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# Biosolids amendments improve an anthropogenically disturbed urban turfgrass system

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**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 organic C (OC) stocks, but repeated applications of such organic byproducts may result in excess soil P. Here, we present further data that complete the observations for a 5-yr study (September 2013–October 2018) conducted on an anthropogenic soil tall fescue (*Festuca arundinacea* Schreb.) system. This study compared the effects of irrigation strategies (with or without irrigation during summer heat stress) and soil amendments (annual applications of biosolids products and a conventional synthetic fertilizer) for improving soil properties and tall fescue health. Biosolids amendments applied at the agronomic N rate (ANR) reduced soil bulk density at the 0- to 5-cm depth by 33–53% and at the 5- to 10-cm depth by 4–9% relative to synthetic fertilizer. Soil OC in the top 10 cm increased from 1.74 to 13.6 g OC $kg^{-1}$ (i.e., +682%) over the 5-yr period for the conventionally fertilized tall fescue, and larger gains were observed in the biosolids treatments. Repeated applications of biosolids amendments at the ANR increased total P concentrations; however, biosolids containing high Fe concentrations did not increase water-soluble P compared with biosolids applied at the agronomic P rate (APR) and synthetic fertilizer after 5 yr. Biosolids amendments applied at the ANR improved tall fescue visual quality (maintained acceptable quality 86–92% of the time), clipping biomass, and leaf tissue N accumulation ($P < .05$).

## 1 | INTRODUCTION

The urban area of the conterminous United States is ∼3% and expanding, resulting in extensive land use and vegetative change from the formerly surrounding forest, range, or agricultural land (Imhoff, Lawrence, Stutzer, & Elvidge, 1997). Anthropogenic development often results in mechanical topsoil removal, exposing a compacted subsoil, or requires offsite fill as the new soil surface (Lorenz & 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 organic C (OC) and nutrient content and soil compaction impeding root development (Beniston & Lal, 2012; Harris, 1991). Perennial plant cover (e.g., turfgrass), organic amendments, fertilization, and irrigation are restoration practices that can alleviate low soil OC and nutrient

**Abbreviations:** ANR, agronomic nitrogen rate; APR, agronomic phosphorus rate; 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; ET, evapotranspiration; FER, synthetic fertilizer; OC, organic carbon; PAN, plant available nitrogen; PSR, phosphorus saturation ratio.

content (e.g., N and P) and reduce soil compaction (Lal, 2004; Milesi et al., 2005; Post & Kwon, 2000; Post et al., 2004).

Urban turfgrass soil systems have gained interest for their potential to store soil C. Determining the influence of turfgrass and management practices (e.g., irrigation and fertilization) on C storage rates has been the goal of recent research (Pouyat, Groffman, Yesilonis, & Hernandez, 2002; Pouyat, Yesilonis, & Nowak, 2006; Milesi et al., 2005; Zirkle, Lal, & Augustin, 2011). Pouyat, Yesilonis, and Nowak (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. Accumulation of soil OC has been documented to be a major factor offsetting greenhouse gas emissions (Golubiewski, 2006; Law & Patton, 2017; Townsend-Small & Czimczik, 2010).

Achieving the highest C storage potential of turfgrass systems requires the input of irrigation and fertilization (Milesi et al., 2005; Selhourst & 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 & 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 efficient use of 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 K (Soldat & Petrovic, 2008). Until recently, organic amendments, such as locally produced biosolids, have received limited use for lawn fertilization due to accessibility, transportation costs, and quality concerns (Loschinkohl & Boehm, 2001). Wastewater treatment facilities have increasingly adopted the production of exceptional quality biosolids with no application restrictions except for plant available N and P. Such biosolids are treated by processes to further reduce pathogens and have reduced vector attraction and low pollutant concentrations (USEPA, 1994).

Biosolids normally have low N/P stoichiometric ratios (Cogger, Forge, & Neilsen, 2006). Nitrogen is generally the most limiting nutrient for turfgrass growth and is used as the basis of fertility recommendations (Carrow, Waddington, & Rieke, 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 & 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 & 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 Mehlich-3-extractable P/Fe + Al (Breeuwsma & Silva, 1992; Lu, He, & Stoffella, 2012; Maguire & Sims, 2002). The upper few centimeters of soil in turfgrass systems should be sampled to obtain a representative soil P saturation to determine the risk of P surface runoff when fertilizer and organic amendments are surface applied (Soldat & Petrovic, 2007).

Some studies have demonstrated lower P loss risk with organic amendments than with conventional synthetic fertilizers (Ajiboye, Akinremi, & Racz, 2004; He et al., 2000; Maguire, Sims, Dentel, Coale, & Mah, 2001; White, Coale, Sims, & Shober, 2010; Withers, Clay, & Breeze, 2001). 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 (Elliott, O'Connor, Lu, & Brinton, 2002; Elliott, Brandt, & O'Connor, 2005; Penn & 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 (Lu & O'Connor, 2001; Penn & Sims, 2002). Despite the reduction of P solubility in biosolids compared with 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, 1999). Water requirements are based on evapotranspiration (ET), or 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 an inexpensive onsite alternative to traditionally determined ET via the Kimberly–Penman equation that uses weather stations. Irrigating to replace 80% of reference ET has been widely accepted for maintaining acceptable quality of a turfgrass stand (Ervin & Koski, 2001).

The addition of organic amendments and increasing OC has been suggested as a drought management strategy by increasing available water capacity and water retention (Lal, 2004; Rawls, Pachepsky, Ritchie, Sobecki, & Bloodworth, 2003). Johnson, Qian, and Davis (2009) found that compost topdressing resulted in increased soil water content and improved Kentucky bluegrass (*Poa pratensis* L.) visual quality compared with 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 amendments, on drought tolerance in urban turfgrass systems is needed.

Our initial results for the trial (August 2013–June 2016) discussed the effects of biosolids amendments compared with a synthetic fertilizer program on tall fescue turfgrass establishment and soil properties grown with or without irrigation during summer stress (Badzmierowski, Evanylo, Ervin, Boyd, & Brewster, 2019). We hypothesized that the added organic matter from biosolids amendments would improve summer stress tolerance by improving available water capacity. These results were inconclusive as a result of limited moisture stress. Biosolids amendments applied at the agronomic N rate (ANR) for tall fescue resulted in improved turfgrass quality and growth and increased total soil OC and N (Badzmierowski et al., 2019). However, biosolids amendments applied at the agronomic P rate (APR) did not yield acceptable quality turfgrass. This study addresses the shortcomings of our previous study and expands on the longer term effects of topdressing biosolids fertilizer amendments to an anthropogenically disturbed urban turfgrass system.

