agronomy

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Effects of Biochar and Compost on Turfgrass Establishment Rates

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Abstract: Organic soil amendments are a sustainable option for modifying soil structure and improving plant performance in the face of abiotic stressors such as drought and soil salinity. Of these amendments, biochar and compost have the added benefits of carbon sequestration and waste recycling. Establishment studies were conducted on tall fescue (*Festuca arundinacea* Schreb.) (syn., *Schedonorus arundinaceus* (Schreb.) *Dumort* and *Lolium arundinaceum* (Scop.) Holub) to assess the potential inhibition of establishment by compost and biochar products. Both green waste and biosolid compost impaired establishment rates, while biochar did not. In the field study, the green waste treatments were slower to reach 50% coverage than the untreated control or when biochar was added to the soil, but all treatments reached 75% and final coverage at a similar rate. Field application of compost had a positive effect on final root length and volume but a negative effect on tall fescue roots in the greenhouse. The negative effect of higher salts and volatiles in the biosolids compost was reduced when biosolids and biochar were incorporated into the soil simultaneously. This work represents one of the only large-scale field studies on turfgrass establishment comparing the impact of biochar and compost products on turfgrass establishment.

Keywords: digital image analysis; *Festuca arundinacea* Schreb.; soil organic carbon; turf management

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Citation: Montgomery, J.; Crohn, D.; Schiavon, M.; Silva Filho, J.B.; Leinauer, B.; McGiffen, M.E., Jr. Effects of Biochar and Compost on Turfgrass Establishment Rates. *Agronomy* **2024**, *14*, 960. https://doi.org/10.3390/agronomy14050960

Academic Editors: Heike Knicker, Jorge Medina, Marcela Calabi-Floody, Humberto Aponte and Fujiang Hou

Received: 25 February 2024
Revised: 23 April 2024
Accepted: 29 April 2024
Published: 2 May 2024

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1. Introduction

Managed turfgrass covers 35,850 km^2 of the United States, with tall fescue being the most commonly grown residential species [1]. Turfgrass often must be established in urban soils that have been degraded by human activities and may have a suboptimal pH, poor soil structure, and low organic matter [2]. Compost and other organic amendments are often used to overcome suboptimal soils and improve turfgrass establishment and subsequent growth. Organic amendments can increase soil organic content, improve soil fertility and structure, and increase microbial activity [3,4].

Compost may improve turfgrass establishment, but the effect depends on the type of compost used [3,5]. Biosolids compost often contains high levels of salinity, ammonium nitrate, and other factors that can result in delayed turfgrass establishment [6]. Biochar is produced by heating organic materials in a low-oxygen environment, known as pyrolysis. This process gives biochar properties that may complement compost and ameliorate the negative aspects of biosolids [7]. Biochar can adsorb nitrogen species produced by biosolids, potentially reducing toxicity and leaching from the soil [8]. Biochar is much more resistant to degradation, and adding both biochar and compost may synergistically affect soil respiration, nutrient availability, and soil porosity when compared to compost alone [9,10]. Compost is readily degraded in most soils, whereas biochar can persist for decades; thus, compost may fuel microbial cycles and provide nutrients for plant growth, while biochar enhances soil physical properties and soil anion exchange capacity [11].

We conducted experiments in two distinctly different environments: field plots in a semi-arid Mediterranean climate and in pots in a greenhouse experiment. We applied varying amounts of biochar, green waste, and biosolids compost, either with or without biochar, to assess the impact of soil amendment on turfgrass establishment, root growth, and soil parameters. The response of turfgrass parameters in the greenhouse and field experiments are compared using correlation and principal component analysis and discussed in terms of how the environment may affect the response to the different soil amendments.

2. Materials and Methods

2.1. Location and Conditions

The field study was conducted during the growing season of 2014 at the Agricultural Operations, University of California, Riverside, CA, USA (33°57′46.1″ N and 117°20′16.5″ W, 304.8 m above sea level (1000 feet), Figure 1) and in heated greenhouse conditions in the spring of 2015 at the University of California, Riverside, CA, USA (33°58′10.4″ N and 117°19′28.1″ W, 304.8 m above sea level (1000 feet)). The soil at the field site is Hanford fine sandy loam, while one-gallon black plastic plant pots (3 L), measuring 16 cm (diameter top) × 13 cm (bottom) × 17 cm (height) in the greenhouse study, were filled with the same soil but mixed 50:50 with plaster sand to increase drainage and thus prevent waterlogging. Tall fescue (Loveland Products Sentinel CPQ blend; 49% ‘Lexington’, 29% ‘Black Magic’, 21% ‘Sitka’) was seeded on 5 May 2014 in the field and on 14 May 2015 in the greenhouse at a rate of 40 g m^{-2}. Tall fescue was cut to maintain a 6 cm height in both the greenhouse and the field.

Figure 1. Field study site at the University of California, Riverside, for turfgrass establishment experiment.

We describe the averages of soil chemical analysis for the field experiment in Table 1.

Table 1. Means of soil chemical parameters at the site of the field study.

Depth	pH	P	K^+	Ca^{2+}	Mg^{2+}	Na^+	CEC	OM
cm	H_2O	mg dm^{-3}		------ $cmol_c$ dm^{-3} ------				%
0–20	8.32	13.78	306.25	7.31	1.54	0.65	10.29	1.14

CEC: cation exchange capacity; OM: organic matter.

2.2. Amendment Rates

Treatments (amendment rates) included the following: untreated control, 2.2-, 11.2-, and 22.4-tons ha^{-1} of biochar, 5 and 10 cm of composted green waste applied by depth, 5 cm of composted biosolids, and a combined treatment of 5 cm composted green waste plus 11.2 tons ha^{-1} biochar (greenhouse only). Biochar from yellow pine wood was pyrolyzed at 350 °C (Table 2). Green waste compost uses a mixture of materials common to municipal sources provided by Aguinagua Green (Table 3). In contrast, biosolids compost was made from a mixture of stable bedding, green waste, and biosolids provided by the Inland Empire Utilities Agency (Table 4). For the field study, amendments were incorporated following recommendations published by Landschoot [3] and rototilled to a depth of 15 cm. For the greenhouse study, amendments were manually incorporated to a depth of 15 cm from the surface of the soil and sand mixture.

Table 2. Biochar characterization parameters.

