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The Impacts of Biochar on Turfgrass Health and Drought Tolerance

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Jonathan Freedom Montgomery

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Dissertation Committee:
Dr. Milt McGiffen, Chairperson
Dr. Louis Santiago
Dr. Bernd Leinauer

The Dissertation of Jonathan Freedom Montgomery is approved:

Committee Chairperson

University of California, Riverside

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ABSTRACT OF THE DISSERTATION

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Jonathan Freedom Montgomery

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The health of turfgrass, as well as the quality of managed turfgrass areas, relies heavily on the amount of irrigation which can be supplied to plants. As restrictions require that irrigation rates be reduced, many professionals turn to organically derived soil amendments with the potential for reducing irrigation requirements. Compost is a stabilized form of organic matter derived from the biological decomposition of plant, animal, or human waste, and is often used for soil fertilization and amelioration. Biochar is produced through anaerobic heating of plant biomass to produce extremely stable carbon in the form of amorphous graphene sheets. Both technologies increase soil organic matter (SOM), which can convey improvements in soil water retention and Cation Exchange Capacity (CEC). Biochar may also positively impact soil structure, increasing porosity and reducing density in a way which improves root penetration and water infiltration. Biochar is more highly resistant than compost to degradation and recent work has suggested a synergistic effect between biochar and compost materials. Multiple studies were conducted at University of California Riverside from 2014 to 2017 in field and greenhouse conditions to evaluate the effects of compost, biochar, and combined biochar and compost amendments on the establishment and drought tolerance of tall fescue (*Festuca arundinacea* L.). Soil amendments designed for improvement of soil conditions during periods of drought are often evaluated in the lab using measurements of soil water potential. Results of these studies suggest that this measurement does not accurately gauge impacts on plant health. In both field and greenhouse studies, compost amendments significantly slowed establishment, while biochar did not affect establishment rates compared to controls. When subjected to drought, turf grown in soils amended with compost or biochar amendments were able

to maintain higher visual quality with reduced supplemental irrigation. We conducted a series of experiments to analyze the effect of compost and biochar amendments during each stage of development of a healthy turf, allowing managers to more accurately predict the impacts of these products.

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Introduction

Managed turfgrass covers 35,850 km^2 in the United States (Milesi, 2005). Up to 70% of residential sector water use in the United States can be attributed to turfgrass irrigation and reductions in irrigation rates to tall fescue grown in arid regions has been shown to be beneficial in regards to overall community water use (Devitt et al., 2008). Furthermore, the majority of seasonal increases in municipal water use result from supplemental landscape irrigation (Kjelgren et el., 2000). In water-limited ecosystems, managing soil carbon and the availability of soil water is essential for maintaining productivity and plant performance (Artiola, 2012). Furthermore, carbon emissions due to land use and loss from the Soil Organic Carbon (SOC) pool have contributed significantly to the accumulation of CO_2 in the atmosphere, leading to global warming (Lal, 2004). One potential avenue for decreasing turfgrass water consumption as well as improving overall performance comes in the form of biochar, shorthand for biologically active charcoal. Biochar is produced through anaerobic heating of organic matter to produce extremely stable carbon in the form of amorphous graphene sheets (Winsley, 2007). Biochar is a porous material, and can absorb and retain water, resulting in increases to water retention as large as 18% in sandy soils (Glaser et al., 2002). Recent research has confirmed that incorporation of biochar into soils can increase nutrient and water holding capacity (Chan et al., 2007; Karhu et al., 2011; Novak et al., 2012). Research has focused on agricultural soils, suggesting improved plant performance under drought conditions (Laird et al.(a), 2010;Laird et al.(b), 2010), including improvements in crop yield in members of the Poaceae family (Olmo et al., 2014). .

Like biochar, compost can be produced using plant products traditionally considered waste. By encouraging decomposition of these products, nutrients held in plant tissues are made available as fertilizers. Both biochar and compost increase SOM, which can convey improvements in soil water holding capacity, nutrient retention, and soil structure (Xiao et al., 2016). In warm, cultivated soils the benefits of compost additions may not persist due to increased microbial activity and SOM turnover (Zerzghi, 2010). However, biochar is much more resistant to degradation and recent work has suggested a synergistic effect on soils between biochar and compost materials, including increased respiration, nutrient availability, and soil porosity when compared to compost alone (Thies et al., 2009; Steiner et al., 2011). Biochar has a carbon content of 70-80% which has been shown to remain in the soil for hundreds, and potentially thousands, of years (Winsley, 2007). Researchers working with biochar and turfgrass have called for deeper investigation into the effects of biochar on turf in field settings (Brockhoff, 2010; Belle and Lopez, 2014; Glab et al., 2016), inclusion of biochar in turf plantings would represent a major carbon sink.

During establishment, turfgrass requires higher levels of nitrogen and other nutrients than during maturity, which has traditionally been provided with chemical fertilizers that may leach (Basso and Ritchie, 2005). Compost and biochar represent a strategy to provide nutrients in less volatile forms and retain them in targeted areas, making nutrients available over longer periods for the plant (Steiner et al., 2010). Both biochar and compost represent not only an opportunity for highly efficient carbon sequestration, but also an environmentally friendly means of soil improvement to reduce dependence on less sustainable agricultural practices. (Evanylo et al., 2016). The objective of this research was to investigate the effects of biochar and compost on tall fescue establishment rates, as well as combined compost and biochar treatments to evaluate claims of synergistic effects.

Materials and Methods

The field study was conducted at the University of California Turfgrass Research Facility in Riverside, CA (semi-arid, 340 m elevation) during the growing season of 2014, and replicated in greenhouse conditions in Spring 2015. Soil at the field site is a Hanford fine sandy loam, while pots in the greenhouse study were filled with field soil mixed 50:50 with plaster sand to encourage draining and thus prevent water-logging. Tall fescue (Loveland Products Sentinel CPQ blend approximately 49% Lexington, 29% Black Magic, 21%

Sitka) tall fescue was seeded on May 5, 2014 in the field, and on May 14, 2015 in the greenhouse replicate at a rate of 40 g m^{-2}.

Treatments (amendment rates) included: 2.2, 11.2, and 22.4 tons/ha of biochar, 5 and 10 cm of composted greenwaste applied by depth, 5 cm of composted biosolids, and a combined treatment of 5 cm composted greenwaste plus 11.2 tons/ha biochar. Amendments were incorporated in the field study on April 16, 2014 by rototiller to a depth of 15 cm, the recommended depth for compost incorporation in turf (Landschoot, 1996), and manually incorporated to this depth in the greenhouse May, 14, 2015. Field plot size was 2.4 by 2.4 m. Treatments were replicated 8 times in the field and 5 times in the greenhouse using 3.8 L pots. An additional treatment in the greenhouse experiment was 5 cm of biosolids compost mixed with 11.2 tons/ha of biochar. Biochar was produced from Yellow Pine pyrolized at 350 °C. Greenwaste compost used a mixture of materials common to municipal sources, specific components were not provided, while the feedstock for biosolids compost was chicken manure (Table 1.1).

Turf was irrigated 3 times per week. In the field, irrigation was applied at 85% of reference evapotranspiration (ET_0), calculated using on-site weather station data (Table 1.7) from the California Irrigation Management Information System (CIMIS). In the greenhouse, pots were irrigated to field capacity at each irrigation event determined as the point when drainage was noted from the bottom of each pot (Cassel and Nielsen, 1986). Daily air temperature in the greenhouse is reported in Figure 1.1. Plots were fertilized on May 21, 2014 with a 16-16-16 fertilizer at a rate of 5 g N m^{-2} to mimic standard maintenance practices and encourage establishment. 2,4-D Herbicide was applied to field plots June 4, 2014 to control the emergence of broadleaf weeds. Field plots were mowed every Wednesday at 5.75 cm, the nominal height of cut. Turf in the greenhouse was trimmed to the same height July 15 using hand shears. Live turf cover was measured by Digital Image Analysis (DIA), and used to compare establishment rates (Richardson, 2001). Pictures were taken every two weeks in the field and weekly in the greenhouse beginning at seedling emergence and continuing until establishment was complete. Soil analysis was conducted only in the greenhouse portion of the study. Soil was collected August 10, 2015 and analyzed for levels of Nitrate (NO_3), Phosphorous (P_2O_5), and Potassium (K_20) (Table 1.6). Root samples were collected in the field May 4, 2015 and in the greenhouse August 17, 2015. Roots were analyzed for length and volume using the WinRhizo system (ALLtech laboratories).

Both field and greenhouse components of the study had a complete randomized block experimental design. All data was subjected to ANOVA followed by comparisons of means using Fisher's protected least significant difference test (α=0.05).

Measurement of Live Turf Cover

A sigmoidal association of live turf cover to DAS most accurately describes turf establishment (Busey and Myers, 1979; Leinauer et al., 2010; Schiavon et al., 2012). Live turf cover was measured for each replicate, and sigmoidal models were used to calculate DAS needed to reach threshold values for each replicate separately. Live turf cover was averaged across replicates, and a sigmoidal curve fitted from the date at which each treatment reached specific levels of live turf cover was calculated (GraphPad Prism 5.0 for Windows; GraphPad Software). In the field, we compared the number of DAS required to reach 50, 75, and 95% turf cover (DAS50, DAS75, and DAS95, respectively). Establishment is considered successful when turf cover reaches 75% of photographed area (Schiavon et al., 2012). Images collected in the greenhouse included space outside of the pot surface, which comprised a consistent 10% of the photographed area. Reported data includes this space, resulting in lower measurements. To compensate, establishment in the greenhouse was measured at lower thresholds, and presented as DAS25, DAS50, and DAS75.

Images were collected using a Casio Exilim EX-S12BK camera. For the field study, the camera was housed in an enclosed box equipped with 4 fluorescent light bulbs providing uniform lighting conditions. In the greenhouse portion of the study a black plastic tube was placed over pots to exclude incoming light, and light was provided by the camera's flash. Pictures were collected every week during the study period.

Results

Field Final Cover

All turf plots in the field reached complete establishment July 29, 2014, and images collected on that date were used to compare final turf cover. Both biochar and compost amendments affected the establishment of tall fescue in both the greenhouse and field experiments (Tables 1.2-1.3). In the field only those plots amended with 5 cm biosolids compost had significantly reduced cover (79%) compared to control plots (91%; Table 1.2).

Greenhouse Final Cover

Turf in the greenhouse reached full establishment on August 10, 2015. Untreated controls reached 83% live turf cover. Greenwaste compost reduced final turf cover for both the 5 cm (48%) and 10 cm (44%) treatments, as well as the combined treatment of 5 cm greenwaste compost with 11.2 t/ha biochar (51%; Table 1.3). Incorporation of 5 cm biosolids compost reduced final cover compared to controls (67%), but was improved compared to greenwaste treatments. Biochar apparently ameliorated some of the negative effects of biosolids, as 11.2 t/ha of biochar combined with the 5 cm biosolids compost treatment resulted in a final cover comparable to controls (73%).

Field Establishment Rate

In the field, untreated plots and those amended with any of the three rates of biochar reached 50% and 75% cover most rapidly. It took longer to reach DAS75 in plots amended with 5 cm biosolids compost (39 d), 5 cm greenwaste compost (42 d), or the combined treatment of 5 cm greenwaste with 11.2 t/ha biochar (42 d). Amendment with 10 cm greenwaste compost caused the slowest establishment rate (51 d). DAS50 values showed an identical pattern (Table 1.2).

Greenhouse Establishment Rate

Establishment in the greenhouse was greatly impaired in those pots amended with 5% or 10% greenwaste compost, or 5 cm greenwaste with 11.2 t/ha biochar. Turf grown in pots containing only greenwaste did not reach 50% cover during the study period. Of those treatments which did reach 50% cover, establishment was slowed when using the 5 cm biosolids treatment (57 d) and the combined greenwaste and biochar treatment (71 d). All other treatments established at rates comparable to controls. Additionally, turf grown in soil amended with 5 cm biosolids compost did not reach 75% cover (Table 1.3). The first treatment to reach 75% cover was the untreated control, 59 days after seeding (Table 1.3). It took longer for pots amended with 5 cm biosolids compost combined with 11.2 t/ha biochar (77 d) or 22.4 t/ha biochar with no compost added (70 d) to reach 75% cover.

Field Rooting Analysis

Rooting data collected in the field demonstrated an effect of amendment on root architecture. The composted greenwaste treatments resulted in the greatest root length, including the plots amended with both greenwaste compost and biochar. Control plots and those amended with biochar alone had comparable root lengths, though the effect of amending with 11.2 t/ha of biochar were comparable to 10 cm of greenwaste compost. Root length was shortest in plots amended with composted biosolids (Table 1.4).

Treatment differences in root volume mirrored those seen in root length. Plots amended with 5 cm composted greenwaste or a combination of 5 cm composted greenwaste and 11.2 t/ha biochar had the greatest root volumes, though control plots were not significantly different from the 10 cm greenwaste or combined greenwaste and biochar treatment. All biochar-amended plots had similar root length to controls, but were significantly lower than greenwaste-amended plots. Root volume was lowest in plots amended with biosolids compost.

Greenhouse Rooting Analysis

Results from the greenhouse study differed from those seen in the field. Root length was greatest in control pots and those amended with 11.2 t/ha or 22.4 t/ha biochar. Root length was decreased in pots amended with 5 cm biosolids, 5 cm biosolids combined with 11.2 t/ha biochar and 5 cm greenwaste including 11.2 t/ha biochar (Table 1.5).

Pots amended with 11.2 or 22.4 t/ha of biochar had the greatest root volume. Root volume was reduced in control pots and those amended with 2.2 t/ha biochar, though these were similar to turf grown in soil amended with 22.4 t/ha of biochar. Root volume was further reduced by amendment with 5 or 10 cm composted greenwaste, combined greenwaste and biochar and the combined biosolids compost and biochar amendment. The lowest root volume was seen in pots amended with 5 cm biosolids, which was similar to amendments combining compost and biochar amendments (Table 1.5).

Soil Chemistry

Compost amendments, including those combining compost and biochar, altered all measured aspects of soil chemistry compared to controls, while biochar treatments did not (Table 1.6). Nitrate levels were highest in soils amended with 5 cm biosolids compost (133 ppm) and the amendment combining 5 cm biosolids with 11.2 t/ha biochar (89 ppm), greatly exceeding those levels seen in control pots (4 ppm). Amendment with 5 cm greenwaste compost did not significantly reduce nitrate levels compared to controls, but produced the lowest values (1 ppm).

Phosphorous levels were highest in pots amended with 5 cm of biosolids compost (473 ppm). Including 11.2 t/ha biochar with 5 cm biosolids compost raised levels compared to controls, but resulted in lower total phosphorous (276 ppm) compared to amendment with biosolids compost alone. Amendment with 10 cm greenwaste compost also increased phosphorous levels (95 ppm) compared to controls (26 ppm). All other treatments did not affect phosphorous levels.

Potassium levels were highest in soils amended with 10 cm greenwaste compost (351 ppm), followed by those amended with 5 cm biosolids compost (246 ppm). The combined biosolids and biochar amendment (148 ppm) as well as the 5 cm rate of greenwaste compost (135 ppm) also increased potassium levels compared to controls (66 ppm), though to a lesser degree than treatments including biosolids. Control pots and those amended with all rates of biochar (61-64 ppm) possessed the lowest levels of potassium, and were similar to one another.

Analysis of soil pH levels demonstrated an effect of both compost types. The highest pH levels (8.5-8.6) were seen in control pots and those amended with all rates of biochar. Greenwaste compost and the combined greenwaste and biochar amendments reduced pH levels (8). The lowest pH levels (6.4-6.5) were detected in soils amended with either biosolids compost alone or biosolids combined with biochar.

Weather Conditions

During the field portion of the study, no precipitation events occurred. Total evapotranspiration and precipitation data were collected from the on-site California Irrigation Management Information System (CIMIS) station (Table 1.7). Greenhouse temperatures were controlled using industrial air conditioners, and temperature data was collected daily using a WatchDog 1000 Series datalogger produced by Spectrum Technologies (Figure 1.1). Temperatures between the greenhouse and field did not significantly vary, with the greenhouse maintaining a slightly warmer temperature as it did not cool as rapidly as the field at night.

Discussion

While all other measured characteristics of composts fell within tolerable levels, Biosolids compost was determined to have excessively high levels of salinity (Table 1.1) which would normally classify it as immature (Cai et al., 2010). The greenwaste compost treatment was shown to have a very large particle size (Table 1.1), which when incorporated into a soil, reduces bulk density (Rivenshield et al., 2007; Tester, 1990). These traits have been shown to affect rooting characteristics and establishment rates of turfgrass (Carrow et al., 2001).

The compost amendments used in our study negatively impacted establishment in both field and greenhouse conditions, while biochar amendments did not affect establishment (Tables 1.2-1.3). However, combining biochar with biosolids compost ameliorated some of the negative impact of the biosolids and improved turfgrass establishment. Final turf cover was also reduced by compost amendments. Field data showed reductions with biosolids compost, while in the greenhouse all compost amendments reduced final cover except when biosolids compost was combined with biochar. It is significant to note that, in the greenhouse study, pots amended with only biosolids compost did not reach 75% cover, while those amended with combined biosolids compost and biochar did. Additionally, pots amended with composted greenwaste never exceeded 50% cover, while pots containing both greenwaste compost and biochar did, albeit more slowly than the untreated controls.

In addition to impacts on above ground growth, both compost and biochar amendments affected root architecture (Tables 1.4-1.5). Effects differed between the greenhouse and field sites, most likely due to the modified soil used in the greenhouse. We have found that, under greenhouse conditions, soil taken from our field site tends to become waterlogged. The incorporation of plaster sand, a very fine sand, into rooting media facilitates drainage. Incorporating sand serves some of the same purposes as compost and biochar, including reductions in bulk density and facilitating drainage, and may offset the impact of amendments meant to improve these soil characteristics.

The saltier biosolids compost slowed establishment in both the greenhouse and field trials, Salt stress impairs turfgrass growth by reducing the ability of roots to take up water present in the soil (Alshammary et al., 2003; Horst et al., 1984). Further support for this theory comes from comparison of the biosolids compost treatment alone with the treatment combining biochar and biosolids compost. Biochar has been suggested for use in salt affected sites, as it may improve plant growth in salt-affected sites by adsorbing Na^+ from the soil solution (Akhtar et al., 2015). Incorporating both biochar and biosolids compost together put them in direct physical contact, which may have facilitated biochar amelioration of salts from the biosolid compost. This suggests that including biochar along with amendments that contain excessive salts may allow for application of otherwise unusable products.

The larger particle size of greenwaste compost noted earlier (Table 1.1) may explain the increased root length observed at our field site (Table 1.4). Greenwaste most likely reduced soil bulk density, reducing the physical resistance of the soil to root penetration, allowing an increase in root length (Wiecko et al., 1993). Under well-watered conditions, bulk density plays a much smaller role in resistance to root growth, which may explain the disparity in results between our greenhouse and field sites (Taylor et al., 1963). We were able to maintain soil in the greenhouse near field capacity, and maintained air temperatures controlling variations in soil moisture. Soil density could have been more of a limiting factor in the field. Additionally, the inclusion of sand in our greenhouse trial decreased soil density regardless of compost incorporation, compounding this effect.

Although turfgrass root length was increased with the use of greenwaste compost, establishment was delayed in both the field and greenhouse sites (Tables 1.2-1.3). This apparent contradiction can also be explained by reductions in bulk density, which can cause reduced contact between the root and soil (Schoonderbeek et al, 1994). In response, plants may partition more resources toward rooting, causing reductions in above ground growth (Schoonderbeek et al, 1994). In comparing turf grown in the 5 cm greenwaste treatment to 5 cm greenwaste combined with 11.2 t/ha biochar, we find support for this explanation. Biochar has been shown to improve low density soils by filling macropores and air spaces, increasing their density and improving contact between soil and roots (Laird et al., 2010; Lim et al., 2015). Our results suggest that biochar amendments do not negatively impact establishment rates of tall fescue turfgrass when compared to establishment in untreated soils, though it does not improve establishment rates (Tables 2.2-2.3). However, this trial was conducted under adequate irrigation. It is likely that beneficial effects of biochar such as increases in water holding capacity would not affect plant growth under these conditions. Turf managers may wish to utilize biochar and compost products to reduce negative impacts of necessary irrigation reductions, but these drought conditions will most likely be imposed after the establishment phase. It is therefore significant to establish that biochar will not impede turf establishment. Compost products may be used in much the same way, though as shown in our study, highly saline or low density composts can be harmful to establishing turf. As these products may still benefit mature turf, or may be produced as a way to dispose of plant or animal waste, a strategy to allow their use is valuable. Based on our results, incorporation of biochar along with non-ideal compost products represents an acceptable strategy. If incorporated into compost application recommendations, many products previously unfit for use may become acceptable as soil amendments.

In conducting this research, multiple potentially confounding factors were identified. In order to make effective recommendations regarding the use of compost and biochar during turf establishment, a more in-depth investigation of potentially harmful factors should be conducted. Our study focused primarily on particle size and salinity of amendments as likely causal agents. Future work should include more measurements of soil salinity and bulk density prior to and during the study period along with pH and ammonium levels (Cheng et al., 2007). Studies comparing the impact of these variables on turfgrass establishment will allow targeted recommendations of specific biochar and compost products based on specific soil and amendment factors.