Our objectives were (a) to compare two irrigation strategies and the use of a conventional synthetic fertilizer program to exceptional quality biosolids products of varying C, N, and P concentrations to enhance physical and chemical properties of an anthropogenically disturbed urban soil, (b) to determine the irrigation and fertility strategy that maximized OC and N accumulation, (c) to determine if applying biosolids at sufficient PAN levels will increase soil P to excessive concentrations, and (d) to improve tall fescue quality and growth. Our hypothesis was that biosolids amendments would improve turfgrass quality, growth, drought resistance, and drought recovery of tall fescue compared with a conventional synthetic fertilizer program. We hypothesized that the added organic matter from biosolids amendments would increase available water capacity. Additionally, we hypothesized that increased inputs (e.g., nutrients and irrigation) would increase OC and N stocks in the soil.

## 2 | MATERIALS AND METHODS

### 2.1 | 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), located in Cold Hardiness Zone 6b (Daly, Widrlechner, Halbleib, Smith, & Gibson, 2012). The site was located on fine, mixed, semiactive, mesic Typic Hapludults that were graded for an airport runway in the 1940s. The graded area was converted to a tall fescue stand after plans for a runway were abandoned. Prior to beginning the study, the topsoil that had developed was removed to the Bt1 horizon. 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).

### 2.2 | 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 organic amendments, initially tilled into the soil, with subsequent applications surface applied. Irrigation water characteristics were pH = 7.2, electrical conductivity = 0.16 dS $m^{-1}$, nitrate = 0.67 mg $L^{-1}$, ammonium = 0.23 mg $L^{-1}$, and orthophosphate = 0.46 mg $L^{-1}$. Irrigation treatments were (a) no water applied during critical summer months, unless necessary to keep turfgrass alive, and (b) water applied every 3 d 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 nonirrigated main plots from 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 × 3.7 m. Results reported here describe the effects of drought stress during 2016–2018.

The five subplot treatments were synthetic fertilizer and four exceptional quality biosolids products. Fertility amendments were applied annually (September–August) to provide an estimated PAN rate of 224 kg $ha^{-1}$ from September 2013 to June 2015, and applications resumed 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 first application in September 2013 was incorporated to a depth of 10 cm. All subsequent applications were surface applied and temporally split, as shown in Table 1. The dimensions of each subplot were 3.66 × 3.66 m, and each subplot was separated by a 0.61-m buffer strip.

### 2.3 | Amendment treatments, biosolids analysis, and soil fertility

Four exceptional quality anaerobically digested biosolids treatments were used in the study: (a) dewatered biosolids applied annually at rates to supply required PAN (DBN), (b) dewatered biosolids blended with sand and sawdust annually applied at rates to supply required PAN (BBN), (c) dewatered biosolids blended with sand and sawdust annually applied at rates to supply P recommended by the Virginia Tech Soil Testing Laboratory plus supplemental S-coated urea fertilizer to provide equal annual PAN per hectare (BBP), and (d) biosolids compost annually applied at rates to supply required PAN (CBN). Plant available N was based on the sum of estimates of organic N that mineralize during the first year after application (VA DCR, 2014) and 100% of the inorganic ($NH_4$– and $NO_3$–) N. Estimated organic N mineralization rates were 30% for DBN, 20% for biosolids–sand–sawdust blend, and 15% for the CBN as described by Yu, Evanylo, and Haering (2013) and Virginia Department of Conservation and Recreation nutrient management standards (VA DCR, 2014). 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–$P_2O_5$–K) and muriate of potash (0–0–60 N–P–$K_2O$) applications for 2016–2018 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 1 for application rates and dates.

Exceptional quality unblended biosolids (DBN) used throughout the study were either processed by anaerobic digestion and pasteurization (Alexandria Renew Enterprises; see Badzmierowski et al., 2019) or by thermal hydrolysis and anaerobic digestion (DC Water Blue Plains Advanced Wastewater Treatment Plant). The digested biosolids were dewatered and either applied "as is" or blended with sand and sawdust to create a low moisture, greater C-containing product. The Alexandria Renew Enterprises biosolids were applied from 2013 to 2015, and the DC Water Biosolids were applied from 2016 to 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 et al. (2013) to achieve a C/N ratio of 13:1 and a moisture content of ∼50%, and later tested in a greenhouse bioassay by Alvarez-Campos, Evanylo, and Badzmierowski (2018). DC Water creates an exceptional quality 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, Virginia, Livingston compost facility was used through the duration of the study. The biosolids used in the compost were originally from Massaponax wastewater treatment plant.

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, 1995d), total and volatile solids (SM-2540G; APHA, 1995c), organic N (calculated as the difference between total Kjeldahl N and $NH_4$–N), ammonia + ammonium N (SM-4500-NH3C; APHA, 1995a), nitrate + nitrite-N (SM-4500NO3F; APHA, 1995b), and P, K, Fe, and Al (SW-6010C; USEPA, 2000).

### 2.4 | Sampling and analysis

#### 2.4.1 | Soil analyses

Soil was sampled using a 2-cm diam. probe to a depth of 10 cm at the conclusion of the study period (1 Oct. 2018). Soil sampled was subdivided into depths of 0–5 and 5–10 cm. Soil samples were air dried and sieved through a 2-mm sieve. Total soil OC and N concentrations of the 0- to 5- and 5- to 10-cm depths were analyzed using a Vario Max CNS macro elemental analyzer (Elementar Analysensysteme), which uses a combustion chamber at 1,200 °C. Soil OC and N concentrations were converted to OC 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 0–5 and 5–10 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, 0–5 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 0.2 M $CH_3COOH$, 0.25 M $NH_4NO_3$, 0.015 M $NH_4F$, 0.013 M $HNO_3$, and 0.001 M ethylenediaminetetraacetic acid (EDTA), respectively (Kuo, 1996; Mehlich, 1984). 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

**TABLE 1** Application schedule and cumulative amount for each treatment and total C, N, and P applied on a dry weight basis[a]

| Treatment | 14 June 2016 | 22 Sept. 2016 | 29 Mar. 2017 | 20 Sept. 2017 | 18 Oct. 2017 | 3 Apr. 2018 | Total applied, 2013–2018[b] | Total C applied | Total N applied | Total P applied |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg ha$^{-1}$ | | | | | | | | | |
| Synthetic (FER[c]) | 159 | 159 | 53.0 | 159 | 159 | 53.0 | 1,500 (urea[d]) + 400 (Pro-mate[e]) | 0 | 788 | 204.8 |
| Dewatered biosolids (DBN) | 3,810[f] | 11,420 | 2,540 | 7,610 | 7,610 | 2,540 | 16,630 ARE[g] + 35,530 DC[h] | 15,791 | 2,175 | 1,802 |
| 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 | 2,087 |
| 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 | 204.8 |
| Composted biosolids (CBN) | 8,350 | 8,350 | 2,790 | 8,350 | 8,350 | 2,790 | 124,180 | 45,981 | 3,469 | 1,661 |

[a] Application schedule shown is for June 2016–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.

