVI, normalized difference vegetation index; RVI, simple ratio vegetation index; GRI, green-to-red ratio index; WBI, water band index. Multispectral Crop Circle ACS-430 calculated indices represented by "cc". Indices not denoted with "cc" were calculated by the hyperspectral radiometer; * All significant at p <0.001 except for soil volumetric water content (VWC) × WBI 80% ET (p <0.01) and those denoted as "NS" are not significant at p = 0.05.

Nonlinear regression using a four-parameter logistic model of representative indices and tall fescue responses highlight the need for variability in data collected and collecting more data using tools like the Crop Circle ACS-430 radiometer (Figure 4.2; Table 4.7). The multispectral Crop Circle ACS-430 outperformed the hyperspectral radiometer in correlation to turfgrass quality and biomass for all dates except for RVI x biomass on 6 June 2018. This is most likely a result of the collection of approximately 100 readings per experimental unit vs. the four readings per experimental unit using the hyperspectral radiometer. The NDVIcc was strongly correlated to the maximum drought day during each year (26 July 2017: r = 0.87; 12 July 2017: r = 0.98). The maximum drought day was considered when irrigation was needed to prevent crop failure. Figure 2 emphasizes that the indices performed well during drought stress that 12 July 2018 had a r^2 = 0.98 compared to other assessment dates when no visible drought stress was evident. Dates such as 2 May 2018 were poorly correlated as a consequence of a lack of variation in data (Figure 2). Well-maintained turfgrass (e.g., irrigation and fertilization) was not able to be used in developing strong index relationships due to a lack of stress and thus, a lack of variation in the data. The RVIcc had strong relationships to tall fescue biomass (r = 0.61–0.93) with the exceptions of 23 May 2018 and 6 June 2018 (Table 4.7).

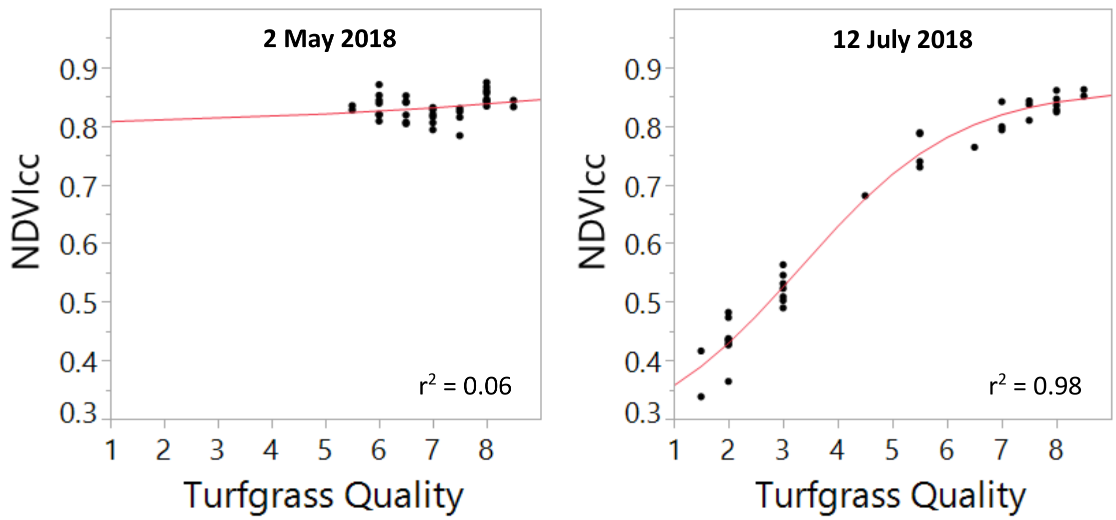


Figure 4.2. Example of nonlinear four parameter logistic regression used for the normalized difference vegetation index measured by the Crop Circle ACS-430 (NDVIcc) on the individual dates of 2 May 2018 and 12 July 2018.

Table 4.7. Coefficient of determination (r^2) of individual dates comparing hyperspectral and multispectral responses between vegetation indices and measured turfgrass parameters using a nonlinear regression four-parameter logistic model.