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Table 1.1. Biosolids and greenwaste compost characterization conducted by Soil Control Lab, Watsonville, CA April 27, 2015. Pass/fail values are based on US EPA Class A standards, 40 CFR 503.32 and 503.13.

Parameter	**Unit of measure**	**Biosolids**	**Greenwaste**
Total Nitrogen	% Dry Weight	4	0.67
Ammonia (NH_4-N)	ppm (mg/kg dry weight)	10000	21
Nitrate (NO_3-N)	ppm (mg/kg dry weight)	6	< 1
Organic Nitrogen	% Dry Weight	3	0.67
Phosphorous (P)	ppm (mg/kg dry weight)	21000	1300
Potassium (as K_20)	% Dry Weight	0.66	0.73
Potassium (K)	ppm (mg/kg dry weight)	5500	6100
Organic Carbon	% Dry Weight	29	38
C/N Ratio	Ratio	7.1	57
pH	Units	7.59	7.71
Soluble Salts (EC5)	dS/m (mmhos/cm)	20	2.4
Particle Size	Maximum aggregate size (cm)	0.97	11.7
Heavy Metals Content	Pass/Fail	Pass	Pass
	Stability Indicator (respirometry)		
CO_2 Evolution	mg CO_2-C/g OM/day	2.9 (Stable)	1.1 (Stable)
	mg CO_2-C/g TS/day	1.7 (Stable)	2.5 (Stable)
	Maturity Indicator (bioassay of cucumber emergence)		
Percent Emergence	Average % of control	0.0 (Immature)	100 (Mature)
Relative Seedling Vigor	Average % of control	NA (Immature)	100 (Mature)
	Pathogens		
Fecal Coliforms	Pass/Fail	Pass	Pass
Salmonella	Pass/Fail	Pass	Pass

Table 1.2. Field establishment rates presented as days after seeding required to reach 50 and 75% ground cover (DAS50 and DAS75), and final cover at end of establishment study period. Values are averaged over 8 replicates.

Treatment	DAS50	DAS75	Final Cover %
Control	19 c	25 c	90.97 a
2.2 t/ha Biochar	18 c	24 c	92.26 a
11.2 t/ha Biochar	22 c	28 c	85.25 ab
22.4 t/ha Biochar	22 c	28 c	91.46 a
5 cm Biosolids	32 b	39 b	79.74 b
5 cm Greenwaste	32 b	42 b	88.15 ab
5 cm Greenwaste + 11.2 t/ha Biochar	34 b	42 b	91.62 a
10 cm Greenwaste	39 a	51 a	86.72 ab

Values in each column followed by same letter are not significantly different (Fisher's protected least significant difference, $\alpha = 0.05$).

Table 1.3. Greenhouse establishment rates presented as days after seeding required to reach 25, 50 and 75% ground cover (DAS25, DAS50 and DAS75 respectively), and final cover at end of establishment study period. Values are averaged over 8 replicates.

Treatment	DAS25	DAS50	DAS75	Final Cover %
Control	33 d	42 c	59 b	83 a
2.2 t/ha Biochar	36 d	45 c	64 ab	81 a
11.2 t/ha Biochar	35 d	45 c	69 ab	83 a
22.4 t/ha Biochar	33 d	44 c	70 a	78 ab
5 cm Biosolids	48 c	57 b	-	67 b
5 cm Biosolids + 11.2 t/ha Biochar	40 d	47 c	77 a	75 ab
5 cm Greenwaste	65 ab	-	-	48 c
5 cm Greenwaste + 11.2 t/ha Biochar	53 bc	71 a	-	52 c
10 cm Greenwaste	73 a	-	-	44 c

Values in each column followed by same letter are not significantly different (Fisher's protected least significant difference, α = 0.05).

Table 1.4. Root length and volume from field portion of study. Root samples were collected May 4, 2015 and analyzed using Winrhizo software at AllTech Labs.

Treatment	Root Length (cm)	Root Volume (cm^3)
Control	4642 c	10.9 bc
2.2 t/ha Biochar	4183 c	9.0 c
11.2 t/ha Biochar	4974 bc	10.4 c
22.4 t/ha Biochar	4792 c	10.2 c
5 cm Biosolids	2407 d	4.3 d
5 cm Greenwaste	7341 a	15.8 a
5 cm Greenwaste + 11.2 t/ha Biochar	6655 a	13.8 ab
10 cm Greenwaste	6436 ab	13.8 ab

Table 1.5. Root length and volume from the greenhouse portion of the study. Root samples were collected August 17, 2015 and analyzed using Winrhizo software at AllTech Labs.

Treatment	**Root Length (cm)**	**Root Volume (cm^3)**
Control	10806 a	20.8 b
2.2 t/ha Biochar	9,225 ab	22.6 b
11.2 t/ha Biochar	11655 a	26.9 a
22.4 t/ha Biochar	12,168 a	23.7 ab
5 cm Biosolids	4649 b	6.0 e
5 cm Biosolids + 11.2 t/ha Biochar	5554 b	8.2 de
5 cm Greenwaste	8395 ab	10.3 cd
5 cm Greenwaste + 11.2 t/ha Biochar	5728 b	9.1 cde
10 cm Greenwaste	7720 ab	12.7 c

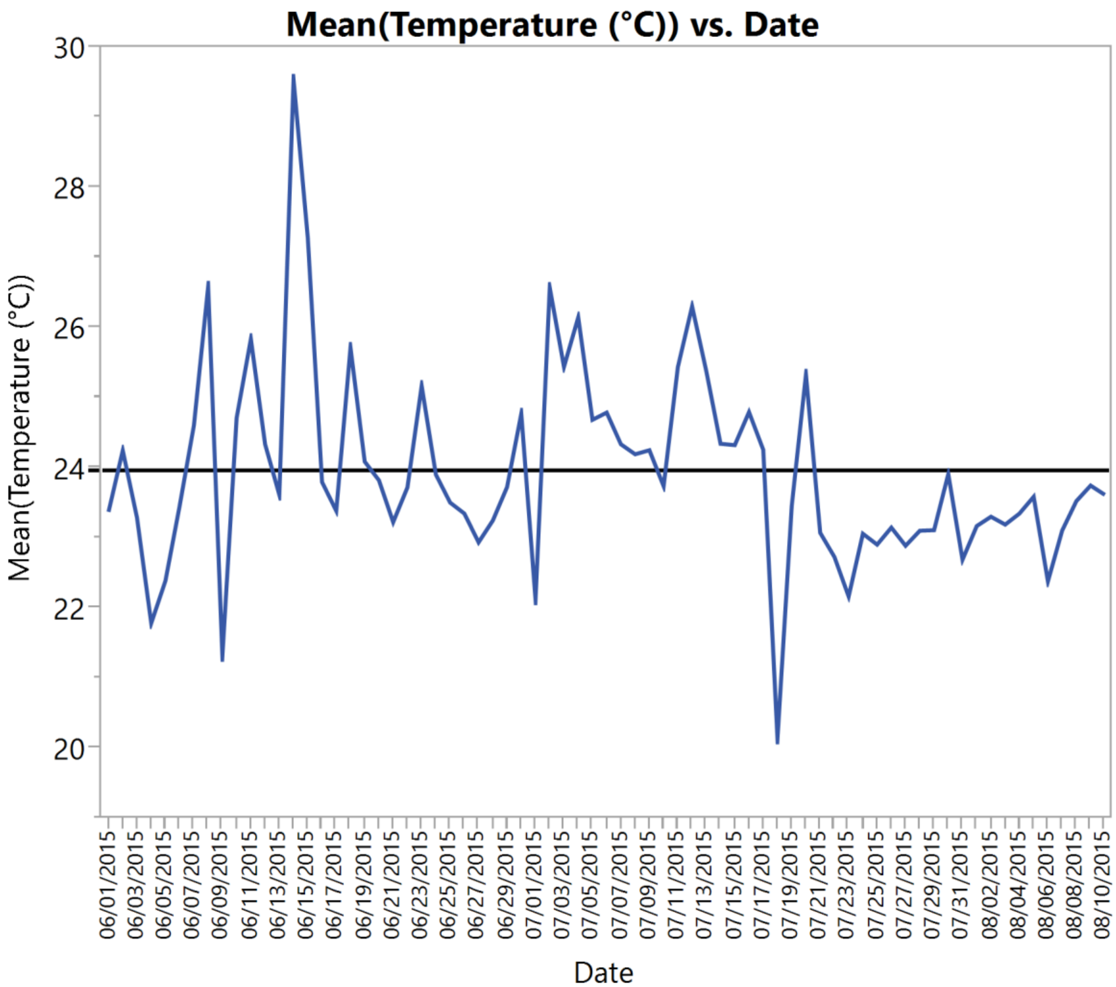
Table 1.6. Soil analysis from the greenhouse portion of the study collected August 10, 2015 and analyzed at Oklahoma State soil testing lab.

Treatment	**NO_3 (ppm)**	**Phosphorous (ppm P_2O_5)**	**Potassium (ppm K_2O)**	**pH**
Control	4.2 b	26.3 d	65.7 d	8.5 a
2.2 t/ha Biochar	3.4 b	22.4 d	63 d	8.6 a
11.2 t/ha Biochar	2.7 b	23.6 d	61.6 d	8.6 a
22.4 t/ha Biochar	2.8 b	19.9 d	63.5 d	8.5 a
5 cm Biosolids	132.8 a	473.1 a	246.2 b	6.4 c
5 cm Biosolids + 11.2 t/ha Biochar	88.8 a	276.8 b	147.6 c	6.5 c
5 cm Greenwaste	1.25 b	69.1 cd	134.6 c	8.0 b
5 cm Greenwaste + 11.2 t/ha Biochar	1.5 b	70.8 cd	141.9 c	8.0 b
10 cm Greenwaste	1.3 b	95.4 c	350.9 a	8.0 b

Table 1.7. Monthly average air temperatures, precipitation, and reference evapotranspiration (ET_o) for the University of California Agricultural Operations Center in Riverside, CA during the field study duration (May 2014-July 2014). Data provided by California Irrigation Management Information System.

Date	Eto, mm	Precipitation, mm	Air Temperature, °C
May-14	194.41	0	20.8
Jun-14	193.54	0	21.6
Jul-14	196.99	0	25.4

Figure 1.1. Average daily temperatures for greenhouse portion of the study. Temperature data collected using WatchDog 1000 Series datalogger (Spectrum technologies).



Chapter 2

Introduction

Managed turfgrass requires a very large irrigation investment by communities compared to most field crops. Estimates of turfgrass cover indicate that, as of 2005, managed turfgrass accounts for 35,850 km^2 in the United States alone (Milesi, 2005). In comparison, croplands cover an estimated 1.65 million km^2 (Nickerson et al., 2012). As the availability of potable water decreases and irrigation restrictions are suggested or imposed by local governments, it has become necessary to investigate strategies for reducing turfgrass irrigation requirements (Cockerham et al., 2011). Primary strategies for improving turf performance under high temperatures and low water availability include more efficient environmentally informed irrigation scheduling, selection of drought tolerant species, and modifications to soil structure that improve soil water dynamics. Soil amendments primarily affect soil structure by increasing water holding capacity, water infiltration, and the availability soil solution to plant roots (Farrell et al., 2013; Nguyen et al., 2009). Water use regulations imposed by municipal water districts focus on the residential sector and non-agricultural irrigation, including lawns and recreational areas (Mansur et al., 2012). Turfgrass comprises a large portion of these areas, making it especially likely to be targeted during periods of drought. Municipal regulators also have an interest in redirecting waste streams due to both budgetary constraints and regulations encouraging recycling (Lave et al., 1999). Professional turfgrass managers, such as those in the golf industry, have an expressed interest in maintaining a green surface during necessary reductions in irrigation.

Social and economic factors make soil amendments produced from organic waste, desirable products for increasing the resilience of turfgrass exposed to drought. Both biochar and compost can be produced from organic waste products generated and available in urban areas where turfgrass is traditionally concentrated. These feedstocks include yard waste, paper, garbage, and crop residues (Barker, 1997; Enders et al., 2010). Decomposition of the feedstock by a mixed microbiological population in aerobic conditions produces compost (Dalzell et al., 1987), while anaerobic heating (pyrolysis) of the feedstock produces biochar (Winsley, 2007). A large body of research has demonstrated that both can positively affect soil characteristics and reduce the negative impacts of drought conditions on both turfgrass and agricultural crops (Fischer et al., 2012; Chan et al., 2007; Glaser et al., 2002; Hartmann, 2003; Karhu et al., 2011).

While biochar and compost are often used in similar applications, their chemical compositions differ greatly and research suggests combined application may have a synergistic effect. Biochar is composed of 70-80% carbon and supplies little to no nutrients, but remains in soils at relatively consistent levels over time (Winsley, 2007). The porous structure and high surface area of biochar allows adsorption of water and nutrients (Atkinson et al. 2010). Compost supplies essential plant nutrients (Amlinger et al., 2007), but degrades much more rapidly than biochar. The nutrients present in compost are present in less volatile forms than chemical fertilizers (Steiner et al., 2010), but still require repeated applications to maintain acceptable levels in soil due to their reduced solubility. Biochar adsorbs nutrients present within compost as well as water which may otherwise be leached from the soil, stabilizing their availability over time (Thies et al., 2009; Steiner et al., 2011). These products address concerns of negative environmental impacts of turf, primarily the use of water resources, while providing the additional benefit of carbon sequestration in soil. Converting organic materials to biochar and compost followed by incorporation into soils effectively sequesters carbon and slows the accumulation of greenhouse gases in the atmosphere (Lal, 2009).

Most of the previous turfgrass research evaluating the use of compost and biochar has been greenhouse experiments with turf grown in the sand-based root zones common to the golf and other sport industries; these papers often include recommendations of further evaluation under field conditions (Brockhoff, 2010; Carey et al., 2015; Głąb et al., 2016; Li Hua et al., 2010). We conducted field experiments to evaluate the effect of compost and biochar amendments on turfgrass performance during high evaporative demand. Growth, plant health, and aesthetic quality of tall fescue (*Festuca arundinacea*), as well as soil physical and chemical characteristics, were evaluated in soils amended with compost, biochar, or combinations of both supplied with recommended or substantially reduced irrigation levels.

Materials and Methods

The study was conducted from May-September in both 2015 and 2016 at the University of California Turfgrass Research Facility in Riverside, CA (semi-arid, 340 m elevation). This period was chosen to include the months of greatest evapo-transpiration demand while allowing turf recovery between seasons (Table 2.1). Research was conducted using a mix of tall fescue cultivars, 49% Lexington, 29% Black Magic, 21% Sitka (Loveland Products Sentinel CPQ) which were seeded on May 5, 2014 in a Hanford fine sandy loam at a rate of 40 g m^{-2}. The experimental design was a split-plot, randomized complete block design with four replications per treatment. Main plots were two irrigation regimes – irrigation 3x per week at either 50% or 85% replacement of the previous week's reference evapotranspiration, (ET_0) as determined by an on-site weather station. Main plots were the two irrigation regimes. Subplots were the eight soil amendment regimes: untreated control, 2.2, 11.2, and 22.4 tons/ha of biochar; 5 and 10 cm of composted greenwaste applied by depth; 5 cm of composted biosolids, and a combined treatment of 5 cm composted greenwaste plus 11.2 tons/ha biochar. Amendments were incorporated April 16, 2014 by rototiller to a depth of 15 cm, the recommended depth for compost incorporation in turf (Landschoot, 1996). Each replicate plot measured 2.4 by 2.4 m.

Biochar was produced from sawdust pyrolized at 350 °C for 3 hours using a specialized reactor designed to allow control of oxygen and vapor levels so as to increase the adsorptive capacity of the product (McLaughlin, 2016). Greenwaste compost used a mixture of materials common to municipal sources, while the feedstock for biosolids compost was chicken manure. Compost characterizations may be found in tables 16-17.

Plots were fertilized on May 21, 2014 with a 16-16-16 fertilizer at a rate of 5 g N m^{-2} to mimic standard maintenance practices and encourage establishment. 2,4-D herbicide (Speedzone Southern, 4.6 kg ha^{-1}) was applied to field plots each June to control the emergence of broadleaf weeds. Turf was mowed every

Wednesday to the height of 5.75 cm. Every two weeks the following ratings were collected: live turf cover and Dark Green Color Index (DGCI), indicators of turf health and aesthetic quality, using Digital Image Analysis (DIA; Richardson, 2001); Normalized Difference Vegetation Index (NDVI), a measure of photosynthetic activity related to aesthetic quality (Bremer et al., 2011), measured using the Trimble Greenseeker; canopy temperature (°C) measured via infrared thermometer; Soil Volumetric Water Content (SVWC) using Time Domain Reflectometry (TDR; 15 cm probes; Field Scout TDR 300, Spectrum Technologies, Plainfield, IL) and visual quality based on guidelines set by the National Turf Evaluation Program (NTEP; Morris et al., 1998). To evaluate aboveground biomass production, clipping yield was collected monthly from a single 56 cm strip crossing the center of each plot. Root samples were collected at the beginning of the first study period using 8 by 15 cm soil cores, 3 per plot, rinsed and analyzed for length and volume using WinRhizo.

Photos used for DIA were collected with a digital camera housed in a light box to provide uniform lighting conditions and analyzed with SigmaScan Pro 5 software based on methods described by Richardson et al. (2001). NDVI is based on turf's absorption of photosynthetically active radiation, and has been used as an indicator of plant health and visual quality, reductions in which can indicate drought stress (Goodin and Henebry, 1998).

All data was subjected to ANOVA followed by comparisons of means at each rating date using Fisher's protected least significant difference test (α=0.05).

Results

Differences within low irrigation treatment

Year 1

Visual quality In plots receiving reduced irrigation (50% ET_0), visual quality was found to vary between amendments beginning 42 DAI (Table 2.2), when quality was reduced in plots amended with 5 cm greenwaste (6.75) and 5 cm biosolids (6.5), though the ratings were nonetheless 'acceptable' (>6) under NTEP standards (Morris et al., 1998). All plots fell below acceptable levels 70 DAI but maintained similar quality between treatments until 126 DAI when the 5 cm greenwaste treatment showed reduced visual quality compared to 2.2 t ha^{-1} biochar. Later in the season, the 22.2 t ha^{-1} biochar (4.75-5.5) or 10 cm greenwaste compost (4.25-5) amendments had better visual quality ratings than either the 5 cm biosolids (3-3.75) or greenwaste (2.75-3) compost treatments.

NDVI Treatment differences in NDVI were minor (<.11) until 126 DAI (Table 2.3). Though all treatments were similar to controls, plots amended with 5 cm greenwaste compost showed the lowest values from 126 DAI through to the study's conclusion, and the 2.2 and 22.4 t ha^{-1} biochar treatments maintaining the highest values.

SVWC From initiation until 42 DAI, the 5 cm biosolids compost treatment had the highest soil water content (Table 2.4). From 84-106 DAI the 10 cm greenwaste compost treatment had the highest water content. On 140 DAI plots amended with 2.2 t ha^{-1} biochar had the highest water content, while 154 DAI, the final rating date, the 5 cm biosolids treatment showed increased SVWC.

Live turf cover (%) and DGCI Significant reductions in turf cover did not occur until 126 DAI, though no differences were detected between treatments (Table 2.5). Photographs for DIA were collected through 140 DAI, due to issues with equipment availability. On the final rating date, all treatments performed similarly to controls, though the 5 cm biosolids treatment had less cover than either the 2.2 t ha^{-1} or 22.4 t ha^{-1} biochar treatments.

Treatment effects on DGCI were significantly different only on 70 DAI (Table 2.6), and while differences were minimal (<0.02), values were highest in plots amended with 5 cm biosolids, 5 cm greenwaste, 22.4 t ha^{-1} biochar and 5 cm greenwaste mixed with 11.2 t ha^{-1} biochar.

Year 2

Visual quality At the initiation of year 2, the highest visual quality was found in plots amended with 2.2 t ha^{-1} biochar (7.8), while the lowest quality was measured in those amended with 5 cm greenwaste compost with 11.2 t ha^{-1} biochar (6), though no treatments differed significantly from controls (Table 2.7). Amendment with 5 and 10 cm greenwaste compost reduced visual quality 57 DAI, which was the only rating date where amended plots differed from controls. However, differences between amendments were detected at 16 and 108 DAI; amending with 2.2 or 22.4 t ha^{-1} produced higher visual quality of turf compared to 5 cm greenwaste or biosolids compost.

NDVI No differences were detected between the control and amended plots, though in general amendments containing biochar produced higher NDVI values compared to the 5 cm greenwaste amendment (Table 2.8).

SVWC At initiation of the study's second year, 5 cm biosolids, 5 and 10 cm and greenwaste compost and 11.2 t ha^{-1} amendments produced higher values than controls; by 16 DAI only 10 cm greenwaste, 2.2 t ha^{-1} biochar and 5 cm biosolids compost showed this effect. No differences were detected on later rating dates.