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

[c] 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.

[d] Sulfur-coated urea (46–0–0 N–P–K; Potash Corporation, Saskatchewan, CA).

[e] Pro-Mate (25–5–11 N–P–K; Helena Chemical, Collierville, TN).

[f] The dewatered biosolids (DBN) received only half of required application in June 2016. The half that was not applied in June 2016 was applied with the September 2016 application.

[g] Anaerobically digested biosolids produced at Alexandria Renew Enterprises (ARE) and applied during the trial years 2013–2015.

[h] Anaerobically digested biosolids produced at DC Water Blue Plains Advanced Wastewater Treatment Plant, DC Water, and applied during the trial years 2016–2018.

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 offsite (Brandt, Elliott, & O'Connor, 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).

#### 2.4.2 | 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 elemental analyzer (Elementar Analysensysteme) at 1,200 °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 visually by integrating the color, density, uniformity, and leaf texture on an ordinal scale of 1–9, 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.

### 2.5 | Weather conditions

Mean monthly temperature and precipitation were 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. Precipitation was variable and increased rain during the late summer of 2015 to 2018 (Figure 1). 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.

### 2.6 | Statistical analysis

Data were statistically analyzed using JMP Pro software by SAS version 14.1 and R software (R Development Core Team, 2019). A first-order autoregressive repeated measures mixed model was used to reflect main factors (with or without irrigation during summer stress), subfactors (amendment types), blocking factor, and their interactions to determine significance of differences ($P < .05$). 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 | RESULTS AND DISCUSSION

### 3.1 | Exceptional quality biosolids chemical composition

Organic N was the largest N fraction within each biosolids product used from June 2016 to April 2018 (Table 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 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 2). Total C was highest in the CBN due to the addition of woody fines. All biosolids products had 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).

### 3.2 | Overall study statistical trends

Contrary to the first 2 yr of the study, as reported in Badzmierowski et al. (2019), irrigation × amendment interactions were often detected. The final 2018 total soil OC and N and water-soluble P had significant ($P < .05$) irrigation × fertility amendment interactions. However, water-soluble P had no differences detected among means separated by Tukey honestly significant difference of fertility treatments within each irrigation treatment. This may be due to Tukey's post-hoc test having a conservative alpha level. We reported water-soluble P based on fertility effects due to the lack of differences.

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 ($P < .05$) 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

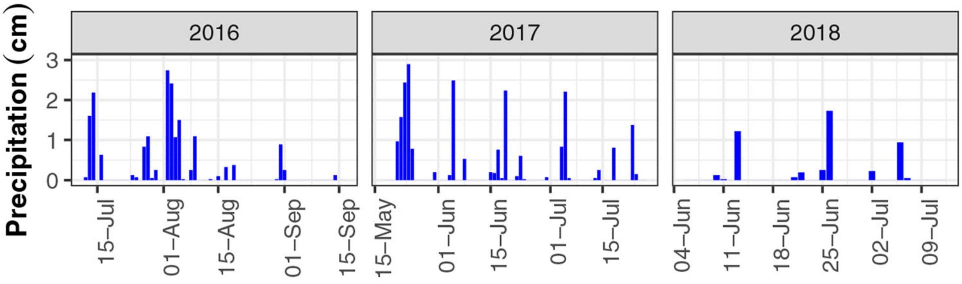


**FIGURE 1** Daily precipitation at the trial location in Blacksburg, VA, during summer drought stress (12 July 2016 to 16 Sept. 2016, 18 May 2017 to 26 July 2017, and 6 June 2018 to 12 July 2018)

**TABLE 2** Chemical composition[a] of the biosolids products used from 2016 to 2018[b]

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

[a]All analysis was performed by A&L Eastern Laboratories, Richmond, VA.
[b]Analyses shown are from subsamples taken in June 2016. Biosolids were analyzed annually to adjust loading rates as necessary. Analyses of original biosolids used from 2013 to 2015 can be seen in Badzmierowski et al. (2019).
[c]TKN, total Kjeldahl N.
[d]DBN, anaerobically digested biosolids (DC Water, Washington DC).
[e]BBN/BBP, anaerobically digested biosolids blended with sand and sawdust (DC Water, Washington DC).
[f]CBN, anaerobically digested biosolids composted with wood fines (Spotsylvania County, Virginia).

0% ET CBN visual quality (5.1) for 26 July 2016 was greater than that of all other 0% ET fertility treatments. The visual quality of the other two biosolids N rates (BBN, DBN) was greater (4.6 and 4.5, respectively) than for FER (3.9). The BBP visual quality (4.4) was equal to that of 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, after summer stress. We expected biosolids amendments to promote more rapid vegetative recovery. The lack of statistical differences in the 0% ET × fertility amendment may be a consequence of infrequent (every other week) sampling. It is possible that differences may have been observed with increased sampling frequency. It is also possible that longer term additions are needed to observe biological benefits (e.g., improved turfgrass drought recovery). 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 5 yr 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.

## 3.3 | Soil responses

### 3.3.1 | Soil bulk density

There was no interaction between the main factor (irrigation treatment) and subfactor (amendments). Both the main factor and subfactor did affect soil bulk density at 0–5 cm, and the subfactor affected 5- to 10-cm bulk density ($P < .05$). Greater bulk density occurred in the 0% ET than in the 80% ET treatment at 0–5 cm. 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 do not provide much biological significance.