Index	18 May 2017	14 June 2017	28 June 2017	12 July 2017	26 July 2017	16 August 2017	13 September 2017	29 September 2017	10 November 2017	18 April 2018	2 May 2018	23 May 2018	6 June 2018	19 June 2018	12 July 2018	19 July 2018	9 August 2018
NDVI [1] × Turfgrass Quality (TQ) [2]	0.06	0.16	--- [3]	0.26	0.69	---	---	0.22	0.01	0.04	0.04	0.11	0.20	---	0.90	---	0.27
NDVIcc × TQ	0.35	0.69	0.77	0.61	0.81	0.79	0.81	0.56	---	---	0.06	0.15	0.29	0.91	0.98	0.93	0.76
RVI × Biomass [4]	---	0.11	---	0.34	0.62	---	---	0.06	0.15	0.04	---	0.32	0.33	---	0.72	---	0.34
RVIcc × Biomass	---	0.81	0.84	0.83	0.85	0.84	0.93	0.64	---	---	---	0.34	0.11	0.77	0.83	---	0.61

[1] NDVI, normalized difference vegetation index; RVI, simple ratio vegetation index. Multispectral Crop Circle ACS-430 calculated indices represented by "cc". Indices not denoted with "cc" were calculated by the hyperspectral radiometer; [2] Relationship between turfgrass quality (TQ) and NDVI and NDVIcc by date; [3] Dashes indicate measurement unable to be taken on that date; [4] Relationship between tall fescue biomass and RVI and RVIcc by date.

All indices were more associated with soil VWC for the 0% ET treatment than the 80% ET treatment (Table 4.6). The WBI, GRI, and NDVI indices were the strongest correlated to soil VWC in the 0% ET treatment (r = 0.60, 0.54, and 0.54, respectively). The lack of correlation to soil VWC for the 80% ET suggests that the well-watered turfgrass was influenced by other factors (e.g., nutrient availability). Indices related to chlorophyll pigments such as NDVI are likely not a good indicator of water availability prior to drought stress as its decline only comes after drought stress [26]. The red reflectance used in NDVI is known to be significantly affected by chlorophyll content and absorption [48]. DaCosta et al. [49] found that chlorophyll concentrations decrease with drought stress. The WBI can provide a better indication of water stress prior to chlorophyll degradation as it utilizes reflectance outside the PAR.

Nonlinear regression using a four-parameter logistic of WBI and GRI by date provides evidence that these indices can be used as a soil moisture management tool once relationships between spectral reflectance and soil and turfgrass parameters have been fully established. While WBI continues to be a narrowband index that is closely associated with drought stress, we also examined the GRI as a cheaper alternative to WBI with more immediate practical application. In 2017, as drought is imposed in early summer the WBI and GRI have low correlation to soil VWC (Figure 4.3). As the soil dries down, the relationship between the indices and VWC increases and the strongest relationship for both WBI (r^2 = 0.69) and GRI (r^2 = 0.64) occurs at the maximum drought day (26 July 2017) (Figure 4). This agrees with Figure 4.2 where increased variability of data provided stronger relationships. Nonlinear four parameter logistic regression indicates that the inflection point occurs at 36% soil VWC for WBI and 38% soil VWC for GRI. After this date, irrigation was applied to all plots and the relationship between indices and soil VWC was no longer significant (p > 0.15–0.84) for the remainder of 2017. A similar trend was observed in 2018 (Figure

4.3). During dates of limited water stress, there is a lack of strong correlation between indices. The greatest water stress date measured in 2018 (12 July 2018) indicated the strongest relationship of all dates measured (WBI: $r^2 = 0.79$; GRI: $r^2 = 0.75$) (Figure 4.5). Nonlinear four-parameter logistic regression indicates that the inflection point occurs at 32% soil VWC for both WBI and GRI. The results from 2017 and 2018 suggest that the onset of drought stress in tall fescue around 32–38% soil VWC, meaning that the soil VWC should be maintained above this level to prevent drought stress for tall fescue in a clay soil. Indices were separated by date as the pooled data for both irrigation treatments across all dates resulted in weak relationships for WBI ($r^2 = 0.20$) and GRI ($r^2 = 0.21$) to soil VWC.