Live turf cover (%) and DGCI 59 DAI live turf coverage was highest in plots amended with 22.4 t ha^{-1} biochar (79.7%) and 5 cm greenwaste (80.2%), significantly outperforming controls (62%). DGCI was reduced 88 DAI in those plots treated with 22.4 t ha^{-1} biochar, though this reduction was small (<0.02). No other dates showed significant difference between plots (Tables 2.10 -2.11).

Differences within high irrigation treatment

As all plots received recommended levels of irrigation (80% ET_o), differences were less pronounced than under the low irrigation regime. Therefore, results will not be split by year, and will instead be separated based on type of measurement.

Visual quality During year 1, all plots maintained acceptable visual quality until 70 DAI. Beginning 84 DAI, amendment with 5 cm biosolids reduced quality (Table 2.2). On the final rating day of year 1, the highest rate of biochar (22.4 t ha^{-1}) also showed lower visual quality ratings. In the study's second year, initial reductions in visual quality were noted in plots amended with 5 cm biosolids (6.3) or 5 cm greenwaste combined with 11.2 t ha^{-1} biochar (6.5; Table 2.7). The 5 cm biosolids treatment continued to show lower quality until 32 DAI, as well as 88 and 108 DAI when reductions were also measured in plots containing or 5 cm greenwaste with 11.2 t ha^{-1} biochar.

NDVI Slight reductions in NDVI were detected in year 1 at 57 and 70 DAI in plots amended with 5 cm biosolids, with additional reductions 57 DAI in plots amended with 10 cm greenwaste (Table 2.3). In the second year, the same pattern was detected 108 DAI in plots containing 5 cm greenwaste combined with 11.2 t ha^{-1} biochar (Table 2.8).

SVWC At initiation of the study's first year, SVWC was increased in plots amended with 5 cm biosolids or greenwaste compost (Table 2.4). From 28-57 DAI, these same treatments along with 10 cm greenwaste compost increased soil water content. At 70 and 84 DAI only the 10 cm greenwaste treatment increased SVWC. On the final rating date of year 1, the only treatment significantly different from the control was the highest rate of biochar (22.4 t ha^{-1}), which reduced water content. In the second year, 5 cm biosolids, 5 cm greenwaste and 10 cm greenwaste both increased initial values of SVWC (Table 2.9). 11.2 t ha^{-1} biochar reduced SVWC 16 and 59 DAI only, while values were increased in plots amended with 10 cm greenwaste 88 and 108 DAI and in plots amended with 5 cm biosolids 108 DAI.

Live turf cover (%) and DGCI Live turf cover was similar for all treatments during the first year of the study, with the exception of a reduction 70-84 DAI in plots amended with 5 cm biosolids as well as 5 cm greenwaste plus 11.2 t ha^{-1} biochar 98 DAI (Tables 2.5-2. 6). DGCI did vary slightly between treatments, though no consistent pattern was detected over rating dates and differences were <0.02. In year 2, live turf cover was found to be higher 16 DAI in those plots amended with the combined greenwaste and biochar treatment, though no subsequent differences were detected. DGCI showed slight reductions in plots containing 5 cm greenwaste 16 DAI, while 5 cm biosolids reduced DGCI 32 and 88 DAI (Tables 2.10-2.11).

Percent change due to irrigation

In order to gauge the effect of treatments on turfgrass drought tolerance, each amendment's performance under low irrigation was compared to that under high irrigation rates. This normalizes the impact of drought on each treatment to the ideal performance expected with the amendment, which may be useful in making decisions when reduced irrigation is required. Percent change was calculated as (((value under high irrigation-value under low irrigation)/value under high irrigation)*100).

In both years of the field study, visual quality, NDVI and TDR showed consistent reductions within treatments for the reduced irrigation regime beginning with the rise in temperatures around 98 DAI (Table 2.1 &2.12-2.13), continuing until the end of the season. During this period, untreated controls showed similar % change values each year of the study, ranging from 24.4-43.9%, 12.4-28.9%, and 27.1-42.4% for quality, NDVI and TDR, respectively (Tables 2.3-2.4).

The only treatment showing consistent and significantly different reductions from the control was the 22.4 t ha^{-1} biochar amendment. Within this treatment during the first year of the study, the % change due to irrigation was improved 98 and 112 DAI. Quality and NDVI showed the same effect 126 and 140 DAI, most likely due to improved soil water content prior to these dates. The 2.2 t ha^{-1} biochar treatment showed the same result in quality, but only on the 126 DAI rating date (Table 2.12). During year 2, the 22.4 t ha^{-1} demonstrated the same effect on TDR 112 DAI, and on visual quality and NDVI 126-154 DAI (Table 2.13).

Root length and volume

Root samples were collected May 20, 2015, prior to initiation of differential irrigation. Therefore, any changes to root architecture are due to amendment effects, and average values were calculated from 8 replicates of each amendment (Table 2.14). Root length and volume were greatly reduced in plots amended with 5 cm biosolids compost (2406 cm and 4.3 cm^3 respectively). The second lowest values were found under the 2.2 t ha^{-1} biochar treatment, and were nearly double those measured using the biosolids treatment. Biochar amendments did not affect root length or volume, regardless of rate. Greenwaste compost increased turfgrass root growth compared to controls; the 10 cm (6436 cm), 5 cm (7340 cm) and 5 cm combined with 11.2 t ha^{-1} biochar (6655 cm) treatments produced longer roots, though only 5 cm greenwaste compost increased root volume (15.8 cm^3).

Clipping yield

Year 1 Treatments affected clipping yield most consistently under reduced irrigation (Table 2.15). When irrigated at recommended levels, the only difference noted was between the lowest rate of biochar (48.1 g) and the 5 cm greenwaste (30.9 g) treatments. Under reduced irrigation, yields were lowest in plots amended with 5 cm greenwaste. The combined amendment of 5 cm greenwaste along with 11.2 t ha^{-1} biochar showed reductions in yield only 45 DAI. Ratings collected 129 DAI occurred closer to regularly scheduled mowing events, resulting in lower values overall; however there were no treatment differences for either irrigation regime.

Compost and soil analyses

Characterization of compost amendments used in this study revealed that greenwaste compost had a larger particle size than recommended while biosolids compost showed high levels of salinity (Tables 2.16-2.17). Biosolids and greenwaste compost were found to impair establishment in a prior study done on this same site, though all turf had reached comparable levels of visual quality and live turf coverage by the beginning of work discussed in this article (Tables 2. 2-2.5). Field soil was mixed with amendments in 3.8 L pots at equal rates to the field site April 10, 2015, irrigated for 3 months, and collected to allow more controlled measurement of amendment effects on soil chemistry. Treatments including compost altered all measured aspects of soil chemistry compared to controls, while biochar treatments did not (Table 2.18). Amendment with 5 cm biosolids compost (133 ppm) resulted in the highest levels of nitrate, greatly exceeding those levels seen in control pots (4 ppm).

Phosphorous levels were highest in pots amended with 5 cm of biosolids compost (473 ppm) or 10 cm greenwaste compost (95 ppm) compared to controls (26 ppm). Potassium levels were highest in soils amended with 10 cm greenwaste compost (351 ppm), followed by those amended with 5 cm biosolids compost (246 ppm). The 5 cm rate of greenwaste compost (135 ppm) also increased potassium levels compared to controls (65 ppm), though to a lesser degree than the treatments mentioned above. Control pots and those amended with all rates of biochar (61-63 ppm) possessed the lowest levels of potassium, and were similar to one another.

Analysis of soil pH levels demonstrated an effect of both compost types. The highest pH levels (8.5-8.6) were seen in control pots and those amended with all rates of biochar. Greenwaste compost and the combined greenwaste and biochar amendments reduced pH levels (8). The lowest pH levels (6.4-6.5) were detected in soils amended with biosolids compost alone (Table 2.18).

Discussion

The results obtained in this experiment support some application for biochar and compost in drought management. A more nuanced method of selecting products must be adapted, which takes into account physical and chemical characteristics of both soil and amendments. Previous work has shown that biochar may only affect hydraulic properties of soils when small particle size biochar is added to sandy soils (Glab et al., 2016; Jeffery et al., 2016). Large particle size products, such as the compost used in this work, may only be effective in soils with a high proportion of clay or small particles. It is important to note that if these amendments are used without an adjustment to general management practices, turf may show no improved performance. Most work attempting to demonstrate the application of biochar and compost with turfgrass looks at differences between amendment types rather than at the effect of reduced irrigation within amendment types. This work suggests that the suitability of biochar and compost amendments can more accurately be measured by comparing performance between irrigation types within amendment treatments, controlling for other management practices designed for unaltered soils. We found no demonstrable benefit of combining biochar and compost amendments in initial application, though previous work has shown benefits if repeated surface applications of compost amendments are used as biochar can improve retention of nutrients supplied by these products (Major, 2010).

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Table 2.1. Monthly average air temperatures, cumulative precipitation and cumulative reference evapotranspiration (ET_0) for turfgrass research plots in Riverside, CA during the research period (data provided by California Irrigation Management System).

Season	**May**	**June**	**July**	**Aug.**	**Sept.**
			Air Temperature, °C		
2015	17	23.4	23.5	25.6	25.1
2016	17	23.6	25.3	24.7	22.7
			Precipitation, mm		
2015	18.1	0.6	30.1	0	26.4
2016	0.5	0.1	0	0	0
			ET_0, mm		
2015	136.5	189.4	171.5	194.5	147.6
2016	157.7	183.1	196.6	174.8	134.7

Table 2.2. Average visual quality of plots by amendment and irrigation rate during year 1 of the field study for each amendment and irrigation treatment. The study lasted 154 days, beginning May 4, 2015.

Amendment	Irrigation Rate	DAI											
		0	14	28	42	57	70	84	98	112	126	140	154
10 cm Greenwaste	Low	8Aa	7.5Aa	7.75Aa	7Aab	6Ab	4.25Aa	5Aa	4.5Aa	4.25Aa	4.25Aab	4.25Babc	5Aa
11.2 t/ha BC	Low	8Aa	7.75Aa	7.5Aa	7Aab	7.25Aab	4Aa	4.75Aa	4.5Aa	3.5Ba	3.5Bab	3.75Bbc	4.25Aabc
2.2 t/ha BC	Low	8Aa	7.5Aa	7.75Aa	7.25Aab	7.5Aa	3.75Aa	4.75Aa	4.25Aa	4.25Aa	4.5Aa	4.75Aab	4.75Aab
22.4 t/ha BC	Low	8Aa	7.5Aa	7.5Aa	7.5Aab	6.75Bab	4Aa	5.25Aa	4.75Aa	4.25Aa	4.25Aab	5.5Aa	4.75Aab
5 cm Biosolids	Low	7.75Ba	7.25Aa	7.5Aa	6.5Ab	6.25Aab	3Aa	3.75Aa	3Aa	3Aa	3.25Aab	3.75Abc	3Abc
5 cm Greenwaste	Low	7.25Ab	7.25Aa	7.25Aa	6.75Bb	7Aab	4.25Aa	5.25Aa	3.75Ba	3Ba	2.75Bb	3Bc	2.75Bc
5 cm Greenwaste + 11.2 t/ha Biochar	Low	7.75Aa	7.75Aa	8Aa	8Aa	6.5Aab	3.25Aa	4.25Ba	3.5Ba	3.25Ba	3Bab	3.5Bbc	3.5Babc
Control	Low	8Aa	7.75Aa	7.75Aa	7.25Aab	6Ab	4Aa	4.75Aa	3.5Aa	3.5Ba	3.5Aab	4.25Babc	4.25Babc
10 cm Greenwaste	High	8Aa	7.75Aa	7.75Aa	7.75Aa	6.5Abc	5.5Aa	5.5Aa	5.75Aa	5.75Aab	6.25Aa	6.25Aa	6.5Aab
11.2 t/ha BC	High	8Aa	7.75Aa	7.75Aa	7.5Aa	7.75Aa	4.5Aab	5.75Aa	6Aa	6.25Aa	5.75Aa	6Aa	5.75Aabcd
2.2 t/ha BC	High	7.75Aa	7.5Aa	8Aa	7.5Aa	7.25Aab	5.25Aa	5.75Aa	5.5Aab	5.75Aab	5Aa	5.75Aa	5.5Aabcd
22.4 t/ha BC	High	8Aa	8Aa	8Aa	7.25Aa	8Aa	5.5Aa	5.75Aa	6Aa	4.75Aab	4.75Aa	5Aab	5Acd
5 cm Biosolids	High	8Aa	7.25Aa	7Ab	7.25Aa	6.25Ac	3.75Ab	3.75Ab	4Ab	4.25Ab	4.5Aa	4.25Ab	4.5Ad
5 cm Greenwaste	High	8Aa	8Aa	7.75Aa	8Aa	7.25Aab	5.75Aa	6.25Aa	6Aa	5.75Aab	5.5Aa	5.5Aab	6Aabc
5 cm Greenwaste + 11.2 t/ha Biochar	High	7.75Aa	7.25Aa	7.75Aa	7.25Aa	7.5Aa	4.5Aab	6.25Aa	5Aab	4.75Aab	5Aa	5Aab	5.25Abcd
Control	High	8Aa	7.25Aa	7.75Aa	7.5Aa	7.5Aa	5Aab	6.25Aa	5.75Aa	6.25Aa	6Aa	6.25Aa	6.75Aa

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05). Means followed by the same uppercase letter are not significantly different between irrigation rates within each treatment.

Table 2.3. Average NDVI of plots by amendment and irrigation rate during year 1 of the field study.

		DAI											
Amendment	Irrigation Rate	0	14	28	42	57	70	84	98	112	126	140	154
10 cm Greenwaste	Low	0.87Aa	0.89Aa	0.91Aa	0.77Ab	0.60Ab	0.62Bab	0.64Aa	0.65Aa	0.61Aa	0.60Aa	0.67ab	0.66ab
11.2 t/ha BC	Low	0.86Aa	0.90Aa	0.91Aa	0.79Aab	0.65Aa	0.66Aa	0.67Aa	0.69Aa	0.57Aa	0.54Aab	0.63ab	0.61Babc
2.2 t/ha BC	Low	0.85Aa	0.89Aab	0.89Aab	0.79Aab	0.64Aab	0.62Aab	0.66Aa	0.62Aa	0.58a	0.61Aa	0.72Aa	0.68Ba
22.4 t/ha BC	Low	0.86Aa	0.89Aa	0.91Aa	0.79Aab	0.64Aab	0.63Aa	0.67Aa	0.66Aa	0.62Aa	0.63Aa	0.73Aa	0.68Aa
5 cm Biosolids	Low	0.86Aa	0.89Aa	0.90Aa	0.78Aab	0.60Ab	0.55Ab	0.57Bb	0.60Ba	0.51Ba	0.51Aab	0.58Bab	0.54Bbc
5 cm Greenwaste	Low	0.85Aa	0.87Ab	0.88Bb	0.80Aab	0.63Aab	0.64Aa	0.64Aa	0.60Ba	0.47Ba	0.39Bb	0.47Bb	0.48Bc
5 cm Greenwaste + 11.2 t/ha Biochar	Low	0.87Aa	0.89Aa	0.90Aab	0.79Aab	0.61Aab	0.60Bab	0.63Bab	0.61Aa	0.51Aa	0.50Bab	0.57Bab	0.52Bc
Control	Low	0.85Aa	0.90Aa	0.91Aa	0.82Aa	0.63Aab	0.63Aa	0.67Aa	0.64Aa	0.55Aa	0.50Aab	0.57Aab	0.57Babc
10 cm Greenwaste	High	0.86Aa	0.89Aa	0.90Ab	0.79Aa	0.61Ab	0.66Aab	0.67Aa	0.71Aab	0.66Aa	0.70Aa	0.79Aa	0.73Aab
11.2 t/ha BC	High	0.85Aa	0.89Aa	0.91Aab	0.81Aa	0.63Aab	0.63Aab	0.67Aa	0.71Aa	0.68Aa	0.70Aa	0.77Aa	0.72Aab
2.2 t/ha BC	High	0.87Aa	0.89Aa	0.91Aab	0.81Aa	0.65Aa	0.69Aa	0.70Aa	0.71Aab	0.67Aa	0.66Aa	0.75Aa	0.75Aa
22.4 t/ha BC	High	0.86Aa	0.90Aa	0.91Aab	0.81Aa	0.64Aab	0.68Aab	0.68Aa	0.71Aa	0.63Aa	0.60Aa	0.68Aa	0.68Ab
5 cm Biosolids	High	0.86Aa	0.89Aa	0.92Aa	0.78Aa	0.61Ab	0.63Ab	0.68Aa	0.72Aa	0.68Aa	0.65Aa	0.78Aa	0.68Ab
5 cm Greenwaste	High	0.86Aa	0.90Aa	0.91Aab	0.81Aa	0.63Aab	0.68Aab	0.68Aa	0.72Aa	0.67Aa	0.67Aa	0.75Aa	0.72Aab
5 cm Greenwaste + 11.2 t/ha Biochar	High	0.86Aa	0.89Aa	0.90Ab	0.81Aa	0.63Aab	0.68Aab	0.68Aa	0.63Ab	0.64Aa	0.66Aa	0.74Aa	0.71Aab
Control	High	0.86Aa	0.89Aa	0.91Aab	0.81Aa	0.66Aa	0.69Aa	0.70Aa	0.73Aa	0.69Aa	0.70Aa	0.79Aa	0.76Aa

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05). Means followed by the same uppercase letter are not significantly different between irrigation rates within each treatment.

Table 2.4. Average SVWC of plots by amendment and irrigation rate during year 1 of the field study.

		DAI											
Amendment	Irrigation Rate	0	14	28	42	57	70	84	98	112	126	140	154
10 cm Greenwaste	Low	33.7Aabc	20.6Aa	22.6Bab	59.4Ba	52.8Ba	28.5Ba	45.4Ba	38.2Aa	38.3Aa	33.3Aa	25.9Aab	30.2Bab
11.2 t/ha BC	Low	32.0Abc	20.1Aa	21.1Abc	50.8Abc	44.2ab	23.6Aab	39.9Aab	31.6Aa	29.1Aa	26.3Aab	27.1Aab	28.5Ab
2.2 t/ha BC	Low	29.6Ac	19.3Aa	20.4Abc	49.9Bc	44.3Bab	17.4Bb	41.3Aab	34.3Aa	34.5Aa	30.3Bab	30.5Aa	28.2Bb
22.4 t/ha BC	Low	29.8Ac	19.8Aa	20.3Ac	50.8Abc	43.6Bab	20.0Aab	38.7Aab	36.3Aa	37.7Aa	26.7Aab	23.4Aab	27.7Ab
5 cm Biosolids	Low	36.7Aa	21.7Aa	23.3Ba	61.5Aa	51.9ab	28.5Aa	43.3Bab	33.7Ba	37.1Aa	31.0Bab	27.1Bab	37.6Aa
5 cm Greenwaste	Low	35.6Aab	20.0Aa	20.8Abc	58.5Ba	48.4Bab	29.0Aa	39.3Bab	28.3Ba	28.2Ba	23.9Ab	22.0Bb	25.9Bb
5 cm Greenwaste + 11.2 t/ha Biochar	Low	34.1Aabc	21.3Aa	22.5Aabc	57.9Bab	49.1ab	26.8Aab	43.1Aab	32.2Aa	27.9Ba	26.3Bab	22.3Bb	27.3Ab
Control	Low	29.5Ac	21.8Aa	20.8BAbc	48.6Ac	41.3Bb	17.3Ab	35.2Bb	28.9Ba	27.6Aa	23.1Bab	23.9Bb	27.2Ab
10 cm Greenwaste	High	33.7Aabc	20.7Aa	25.1Aa	72.3Aa	70.0Aa	49.1Aa	59.0Aa	56.0Aa	51.9Aa	49.2Aa	38.0Aab	40.5Aa
11.2 t/ha BC	High	32.0Abc	18.7Ab	21.7Ad	54.7Ad	49.9e	27.8Ac	46.0Acd	42.2Ab	41.6Aa	39.2Aab	31.5Aab	30.6Acd
2.2 t/ha BC	High	29.6Ac	19.6Aab	21.6Ad	59.3Ac	56.7Acde	33.1Abc	47.8Abcd	44.7Aab	42.9Aa	38.9Aab	36.7Aab	38.0Aab
22.4 t/ha BC	High	29.8Ac	19.2Aab	22.1Ad	57.2Acd	53.3Ade	31.5Abc	42.9Ad	39.2Ab	35.5Aa	33.7Ab	30.3Ab	30.0Ad
5 cm Biosolids	High	36.7Aa	20.4Aa	24.5Aab	65.3Ab	63.9ab	39.3Aabc	53.7Aab	49.4Aab	44.9Aa	48.2Aa	41.2Aa	39.7Aab
5 cm Greenwaste	High	35.6Aab	20.2Aab	24.5Aab	66.5Ab	63.3Aabc	43.8Aab	51.6Abc	48.0Aab	45.9Aa	35.7Ab	34.1Aab	35.9Aabcd
5 cm Greenwaste + 11.2 t/ha Biochar	High	34.1Aabc	19.6Aab	23.6Abc	63.6Ab	57.9Abcd	38.6Aabc	49.9Abc	47.6Aab	48.6Aa	37.8Aab	34.3Aab	33.6Abcd
Control	High	29.5Ac	19.8Aab	22.6Acd	57.0Acd	55.2Ade	33.5Abc	49.1Abcd	47.1Aab	42.6Aa	40.0Aab	39.0Aab	37.1Aabc

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05). Means followed by the same uppercase letter are not significantly different between irrigation rates within each treatment.