Fertility amendments yielded greater contrast in bulk densities than irrigation treatment (Table 3). The trends observed for the 0- to 5-cm depth at the midpoint of this study in Badzmierowski et al. (2019) remained similar, except for BBP, which had lower bulk density than the FER treatment for the 0- to 5-cm depth by the final sampling time (Badzmierowski et al., 2019). The bulk densities were correlated with total C loading rates (Table 1), with the lowest bulk densities occurring with the highest C addition (Table 3). The ANR biosolids decreased bulk density compared with the FER treatment. Our results provide further evidence that surface-applied organic amendments reduce bulk density (García-Orenes et al., 2005; Ouimet, Pion, & Hébert,

**TABLE 3** Biosolids amendment effects after 5 yr on bulk density for a clayey, disturbed urban soil at depths of 0–5 and 5–10 cm

| Treatment | Bulk density | |
|---|---|---|
| | 0–5 cm | 5–10 cm |
| | g cm$^{-3}$ | |
| Synthetic (FER[a]) | 1.1a[b] (SD[c] = 0.051) | 1.20a (SD = 0.044) |
| Dewatered biosolids (DBN) | 0.79c (SD = 0.036) | 1.15ab (SD = 0.036) |
| Biosolids–sand–sawdust N rate (BBN) | 0.71cd (SD = 0.086) | 1.13bc (SD = 0.022) |
| Biosolids–sand–sawdust P rate (BBP) | 0.99b (SD = 0.020) | 1.16ab (SD = 0.052) |
| Composted biosolids (CBN) | 0.64d (SD = 0.058) | 1.10c (SD = 0.042) |

[a]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.

[b]Means in the same column followed by a common lowercase letter are not significantly different at $P < .05$.

[c]Standard deviation of mean ($n = 8$).

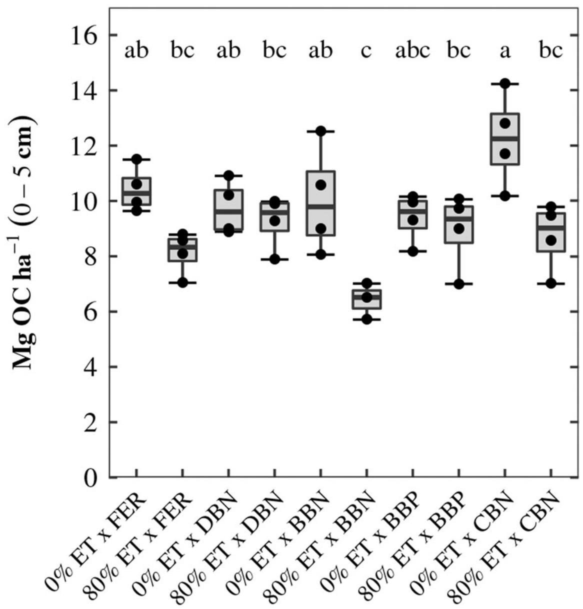


**FIGURE 2** Irrigation and fertility amendments effects ($n = 4$) on soil organic C (OC) to a depth of 0–5 cm after 5 yr of tall fescue growth in a clayey, disturbed urban soil. Common letters indicate significant difference at $P < .05$. FER, synthetic fertilizer; DBN, dewatered biosolids applied annually 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

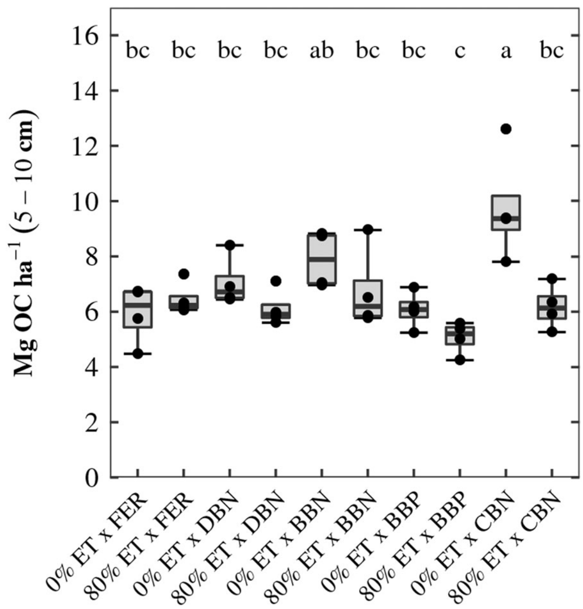


**FIGURE 3** Irrigation and fertility amendments effects ($n = 4$) on soil organic C (OC) to a depth of 5–10 cm after 5 yr of tall fescue growth in a clayey, disturbed urban soil. Common letters indicate significant difference at $P < .05$. FER, synthetic fertilizer; DBN, dewatered biosolids applied 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

2015; Rivenshield & Bassuk, 2007; Sloan, Ampim, Boerth, Heitholt, & Wu, 2016). The reduced bulk density would be expected to promote improved rooting conditions and promote increased turfgrass biomass growth.

### 3.3.2 | Soil organic carbon and nitrogen stocks

Effects of treatments on soil OC and N stocks were closely linked. At the conclusion of the trial, soil OC at 5–10 cm and N stocks at both depths measured were affected by the interaction of irrigation × amendment ($P < .05$). Soil OC at the 0- to 5-cm depth was significant at $P = .074$ and is presented on an interaction basis (Figure 2). Based on previous turfgrass studies (Law & Patton, 2017; Milesi et al., 2005; Qian, Follett, & Kimble, 2010; Selhourst & Lal, 2013), increased inputs (e.g., irrigation and fertilizer) increased soil OC and N. Our results surprisingly indicate that less irrigation gave greater soil OC and N for CBN (Figures 2–5). The CBN

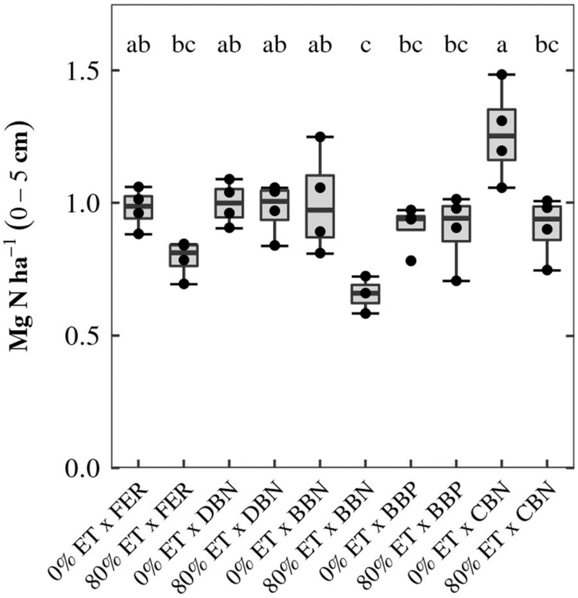


**FIGURE 4** Irrigation and fertility amendments effects ($n = 4$) on soil N to a depth of 0–5 cm after 5 yr of tall fescue growth in a clayey, disturbed urban soil. Common letters indicate significant difference at $P < .05$. FER, synthetic fertilizer; DBN, dewatered biosolids applied annually at an 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