Parameter	Unit of Measure	Value
Ammonia (NH_4-N)	ppm (mg kg^{-1} dry weight)	24.00
Nitrate (NO_3-N)	ppm (mg kg^{-1} dry weight)	1.00
Organic Nitrogen	ppm (mg kg^{-1} dry weight)	3321.00
Phosphorous (P)	ppm (mg kg^{-1} dry weight)	122.00
Potassium (as K_2O)	% Dry Weight	902.00
Potassium (K)	ppm (mg kg^{-1} dry weight)	1476.00
Organic Carbon	% Dry Weight	75.60
pH	Units	7.45
Soluble Salts (EC20)	dS/m (mmhos cm^{-1})	0.12
Particle Size Distribution		
<0.420 mm	Percent	1.60
0.420–2.38 mm	Percent	92.10
2.38–4.76 mm	Percent	6.10
>4.76 mm	Percent	0.20

2.3. Irrigation and Fertilization

Field plots were irrigated thrice weekly at 85% of reference evapotranspiration (ET_o). Climate data to calculate ET_o were collected at an on-site California Irrigation Management Information System (CIMIS) station [12] (Figure 2). Greenhouse temperatures were controlled using industrial air conditioners, and temperature data were collected daily using a WatchDog 1000 Series datalogger (Spectrum Technologies, Aurora, IL, USA, Figure 3). The turf was irrigated three times per week. In the field, irrigation was applied at 85% of reference evapotranspiration (ET_o). There was no precipitation during the field experiment, and irrigation supplied water only. In the greenhouse, pots were irrigated three times per week to field capacity at each irrigation event, determined as the point when drainage was noted from the bottom of each pot [13]. Greenhouse and field temperatures were similar, although the greenhouse was slightly warmer as it did not cool as rapidly as the field at night (Figure 3). Additionally, although it has not been measured, wind may be a factor that had different behavior in the field and greenhouse experiments.

Field plots were fertilized on 21 May 2014, with a 16–16–16 fertilizer rate of 5 g N m^{-2}. 2,4-D herbicide was applied to field plots on 4 June 2014 to control broadleaf weeds. Plots were mowed weekly at a height of 5.75 cm, and clippings were collected. The turf in the greenhouse was trimmed to the same height on July 15 using hand shears.

Table 3. Green waste compost characterization. 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^{-1} dry weight)	21.00	
Nitrate (NO_3-N)	ppm (mg kg^{-1} dry weight)	<1.00	
Organic Nitrogen	% Dry Weight	0.67	
Phosphorous (P)	ppm (mg kg^{-1} dry weight)	1300.00	
Potassium (as K_2O)	% Dry Weight	0.73	
Potassium (K)	ppm (mg kg^{-1} dry weight)	6100.00	
Organic Carbon	% Dry Weight	38.00	
C/N Ratio	Ratio	57.00	
pH	Units	7.71	
Soluble Salts (EC5)	dS/m (mmhos cm^{-1})	2.40	
Particle Size	% Larger than 0.64 cm	11.70	
Heavy Metals Content	Pass/Fail	Pass	
Stability Indicator (respirometry)			Stability Rating
CO_2 Evolution	mg CO_2-C/g OM/day mg CO_2-C/g TS/day	1.10 2.50	Stable
Maturity Indicator (bioassay of cucumber emergence)			Maturity Rating
Percent Emergence	Average % of control	100.00	Mature
Relative Seedling Vigor	Average % of control	100.00	
Pathogens			
Fecal Coliforms	Pass/Fail	Pass	
Salmonella	Pass/Fail	Pass	

Table 4. Biosolids compost characterization. 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	4.00	
Ammonia (NH_4-N)	ppm (mg kg^{-1} dry weight)	10,000.00	
Nitrate (NO_3-N)	ppm (mg kg^{-1} dry weight)	6.00	
Organic Nitrogen	% Dry Weight	3.00	
Phosphorous (P)	ppm (mg kg^{-1} dry weight)	21,000.00	
Potassium (as K_2O)	% Dry Weight	0.66	
Potassium (K)	ppm (mg kg^{-1} dry weight)	5500.00	
Organic Carbon	% Dry Weight	29.00	
C/N Ratio	Ratio	7.10	
pH	Units	7.59	
Soluble Salts (EC5)	dS/m (mmhos cm^{-1})	20.00	
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 mg CO_2-C/g TS/day	2.90 1.70	Stable
Maturity Indicator (bioassay of cucumber emergence)			Maturity Rating
Percent Emergence	Average % of control	0.00	Mature
Relative Seedling Vigor	Average % of control	N/A	
Pathogens			
Fecal Coliforms	Pass/Fail	Pass	
Salmonella	Pass/Fail	Pass	

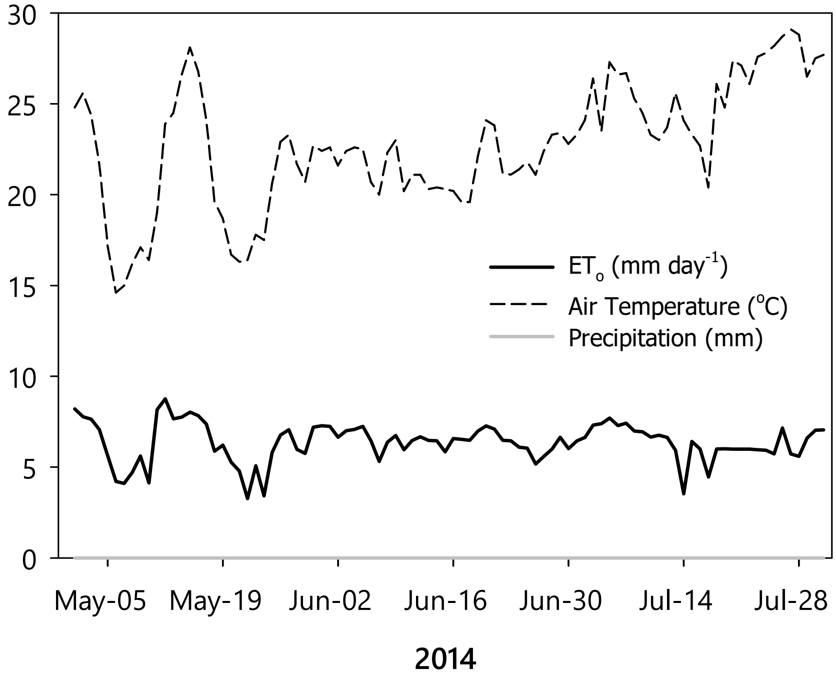

Figure 2. Average daily temperatures and reference evapotranspiration (ET_o) for the University of California Agricultural Operations Center in Riverside, CA, from May 2014 to July 2014. No precipitation events occurred during this period. The data were provided by the California Irrigation Management Information System (cimis.water.ca.gov).