Table 2.5. Average live turf cover of plots by amendment and irrigation rate during year 1 of the field study.

Amendment	Irrigation Rate	DAI 14	28	42	57	70	84	98	112	126	140
10 cm Greenwaste	Low	99.8a	99.9a	99.6a	95.5a	98.1a	98.7ab	97.6a	97.3a	82.9a	84.7ab
11.2 t/ha BC	Low	99.8a	99.9a	99.5a	97.4a	98.4a	99.3a	96.7a	98.2a	91.4a	90.6ab
2.2 t/ha BC	Low	99.7a	99.9a	99.4a	97.5a	99.0a	98.5ab	92.5a	96.6a	93.5a	95.5a
22.4 t/ha BC	Low	99.7a	99.9a	99.6a	96.2a	98.1a	98.4ab	94.7a	97.0a	95.3a	94.4a
5 cm Biosolids	Low	99.9a	99.9a	99.3a	95.7a	98.2a	97.4b	89.8a	95.3a	80.9a	74.2b
5 cm Greenwaste	Low	99.7a	99.8a	99.7a	97.4a	97.0a	98.8ab	98.6a	91.0a	76.6a	83.9ab
5 cm Greenwaste + 11.2 t/ha Biochar	Low	99.8a	99.9a	99.5a	96.0a	98.7a	99.1a	97.3a	90.8a	84.2a	84.8ab
Control	Low	99.8a	99.9a	99.6a	97.2a	99.0a	99.0a	96.9a	96.0a	85.8a	88.2ab
10 cm Greenwaste	High	99.8a	99.9a	99.6a	98.1a	99.1a	99.5ab	99.1ab	98.9a	99.2a	99.6a
11.2 t/ha BC	High	99.7a	99.9a	99.8a	97.6ab	98.6a	99.0bc	99.4ab	96.9a	98.5a	99.2a
2.2 t/ha BC	High	99.8a	100.0a	99.7a	97.9a	98.9a	99.4ab	99.3ab	97.5a	94.3a	97.4a
22.4 t/ha BC	High	99.7a	99.9a	99.8a	97.8a	98.9a	99.7a	98.0ab	97.5a	95.1a	90.7a
5 cm Biosolids	High	99.7a	99.9a	99.5a	96.1b	96.8b	98.8c	99.3ab	99.4a	88.6a	90.2a
5 cm Greenwaste	High	99.8a	100.0a	99.6a	97.6ab	99.3a	99.7a	99.6a	99.2a	94.5a	96.5a
5 cm Greenwaste + 11.2 t/ha Biochar	High	99.8a	99.9a	99.7a	97.7ab	98.7a	99.6a	86.5b	99.0a	98.8a	96.6a
Control	High	99.8a	99.9a	99.7a	98.2a	98.8a	99.5ab	99.5a	98.6a	97.9a	99.7a

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05).

Table 2.6. Average DGCI of plots by amendment and irrigation rate during year 1 of the field study.

Amendment	Irrigation Rate	DAI 14	28	42	57	70	84	98	112	126	140
10 cm Greenwaste	Low	0.44a	0.42a	0.40a	0.40a	0.36abc	0.37ab	0.39a	0.38a	0.40a	0.42a
11.2 t/ha BC	Low	0.43a	0.42a	0.41a	0.40a	0.36bc	0.38a	0.41a	0.38a	0.41a	0.43a
2.2 t/ha BC	Low	0.44a	0.42a	0.40a	0.40a	0.36abc	0.38a	0.41a	0.38a	0.40a	0.42a
22.4 t/ha BC	Low	0.44a	0.43a	0.41a	0.41a	0.37a	0.38a	0.40a	0.37a	0.40a	0.42a
5 cm Biosolids	Low	0.44a	0.43a	0.40a	0.41a	0.37ab	0.38a	0.40a	0.38a	0.39a	0.42a
5 cm Greenwaste	Low	0.43a	0.42a	0.40a	0.40a	0.37ab	0.37b	0.39a	0.38a	0.40a	0.42a
5 cm Greenwaste + 11.2 t/ha Biochar	Low	0.43a	0.42a	0.40a	0.41a	0.37ab	0.37ab	0.39a	0.36a	0.39a	0.42a
Control	Low	0.43a	0.42a	0.40a	0.41a	0.35c	0.38a	0.41a	0.39a	0.40a	0.43a
10 cm Greenwaste	High	0.44a	0.41b	0.40a	0.41ab	0.37a	0.37b	0.40a	0.39ab	0.39a	0.42ab
11.2 t/ha BC	High	0.44a	0.43ab	0.41a	0.41ab	0.37a	0.38ab	0.41a	0.39ab	0.39a	0.42ab
2.2 t/ha BC	High	0.43a	0.42ab	0.40a	0.41ab	0.38a	0.39ab	0.41a	0.39a	0.41a	0.44a
22.4 t/ha BC	High	0.44a	0.43ab	0.41a	0.41a	0.36a	0.38ab	0.40a	0.39ab	0.41a	0.44a
5 cm Biosolids	High	0.44a	0.43ab	0.40a	0.40ab	0.35a	0.38ab	0.41a	0.38ab	0.38a	0.42ab
5 cm Greenwaste	High	0.43a	0.41ab	0.41a	0.40ab	0.37a	0.38ab	0.38a	0.36b	0.38a	0.41b
5 cm Greenwaste + 11.2 t/ha Biochar	High	0.43a	0.42ab	0.40a	0.40b	0.36a	0.38ab	0.39a	0.37ab	0.39a	0.41b
Control	High	0.44a	0.43a	0.41a	0.41ab	0.38a	0.39a	0.40a	0.39ab	0.40a	0.43ab

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05).

Table 2.7. Average visual quality of plots by amendment and irrigation rate during year 2 of the field study for each amendment and irrigation treatment. This table represents the first 108 days of the 154 day study beginning May 20, 2016.

		DAI					
Amendment	Irrigation Rate	0	16	32	59	88	108
10 cm Greenwaste	Low	7.0Aabc	7.0Aab	5.5Aa	3.8Ab	3.3Ba	3.8Bab
11.2 t/ha BC	Low	7.5Aab	6.5Aabc	5.8Aa	4.5Aa	4.8Ba	4.5Aab
2.2 t/ha BC	Low	7.8Aa	7.8Aa	5.8Aa	5.8Aa	5.0Aa	5.0Aa
22.4 t/ha BC	Low	7.3Aabc	7.8Aa	6.3Aa	4.8Aa	5.0Aa	4.0Aab
5 cm Biosolids	Low	6.8Aabc	6.3Abc	5.0Aa	4.5Aa	4.3Aa	3.3Ab
5 cm Greenwaste	Low	6.3Abc	5.5Bc	5.0Aa	3.8Ab	3.5Ba	3.5Bab
5 cm Greenwaste + 11.2 t/ha Biochar	Low	6.0Ac	6.3Ac	5.8Aa	4.5Aa	4.3Aa	3.8Aab
Control	Low	7.3Aabc	7.5Aab	6.5Aa	4.5Aa	4.8Ba	4.0Bab
10 cm Greenwaste	High	7.8Aab	8.3Aa	6.8Aa	6.0Aa	6.5Aab	5.5Aab
11.2 t/ha BC	High	7.8Aab	7.5Aa	6.3Aa	5.5Aa	6.3Aab	5.8Aab
2.2 t/ha BC	High	8.3Aa	7.3Aa	6.0Aa	6.3Aa	6.8Aa	5.5Aab
22.4 t/ha BC	High	7.3Aabc	7.5Aa	6.8Aa	6.3Aa	6.8Aa	5.8Aab
5 cm Biosolids	High	6.3Ac	5.8Ab	4.3Ab	4.3Aa	5.3Ab	4.0Ac
5 cm Greenwaste	High	7.5Aabc	7.8Aa	6.5Aa	6.0Aa	6.5Aab	6.0Aa
5 cm Greenwaste + 11.2 t/ha Biochar	High	6.5Abc	8.0Aa	5.5Aab	5.0Aa	5.3Ab	4.5Abc
Control	High	8.0Aa	7.5Aa	6.5Aa	5.5Aa	6.8Aa	6.5Aa

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05). Means followed by the same uppercase letter are not significantly different between irrigation rates within each treatment.

Table 2.8. Average Normalized Difference Vegetation Index (NDVI) of plots by amendment and irrigation rate during year 2 of the field study. This table represents the first 108 days of the 154 day study beginning May 20, 2016.

		DAI					
Amendment	Irrigation Rate	0	16	32	59	88	108
10 cm Greenwaste	Low	0.75Aab	0.77Aa	0.80Aa	0.72Bab	0.65Bab	0.66Ba
11.2 t/ha BC	Low	0.77Aa	0.82Aa	0.79Aa	0.72Aab	0.74Aa	0.74Aa
2.2 t/ha BC	Low	0.75Aab	0.82Aa	0.76Aa	0.78a	0.74Ba	0.69Aa
22.4 t/ha BC	Low	0.75Aab	0.81Aa	0.79Aa	0.75Aab	0.68Aab	0.60Aa
5 cm Biosolids	Low	0.73Aab	0.80Aa	0.77Aa	0.74Aab	0.66Aab	0.62Ba
5 cm Greenwaste	Low	0.72Aab	0.73Aa	0.77Aa	0.69Ab	0.61Bb	0.59Ba
5 cm Greenwaste + 11.2 t/ha Biochar	Low	0.72Ab	0.80Aa	0.80Aa	0.76Aab	0.68Aab	0.60Aa
Control	Low	0.73Aab	0.81Aa	0.78Aa	0.76Aab	0.72Aab	0.73Ba
10 cm Greenwaste	High	0.76Aa	0.81Aab	0.81Aa	0.80Aa	0.80Aa	0.81Aa
11.2 t/ha BC	High	0.75Aab	0.78Ab	0.74Aa	0.74Aa	0.75Aab	0.78Aa
2.2 t/ha BC	High	0.77Aa	0.81Aab	0.77Aa	0.80Aa	0.78Aab	0.80Aa
22.4 t/ha BC	High	0.75Aab	0.81Aab	0.78Aa	0.79Aa	0.80Aa	0.81Aa
5 cm Biosolids	High	0.69Ab	0.83Aa	0.75Aa	0.77Aa	0.77Aab	0.79Aa
5 cm Greenwaste	High	0.76Aa	0.81Aab	0.79Aa	0.80Aa	0.79Aab	0.80Aa
5 cm Greenwaste + 11.2 t/ha Biochar	High	0.74Aab	0.82Aab	0.78Aa	0.80Aa	0.70Ab	0.59Ab
Control	High	0.73Aab	0.81Aab	0.77Aa	0.77Aa	0.77Aab	0.80Aa

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05). Means followed by the same uppercase letter are not significantly different between irrigation rates within each treatment.

Table 2.9. Average Soil Volumetric Water Content (SVWC) of plots by amendment and irrigation rate during year 2 of the field study. This table represents the first 108 days of the 154 day study beginning May 20, 2016.

		DAI					
Amendment	Irrigation Rate	0	16	32	59	88	108
10 cm Greenwaste	Low	52.2Ba	64.5a	-	39.8Ba	46.5Ba	40.7Ba
11.2 t/ha BC	Low	50.0a	55.9ab	-	34.1a	41.6Ba	34.7a
2.2 t/ha BC	Low	49.4ab	63.5a	-	44.7a	44.3a	38.7a
22.4 t/ha BC	Low	46.7ab	55.6Bab	-	32.5a	36.8a	34.4Ba
5 cm Biosolids	Low	52.3Ba	63.4Ba	-	42.2Ba	52.3a	40.3a
5 cm Greenwaste	Low	50.2a	56.6ab	-	37.7a	42.9Ba	40.8a
5 cm Greenwaste + 11.2 t/ha Biochar	Low	48.0ab	61.4ab	-	39.0a	51.7a	36.4Ba
Control	Low	43.1b	52.9b	-	32.8a	42.0Ba	28.9Ba
10 cm Greenwaste	High	58.6ab	70.0a	-	52.9a	68.0a	56.8ab
11.2 t/ha BC	High	49.4bcd	54.3b	-	35.0b	53.9c	43.7e
2.2 t/ha BC	High	55.5abcd	64.9a	-	48.4ab	60.9abc	51.7bcd
22.4 t/ha BC	High	47.7d	62.6ab	-	43.7ab	55.9bc	46.1de
5 cm Biosolids	High	62.8a	70.1a	-	55.7a	62.3ab	58.7a
5 cm Greenwaste	High	59.5a	70.3a	-	52.0a	62.3ab	54.7abc
5 cm Greenwaste + 11.2 t/ha Biochar	High	58.0abc	67.5a	-	52.9a	62.8ab	50.4cd
Control	High	48.6cd	63.7a	-	42.5ab	57.1bc	49.1cde

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05). Means followed by the same uppercase letter are not significantly different between irrigation rates within each treatment.

Table 2.10. Average live turf cover (% of photo area) of plots by amendment and irrigation rate during year 2 of the field study. This table represents the first 108 days of the 154 day study beginning May 20, 2016.

		DAI				
Amendment	Irrigation Rate	16	32	59	88	108
10 cm Greenwaste	Low	87.4a	90.6a	70.2ab	83.2a	92.2a
11.2 t/ha BC	Low	93.1a	96.8a	60.7b	98.5a	99.9a
2.2 t/ha BC	Low	95.4a	89.8a	61.0b	81.8a	100.0a
22.4 t/ha BC	Low	93.6a	96.5a	79.7a	78.6a	99.9a
5 cm Biosolids	Low	93.2a	95.4a	60.4b	83.5a	99.7a
5 cm Greenwaste	Low	90.4a	94.9a	80.2a	90.9a	93.1a
5 cm Greenwaste + 11.2 t/ha Biochar	Low	95.4a	97.7a	71.8ab	91.2a	90.2a
Control	Low	96.0a	94.3a	62.0b	95.3a	99.0a
10 cm Greenwaste	High	93.4ab	93.1a	65.4a	99.6a	99.9a
11.2 t/ha BC	High	96.0ab	89.4a	66.0a	99.3a	99.9a
2.2 t/ha BC	High	94.8ab	92.5a	74.4a	99.1a	100.0a
22.4 t/ha BC	High	94.1ab	91.5a	65.8a	99.5a	99.7a
5 cm Biosolids	High	91.4ab	96.7a	62.3a	98.7a	99.7a
5 cm Greenwaste	High	95.9ab	90.1a	72.6a	99.6a	99.9a
5 cm Greenwaste + 11.2 t/ha Biochar	High	97.1a	97.0a	74.9a	96.6a	99.3a
Control	High	86.7b	89.4a	75.6a	99.5a	99.9a

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05).

Table 2.11. Average Dark Green Color Index (DGCI) of plots by amendment and irrigation rate during year 2 of the field study. This table represents the first 108 days of the 154 day study beginning May 20, 2016.

Amendment	Irrigation Rate	DAI 16	32	59	88	108
10 cm Greenwaste	Low	0.63a	0.81a	0.89a	0.37a	0.53ab
11.2 t/ha BC	Low	0.61a	0.67b	0.93a	0.36ab	0.45b
2.2 t/ha BC	Low	0.55a	0.77ab	0.93a	0.36ab	0.48ab
22.4 t/ha BC	Low	0.61a	0.72ab	0.81a	0.35b	0.42b
5 cm Biosolids	Low	0.55a	0.74ab	0.93a	0.38a	0.48ab
5 cm Greenwaste	Low	0.56a	0.78ab	0.80a	0.38a	0.55ab
5 cm Greenwaste + 11.2 t/ha Biochar	Low	0.55a	0.69ab	0.88a	0.36ab	0.67a
Control	Low	0.55a	0.78ab	0.93a	0.37a	0.61ab
10 cm Greenwaste	High	0.61ab	0.81a	0.90a	0.36ab	0.44a
11.2 t/ha BC	High	0.55ab	0.79a	0.92a	0.36a	0.47a
2.2 t/ha BC	High	0.60ab	0.80a	0.82a	0.36ab	0.45a
22.4 t/ha BC	High	0.62ab	0.81a	0.92a	0.36ab	0.43a
5 cm Biosolids	High	0.62ab	0.65b	0.89a	0.34b	0.45a
5 cm Greenwaste	High	0.53b	0.80a	0.88a	0.36a	0.46a
5 cm Greenwaste + 11.2 t/ha Biochar	High	0.56ab	0.74ab	0.83a	0.36ab	0.46a
Control	High	0.71a	0.82a	0.83a	0.36a	0.44a

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05).

Table 2.12. Percentage change in measured characteristics due to reduced irrigation during year 1 of the study. Only those dates showing a significant effect of amendment on turfgrass drought stress. Change is calculated for each date as (((value under high irrigation-value under low irrigation)/value under high irrigation)*100).

	DAI									
	98	98	98	98	98	112	112	112	112	112
Amendment	Quality	NDVI	TDR	%Cover	DGCI	Quality	NDVI	TDR	%Cover	DGCI
22.4 t/ha BC	21.3a	7.6a	5.6b	3.5ab	1.0ab	8.3b	1.5c	-14.9b	0.6ab	-7.1c
2.2 t/ha BC	23.8a	11.9a	22.1ab	6.8a	0.4ab	24.0ab	13.7abc	13.6ab	1.0ab	-1.7abc
5 cm Biosolids	20.4a	15.9a	31.3ab	9.5a	-0.3ab	28.3ab	24.3ab	17.5a	4.1ab	0.6ab
5 cm Greenwaste	37.5a	17.7a	40.3a	1.0ab	3.3a	47.6a	30.8a	37.4a	8.3a	5.7a
5 cm Greenwaste + 11.2 t/ha Biochar	27.5a	1.9a	28.5ab	-22.9b	-1.8b	30.0ab	19.6abc	42.2a	8.3a	-2.6bc
10 cm Greenwaste	22.5a	7.9a	32.3ab	1.5ab	-1.6b	27.7ab	8.0bc	27.1a	1.6ab	-3.7bc
11.2 t/ha BC	22.0a	2.5a	18.3ab	2.7ab	-0.4ab	37.2ab	15.5abc	23.2a	-1.7b	-1.0abc
Control	36.8a	12.8a	37.8a	2.7ab	0.4ab	42.7ab	20.5abc	30.7a	2.6ab	0.2abc
	DAI									
	126	126	126	126	126	140	140	140	140	140
22.4 t/ha BC	6.3b	-9.8c	17.6a	-0.5a	-1.6a	-16.4c	-13.9c	21.6ab	-8.7b	-3.7bc
2.2 t/ha BC	6.3b	7.6bc	19.9a	0.4a	-1.1a	14.9abc	2.8bc	16.6ab	1.7ab	-3.9c
5 cm Biosolids	28.3ab	22.6ab	34.0a	4.8a	0.8a	7.9bc	26.0ab	31.8ab	17.0a	0.8a
5 cm Greenwaste	47.6a	42.3a	32.0a	18.9a	4.2a	43.8a	36.9a	35.1ab	12.9ab	2.0a
5 cm Greenwaste + 11.2 t/ha Biochar	37.5ab	25.4ab	30.7a	14.8a	0.9a	30.0ab	24.0ab	32.3ab	12.3ab	1.8a
10 cm Greenwaste	28.9ab	13.5bc	30.3a	16.3a	1.2a	32.7ab	14.9abc	31.9ab	15.0ab	0.1ab
11.2 t/ha BC	34.5ab	22.1ab	28.0a	7.1a	3.3a	35.0ab	17.0abc	11.9b	8.6ab	0.7a
Control	42.9a	28.9ab	41.1a	12.5a	1.4a	30.0ab	28.4ab	37.0a	11.6ab	-0.7abc

Within columns for each rating date, means followed by the same lowercase letter are not significantly different between treatments according to LSD (0.05).

Table 2.13. Percentage change in measured characteristics due to reduced irrigation from year 2 of the study. Only dates showing a significant effect of amendment on turfgrass drought stress are listed. Change is calculated for each date as (((value under high irrigation-value under low irrigation)/value under high irrigation)*100).