We believe that with increased sampling frequency and data points, predicting water stress prior to the onset of visible symptoms could be accomplished using indices such as WBI and GRI. This was observed in a greenhouse trial by Roberson [27], where WBI and GRI detected moisture stress 27 h before NDVI. More research into validating the GRI as a water stress predictor should be prioritized as it is a far cheaper option compared to WBI. Determining turfgrass quality reduction by using indices in combination such as the NDVIcc and WBI or GRI can potentially provide indication of stress such as drought stress or quality reductions due to other stresses such as fertility.

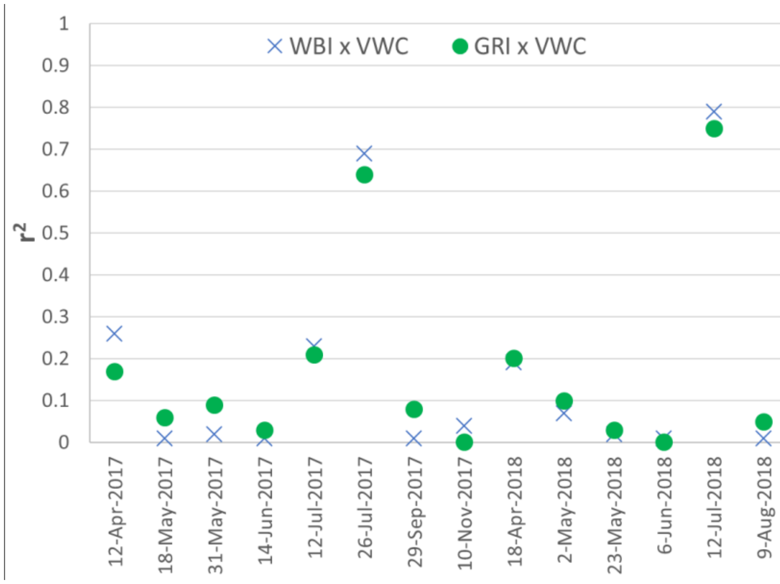


Figure 4.3. Nonlinear four parameter logistic regression between soil volumetric water content (VWC) and the narrowband water band index (WBI) and the green-to-red ratio index (GRI) by date.

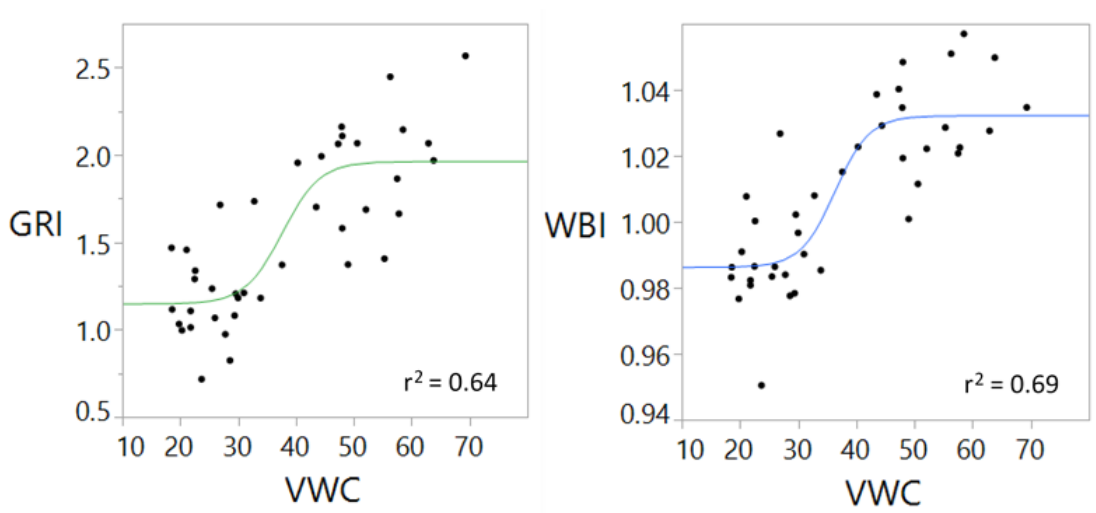


Figure 4.4. Nonlinear four parameter logistic regression for the green-to-red ratio index (GRI) and the water band index (WBI) compared to soil volumetric water content (VWC) for 26 July 2017.