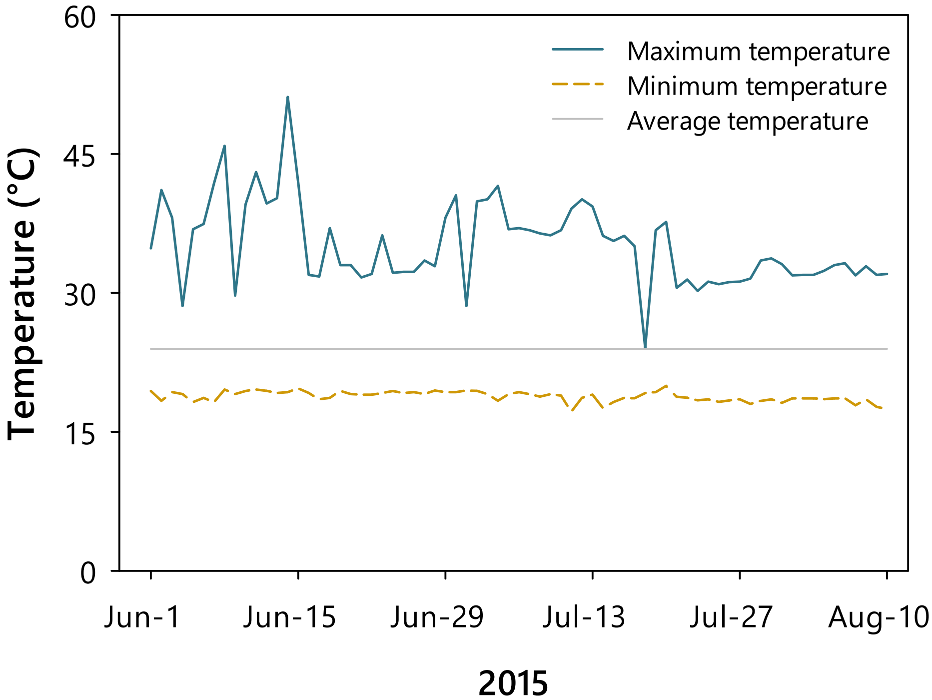

Figure 3. Daily maximum, minimum, and average temperatures for the greenhouse portion of the study. Temperature data were collected using the WatchDog 1000 Series datalogger (Spectrum Technologies, Aurora, IL, USA).

2.4. Data Collection

Digital Image Analysis (DIA) was performed to measure the percent green turf coverage and compare establishment rates [14]. A sigmoidal association of live turf coverage to days after seeding (DAS) most accurately describes turf establishment [15–17]. Live turf coverage was measured for each replicate, and sigmoidal models were used to calculate the DAS needed to reach threshold values for each replicate separately. Live turf coverage was averaged across replicates, and a sigmoidal curve fitted from the date at which each treatment reached specific levels of live turf coverage was calculated (GraphPad Prism Software, version 5.0 for Windows; Boston, MA, USA). We compared the number of DAS required to reach 50 and 75% coverage (DAS50 and DAS75, respectively). The establishment was considered successful when turf coverage reached 75% of the photographed area [17].

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 the camera's flash provided light. Pictures were collected every week during the study period. 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 at the conclusion of the study's field and greenhouse portions. Root samples were collected at 15 cm in the field on 4 May 2015 and in the greenhouse on 17 August 2015. The WinRhizo system (Alltech Laboratories) was used to analyze roots for length and volume.

2.5. Design and Data Analysis

The study's field and greenhouse components were arranged as randomized complete block experimental designs. For the field study, eight treatments were used, each with eight replications (n = 64). The treatments were as follows: (1) untreated control, (2) 2.2 t ha^{-1} biochar, (3) 11.2 t ha^{-1} biochar, (4) 22.4 t ha^{-1} biochar, (5) 5 cm biosolids, (6) 5 cm green waste, (7) 5 cm green waste + 11.2 t ha^{-1} biochar, and (8) 10 cm green waste. The greenhouse study had nine treatments, each with five replications (n = 45). The treatments were as follows: (1) untreated control, (2) 2.2 t ha^{-1} biochar, (3) 11.2 t ha^{-1} biochar, (4) 22.4 t ha^{-1} biochar, (5) 5 cm biosolids, (6) 5 cm biosolids + 11.2 t ha^{-1} biochar, (7) 5 cm green waste, (8) 5 cm green waste + 11.2 t ha^{-1} biochar, and (9) 10 cm green waste.

Data were subjected to analysis of variance (ANOVA) followed by comparisons of means using Fisher's protected least significant difference test ($p < 0.05$). Additionally, we used Pearson correlation to explore the potential relationships between the data collected in the field and greenhouse studies. A principal components analysis (PCA) was performed to ascertain the impact of the factors on the characterization of the parameters from both studies. We conducted all statistical analyses using R software version 4.3.2 (R Core Team 2023, Vienna, Austria) [18], SAEG version 9.1 [19], and OriginPro (OriginLab Corporation, version 2024, Northampton, MA, USA) [20].

3. Results

3.1. Field Results

3.1.1. Field Final Cover

All turf plots in the field exceeded 75% establishment on 29 July 2014, and images collected on that date were used to compare the final turf coverage. All field treatments containing either biosolids or green waste took longer to cover 50% or 75% of the soil surface than the untreated control or any biochar treatment without green waste or biosolids (Figure 4). The 5 cm biosolids compost treatment had significantly reduced coverage relative to any of the other field treatments (Figure 4).