	DAI									
	84	84	84	84	84	98	98	98	98	98
Amendment	Quality	NDVI	TDR	%Cover	DGCI	Quality	NDVI	TDR	%Cover	DGCI
22.4 t/ha BC	5.1a	0.7b	8.1a	1.3a	-0.3a	17.9a	6.7a	3.0b	3.2a	0.9a
2.2 t/ha BC	16.3a	6.8ab	14.0a	0.9a	-2.0a	23.8a	11.9a	22.1ab	6.8a	0.4a
5 cm Biosolids	-5.4a	16.4a	18.7a	1.3a	-1.2a	24.6a	16.0a	31.9ab	9.5a	-0.3a
5 cm Greenwaste	16.7a	5.9ab	23.7a	0.9a	-3.0a	37.5a	17.7a	40.3a	1.0a	3.3a
5 cm Greenwaste + 11.2 t/ha Biochar	32.6a	7.4ab	11.1a	0.5a	-1.8a	27.5a	0.5a	25.4ab	-24.0a	-2.0a
10 cm Greenwaste	9.2a	4.8ab	22.5a	0.8a	-0.4a	21.7a	7.7a	29.0ab	1.5a	-1.6a
11.2 t/ha BC	14.0a	-0.2b	12.9a	-0.3a	-0.9a	19.9a	2.7a	21.1ab	2.7a	-0.4a
Control	24.4a	4.2ab	28.5a	0.5a	-2.3a	40.2a	12.4a	36.1ab	2.7a	0.4a
	DAI									
	112	112	112	112	112	126	126	126	126	126
22.4 t/ha BC	-6.3b	-2.9b	-24.0b	0.5a	-7.2b	-2.1b	-22.0b	15.1a	-1.1a	-1.7a
2.2 t/ha BC	22.9ab	13.8ab	14.0ab	1.0a	-1.7ab	6.3a	7.7ab	21.0a	0.4a	-1.2a
5 cm Biosolids	29.6ab	24.3ab	17.7ab	4.1a	0.4ab	28.3a	22.5ab	33.8a	4.8a	0.8a
5 cm Greenwaste	47.4a	29.8a	35.0a	8.3a	5.7a	43.5a	38.9a	27.6a	17.5a	4.0a
5 cm Greenwaste + 11.2 t/ha Biochar	30.0ab	19.6ab	42.2a	8.3a	-2.6ab	37.5a	24.6ab	30.7a	14.7a	0.9a
10 cm Greenwaste	21.2ab	5.7ab	12.2ab	1.5a	-3.7ab	28.6a	12.8ab	29.1a	16.3a	1.2a
11.2 t/ha BC	36.8ab	16.1ab	26.3ab	-1.7a	-1.1ab	33.0a	23.3ab	30.2a	7.1a	3.2a
Control	43.9ab	20.9ab	31.8a	2.6a	0.2ab	40.8a	28.5a	42.4a	12.5a	1.4a
	DAI									
	140	140	140	140	140	154	154	154	154	154
22.4 t/ha BC	-19.1b	-14.3b	19.7a	-8.8b	-3.7a	-0.4c	-0.4c	6.1ab	N/A	N/A
2.2 t/ha BC	16.3a	3.4ab	16.2a	1.9ab	-3.9a	12.5b	9.1bc	26.3ab	N/A	N/A
5 cm Biosolids	10.0ab	26.0a	31.9a	18.2a	0.7a	32.1ab	20.5ab	4.4ab	N/A	N/A
5 cm Greenwaste	43.8a	35.3a	34.3a	13.1ab	2.0a	53.6a	33.5a	28.1a	N/A	N/A
5 cm Greenwaste + 11.2 t/ha Biochar	30.0a	23.3a	33.6a	11.9ab	1.7a	34.2ab	27.0ab	18.4ab	N/A	N/A
10 cm Greenwaste	31.0a	14.3ab	26.6a	14.9a	0.1a	22.6ab	9.0bc	25.0ab	N/A	N/A
11.2 t/ha BC	36.4a	17.9ab	11.6a	8.6ab	0.7a	23.5ab	15.4abc	3.6b	N/A	N/A
Control	31.2a	28.6a	38.0a	11.6ab	-0.7a	36.9ab	25.2ab	27.1ab	N/A	N/A

Within columns for each rating date, means followed by the same lowercase letter are not significantly different between treatments according to LSD (0.05).

Table 2.14. Average root volume and length by treatment. Root samples were collected May 20, 2015 at initiation of the study. Prior to this date, samples were not subjected to differential irrigation, and measurements were therefore averaged across all 8 replicates of soil amendment treatments.

Amendment	Root Length (cm)	Root Volume (cm^3)
10 cm Greenwaste	6436.1ab	13.8ab
11.2 t/ha BC	4974.3bc	10.4c
2.2 t/ha BC	4183.2c	9.0c
22.4 t/ha BC	4792.3c	10.2c
5 cm Biosolids	2406.7d	4.3d
5 cm Greenwaste	7340.5a	15.8a
5 cm Greenwaste + 11.2 t/ha Biochar	6654.7a	13.8ab
Control	4642.2c	10.9bc

Within columns, means followed by the same lowercase letter are not significantly different according to LSD (0.05).

Table 2.15. Average clipping yield by amendment type and irrigation rate during year 1 of the study.

		DAI				
Amendment	Irrigation Rate	15	45	77	101	129
10 cm Greenwaste	Low	43.6ab	66.8ab	23.4abc	106.6ab	7.7a
11.2 t/ha BC	Low	45.2ab	59.8ab	22.0abc	108.7ab	8.7a
2.2 t/ha BC	Low	45.0ab	63.2ab	25.7a	173.0a	11.0a
22.4 t/ha BC	Low	42.6ab	56.6ab	19.9abc	107.6ab	15.0a
5 cm Biosolids	Low	52.6a	68.9ab	18.1bc	111.9ab	8.1a
5 cm Greenwaste	Low	29.3b	55.0b	17.5c	87.3b	13.2a
5 cm Greenwaste + 11.2 t/ha Biochar	Low	36.5ab	53.8b	22.7abc	103.7ab	6.6a
Control	Low	34.4ab	89.8a	24.8ab	120.0ab	9.9a
10 cm Greenwaste	High	40.2ab	49.0a	13.7a	108.3a	11.0a
11.2 t/ha BC	High	36.2ab	64.0a	16.4a	106.2a	14.4a
2.2 t/ha BC	High	48.1a	45.6a	21.5a	111.5a	15.6a
22.4 t/ha BC	High	34.0ab	54.4a	17.7a	101.4a	18.7a
5 cm Biosolids	High	40.5ab	62.7a	21.0a	113.6a	20.2a
5 cm Greenwaste	High	30.9b	43.5a	16.6a	106.7a	11.2a
5 cm Greenwaste + 11.2 t/ha Biochar	High	35.2ab	41.6a	16.2a	102.9a	11.2a
Control	High	39.7ab	51.1a	18.7a	95.6a	20.2a

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05).

Table 2.16. Biosolids compost characterization conducted by CA April 27, 2015. Pass/fail values are based on US EPA Class A standards, 40 CFR 503.32 and 503.13.

Parameter	**Unit of measure**	**Value**	
Total Nitrogen	% Dry Weight	4	
Ammonia (NH_4-N)	ppm (mg/kg dry weight)	10000	
Nitrate (NO_3-N)	ppm (mg/kg dry weight)	6	
Organic Nitrogen	% Dry Weight	3	
Phosphorous (P)	ppm (mg/kg dry weight)	21000	
Potassium (as K_20)	% Dry Weight	0.66	
Potassium (K)	ppm (mg/kg dry weight)	5500	
Organic Carbon	% Dry Weight	29	
C/N Ratio	Ratio	7.1	
pH	Units	7.59	
Soluble Salts (EC5)	dS/m (mmhos/cm)	20	
Particle Size	Maximum aggregate size (cm)	0.97	
Heavy Metals Content	Pass/Fail	Pass	
Stability Indicator (respirometry)			**Stability Rating**
CO_2 Evolution	mg CO_2-C/g OM/day	2.9	Stable
	mg CO_2-C/g TS/day	1.7	
Maturity Indicator (bioassay of cucumber emergence)			**Maturity Rating**
Percent Emergence	Average % of control	0.0	Immature
Relative Seedling Vigor	Average % of control	NA	
Pathogens			
Fecal Coliforms	Pass/Fail	Pass	
Salmonella	Pass/Fail	Pass	

Table 2.17. Greenwaste compost characterization conducted by Soil Control Lab, Watsonville, CA April 27, 2015. Pass/fail values are based on US EPA Class A standards, 40 CFR 503.32 and 503.13.

Parameter	Unit of measure	Value	
Total Nitrogen	% Dry Weight	0.67	
Ammonia (NH_4-N)	ppm (mg/kg dry weight)	21	
Nitrate (NO_3-N)	ppm (mg/kg dry weight)	< 1	
Organic Nitrogen	% Dry Weight	0.67	
Phosphorous (P)	ppm (mg/kg dry weight)	1300	
Potassium (as K_20)	% Dry Weight	0.73	
Potassium (K)	ppm (mg/kg dry weight)	6100	
Organic Carbon	% Dry Weight	38	
C/N Ratio	Ratio	57	
pH	Units	7.71	
Soluble Salts (EC5)	dS/m (mmhos/cm)	2.4	
Particle Size	% Larger than .64 cm	11.7	
Heavy Metals Content	Pass/Fail	Pass	
Stability Indicator (respirometry)			**Stability Rating**
CO_2 Evolution	mg CO_2-C/g OM/day	1.1	Stable
	mg CO_2-C/g TS/day	2.5	
Maturity Indicator (bioassay of cucumber emergence)			**Maturity Rating**
Percent Emergence	Average % of control	100	Mature
Relative Seedling Vigor	Average % of control	100	
Pathogens			
Fecal Coliforms	Pass/Fail	Pass	
Salmonella	Pass/Fail	Pass	

Table 2.18. Soil analysis from greenhouse portion of the study collected August 10, 2015 and analyzed at Oklahoma State soil testing lab.

Treatment	**NO_3 (ppm)**	**Phosphorous (ppm P_20_5)**	**Potassium (ppm K_20)**	**pH**
Control	4.2 b	26.3 d	65.7 d	8.5 a
2.2 t/ha Biochar	3.4 b	22.4 d	63 d	8.6 a
11.2 t/ha Biochar	2.7 b	23.6 d	61.6 d	8.6 a
22.4 t/ha Biochar	2.8 b	19.9 d	63.5 d	8.5 a
5 cm Biosolids	132.8 a	473.1 a	246.2 b	6.4 c
5 cm Greenwaste	1.25 b	69.1 cd	134.6 c	8.0 b
5 cm Greenwaste + 11.2 t/ha Biochar	1.5 b	70.8 cd	141.9 c	8.0 b
10 cm Greenwaste	1.3 b	95.4 c	350.9 a	8.0 b

Within columns, means followed by the same lowercase letter are not significantly different within irrigation regimes according to LSD (0.05).

Chapter 3

Introduction

Traditionally, the availability of soil water has been determined using pressure plates and similar methods; though some literature suggests that their suitability is highly dependent on soil characteristics which biochar products can modify (Cresswell et al., 2008). Prior research suggests that biochar and compost (Landschoot, 1996) can increase the water holding capacity of soils (Karhu et al., 2011) and ameliorate water regimes under drought conditions (Paetsch et al., 2018). However, this may not translate to improved availability of this water as permanent wilting point can be reached at higher water contents (Abel et al., 2013). Additionally, laboratory measurements of biochar's saturation with water have been shown to conflict with improved water holding capacity seen in amended soils (Artiola et al., 2012), suggesting that the behavior of biochar in field settings can conflict with laboratory measurements of the product by itself. Some research has conflicted with predictions of plant performance based on measurements of soil characteristics, suggesting that greater amounts of irrigation may be necessary to support healthy plant growth (Obia et al., 2016). Biochar's capacity for improving soil water dynamics can be attributed primarily to modifications of soil physical properties (Tayyab et al., 2018). Increased root growth (Bruun et al., 2014) and crop yields (Martinsen et al., 2014) found in agricultural crops may actually become undesirable when evaluating biochar's application for turfgrass, where the primary goal is maximizing visual performance with minimal irrigation input. Furthermore, the effects of biochar have been shown to vary across species (Olmo and Villar, 2018), creating a necessity for development of a site-specific method of evaluating biochar's potential benefit on a case by case basis.

For this work we used turfgrass performance to indicate when irrigation was necessary and correlated soil water potential as well as gravimetric water content to evaluate the suitability of these methods as predictors of plant drought stress in biochar-amended soils. This study will also seek to validate or nullify the claim that the commercial product Turf Rescue (30% biochar + 70% compost, by volume) reduces the need for irrigation in turfgrass application. Combining compost with biochar has been shown to affect plant health differently from either product alone, but some effects may not be beneficial under drought conditions or when using turfgrass (Alvarez et al., 2017). For example, commonly beneficial effects such as increased vegetative growth and seed production (Paneque et al., 2016) or larger leaf areas (Batool et al., 2015) correlate with more frequent mowing, undesirable seeds and less linear leaves. The primary objective of this study was to measure the impacts of biochar and compost on soil-water dynamics while including measurements of plant performance to more accurately predict how these products can be used in the field. Irrigation frequency and quantity was determined based on plant health, allowing a determination of irrigation required by the plant rather than focusing on performance under predetermined irrigation regimes.

Materials and Methods

The study was conducted in a climate-controlled greenhouse (maintained at 24 °C) at the University of California in Riverside, CA (semi-arid, 340 m elevation) November 2015 through May 2016, then repeated February through July 2017. A mix of tall fescue cultivars, 49% Lexington, 29% Black Magic, 21% Sitka (Loveland Products Sentinel CPQ) was seeded in 3.8 liter pots (20.3 cm W X 17.8 cm H) at a rate of 7.1 g per pot (3.84 kg 100 m^{-2}) in biochar and compost-amended soils. Amendments included biochar produced from Yellow Pine pyrolized at 350 °C and the combined biochar and compost amendment (30% biochar + 70% compost). Amendments were evenly mixed into soil using a cement mixer. The base soil used was a Hanford fine sandy loam in a 50:50 mixture with plaster sand. The addition of plaster sand was added for drainage, as initial tests of the base soil found problems with water-logging.

All treatments were applied at rates calculated by volume. Biochar was incorporated at 1, 5 and 10% of media volume, while combined biochar and compost was incorporated at 5, 10 and 20%. Each treatment was replicated 4 times. Ratings were collected at 2-3 day increments to gauge turfgrass health and aesthetic quality. The following ratings were collected: visual quality (1-9 scale, based on National Turf Evaluation Program standards; Morris, 2008); turf coverage measured using digital image analysis (%, Richardson et al., 2001); Dark Green Color Index (DGCI; Karcher and Richardson, 2013), a quantitative measure of turfgrass aesthetic quality, assessed with digital image analysis (0-1 scale); soil gravimetric water content; and soil water tension as measured by Watermark sensors (Model 200SS, Irrometer Co., Riverside, CA). Watermark sensors gauge electric resistance, converting it to a measurement of soil water tension (-cb). Clipping yield was assessed at the end of each study period.

Prior to seeding, soil water-holding characteristics were compared between treatments. All pots were irrigated to field capacity, and then irrigation was completely withheld. The soil was considered completely dry when the weight of the pot and soil remained unchanged for 3 days. Dry-down curves for soils amended with compost and biochar together and pure biochar can be found in Figures 3.1 and 3.2, respectively.

All pots were irrigated three times a week during turfgrass establishment. Upon reaching complete establishment, all pots were irrigated to field capacity, and were supplied with 250 mL of water when exhibiting signs of wilt. Digital photos were collected on all rating dates and processed for live turf cover and Dark Green Color Index (DGCI) using SigmaScan 6 software. Images were collected under controlled light conditions and at a constant height using a Casio Exilim EX-S12BK camera. A black plastic tube was placed over pots to exclude incoming light, and consistent illumination was provided by the camera's flash. Live turf cover was measured as a percentage of photo area. Images included space outside of the pot surface, comprising approx. 10% of the photographed area. This area was constant between photographs.

DGCI is a quantitative measure of aesthetic quality calculated from hue, saturation, and brightness measurements of turf tissue (Leinauer et al., 2014; Karcher et al., 2003). Digital photos were collected on all rating dates and processed for live turf cover and Dark Green Color Index (DGCI). Note that on November 2, 2016/May 1, 2017 irrigation was supplied equally to all pots, and then withheld until November 16, 2016/May 15, 2017.

Results

Soil dry-down curves

In both study periods, soils amended with the combined treatment or biochar held significantly greater amounts of water at field capacity than untreated controls. Amended soils lost water at a similar rate to controls based on the slope of each treatment's decline in water content **(Figures 3.1-3.2)**. With both amendments, the 10% rate performed best, resulting in the highest water holding capacity and an increased water content on all rating days. These results indicate that, during periods of drought, both amendment types may cause soils to retain higher quantities of water.

Turfgrass Irrigation Requirements / Visual Quality

Turfgrass reached full establishment on September 21, 2016 in the first run of the experiment, and on April 8, 2017 when the experiment was repeated. Soils amended with biochar and compost together maintained a higher visual quality than untreated controls during this phase of the study in both years. Pure biochar at the 10% rate outperformed controls, while all other rates performed at comparable levels (Table 3.3).

In year one, untreated controls showed signs of wilt beginning 4 days after withholding irrigation. Control pots were slower to recover following irrigation when compared to turfgrass grown with compost and biochar together (Figure 3.3). While all amended pots maintained a similar quality during the study's differential irrigation period, the 10% treatment resulted in the lowest irrigation requirement, maintaining an acceptable quality with an average irrigation requirement of 250 mL water at each irrigation event (Table 3.1). Controls required an average of 812 mL at each irrigation event, with 5% and 20% treatments requiring 500 and 437 mL, respectively (Table 3.1).

In the study's second replicate, compost and biochar together outperformed untreated controls beginning May 8, 2017. All amendment rates resulted in improved quality compared to controls (Table 3.4). The 10% amendment rate reduced irrigation requirements to maintain acceptable quality. Controls required an average of 750 mL, while pots amended with 10% compost and biochar combined required only 187.5 mL. 5% and 20% amendment rates required 375 mL (Table 3.1).

Pure biochar maintained visual quality with the least irrigation (Figure 3.2). The 5 and 10% biochar treatments resulted in the lowest irrigation requirement, maintaining an acceptable quality with an irrigation requirement of 187 and 62.5 mL water respectively at each irrigation event (Table 3.2). Controls required an average of 375 mL, with 1% treatments requiring 312 mL (Table 3.2). Biochar amendments performed comparably in the second year, with both 5 and 10% amendment rates leading to general improvements in turfgrass quality (Table 3.6). These same amendment rates required less irrigation to maintain acceptable visual quality. Controls required an average of 500 mL, comparable to the 312.5 mL required in pots amended with 1% biochar. The 5 and 10% amendment rates required 187.5 and 125 mL, respectively (Table 3.2). These results support the claim that both amendments evaluated in this study may allow for reductions in irrigation while maintaining aesthetic quality.

Quality Decline upon Irrigation Withholding

In order to evaluate the impact of amendments on turf health during complete irrigation withholding, all amendments were allowed to reach comparable quality and irrigated to field capacity, following which no irrigation was applied. All pots were irrigated to field capacity on November 2, 2016. During the period of withheld irrigation, the decline in quality was compared. On November 17, 2016, all pots were irrigated to field capacity and turf recovery was gauged. On this date, turf grown in unamended soils had reached a visual quality of 1 and would not have recovered without supplemental irrigation. Turf grown with 10% biochar or 10% combined compost and biochar maintained the highest quality during the complete withholding of water (Tables 3.3 and 3.5). All turfgrass recovered at comparable rates, and reached similar levels following irrigation to field capacity on November 17, 2016. The study was concluded on December 6, 2016. The same process was repeated in year 2 of the study. Irrigation was withheld May 1, 2017 and irrigated to field capacity on May 15th, 2017. Both amendment types at the rate of 10% maintained higher quality during the simulated drought period as in the first year, with comparable recovery following irrigation to field capacity (Tables 3.4 and 3.6).

Live Turf Cover

Significant differences in live turf cover were detected beginning October 2, 2016, during the period of differential irrigation. The 10% treatment resulted in higher coverage than controls on October 3 and 8, 2016 (Figure 3.3). On November 8, 2016, the conclusion of differential irrigation, all combined compost and biochar amendments resulted in increased cover compared to controls. For the pure biochar portion, significant differences in live turf cover were detected on November 15, 2016, when irrigation had been withheld 8 days. The 5% treatment resulted in higher coverage than controls (Figure 3. 4).

During the study's second replicate, similar patterns were found in DIA data. For compost and biochar together, differences in live turf cover were first detected in pots May 3, 2017. Both the 5 and 10% amendment rates showed higher coverage on this date, but only the 10% rate maintained this increased cover for the following week (Figure 3.5). All rates of combined compost and biochar maintained higher coverage than controls June 1-14. Amendment with pure biochar showed no effect on turf cover until May 6, 2017, 5 days into the complete withholding of water. From this point through June 1, 2017, the 5% biochar treatment maintained higher cover than all other treatments (Figure 3.6).

Dark Green Color Index (DGCI)

Turf grown in soils amended with 10% compost and biochar combined showed higher DGCI than controls on October 2 and 8, 2016. The 5% treatment resulted in increased DGCI on October 8, and November 8, 2016 (Figure 3.7). For the pure biochar portion of the study, unamended controls and 1% biochar treatments showed the highest DGCI on October 10, 2016 (Figure 3.8), though this is most likely due to the effect of excessive wilt on DGCI measurements. Reductions in live turf cover correlate with DGCI increases and indicate that turf is actively wilting. As tissue contracts, pigments become more concentrated and demonstrate a darker color. The increased DGCI seen with compost and biochar together did not correspond with visible wilt, meaning that the treatment including compost and biochar together led to genuine improved aesthetic quality as opposed to pure biochar. During year 2 of the study unamended controls showed increased DGCI May 8, 2017 during the simulated drought period (Figure 3.9). This pattern was seen in both the pure biochar and combined compost and biochar components of the study. Following irrigation to field capacity the 10% compost and biochar together at the 10% rate showed increased DGCI.