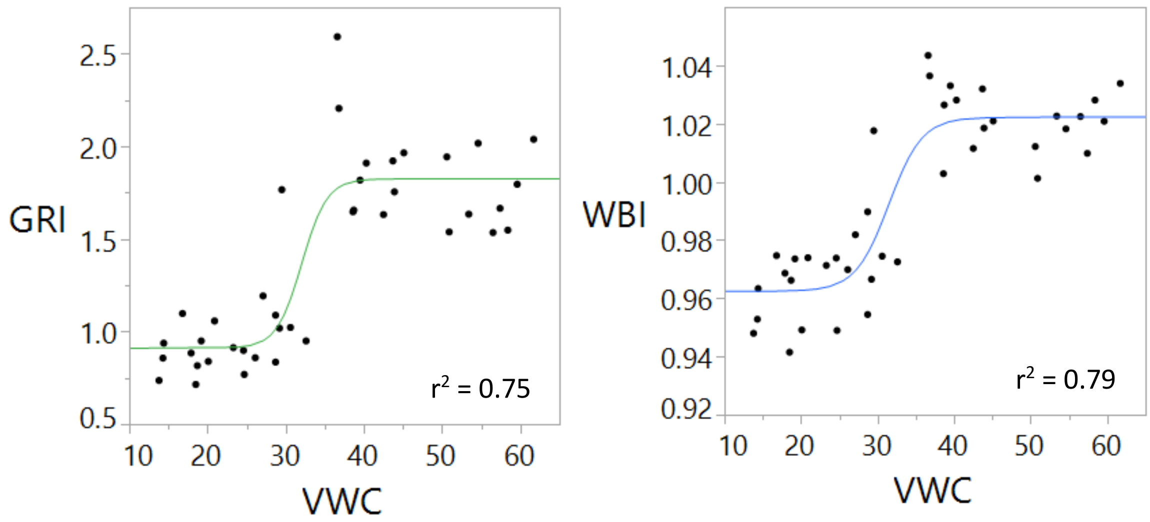


Figure 4.5. Nonlinear four parameter logistic regression for the green-to-red ratio index (GRI) and the water band index (WBI) compared to soil volumetric water content (VWC) for 12 July 2018.

4.4.5. Fertility Effects on Tall Fescue Responses, Soil Volumetric Water Content, and Spectral Indices

Fertility treatment affected all measured turfgrass and soil variables (Table 4.2). Only indices measured by the multispectral Crop Circle ACS-430 detected significant differences among fertility amendments (Table 4.3). This provides further evidence that more information can be obtained from a radiometer that can cover a large area in a cost-effective manner. Biosolids-based amendments applied at the agronomic N rate (BBN, CBN, and DBN) resulted in increased turfgrass quality, biomass, and tissue N accumulation compared to BBP and FER in 2017 (Table 4.8). In the following year, BBN and CBN had yielded the greater turfgrass quality, biomass, and tissue N accumulation. The improved tall fescue response from the BBN, CBN, and DBN amendments is most likely a result of a long-term accumulation of benefits (e.g., slow release of nutrients and reduced soil bulk density) derived from multiple applications of organic matter and organic N inputs beginning in 2013 [41].