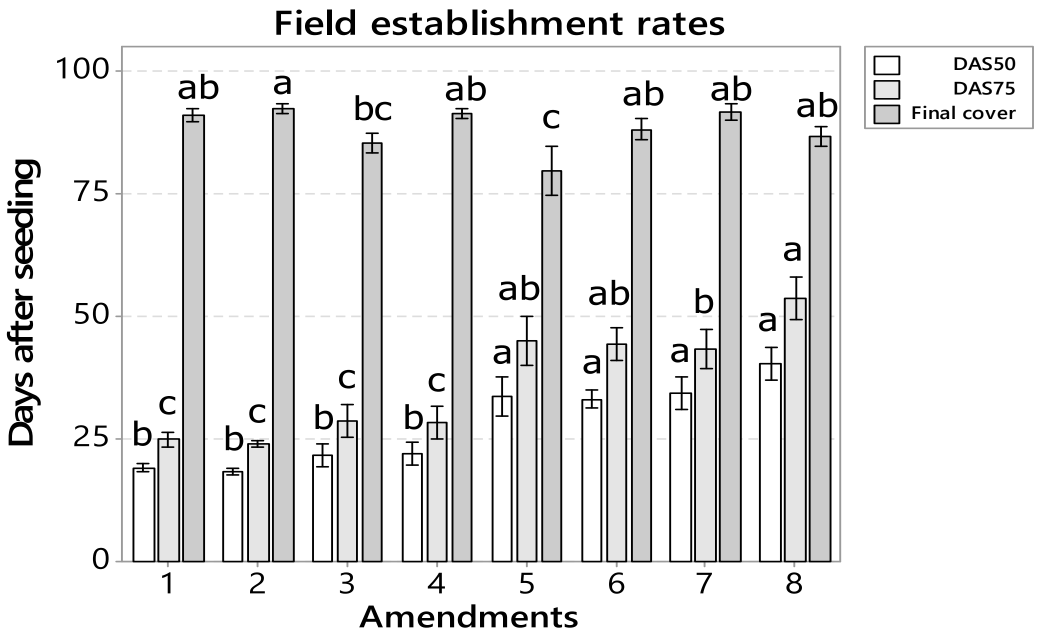

Figure 4. Field establishment rates are presented as the number of days after seeding required to reach 50 and 75% ground coverage (DAS50 and DAS75, respectively) and final coverage (%) at the end of the establishment study period. The mean bars followed by the same letter are not significantly different within each parameter, according to the Fisher LSD test ($p < 0.05$). Interval bars represent the standard errors of means. $n = 8$. Caption: (1) untreated control, (2) 2.2 t ha^{-1} biochar, (3) 11.2 t ha^{-1} biochar, (4) 22.4 t ha^{-1} biochar, (5) 5 cm biosolids, (6) 5 cm green waste, (7) 5 cm green waste + 11.2 t ha^{-1} biochar, and (8) 10 cm green waste.

3.1.2. Field Establishment Rate

In the field, the treatments that most rapidly reached 50% and 75% coverage were the untreated control and the three rates of biochar (Figure 4). It took longer to reach DAS75 in plots amended with 5 cm biosolids compost (45 d), 5 cm green waste compost (44 d), or the combined treatment of 5 cm green waste with 11.2 t ha^{-1} biochar (43 d). Amendment with 10 cm green waste compost caused the slowest establishment rate (54 d). DAS50 values showed an identical pattern (Figure 4).

3.1.3. Field Rooting Analysis

Soil amendment affected the root architecture (Figure 5). The composted green waste treatments had the greatest root lengths, including the plots amended with both green waste 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^{-1} of biochar was comparable to 10 cm of green waste compost. Root length was shortest in plots amended with composted biosolids (Figure 5).

While the green waste treatments may have had less above-ground growth early in the season, the root volume and root length data indicate greater final below-ground growth when green waste was incorporated into the soil. For both root length and root volume, the three treatments containing green waste had both the longest root length and the greatest root volume. The three biochar-only treatments were similar to the control, but the biosolid treatment had both the shortest root length and lowest root volume of any of the eight treatments studied (Figure 5).

Treatment differences in root volume mirrored those seen in root length. Plots amended with 5 cm composted green waste or a combination of 5 cm composted green waste and 11.2 t ha-1 biochar had the greatest root volumes. However, control plots were not significantly different from the 10 cm green waste or combined green waste and biochar treatment. All biochar-amended plots had root lengths similar to the control but were significantly lower than green waste-amended plots. Root volume was lowest in plots amended with biosolids compost.

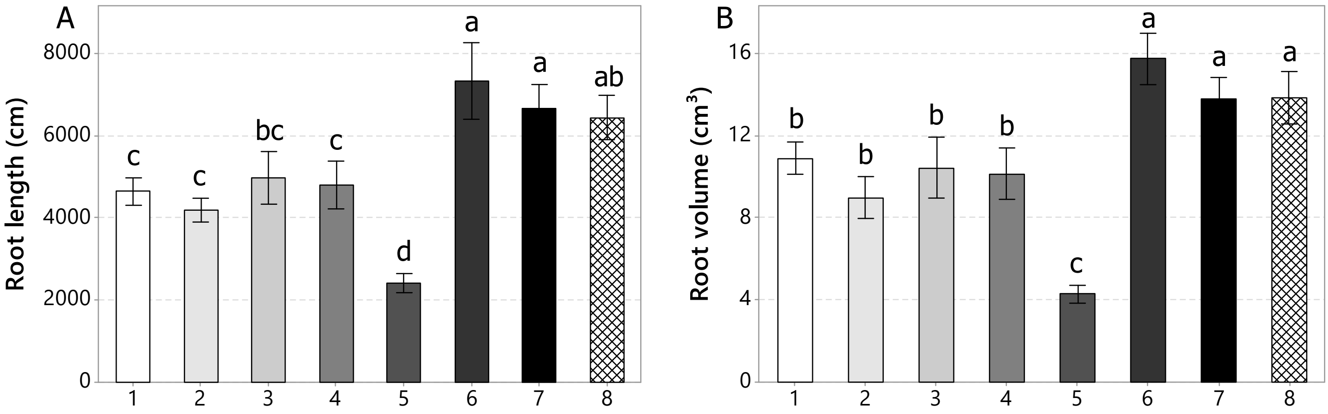

Figure 5. Root length (**A**) and volume (**B**) from the field portion of the study. Root samples were collected on 4 May 2015 and analyzed using Winrhizo software, version Pro, at the AllTech Labs. The mean bars followed by the same letter are not significantly different within each parameter, according to the Fisher LSD test ($p < 0.05$). Interval bars represent the standard errors of means. $n = 8$. Caption: (1) untreated control, (2) 2.2 t ha^{-1} biochar, (3) 11.2 t ha^{-1} biochar, (4) 22.4 t ha^{-1} biochar, (5) 5 cm biosolids, (6) 5 cm green waste, (7) 5 cm green waste + 11.2 t ha^{-1} biochar, and (8) 10 cm green waste.

3.2. Greenhouse Results

3.2.1. Greenhouse Establishment Rate

The greenhouse study was concluded on 10 August 2015. However, even three months after planting, not all treatments reached the complete establishment criteria of 75% live turf coverage. The 5 cm and 10 cm green waste treatments with no biochar had less than 50 percent coverage at the final sampling. For the greenhouse experiment, the three green waste treatments had less final coverage than the biochar or untreated control treatments (Figure 6).