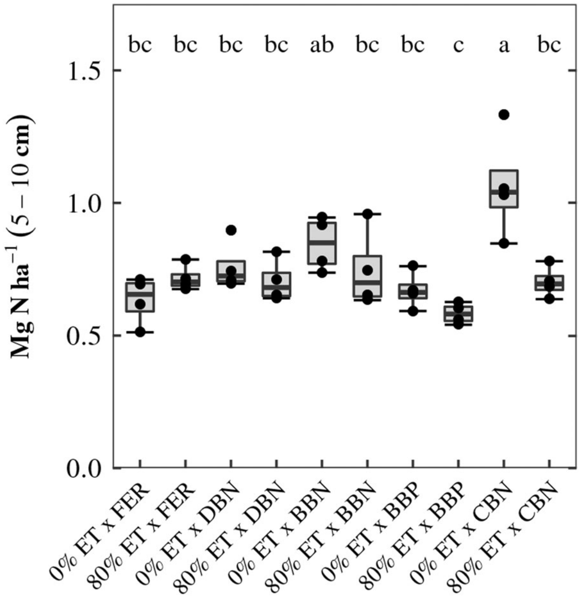


**FIGURE 5** Irrigation and fertility amendments effects ($n = 4$) on soil N to a depth of 5–10 cm after 5 yr of tall fescue growth in a clayey, disturbed urban soil. Common letters indicate significant difference at $P < .05$. FER, synthetic fertilizer; DBN, dewatered biosolids applied annually at an 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

0% ET had the greatest soil OC and N compared with all other treatments at the 5- to 10-cm depth (Figures 3 and 5). We hypothesized that this effect was a result of increased microbial mineralization of soil OC and N due to greater soil moisture in the 80% ET plots relative to no irrigation during summer heat stress, which would result in limited water availability and microbial decomposition of organic matter.

All treatments gained significant quantities of OC relative to the initial starting point of 1.74 g OC kg$^{-1}$ in September 2013. The application of synthetic fertilizer (FER) to tall fescue increased the 0- to 10-cm soil OC to 13.6 g OC kg$^{-1}$ (i.e., +681%) (Figure 6). The addition of biosolids amendments resulted in CBN having the greatest increase to 21.3 g OC kg$^{-1}$, followed by BBN and DBN (18.5 and 16.6 g OC kg$^{-1}$, respectively). The increased soil OC from CBN was expected, as the composted OC should be the most stable and matured treatment (Bernal, Navarro, Sanchez-Monedero, Roig, & Cegarra, 1998; Sanchez-Monedero, Mondini, De Nobili, Leita, & Roig, 2004). The BBP rate did not increase soil OC (13.7 g OC kg$^{-1}$) relative to FER.

During periods of minimal fertility inputs (June 2015–June 2016; 2018), soil OC and N concentrations decreased to the previous year's concentrations (Figures 6 and 7). Without continuous additions, regular C mineralization prevents maintenance of soil OC and N and resulted in a loss of OC and N from 2017 to 2018 for treatments CBN and BBN ($P < .05$) (Figure 6).

### 3.3.3 | Soil chemical properties

Fertility treatments increased all measures of soil P, and biosolids increased Mehlich-3 P above inorganic fertilizer by an order of magnitude; however, only the composted biosolids increased water-soluble P above that in the inorganically fertilized soil (Table 4). The highest water-soluble P was found in the CBN, a result most likely from the high total loading rate of material and lower concentration of P-binding Fe and Al (Table 1). The soils treated with the biosolids having the highest Fe and Al concentrations (BBN, BBP, and DBN) provided the same concentrations of water-soluble P as the synthetic fertilizer treatment (FER) after 5 yr (Table 4). The application of organic byproducts in Virginia are not permitted if soil PSR > 65%. Applications should not be greater than P crop removal if soil PSR is < 65% but > 30%. Applications can be applied at an ANR if soil PSR < 30% (VA DCR, 2014). Virginia Department of Conservation and Recreation regulations would limit all three treatments applied at the ANR to the P crop removal rate. For a turfgrass system where