The NDVIcc and RVIcc response to fertility treatment was similar to the turfgrass fertility response trends (Table 4.8). The NDVIcc measurements matched the biomass response of 2017, where BBN, CBN, and DBN had increased measured response by NDVIcc (0.75, 0.76, and 0.75, respectively) and lowered measurement response for BBP and FER (0.70 and 0.68, respectively). The RVIcc measurements matched and were strongly correlated (r = 0.51–0.92) to the tissue N accumulation of 2017, where BBN and CBN had increased measured response by RVIcc and lowered measurement response in BBP and FER (Tables 4.8 and 4.9). The NDVIcc was unable to detect differences between fertility treatments in 2018, whereas RVIcc measurement response was similar to the trends observed in turfgrass parameters (Table 4.8). This provides further evidence that the RVI is a better option for established turfgrass systems [47].

Soil VWC was greatest in FER and BBP during 2017 (Table 4.8). This most likely relates to the tall fescue responses observed in 2017. The FER and BBP had the lowest biomass and quality ratings, suggesting that water was remaining in the soil. This contrasts to the BBN, CBN, and DBN amendments that had increased biomass and quality, suggesting that water was translocated from the soil pores to the leaf tissue. In 2018, only the BBN resulted in lower soil VWC despite similar values reported in 2017. Greater variability in the data is a possible explanation for the muted response in 2018 soil VWC. Increased strength between indices and soil VWC relationships were observed in 2018 (r = 0.66–0.78) despite the lack of significant difference in soil VWC during 2018 (Tables 4.8 and 4.9). This data contributes to the idea that NDVI and RVI are not able to adequately differentiate the cause of the plant response (e.g., soil moisture vs. fertility) [16].

Table 4.8. Fertility amendments effects on turfgrass quality, biomass, leaf tissue N accumulation, soil volumetric water content (VWC), normalized vegetation index (NDVI) and simple ratio vegetation index (RVI). Means reported are the average among the sampling dates for each year. Sampling was conducted between April and October for 2017 and between April and August of 2018.

	Tall Fescue Quality [1]		Biomass		Tissue N Accumulation [2]		Soil VWC [3]		NDVIcc [4]		RVIcc	
Treatment [5]	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**
			kg ha^{-1}		**kg ha^{-1}**		**%**					
FER	4.9d [6]	5.7d	54.5b	90.0c	2.1c	2.9c	49a	48a	0.68b	0.75a	5.9c	8.67b
DBN	6.7b	6.5bc	97.5a	126b	3.7b	4.6ab	46bc	45a	0.75a	0.76a	7.8b	8.89ab
BBN	7.4a	7.0ab	139a	162a	6.0a	6.0a	37d	38b	0.77a	0.77a	8.9a	9.98ab
BBP	5.6c	6.2cd	74.4b	101bc	2.9c	3.4bc	47ab	47a	0.70b	0.76a	6.4c	9.33ab
CBN	7.4a	7.2a	122a	165a	4.8ab	6.0a	44c	45a	0.76a	0.78a	8.5ab	10.2a

[1] Visual quality ratings are rated on a scale of 1 to 9, where 9 indicates an ideal turfgrass stand, 6 is the minimum acceptable quality, and 1 indicates the turfgrass is dormant or dead; [2] Based on the product of tissue N% and biomass. [3] Soil volumetric water content determined using time-domain reflectometry TDR; [4] NDVI, normalized difference vegetation index; RVI, simple ratio vegetation index. Multispectral Crop Circle ACS-430 calculated indices represented by "cc"; [5] FER, annually applied synthetic N–P–K fertilizer; DBN, biosolids applied annually at an agronomic N rate; BBN, blended biosolids–sand–sawdust applied annually at an agronomic N rate; BBP, blended biosolids–sand–sawdust applied annually at an agronomic P rate plus supplemental fertilizer N; CBN, composted biosolids applied annually at an agronomic N rate; [6] Means in the same column followed by the same lowercase letter are not significantly different at $p < 0.05$.

Table 4.9. Pearson correlation coefficients (r) between turfgrass quality, leaf tissue N accumulation, soil volumetric water content (VWC), and vegetation indices derived from traditional multispectral Crop Circle ACS-430 of tall fescue grown under five different fertility amendments in Blacksburg, VA.