Soil Water Tension

Differences in soil water tension between treatments in the combined compost and biochar portion were detected only on October 27, 2016. Untreated controls produced the most negative soil water tension compared to all other treatments (Figure 3.11). Note that untreated controls required supplemental irrigation to maintain minimal acceptable quality (Figure 3.1), and that less negative soil water tension is not indicative of treatment effects. Differences between treatments within the pure biochar portion were detected only on October 27, 2016 (Figure 3.12). The 10% amendment produced the lowest (least negative) soil water tension compared to all other treatments. In year 2 both the 10% compost and biochar together and biochar treatments reduced tension during the drought period from May 8-14, 2017 (Figures 3.13-3.14).

The lack of difference within the combined compost and biochar portion during the differential irrigation portion of the study indicates that combining compost and biochar does not increase the availability of water in soils, and most likely conveys benefit during drought through increases in soil water content, as indicated in the soil dry-down (Figure 3.1). During this period, amended soils required less water to maintain visual quality (Tables 3.3-3.6). Though less water was supplied to amended soils, water was available at similar levels between treatments.

Results from the pure biochar portion indicate that biochar may increase the availability of water in soils. During drought events, this effect along with increases in total water-holding capacity as indicated in the soil dry-down should increase turf performance (Figure 3.2).

Clipping Yield

On November 26, 2016, all pots were trimmed to 6 cm. Clippings were collected and dried for 4 days at 60 °C, then weighed. The 10% compost with biochar as well as 1 and 5% biochar amendments produced significantly more aboveground tissue than controls (Figures 3.15-3.16). While increased aboveground growth is indicative of healthy turf, this may indicate an increased mowing requirement with the use of compost and biochar together. This pattern was not seen in year 2 of the study and may have been anomalous (Figures 3.17-3.18). Clippings were harvested June 16,2017.

Discussion

This research indicates that while measurements of soil water potential may be correlated with water content in soils amended with our treatments, these measurements are not always indicative of plant performance. While previous studies investigating soil characteristics have shown biochar to lead to increased water retention under drought conditions (Bordoli et al., 2018), this work has not measured the impact on actual plant performance in these soils. Turfgrass was found to survive with reduced available water in amended soils, requiring less irrigation to maintain acceptable quality. Improved survivability may be tied to effects on available water holding capacity and bulk density which previous researchers have observed (Rodný et al., 2017). However, when evaluating the suitability of these amendments for use with drought-stressed turf it is not sufficient to analyze effects on soil dynamics. Recent research comparing the impacts of biochar on vegetated and bare soils closely mirrors our results, supporting the claim that accurate estimates of biochar's impact on plant health should not solely examine soil characteristics (Ni et al., 2018). Measurements of water content and soil water potential may in fact lead managers to decide biochar and Turf Rescue are not cost-effective means of reducing irrigation requirements. Great variability exists between different types of biochar due to the means by which they are produced, and as new technologies are introduced an accurate means for estimating their effect will be necessary (Zubrik et al., 2018). Future investigations using these products should include incorporation of amendments into field soil, planting of the desired turf, and initiation of drought stress to predict true plant response.

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Table 3.1. Irrigation applied to each Turf Rescue treatment from September 27th to October 13th, 2016 and April 15 through April 30, 2017. During this period, 250 mL H_2O was applied to individual pots of turf only when demonstrating signs of wilting. Irrigation amount is totaled over all 4 replicates of each treatment.

Amount of Irrigation Supplied (mL)						
Treatment (% Turf Rescue)	9/27 2016	9/29 2016	10/02 2016	10/13 2016	Total	Average
0	1000	500	1000	750	3250a	812.5a
5	500	500	500	500	2000a	500a
10	250	250	500	0	1000b	250b
20	750	500	500	0	1750a	437.5b
	4/15 2017	4/17 2017	4/21 2017	4/30 2017		
0	1000	500	500	1000	3000a	750a
5	500	250	250	500	1500a	375a
10	250	250	250	0	750b	187.5b
20	500	500	0	500	1500a	375a

Separation of mean irrigation by treatment follows totals and average irrigation applied per event. Within columns, means followed by the same lowercase letter are not significantly different between treatments (Fisher's protected least significant difference, $\alpha = 0.05$).

Table 3.2. Irrigation applied to each biochar treatment from September 27th to November 4th, 2016 and April 15 through April 30, 2017. During this period, 250 mL H_2O was applied to individual pots of turf only when demonstrating signs of wilt. All treatments maintained acceptable visual quality (≥5) until the final irrigation event. Irrigation amount is totaled over all 4 replicates of each treatment. Separation of mean total irrigation by treatment follows totals (student's t-test).

Amount of Irrigation Supplied (mL)						
Treatment (% Biochar)	9/27 2016	9/29 2016	10/30 2016	11/04 2016	Total	Average
0	1000	0	250	250	1500a	375a
1	500	500	0	250	1250a	312.5a
5	0	250	500	0	750b	187.5b
10	0	250	0	0	250b	62.5b
	4/15 2017	4/17 2017	4/21 2017	4/30 2017		
0	1000	0	500	500	2000a	500a
1	250	500	250	250	1250a	312.5b
5	250	0	500	0	750b	187.5a
10	250	0	250	0	500b	125a

Separation of mean irrigation by treatment follows totals and average irrigation applied per event. Within columns, means followed by the same lowercase letter are not significantly different between treatments (Fisher's protected least significant difference, $\alpha = 0.05$).

Table 3.3. Comparison of average turfgrass quality between Turf Rescue treatments. Irrigation was withheld beginning November 2, 2016 all pots were irrigated to field capacity November 17 2016.

	Date						
Treatment (% Turf Rescue)	9/30/2016	10/02/2016	10/06/2016	10/10/2016	10/12/2016	10/24/2016	11/01/2016
0	3.0b	3.0b	3.5b	4.3b	4.3b	4.5b	5.3b
5	3.0b	4.3a	4.5ab	6.3a	5.8a	6.3a	6.3ab
10	4.3a	5.0a	4.8a	5.0ab	6.5a	6.0a	6.5a
20	3.3b	4.0ab	4.0ab	5.3ab	5.8a	6.5a	6.8a
	11/05/2016	11/08/2016	11/14/2016	11/16/2016	11/17/2016	11/21/2016	
0	3.3b	3.8b	2.5b	2.0b	1.0c	2.8b	
5	4.8ab	5.8a	5.0a	2.8ab	2.0b	3.0ab	
10	5.5a	6.3a	5.5a	3.3a	3.0a	3.5a	
20	5.3ab	6.0a	4.0a	2.8ab	2.0b	3.8a	

Separation of mean quality between treatments. Within columns, means followed by the same lowercase letter are not significantly different between treatments for the given date (Fisher's protected least significant difference, α = 0.05).

Table 3.4. Comparison of average turfgrass quality between biochar treatments. Irrigation was withheld beginning November 2, 2016 all pots were irrigated to field capacity November 17 2016.

	Date				
Treatment (% Biochar)	9/21/2016	9/28/2016	10/02/2016	10/08/2016	10/10/2016
0	3.25b	3.5b	4b	5.5a	5.25b
1	3.5ab	3.5b	5a	5.5a	5.25b
5	3.75ab	4.25ab	5.5a	5.75a	6.25a
10	4.25a	4.5a	4.25ab	5a	5.75ab
	11/02/2016	11/07/2016	11/17/2016	11/20/2016	
0	5a	4.75a	3.5a	2.75b	
1	5.25a	5.25a	2.25b	2.75b	
5	5a	4.75a	3a	3ab	
10	5a	4.75a	3.5a	4.25a	

Separation of mean quality between treatments. Within columns, means followed by the same lowercase letter are not significantly different between treatments for the given date (Fisher's protected least significant difference, $\alpha = 0.05$).

Table 3.5. Comparison of average turfgrass quality between Turf Rescue treatments in 2017. Irrigation was withheld beginning May 1st, all pots were irrigated to field capacity May 15, 2017. (Separation of means by student's t-test).

	Date						
Treatment (% Turf Rescue)	4/08/2017	4/12/2017	4/16/2017	4/20/2017	4/22/2017	4/28/2017	5/01/2017
0	3.5b	4.0b	4.3a	4.5b	5.0b	5.5a	6.0a
5	4.5a	4.8a	4.5a	5.5a	5.0b	5.3a	5.8a
10	4.8a	5.5a	5.0a	6.0a	6.0a	5.8a	6.0a
20	4.0ab	5.3a	4.8a	5.8a	5.8a	6.0a	6.3a
	5/08/2017	5/12/2017	5/15/2017	5/19/2017	5/25/2017	5/27/2017	
0	5.8b	3.3b	1.8b	2.5b	3.0b	3.0b	
5	6.0ab	3.8b	2.3ab	3.3b	4.0ab	4.3a	
10	6.3a	5.3a	3.5a	5.0a	5.0a	5.3a	
20	6.0ab	4.8ab	2.8ab	3.5ab	3.8ab	4.0ab	

Separation of mean quality between treatments. Within columns, means followed by the same lowercase letter are not significantly different between treatments for the given date (Fisher's protected least significant difference, $\alpha = 0.05$).

Table 3.6. Comparison of average turfgrass quality between biochar treatments in 2017. Irrigation was withheld beginning May 1st, all pots were irrigated to field capacity May 15, 2017. (Separation of means by student's t-test).

	Date				
Treatment (% Biochar)	4/08/2017	4/15/2017	4/19/2017	4/25/2017	4/27/2017
0	3.0a	4.0b	4.8b	5.3b	6.0a
1	3.3ab	4.0b	5.0b	5.5ab	6.3a
5	3.3ab	4.3ab	6.0a	6.5a	6.5a
10	4.0a	5.0a	6.0a	6.5a	6.8a
	5/01/2017	5/08/2017	5/15/2017	5/19/2017	5/22/2017
0	6.0a	4.3b	2.0b	2.8b	3.5b
1	6.0a	4.8b	2.3b	2.5b	3.0b
5	6.3a	5.0ab	2.0b	2.8b	3.3b
10	6.5a	5.5a	3.8a	4.5a	5.0a

Separation of mean quality between treatments. Within columns, means followed by the same lowercase letter are not significantly different between treatments for the given date (Fisher's protected least significant difference, $\alpha = 0.05$).

Figure 3.1. Gravimetric water content of Turf Rescue treatments during dry-down. Results are averaged over both years. DAI (Days After Initiation) 0 represents the date when all pots were irrigated to field capacity, after which irrigation was completely withheld.

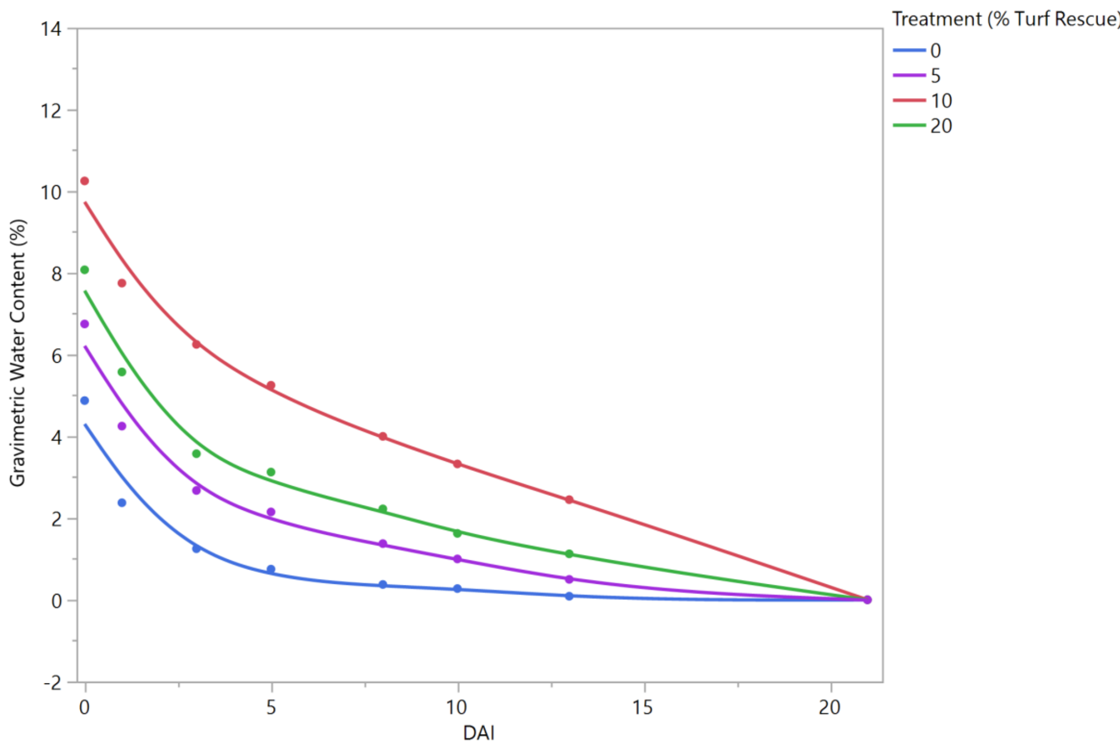


Figure 3.2. Gravimetric water content of biochar treatments during dry-down. Results are averaged over both years. DAI (Days After Initiation) 0 represents the date when all pots were irrigated to field capacity, after which irrigation was completely withheld.

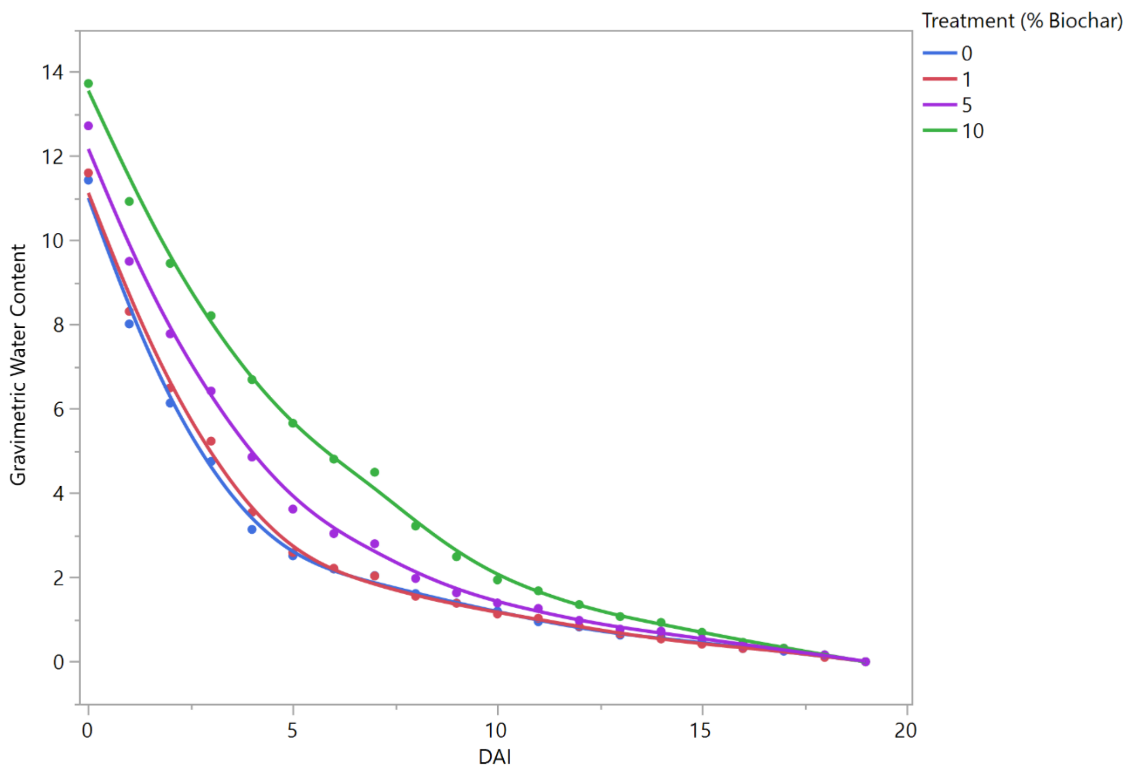


Figure 3.3. Comparison of live turf cover by Turf Rescue treatment in 2016. Turf cover was assessed using digital image analysis as percentage of photo area.

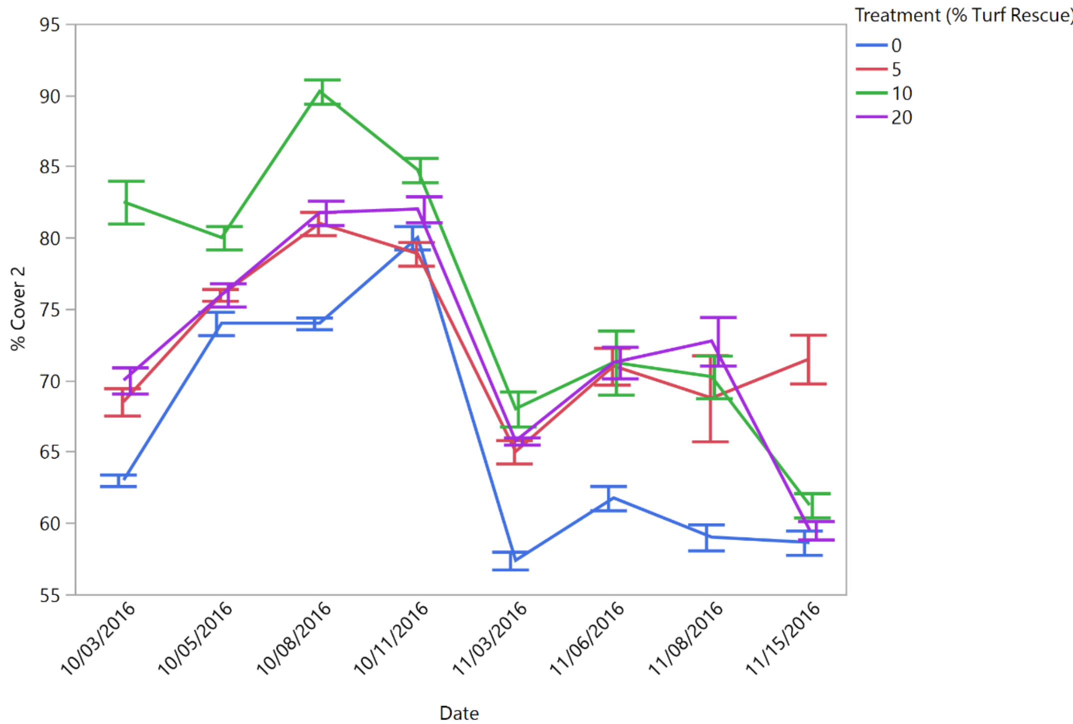


Figure 3.4. Comparison of live turf cover by biochar treatment in 2016. Turf cover was assessed using digital image analysis as percentage of photo area.

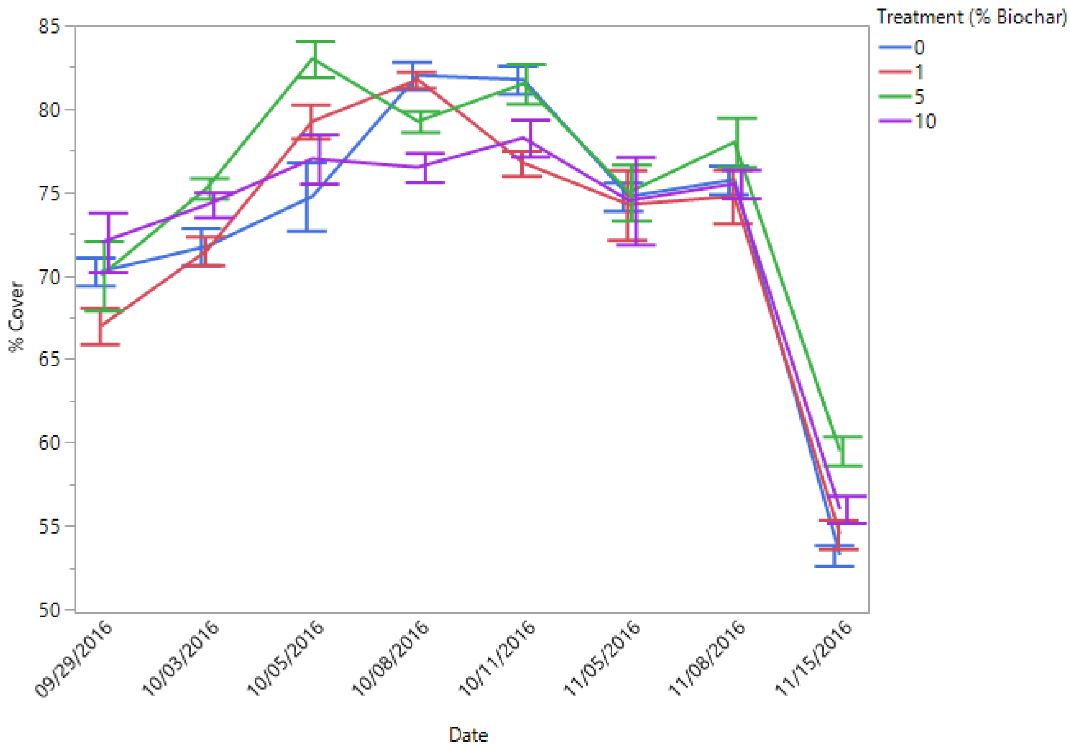


Figure 3.5. Comparison of live turf cover by Turf Rescue treatment in 2017. Turf cover was assessed using digital image analysis as percentage of photo area.