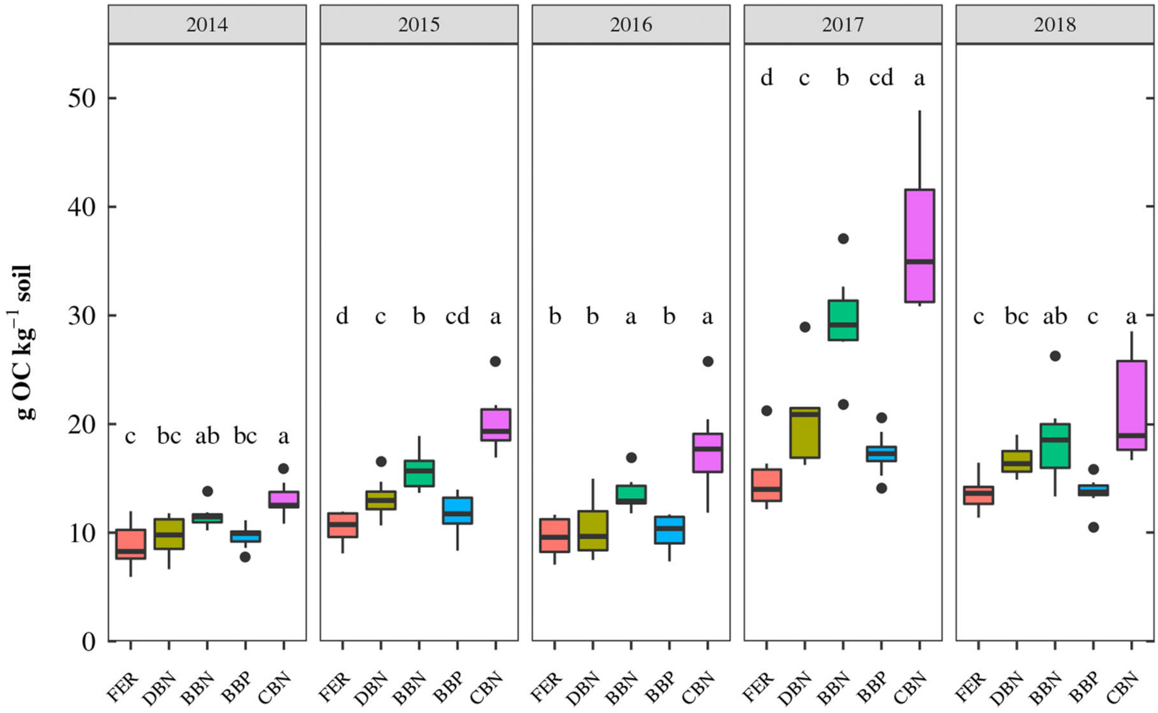


**FIGURE 6** Fertility amendments effects ($n = 8$) on soil organic C (OC) to a depth of 0–10 cm. From left to right in each year: FER, annually applied synthetic N–P–K fertilizer; DBN, biosolids applied annually at an agronomic N rate; BBN, blended biosolids–sand–sawdust applied annually at an agronomic 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 are only compared within each year. Common letters indicate significant difference at $P < .05$

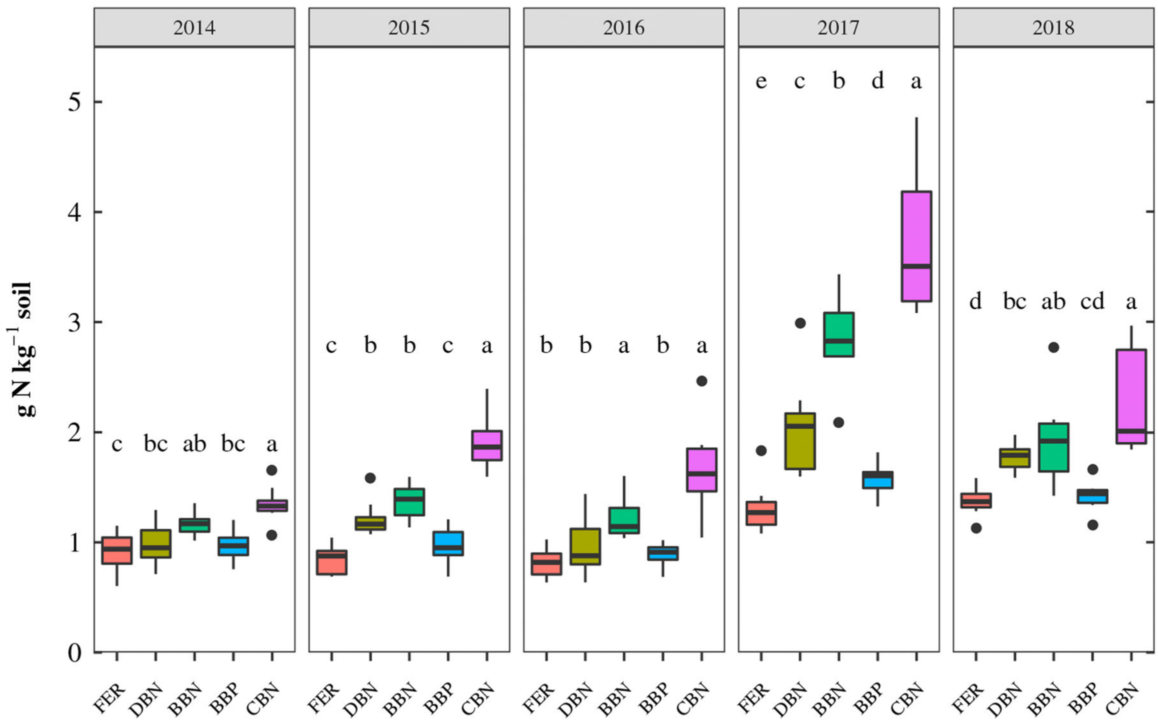


**FIGURE 7** Fertility amendments effects ($n = 8$) on soil N to a depth of 0–10 cm. From left to right in each year: FER, annually applied synthetic N–P–K fertilizer; DBN, biosolids applied annually at an agronomic N rate; BBN, blended biosolids–sand–sawdust applied annually at an agronomic N rate; 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 are only compared within each year. Common letters indicate significant difference at $P < .05$

**TABLE 4** End of trial (2013–2018) Mehlich-3-extractable P, ammonium oxalate-extractable P, Al, and Fe, P saturation ratio, and water-soluble P to a soil depth of 5 cm

| Treatment | Mehlich-3-extractable P | Ammonium oxalate-extractable P | Al | Fe | P saturation ratio | Water soluble P |
|---|---|---|---|---|---|---|
| | mg P kg$^{-1}$ | mmol kg$^{-1}$ | | | % | mg P kg$^{-1}$ |
| Synthetic (FER[a]) | 18d[b] (SD[c] = 8.8) | 1.8c (SD = 0.55) | 26b (SD = 2.0) | 11c (SD = 2.0) | 5.0b (SD = 1.7) | 13bc (SD = 4.5) |
| Dewatered biosolids (DBN) | 150c (SD = 21) | 47a (SD = 8.5) | 42a (SD = 5.9) | 65a (SD = 18) | 44a (SD = 4.3) | 15bc (SD = 3.1) |
| Biosolids–sand–sawdust N rate (BBN) | 210b (SD = 58) | 38b (SD = 6.3) | 40a (SD = 7.1) | 49b (SD = 11) | 43a (SD = 6.0) | 18b (SD = 5.2) |
| Biosolids–sand–sawdust P rate (BBP) | 22d (SD = 4.9) | 4.4c (SD = 1.2) | 26b (SD = 3.4) | 18c (SD = 6.6) | 10b (SD = 1.4) | 9.6c (SD = 2.9) |
| Composted biosolids CBN | 280a (SD = 50) | 39b (SD = 7.1) | 41a (SD = 3.0) | 44b (SD = 4.6) | 46a (SD = 7.3) | 30a (SD = 9.0) |

[a]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.

[b]Means in the same column followed by a common lowercase letter are not significantly different at $P < .05$.

[c]Standard deviation of mean ($n = 8$).