	Turfgrass Quality				Tissue N Accumulation (kg ha^{-1})				Soil VWC			
	2017		2018		2017		2018		2017		2018	
Index	**NDVIcc** [1]	**RVIcc**	**NDVIcc**	**RVIcc**	**NDVIcc**	**RVIcc**	**NDVIcc**	**RVIcc**	**NDVIcc**	**RVIcc**	**NDVIcc**	**RVIcc**
FER [2]	0.68 *	0.59	0.83	0.73	0.38	0.51	NS	NS	NS	NS	0.71	0.66
BBN	0.67	0.44	0.90	0.84	0.63	0.86	0.25	0.49	0.36	0.33	0.68	0.78
BBP	0.53	0.40	0.82	0.73	0.80	0.92	−0.74	−0.46	0.27	NS	0.70	0.76
DBN	0.41	0.23	0.87	0.82	0.66	0.86	0.46	0.59	0.39	0.30	0.66	0.70
CBN	0.47	0.30	0.87	0.82	0.72	0.91	−0.43	NS	0.47	0.42	0.69	0.77

[1] NDVI, normalized difference vegetation index; RVI, simple ratio vegetation index; [2] FER, annually applied synthetic N–P–K fertilizer; BBN, blended biosolids–sand–sawdust applied annually at an agronomic N rate; BBP, blended biosolids–sand–sawdust applied annually at an agronomic P rate plus supplemental fertilizer N; DBN, biosolids applied annually at an agronomic N rate; CBN, composted biosolids applied annually at an agronomic N rate; * All significant at p <0.001 except those denoted as NS which are not significant at p = 0.05.

4.4.6. Practical Management Implications

Our data shows the need for continuous measurements across turfgrass systems to provide an adequate spatial representation as opposed to limited data collection points. Collecting spectral reflectance data at different heights, including the use of unmanned aerial vehicles, and direct measurements of turfgrass and soil parameters for validation should be conducted in turfgrass research to enable faster data collection over larger areas and continue the development of spectral indices' relationships to measured variables. Our data contributes to this growing dataset that shows how spectral indices could be used to monitor drought stress. Specifically, our data shows tall fescue spectral response under heavy clay soils, which is a prevalent turfgrass-soil system in the transition zone of the United States. Spectral reflectance of various turfgrasses grown on varying soils types should respond differently when subjected to insufficient moisture availability [27]. Despite the strong correlation of WBI to soil moisture stress, it requires narrowband reflectance which increases costs and limits the number of samples collected. The GRI may be calculated using simple digital imagery. This allows for a more robust and rapid dataset collection across larger surfaces that may yield quicker development of vegetation indices relationships to measured variables.

4.5. Conclusions

Turfgrass management strategies that reduce water inputs and maintain turfgrass quality are needed for landowners and turfgrass managers. This research determined the value of spectral reflectance data collected from handheld hyperspectral and mobile multispectral radiometers as management tools to detect water and nutrient stress in turfgrass. In almost all responses measured, the multispectral radiometer outperformed the hyperspectral radiometer for evaluating moisture and nutrient relationships due to increased data collection. Spectral indices were best for detecting differences in turfgrass and soil responses when there was stressed and well-maintained turfgrass tissue. This variability was essential to form strong relationships between spectral indices and turfgrass and soil responses. Water stress was best determined using the water band index and green-to-red ratio index. The strong relationships to soil volumetric water content suggests that these indices can be used at the field scale as a potential tool in turfgrass water management. Continued research using the water band index and green-to-red ratio index with ground validation measurements should be conducted to improve relationships and determine soil volumetric water contents that should be maintained before visible drought stress. The detection of differences as a result of N fertility source was only able to be captured by the increased data collection from the mobile multispectral radiometer. The simple ratio vegetation index was best correlated to growth and quality of the established turfgrass stands. Increased sampling frequency and data collection of various turfgrass-soil systems should advance the turfgrass industry and managers in their ability to reduce their water usage and maintain turfgrass quality using spectral indices.