Establishment in the greenhouse was impaired in pots amended with 5% or 10% green waste compost or 5 cm green waste with 11.2 t ha^{-1} biochar. Turf grown in media amended with green waste without biochar did not reach 50% coverage during the study period. Of the treatments that reached 50% coverage, the establishment was slowed when using the 5 cm biosolids treatment (57 d) or the combined green waste and biochar treatment (71 d). All other treatments were established at rates comparable to the control. Some treatments did not reach 75%, so DAS75 could not be calculated (Figure 6).

The untreated control was the first treatment to reach 75% coverage 59 days after seeding (Figure 6). Pots amended with 5 cm biosolids compost combined with 11.2 t ha^{-1}biochar (77 d) or 22.4 t ha^{-1} biochar t ha^{-1} with no compost added (70 d) took longer to reach 75% coverage.

3.2.2. Greenhouse Rooting Analysis

Results from the greenhouse study differed from those seen in the field (Figure 7). Root length was greatest in control pots and those amended with 11.2 t ha^{-1} or 22.4 t ha^{-1} biochar. Root length decreased in pots amended with 5 cm biosolids, 5 cm biosolids combined with 11.2 t ha^{-1} biochar, or 5 cm green waste with or without 11.2 t ha^{-1} biochar. The greenhouse root length and root length data showed similar treatment differences, with generally longer roots and greater root volumes for the control and greenhouse treatments with biochar alone (Figure 7).

Pots amended with 11.2 or 22.4 t ha^{-1} of biochar had the greatest root volume. Root volume was reduced by amendment with 5 or 10 cm composted green waste, combined green waste and biochar, and the combined biosolids compost and biochar amendment. The lowest root volume was seen in pots amended with 5 cm biosolids (Figure 7).

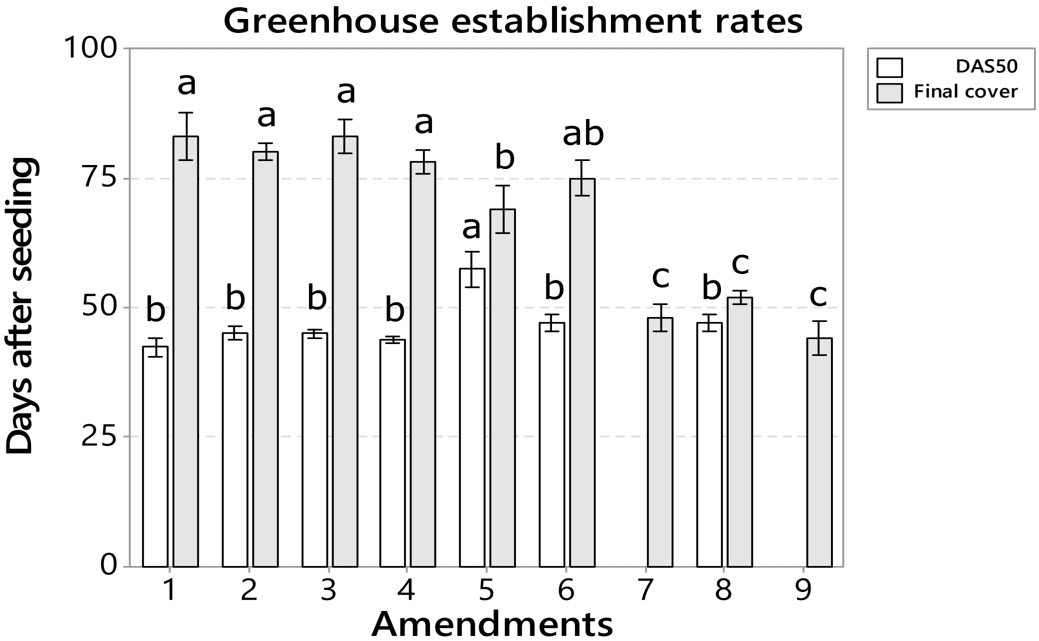

Figure 6. Greenhouse establishment rates are presented as the number of days after seeding required to reach 50% ground coverage (DAS50) and final coverage (%) at the end of the establishment study period. The mean bars followed by the same letter are not significantly different within each parameter, according to the Fisher LSD test ($p < 0.05$). Interval bars represent the standard errors of means. $n = 5$. Caption: (1) untreated control, (2) 2.2 t ha^{-1} biochar, (3) 11.2 t ha^{-1} biochar, (4) 22.4 t ha^{-1} biochar, (5) 5 cm biosolids, (6) 5 cm biosolids + 11.2 t ha^{-1} biochar, (7) 5 cm green waste, (8) 5 cm green waste + 11.2 t ha^{-1} biochar, and (9) 10 cm green waste.

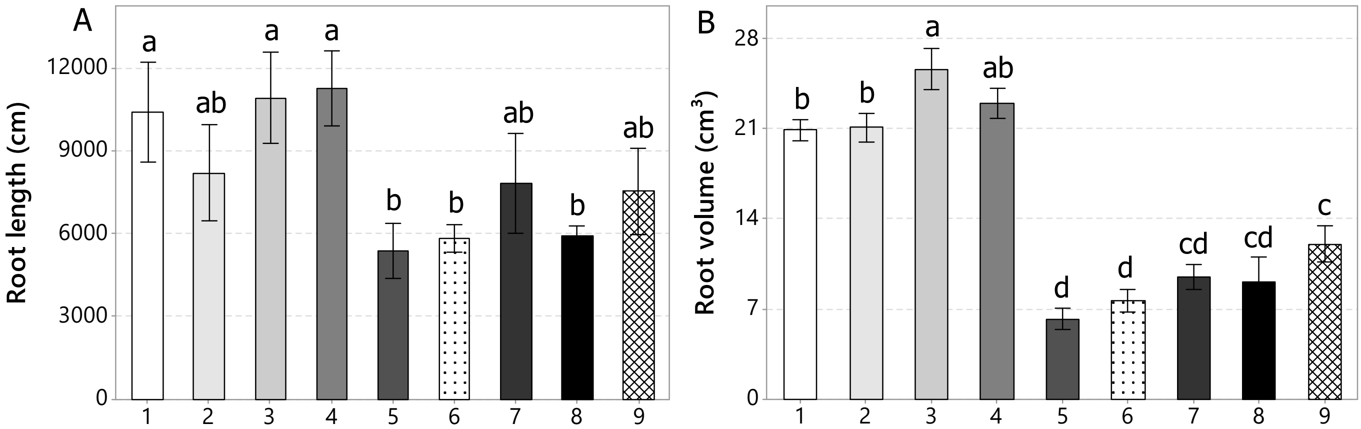

Figure 7. Root length (**A**) and volume (**B**) from the greenhouse portion of the study. Root samples were collected on 17 August 2015 and analyzed using Winrhizo software, version Pro, at the AllTech Labs. The mean bars followed by the same letter are not significantly different within each parameter, according to the Fisher LSD test ($p < 0.05$). Interval bars represent the standard errors of means. $n = 4$. Caption: (1) untreated control, (2) 2.2 t ha^{-1} biochar, (3) 11.2 t ha^{-1} biochar, (4) 22.4 t ha^{-1} biochar, (5) 5 cm biosolids, (6) 5 cm biosolids + 11.2 t ha^{-1} biochar, (7) 5 cm green waste, (8) 5 cm green waste + 11.2 t ha^{-1} biochar, and (9) 10 cm green waste.