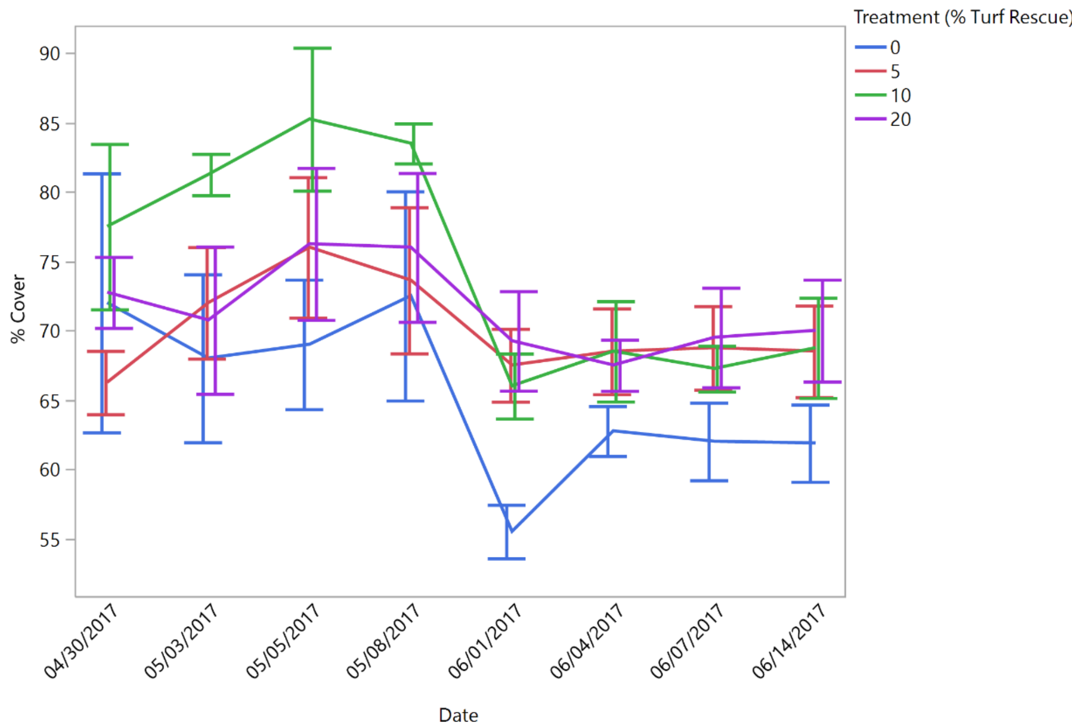


Figure 3.6. Comparison of live turf cover by biochar treatment in 2017. Turf cover was assessed using digital image analysis as percentage of photo area.

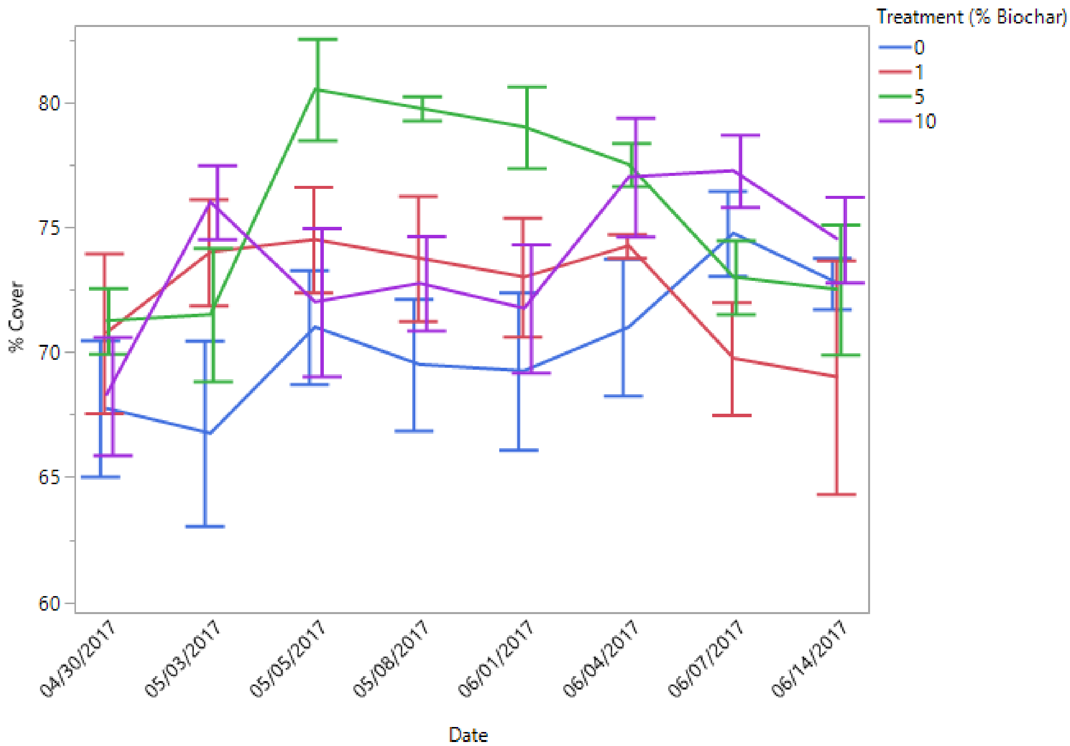


Figure 3.7. Comparison of Dark Green Color Index (DGCI) by Turf Rescue treatment in 2016. DGCI was assessed using digital image analysis (SigmaScan 6).

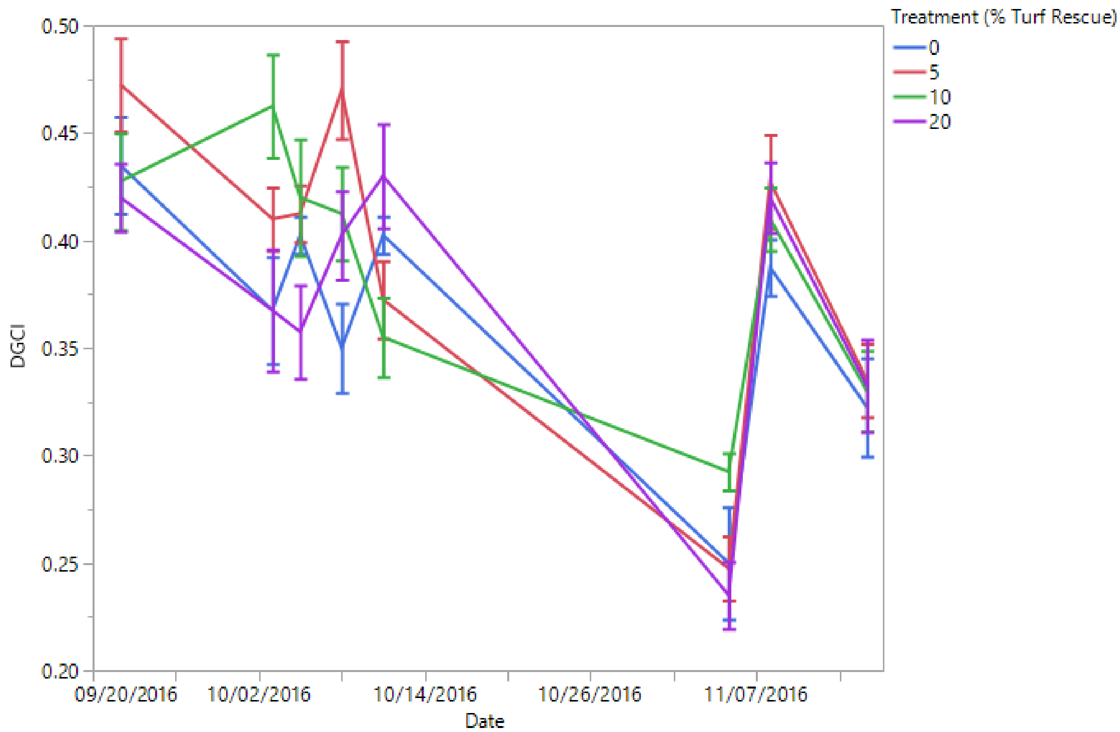


Figure 3.8. Comparison of Dark Green Color Index (DGCI) by biochar treatment in 2016. DGCI was assessed using digital image analysis (SigmaScan 6).

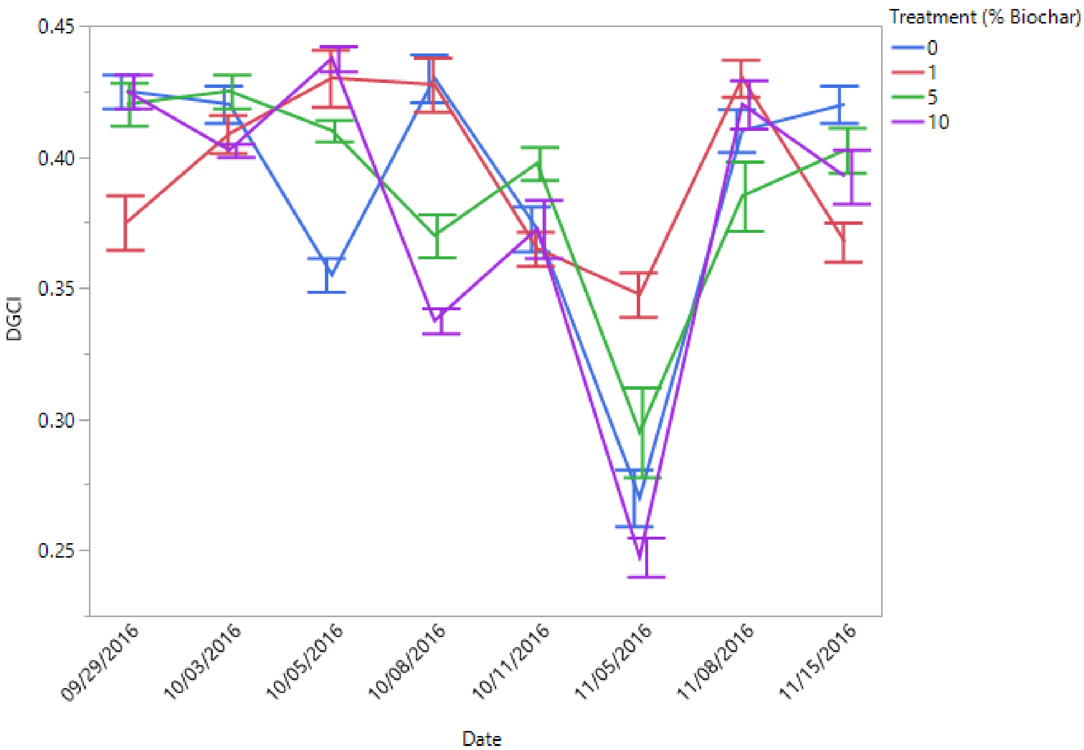


Figure 3.9. Comparison of Dark Green Color Index (DGCI) by Turf Rescue treatment in 2017. DGCI was assessed using digital image analysis (SigmaScan 6).

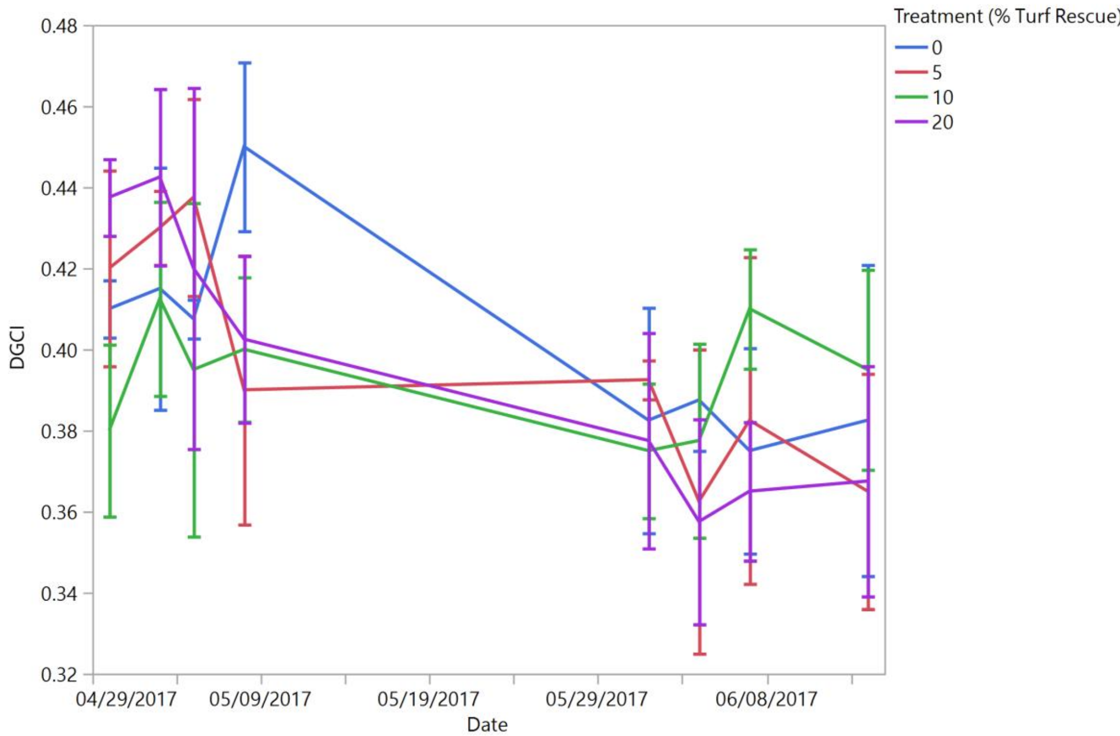


Figure 3.10. Comparison of Dark Green Color Index (DGCI) by biochar treatment in 2017. DGCI was assessed using digital image analysis (SigmaScan 6).

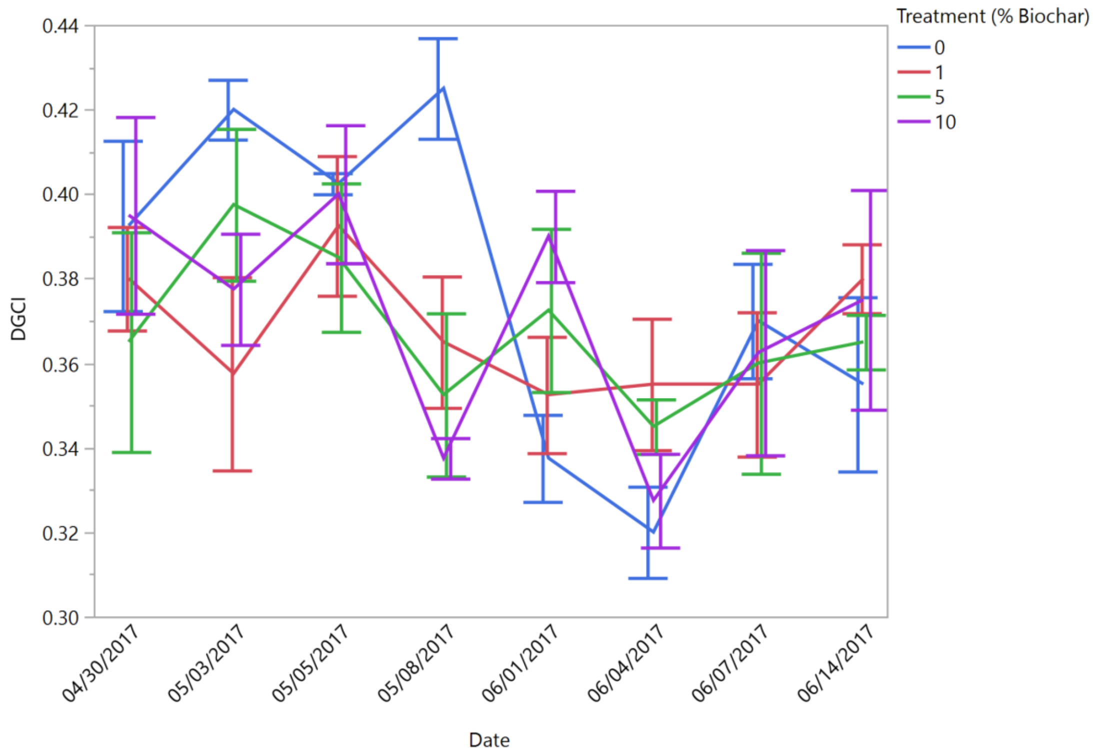


Figure 3.11. Soil water tension by Turf Rescue treatment in 2016. Soil water tension was measured using Watermark sensors, and represents the force with which soil attracts water, and the force required for extraction by plants.

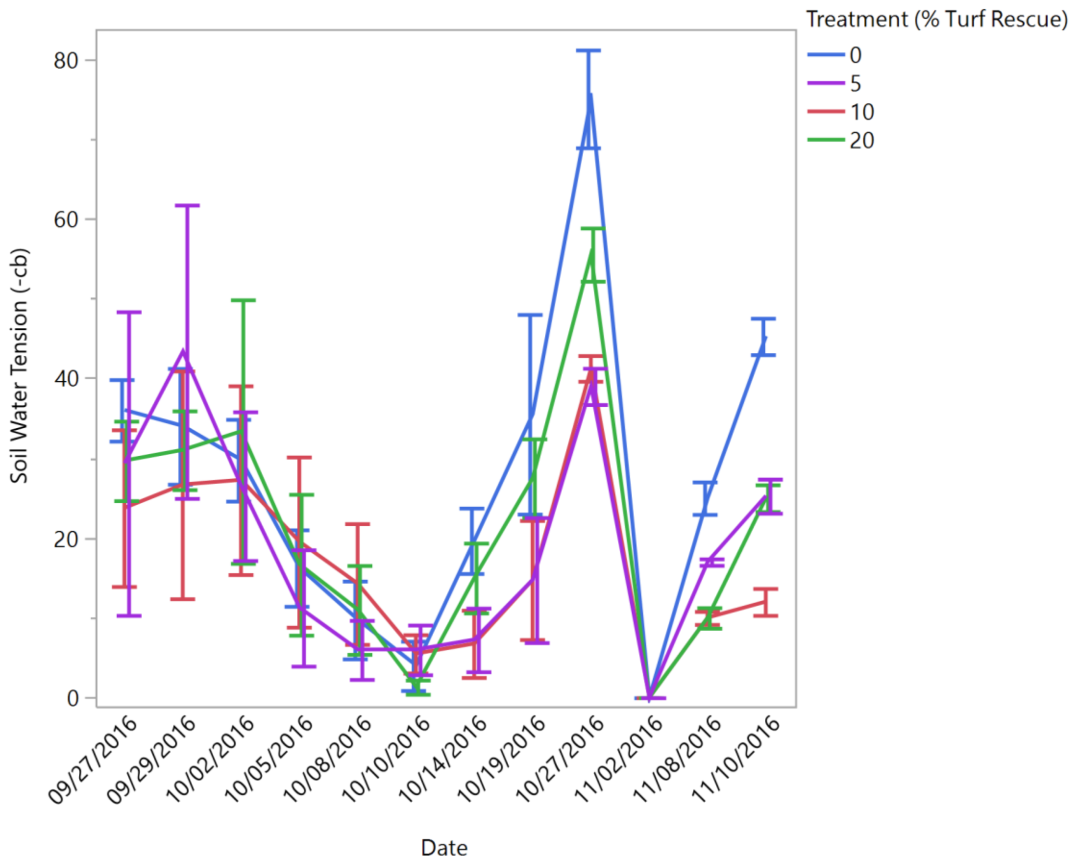


Figure 3.12. Soil water tension by biochar treatment in 2016. Soil water tension was measured using Watermark sensors, and represents the force with which soil attracts water, and the force required for extraction by plants.