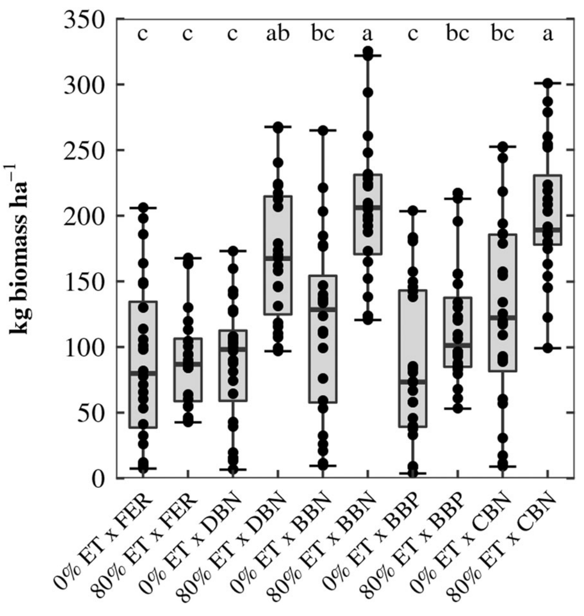


**FIGURE 8** Irrigation and fertility amendments interaction effects ($n = 4$) on tall fescue aboveground biomass from all sampling dates during the final sampling year (April–August 2018). Common letters indicate significant difference at $P < .05$. FER, synthetic fertilizer; DBN, dewatered biosolids 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

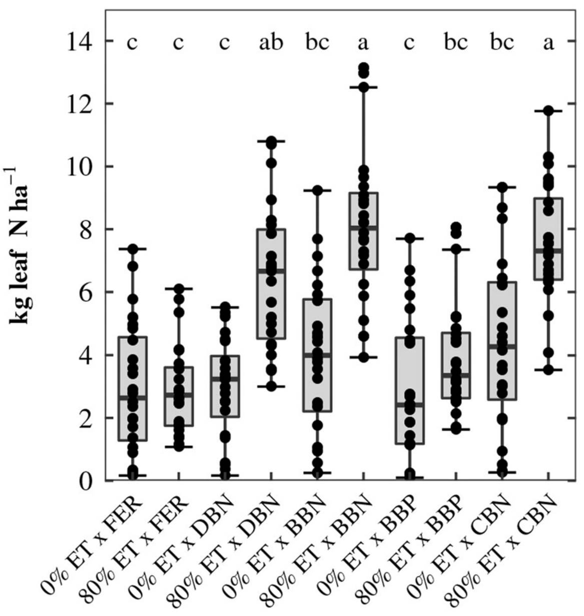


**FIGURE 9** Irrigation and fertility amendments interaction effects ($n = 4$) on tall fescue leaf tissue N accumulation from all sampling dates during the final sampling year (April–August 2018). Common letters indicate significant difference at $P < .05$. FER, synthetic fertilizer; DBN, dewatered biosolids 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

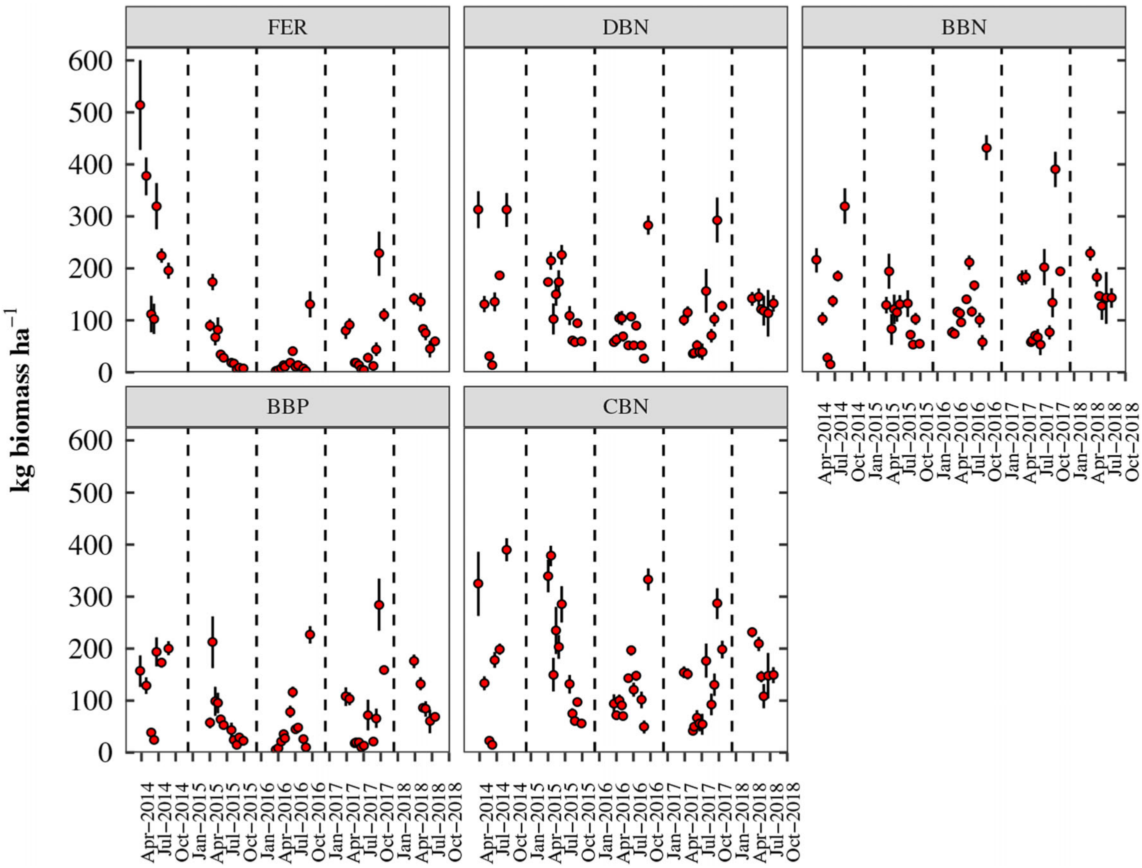


**FIGURE 10** Biosolids amendments effect on turfgrass biomass throughout the duration ($N = 48$) of the sampling period (April 2014–August 2018). FER, annually applied synthetic N–P–K fertilizer; DBN, biosolids applied annually at an agronomic N rate; BBN, blended biosolids–sand–sawdust applied annually 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. Dashed vertical lines separate years of trial (2014–2018). Error bars are one standard error from the mean ($n = 8$)

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 reduced water-soluble P 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 or treatment process and composition for biosolids P management. Biosolids regulations should address the solubility of P, not just total P, in the amended soil for determination of application rates.