3.3. Soil Chemistry

Only the amendment type affected soil chemistry in both greenhouse and field experiments. In the field, the experimental treatments had the greatest impact on pH and organic matter content (Table 5). The pH was reduced in plots amended with biosolids compost (7.4); all compost amendments increased the organic matter content, with the greatest increase found in the biosolids treatment (Table 5).

Table 5. Soil analysis from the field portion of the study was collected at the end of the study period and analyzed at AgSource Laboratories.

Amendment	pH †	Organic Matter, OM (%) †
Control	8.3 a	1.1 c
2.2 t ha^{-1} Biochar	8.3 a	1.2 c
11.2 t ha^{-1} Biochar	8.3 a	1.2 c
22.4 t ha^{-1} Biochar	8.3 a	1.2 c
5 cm Biosolids	7.4 b	2.3 a
5 cm Green Waste	8.2 a	1.8 b
5 cm Green Waste + 11.2 t ha^{-1} Biochar	8.2 a	1.9 b
10 cm Green Waste	8.2 a	1.9 b

† Within columns, means followed by the same letter are not significantly different according to the Fisher LSD test ($p < 0.05$).

In the greenhouse, compost amendments, including those combining compost and biochar, altered all measured aspects of soil chemistry compared to controls, while biochar treatments did not (Table 6). 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 biochar. Green waste compost and the combined green waste and biochar amendments reduced the pH levels (8.0). The lowest pH levels (6.4–6.5) were detected in soils amended with either biosolids compost alone or biosolids combined with biochar. Biochar had no effect on the pH.

Table 6. Soil analysis from the greenhouse portion of the study was collected on 10 August 2015, and analyzed at the Oklahoma State Soil Testing Lab.

Treatment	NO_3^- (ppm) †	Phosphorous (ppm P_2O_5) †	Potassium (ppm K_2O) †	pH †
Control	4.20 b	26.30 d	65.70 d	8.50 a
2.2 t ha^{-1} Biochar	3.40 b	22.40 d	63.00 d	8.60 a
11.2 t ha^{-1} Biochar	2.70 b	23.60 d	61.60 d	8.60 a
22.4 t ha^{-1} Biochar	2.80 b	19.90 d	63.50 d	8.50 a
5 cm Biosolids	132.80 a	473.10 a	246.20 b	6.40 c
5 cm Biosolids + 11.2 t ha^{-1} Biochar	88.80 a	276.80 b	147.60 c	6.50 c
5 cm Green Waste	1.25 b	69.10 cd	134.60 c	8.00 b
5 cm Green Waste + 11.2 t ha^{-1} Biochar	1.50 b	70.80 cd	141.90 c	8.00 b
10 cm Green Waste	1.30 b	95.40 c	350.90 a	8.00 b

† Within columns, means followed by the same letter are not significantly different according to the Fisher LSD test ($p < 0.05$).

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^{-1} biochar (89 ppm), greatly exceeding the levels seen in control pots (4 ppm). Amendment with 5 cm green waste 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^{-1} 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. Amending with 10 cm of green waste compost also increased phosphorous levels (95 ppm) compared to controls (26 ppm). Potassium levels were highest in soils amended with 10 cm green waste 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 green waste compost (135 ppm), also increased the 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 potassium levels.

For field and greenhouse studies, soil samples were collected at the end of the experiment for chemical analysis in the laboratory (Tables 5 and 6).

3.4. Correlations

Figure 8 presents the linear correlations between parameters in the field and greenhouse studies. The field and greenhouse data for the number of days after seeding needed to reach 50% and 75% ground coverage were negatively correlated with the parameters in the greenhouse, specifically the final coverage at the end of the greenhouse establishment study period, root length, and root volume. These relationships were all significant.

There were positive relationships between the field study and the number of days after seeding needed to reach 75% and 50% ground coverage (1.00), root volume and root length for the field study (0.99), root volume and final coverage at the end of the greenhouse establishment study period (0.78), and root volume and root length for the greenhouse study (0.91) (Figure 8).