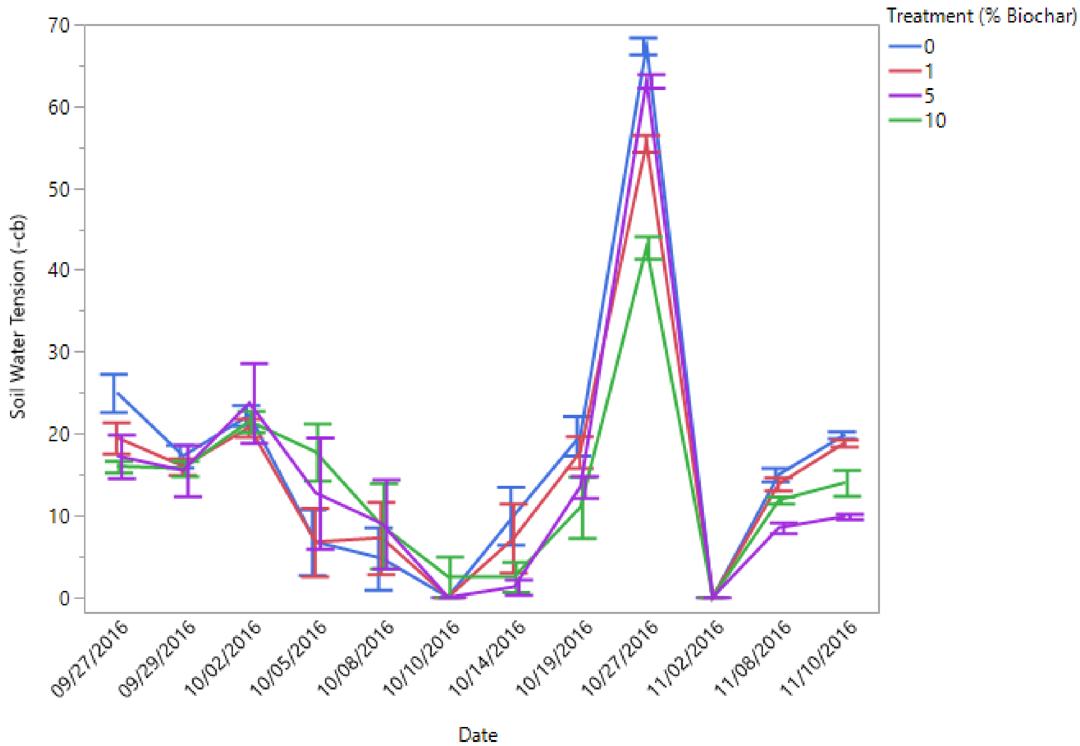


Figure 3.13. Soil water tension by Turf Rescue treatment in 2017. Soil water tension was measured using Watermark sensors, and represents the force with which soil attracts water, and the force required for extraction by plants.

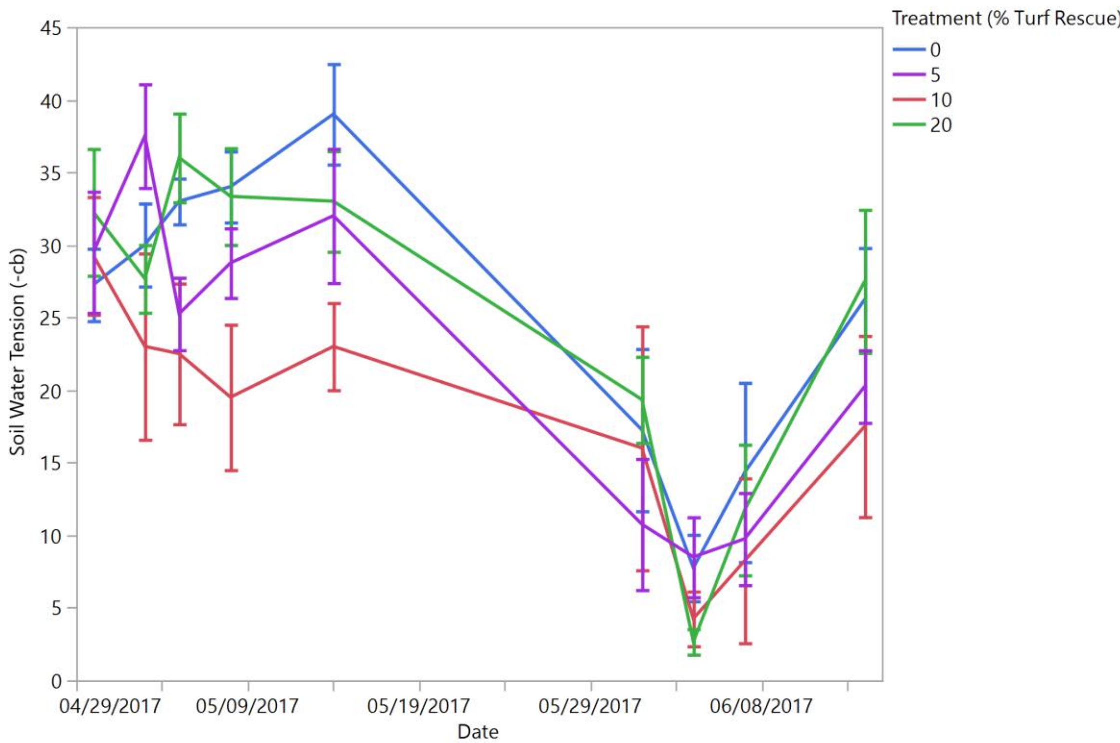


Figure 3.14. Soil water tension by biochar treatment in 2017. Soil water tension was measured using Watermark sensors, and represents the force with which soil attracts water, and the force required for extraction by plants.

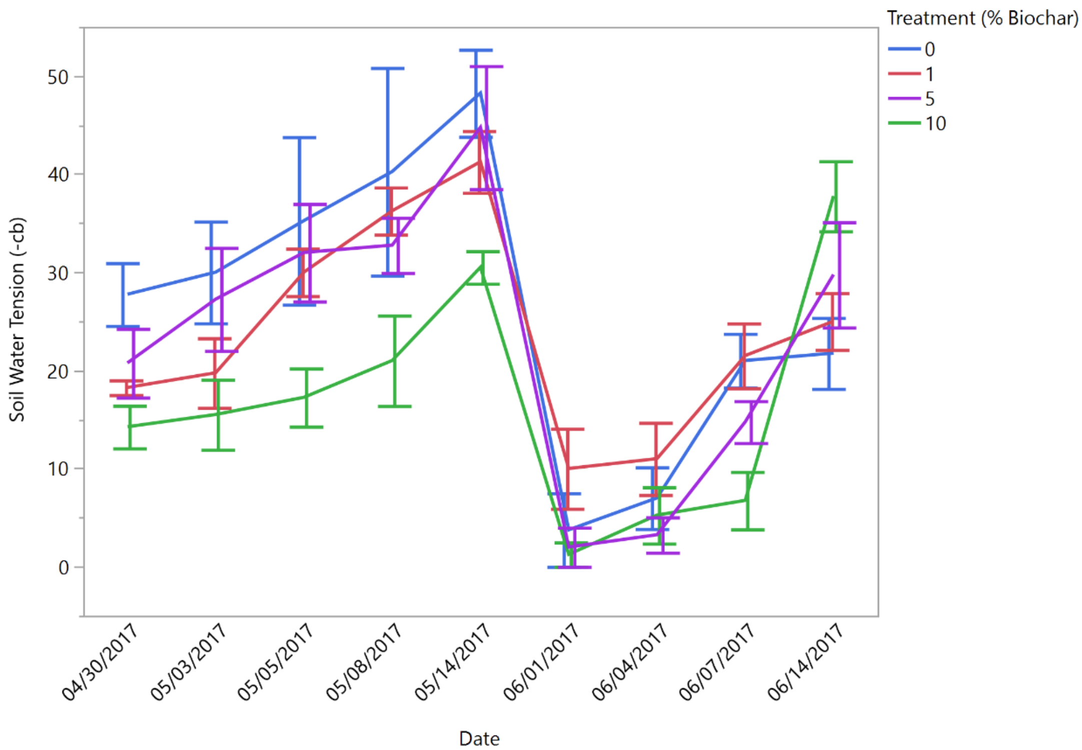


Figure 3.15. Dry clipping yield by Turf Rescue treatment collected November 26, 2016. Median value is represented by the horizontal line within each box, the 25th and 75th percentile values are indicated by the boundaries of the box, and whiskers indicate the highest and lowest values. All pots were trimmed to 6 cm; clippings were dried 4 days at 60 °C before weighing.

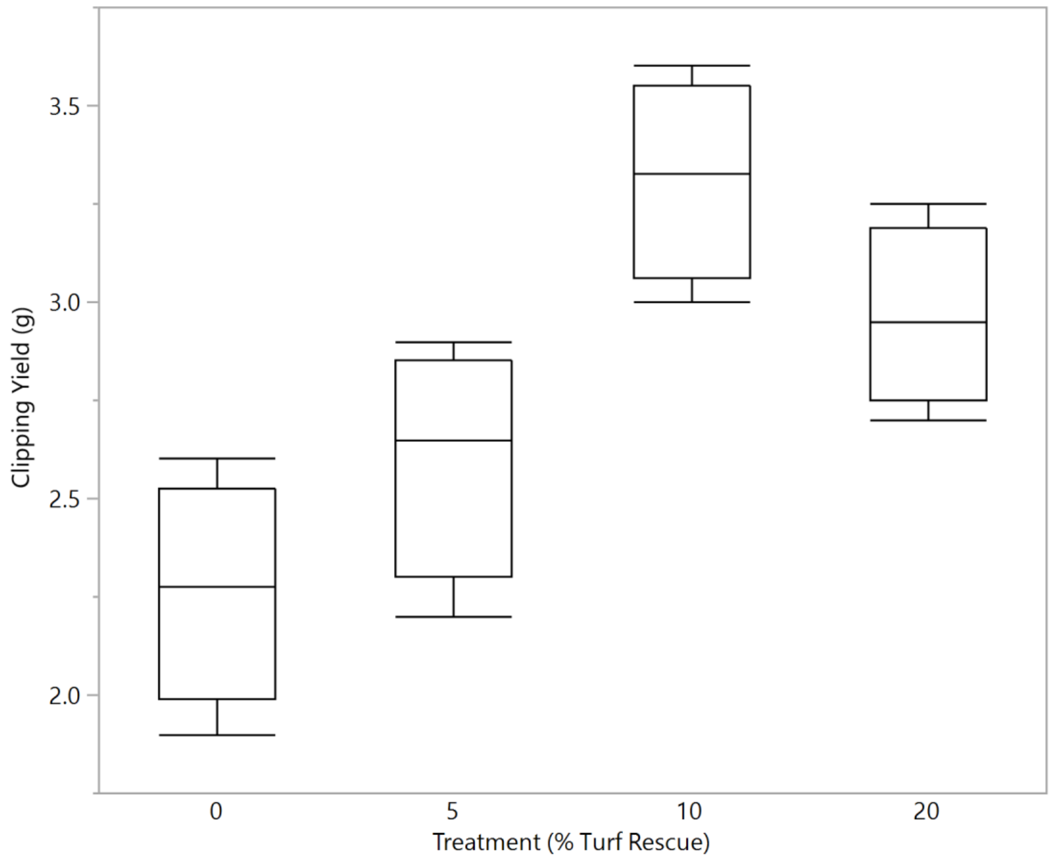


Figure 3.16. Dry clipping yield by biochar treatment collected November 26, 2016. Median value is represented by the horizontal line within each box, the 25th and 75th percentile values are indicated by the boundaries of the box, and whiskers indicate the highest and lowest values. All pots were trimmed to 6 cm; clippings were dried 4 days at 60 °C before weighing.

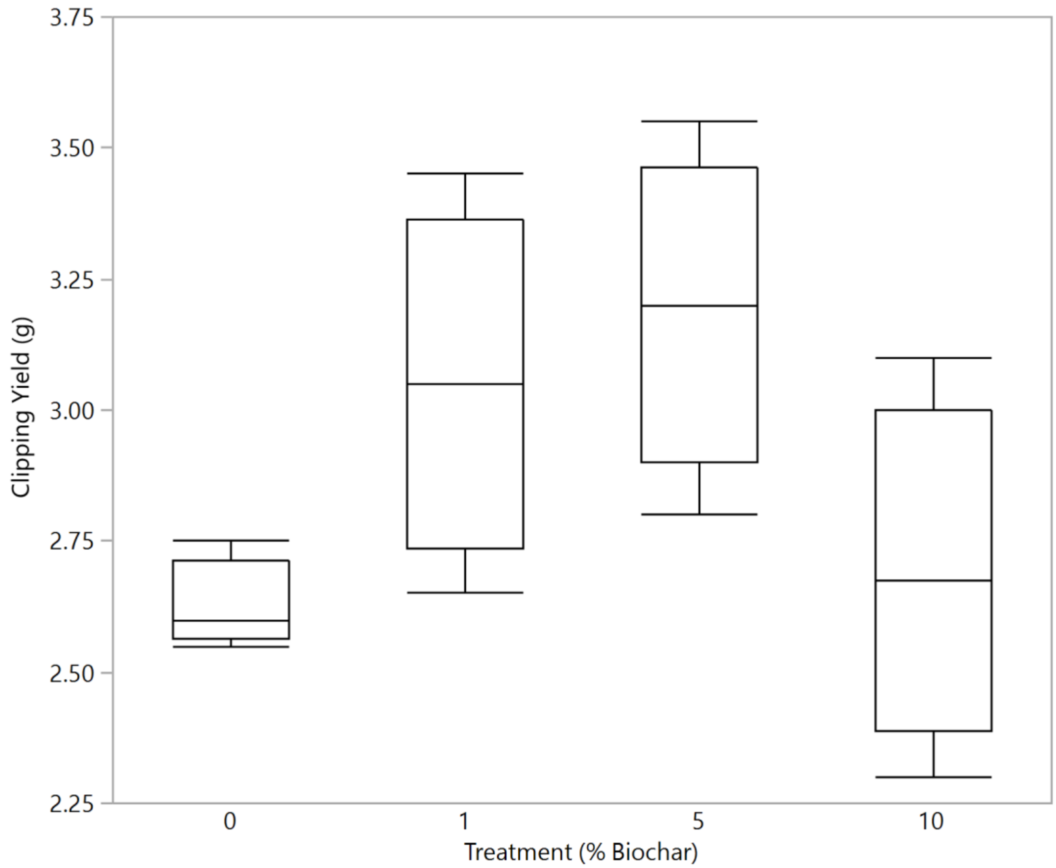


Figure 3.17. Dry clipping yield by Turf Rescue treatment collected June 16th, 2017. Median value is represented by the horizontal line within each box, the 25th and 75th percentile values are indicated by the boundaries of the box, and whiskers indicate the highest and lowest values. All pots were trimmed to 6 cm; clippings were dried 4 days at 60 °C before weighing.

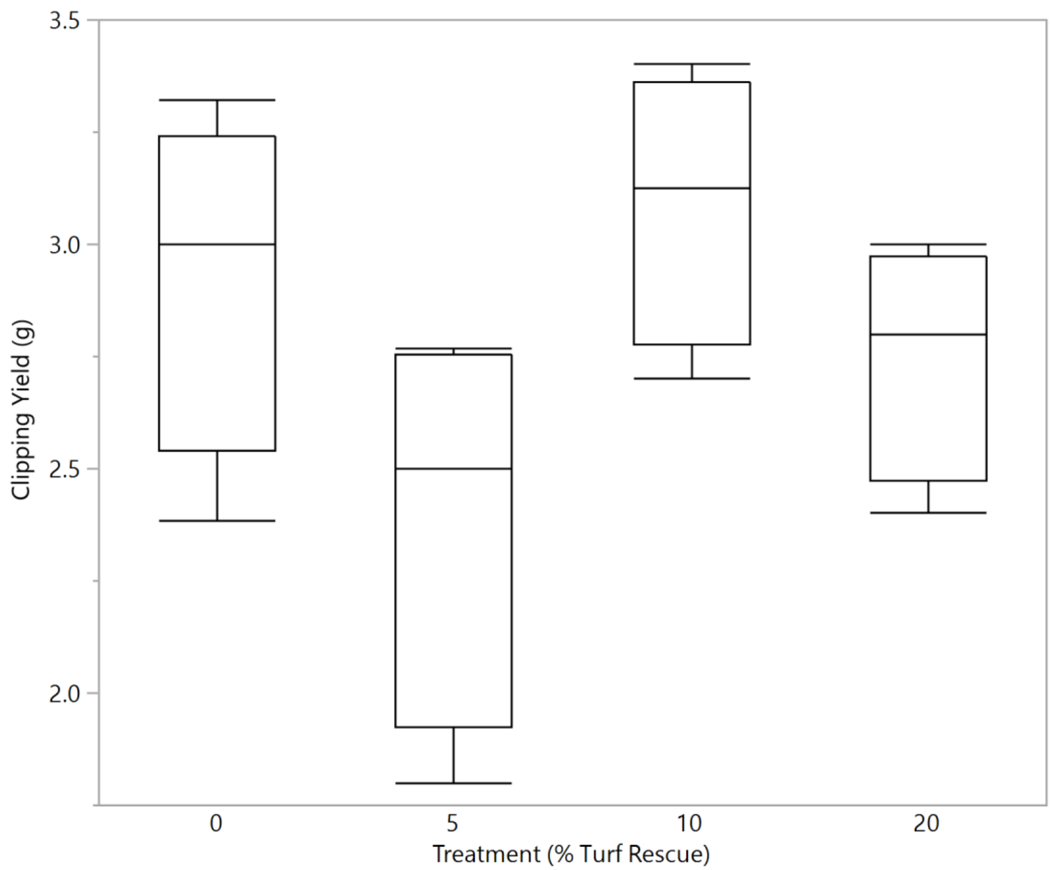
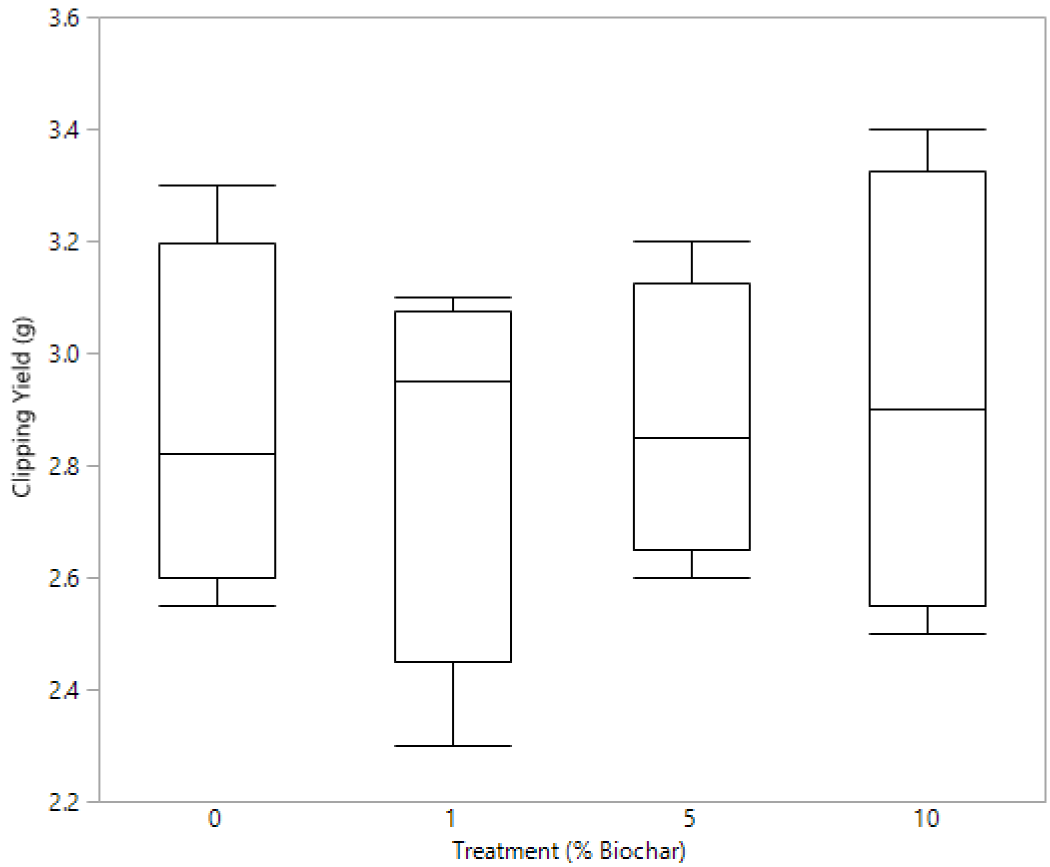


Figure 3.18. Dry clipping yield by biochar treatment collected June 16th, 2017. Median value is represented by the horizontal line within each box, the 25th and 75th percentile values are indicated by the boundaries of the box, and whiskers indicate the highest and lowest values. All pots were trimmed to 6 cm; clippings were dried 4 days at 60 °C before weighing.



Overall Conclusions

This series of studies has demonstrated that the efficient application of biochar and compost amendments to turf requires a modification of irrigation and maintenance practices. No negative impacts were measured using these products with standard management practices, yet benefits were transient if present at all. Neither establishment rates, performance under reduced irrigation nor performance under adequate irrigation were reduced with biochar, though compost amendments did cause negative impacts at each stage of research. When using potentially harmful compost amendments, negative impacts to growth could be mitigated by combining products with biochar. While this would allow for the use of otherwise unsuitable compost amendments, this application would be limited by regulations which control the use of said harmful products.

Only when irrigation was determined by the condition of plants were reductions in irrigation rates possible. Using this irrigation strategy, turfgrass was found to maintain acceptable quality and coverage with an overall lower quantity of applied water. We consistently showed that greater quantities of water could be held in amended soils, but this was found to be of less importance to actual plant performance than the dynamics of water release from soils. There is clearly an as of yet unclear mechanism allowing for the withholding of irrigation which will require further investigation. The high amount of variability in available soil amendments as well as in soils where they may be applied demands a more in-depth investigation of which physical or chemical traits are most important in determining plant health. Therefore, additional studies of this type could be conducted on a site-by-site basis, which would allow more directed and specific prescriptions for application of these products.