4.6. Author Contributions

Conceptualization, M.J.B., D.S.M., and G.E.; methodology, M.J.B. and D.S.M.; formal analysis, M.J.B.; data curation, M.J.B.; writing—original draft preparation, M.J.B.; writing—review and editing, D.S.M. and D.S.M.; funding acquisition, G.E.

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4.9. Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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5. Conclusion

Biosolids are produced and used in substantial quantities. Approximately 50% of the biosolids produced in the United States are land-applied, and their beneficial effects derived from these nutrient-rich organic matter (OM) sources have been well-documented in agriculture, forestry and mined land reclamation. Exceptional quality (EQ) biosolids have been treated through processes to further reduce pathogens, vector attraction, and pollutant concentrations and are being created in greater quantities in hopes to improve land recycling rates, especially to anthropogenically disturbed urban soils. Research regarding biosolids application to disturbed urban soils and the main plant choice, turfgrass, has remained largely unexplored. There is a lack of information evaluating EQ products that best deliver nitrogen (N) to turfgrass and promote improved establishment and maintenance of turfgrass while reducing deleterious environmental impacts such as phosphorus (P) loss. Our research also looked to address best management practices to reduce water use.

Chapters 2 and 3 of this dissertation focused on determining the EQ biosolids effects on establishment and maintenance of tall fescue turfgrass and the changes that occurred over 5 years in soil physical and chemical properties of an anthropogenically disturbed urban soil. Chapter 4 assessed the use of spectral reflectance on our field study described in chapters 2 and 3 to improve soil-water-plant relationships for future development of predicting the onset of water-stress in turfgrass.

We conducted a five-year field study to evaluate EQ biosolids products at the agronomic N rate and agronomic P rate supplemented with sulfur-coated urea fertilizer of tall fescue and a conventional synthetic fertilizer program effects on tall fescue growth and quality and soil physical and chemical properties. Our results found that the biosolids-based products lagged in producing a quality turfgrass stand. This was most likely a result of under estimating N availability and applying the biosolids in a single application rather than splitting application rates to improve N use efficiency. After the first year and for the remainder four years of the field trial, biosolids applied at the agronomic N rate provided the best long-term solution for improved growth and quality of tall fescue turfgrass. Biosolids applied at the agronomic P rate with supplemental synthetic N produced an acceptable quality turfgrass stand in the final year of the study. Repeated applications of biosolids amendments reduced soil bulk density and increased soil OC and N stocks with minimal environmental P risk. There was no increase of risk of P loss as determined by water-soluble P from biosolids applied at the agronomic N rate due to high biosolids Fe concentrations. Our results indicate that current soil P regulations likely overestimate P runoff risk from biosolids containing high Fe concentrations. In areas that require land application based on crop P needs, the biosolids agronomic P rate strategy can be used successfully for maintenance of turfgrass.

We used our field trial during the final two years to assess the value of spectral reflectance data collected from handheld hyperspectral and mobile multispectral radiometers as management tools to detect water and nutrient stress in turfgrass. The multispectral radiometer outperformed the hyperspectral radiometer due to increased, continuous data collection. Developing strong relationships between turfgrass and soil responses was only possible when there was a range of stressed and well-maintained turfgrass tissue. Soil volumetric water content was most correlated to the water band index and the green-to-red ratio index. Development of these indices to various turfgrasses and soils should be a priority for the future of turfgrass water management. Differences in N fertility were measured using the multispectral radiometer as a result of increased data collection. The simple ratio vegetation index was the index best correlated to turfgrass growth and quality. Using tools that allow for increased, continuous sampling, such unmanned aerial vehicles, should advance the turfgrass industry and managers management strategies for improving irrigation and fertilization.

The increase in EQ biosolids production represents a locally-sourced organic amendment that can improve degraded urban soils of the surrounding community. Our study has shown just some of the numerous benefits derived from using EQ biosolids including rehabilitating degraded soils, improving turfgrass growth and quality, and mitigating climate change through the addition of stable organic matter. Wastewater treatment plants producing EQ biosolids can use the biosolids as a source of revenue and the local community can improve their soils and plant growth while reducing the use of energy-intensive synthetic fertilizers.