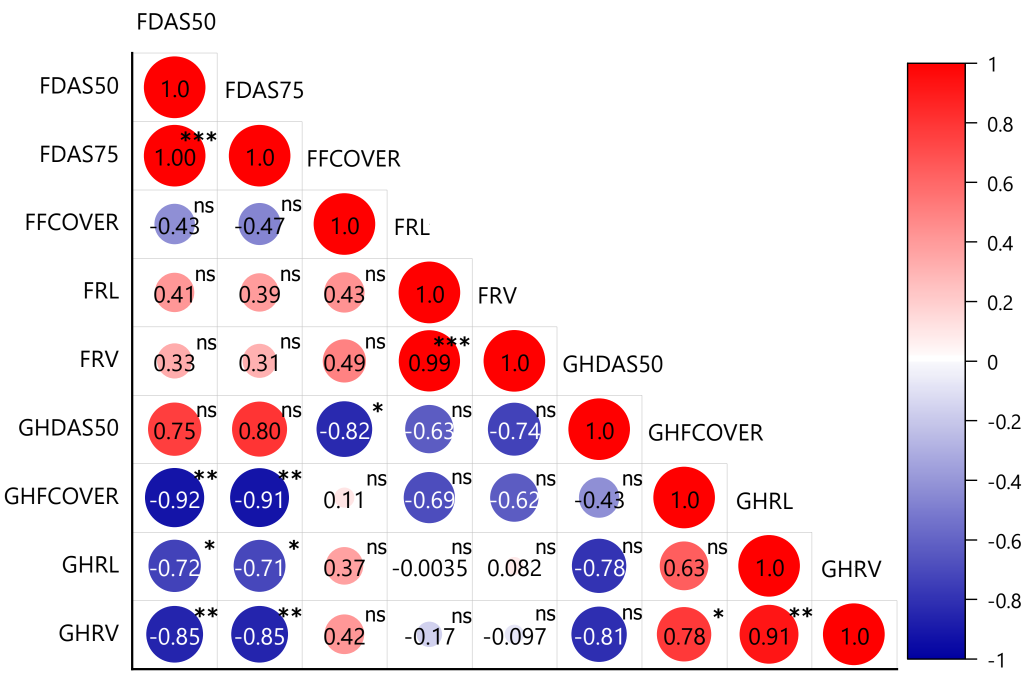

Figure 8. Pearson correlation between the parameters of the field and greenhouse studies. Intensity of red (positive) and blue (negative) and circle size determine the magnitude of the correlation on the turfgrass establishment of field and greenhouse studies. Caption: FDAS50: field study for the number of days after seeding required to reach 50% ground coverage; FDAS75: field study for the number of days after seeding required to reach 75% ground coverage; FFCOVER: final coverage at the end of the field establishment study period; FRL: root length for the field study; FRV: root volume for field study; GHDAS50: greenhouse study for the number of days after seeding required to reach 50% ground coverage; GHFCOVER: final coverage at the end of the greenhouse establishment study period; GHRL: root length for the greenhouse study; and GHRV: root volume for greenhouse study. *, **, and ***: significant at the 0.05, 0.01, and 0.001 probability levels, respectively, using a *t*-test. ns: not significant at the 0.05 probability level using a *t*-test.

3.5. Multivariate Analysis

In principal component analysis (PCA), we used two dimensions: PC1 (56.7% of total variability; eigenvalue = 5.1) and PC2 (34.5% of total variability; eigenvalue = 3.1). Together, these dimensions could explain nearly 91% of the differences between the traits of the field and those of greenhouse studies. Some characteristics did vary slightly, like the final coverage at the end of the field establishment study period (FFCOVER, 4.6%), root length for the field study (FRL, 1.8%), and root volume for the field study (FRV, 0.9%). These differences did not greatly affect the results in Dimension 1. The final coverage at the end of the greenhouse establishment study period (GHFCOVER, 15.2%) and the field study for how many days after seeding are needed to reach 50% and 75% ground coverage (FDAS50, 18.4%, and FDAS75, 18.4%, respectively) made important contributions to the results in Dimension 1 (Figure 9).

The characteristics of the greenhouse study on the number of days after seeding required to reach 50% ground coverage influence Dimensions 1 and 2, with contributions of 9.0% and 16.8%, respectively. Other characteristics that stood out in Dimension 2 were the final coverage at the end of the greenhouse establishment study period (GHFCOVER, 6.8%), the final coverage at the end of the field establishment study period (FFCOVER, 15.0%), and root length and root volume for the field study (FRL, 28.2%, and FRV, 29.9%, respectively).

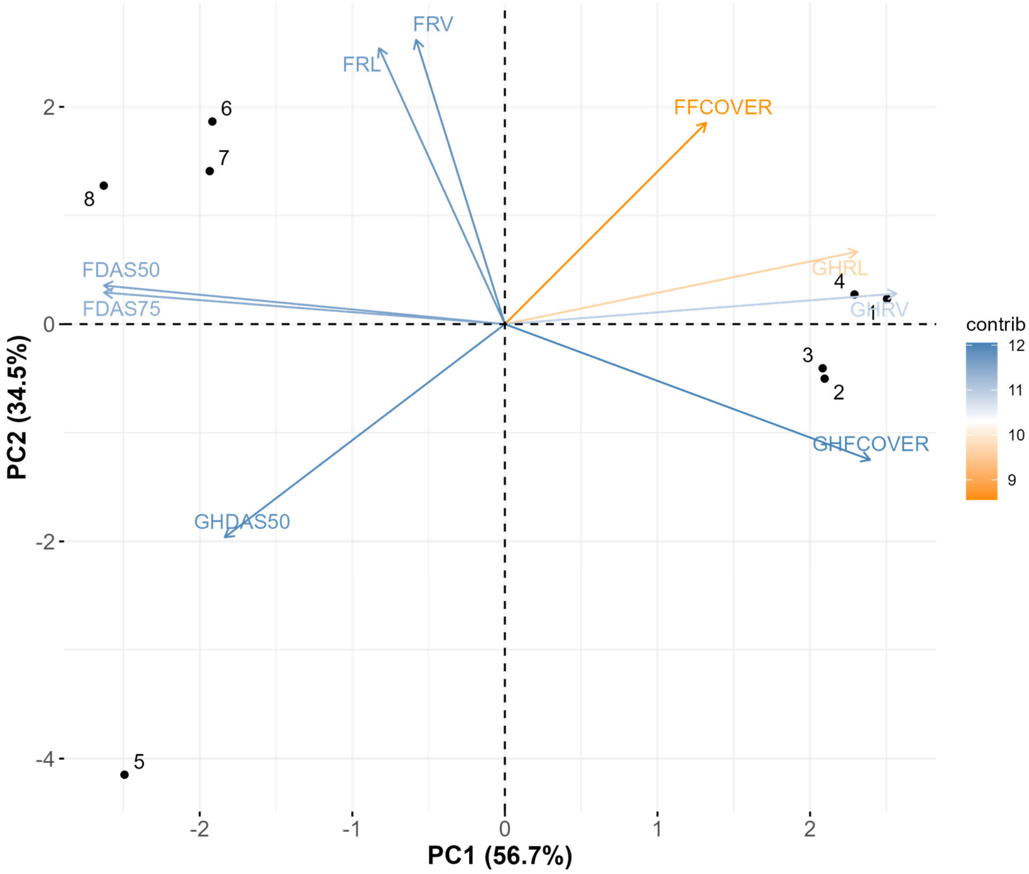

Figure 9. Principal component (PC) analysis, intensity of blue (high contribution of the parameter) and orange (low contribution of the parameter), and line size determine the magnitude of the parameters' contributions to the experiment's overall variation under field and greenhouse conditions. Project lines: FDAS50: field study for the number of days after seeding required to reach 50% ground coverage; FDAS75: field study for the number of days after seeding required to reach 75% ground coverage; FFCOVER: final coverage at the end of the field establishment study period; FRL: root length for the field study; FRV: root volume for field study; GHDAS50: greenhouse study for the number of days after seeding required to reach 50% ground coverage; GHFCOVER: final coverage at the end of the greenhouse establishment study period; GHRL: root length for the greenhouse study; and GHRV: root volume for greenhouse study. Black circles: (1) untreated control, (2) 2.2 t ha^{-1} biochar, (3) 11.2 t ha^{-1} biochar, (4) 22.4 t ha^{-1} biochar, (5) 5 cm biosolids, (6) 5 cm green waste, (7) 5 cm green waste + 11.2 t ha^{-1} biochar, and (8) 10 cm green waste.