## 3.4 | Plant responses

### 3.4.1 | Tall fescue clipping biomass, leaf nitrogen accumulation, and quality

During the final year of the study, tall fescue clipping biomass and leaf N accumulation were influenced by irrigation × amendment interactions ($P < .05$). Tall fescue clipping biomass and N accumulation were increased in BBN, CBN, and DBN at the 80% ET irrigation rate, but BBP and FER elicited no differences between irrigation treatments (Figures 8 and 9). The 80% ET irrigation treatment improved turfgrass visual quality (rating = 7.2) as expected compared with the 0% ET irrigation (rating = 5.8).

The mean tall fescue clipping biomass and quality of each sampling date during the 5 yr is shown in Figures 10 and 11. After the first year of growth through the end of the study in 2018, ANR biosolids (BBN, CBN, and DBN) resulted in increased biomass, N accumulation, and visual quality compared with 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 (Figure 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 acceptable minimum quality (6).

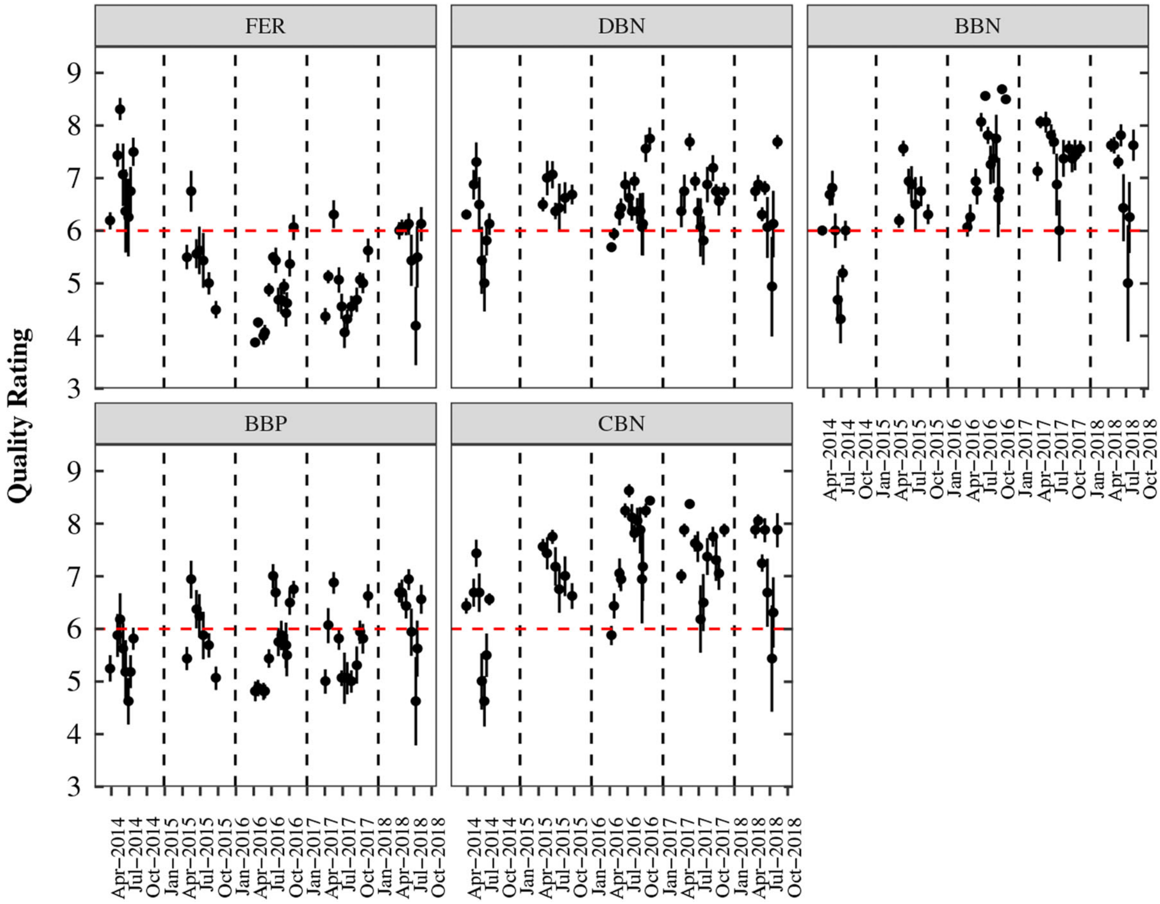


**FIGURE 11** Biosolids amendments effect on turfgrass quality throughout the duration ($N = 49$) of the sampling period (April 2014–August 2018). FER, annually applied synthetic N–P–K fertilizer; DBN, biosolids applied annually at an agronomic N rate; BBN, blended biosolids–sand–sawdust applied annually 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. Red dashed horizontal line indicates minimum acceptable quality. Dashed vertical lines separate years of trial (2014–2018). Error bars are one standard error from the mean ($n = 8$)

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 a longer timeframe to reach acceptable quality (e.g., highway roadsides, parks, industrial lawns, etc.) could find this option useful and reduce potential P loss. Testing the application of a different biosolids product that does not include sawdust at the APR and supplementing it with N fertilizer may yield more desirable results for situations that require a quicker timeline to acceptable quality turfgrass. 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).

## 4 | CONCLUSIONS

Research on the use of exceptional quality biosolids for turfgrass grown in anthropogenically impacted soils has not been well documented. Our longer term results found that biosolids products applied at the ANR improved visual quality and tall fescue growth compared with synthetic fertilizer. The repeated applications of biosolids amendments reduced soil bulk density and increased soil OC and N stocks with minimal environmental P risk. The increase of OC and N stocks is important to improve long-term crop productivity, as well as contributing to potential C storage. Biosolids with high Fe concentrations applied at the ANR did not increase water-soluble soil P. The soil PSR did indicate that all biosolids N rate amendments would be limited to P crop removal rates. This indicates that the soil PSR may be overestimating P runoff risk from biosolids with high Fe concentrations. Environmental risk assessment of P loss needs to be considered in biosolids regulations. Biosolids applied at the APR with supplemental synthetic N resulted in acceptable turfgrass quality and can be an alternative to biosolids application rates to supply the entire crop need where soil P concentrations pose water quality impairment risk.

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## CONFLICT OF INTEREST

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

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