In the greenhouse study, applying 5 cm of biosolids increased the time required to cover 50% of the ground after seeding (GHDAS50). In both dimensions, principal component analysis revealed this (Figure 9). This is consistent with what is shown in Figure 6, where this treatment differs significantly from the others.

For dimension 1 of the PCA, 2.2 t ha^{-1} and 11.2 t ha^{-1} biochar provided higher percentages of final coverage at the end of the greenhouse establishment study period (Figure 9).

4. Discussion

While all other measured chemical characteristics of the composts fell within tolerable levels, the biosolids compost had excessively high levels of salinity (Table 3), causing it to be classified as immature [21]. A large particle size of green waste compost treatment (Table 3) reduces bulk density [22,23]. Both traits affect turfgrass's rooting characteristics and establishment rates [24].

The compost amendments used in our study negatively impacted establishment in both field and greenhouse conditions, while biochar amendments alone did not affect establishment (Figures 4 and 5). In the field, only biosolids compost reduced the final coverage, while in the greenhouse, all compost amendments reduced the final coverage except when biosolids compost was combined with biochar. Notably, in the greenhouse study, pots amended with only biosolids compost were slower to reach 50 percent coverage than those amended with combined biosolids compost and biochar. Additionally, pots amended with composted green waste never exceeded 50% coverage.

In addition to impacts on above-ground growth, both compost and biochar amendments affected the root length and root volume (Figures 5 and 7). Effects differed between the greenhouse and field sites, most likely due to the modified soil used in the greenhouse. Combining biochar with biosolids compost ameliorated some of the negative impacts of the biosolids and improved turfgrass establishment.

The saltier biosolids-compost-treated plots or pots slowed establishment in both the greenhouse and field experiments. Salt stress impairs turfgrass growth by reducing the ability of roots to take up water present in the soil [25]. Salinity levels similar to those expected with biosolids compost products have been shown to require much higher levels of ET_o than those used in our study to prevent turf damage [26]. 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 [27]. Incorporating both biochar and biosolids compost may have facilitated biochar amelioration of salts from the biosolid compost. This suggests that including biochar and amendments that contain excessive salts may allow for the application of otherwise unusable products.

The larger particle size of green waste compost noted earlier (Table 2) may explain the increased root length observed at our field site (Figure 6). Green waste most likely reduced soil bulk density, reducing the physical resistance of the soil to root penetration and allowing an increase in root length [28]. 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 [29]. We maintained soil in the greenhouse near field capacity, and the smaller fluctuations in air temperature in the greenhouse reduced variation in soil moisture. Additionally, including sand in our greenhouse trial decreased soil density regardless of compost incorporation.

The green waste compost treatment increased the turfgrass root length but delayed establishment in both the field and greenhouse sites (Figures 4 and 6). Such a contradiction can also be explained by reductions in bulk density, which can cause reduced contact between the root and soil [30]. In response, plants may partition more resources toward rooting, causing reductions in above-ground growth [30]. In comparing turf grown in the 5 cm green waste treatment to 5 cm green waste combined with 11.2 t ha^{-1} 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 [31,32].

Our results documented that biochar amendments did not impact tall fescue turfgrass establishment rates compared to establishment in untreated soils (Figures 4 and 6). However, this trial was conducted under adequate irrigation and fertilization. Drought treatment was not included; this study site was utilized the following year for a drought study, and similar conditions must be established [33]. The beneficial effects of biochar, such as increases in water and nutrient holding capacity, are more prominent when water and nutrients are limited. Turf managers may wish to utilize biochar and compost products to reduce the negative impacts of necessary irrigation reductions when turf has matured. Germination and establishment rates are common predictors of the ability of plants to reach maturation; it is therefore important to establish that biochar will not impede turf establishment [34]. Compost products may be used in much the same way; however, as shown in our study, highly saline or low-density composts slow establishment.

Although our presented results did not show a significant difference between biochar treatments and untreated control, we found a significant and negative correlation between the parameters studied in the greenhouse and the parameters studied in the field. The relationship indicates that the higher the final coverage at the end of the greenhouse establishment study period, the fewer days after seeding required to reach 50% and 75% ground coverage in the field study. When we connect these results to the non-parametric analysis (principal component analysis), we can see that treatments with 2.2 t ha^{-1} and 11.2 t ha^{-1} biochar tend to work better for a higher final coverage on tall fescue establishments in the greenhouse study.

5. Conclusions

In this study, biochar generally had little effect on turf establishment. It may have some effect on reducing the negative effects of biosolids and other amendments that are known to slow plant growth. Another interesting outcome was the slowing of early-season aboveground growth of tall fescue but apparently greater root growth in the field. Based on the two studies and the parametric and non-parametric analyses, there is a trend that 2.2 t ha^{-1} biochar may help turfgrass establishment rates in a greenhouse study. However, we recommend a more in-depth investigation of potentially harmful factors during turf establishment with biochar use.

Future work should include more soil salinity measurements, bulk density before and during the study period, and pH and ammonium levels. 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.

Author Contributions: Conceptualization, J.M. and M.E.M.J.; methodology, J.M. and M.E.M.J.; formal analysis, J.B.S.F., M.S. and M.E.M.J.; investigation, J.B.S.F. and J.M.; resources, J.M., D.C., M.E.M.J. and B.L.; data curation, J.M.; writing—original draft preparation, J.B.S.F. and J.M.; writing—review and editing, J.B.S.F., M.E.M.J., M.S., D.C., B.L. and J.M.; visualization, J.B.S.F. and M.E.M.J.; supervision, J.M. and M.E.M.J.; project administration, M.E.M.J.; funding acquisition, M.E.M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The new data created here were for the sole purpose of testing our treatments and hypotheses and are not to be entered into any public database or archives. Thus, data sharing does not apply to this article.

Acknowledgments: The authors acknowledge the contributions of the Metropolitan Water District of Southern California for funding this research project.

Conflicts of Interest: The authors declare no conflicts of interest. The use of trade, firm, or corporation names in this publication is simply for the convenience of the reader and does not constitute an official endorsement by the authors, the University of California Riverside, the California State Polytechnic

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