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Biochars impact on water infiltration and water quality through a compacted subsoil layer

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HIGHLIGHTS

- Biochars increased water infiltration through a compacted subsoil layer.
- Water infiltration declined after multiple water leaching events.
- Blending poultry litter biochar with pine chip biochar reduced P concentrations.
- Soluble P released from poultry litter biochar declined with more water leaching.

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ABSTRACT

Soils in the SE USA Coastal Plain region frequently have a compacted subsoil layer (E horizon), which is a barrier for water infiltration. Four different biochars were evaluated to increase water infiltration through a compacted horizon from a Norfolk soil (fine-loamy, kaolinitic, thermic, Typic Kandiudult). In addition, we also evaluated biochars effect on water quality. Biochars were produced by pyrolysis at 500 °C from pine chips (*Pinus taeda*), poultry litter (*Gallus domesticus*) feedstocks, and as blends (50:50 and 80:20) of pine chip:poultry litter. Prior to pyrolysis, the feedstocks were pelletized and sieved to >2-mm pellets. Each biochar was mixed with the subsoil at 20 g/kg (w/w) and the mixture was placed in columns. The columns were leached four times with Milli-Q water over 128 d of incubation. Except for the biochar produced from poultry litter, all other applied biochars resulted in significant water infiltration increases (0.157–0.219 mL min^{-1}; $p < 0.05$) compared to the control (0.095 mL min^{-1}). However, water infiltration in each treatment were influenced by additional water leaching. Leachates were enriched in PO_4, SO_4, Cl, Na, and K after addition of poultry litter biochar, however, their concentrations declined in pine chip blended biochar treatments and after multiple leaching. Adding biochars (except 100% poultry litter biochar) to a compacted subsoil layer can initially improve water infiltration, but, additional leaching revealed that the effect remained only for the 50:50 pine chip:poultry litter blended biochar while it declined in other biochar treatments.

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1. Introduction

Compacted subsoil horizons with limited soil water holding capacities severely impacts crop productivity. The coastal plain region of the Southeastern USA is highly impacted by these yield limiting subsoil horizons (Campbell et al., 1974; Doty et al., 1975). These horizons develop due to various pedogenic processes (Buol et al., 1973; Mullins, 2000). Generally, compacted subsoil horizons have lost soil organic matter due to eluviation which allows closer arrangements between sand grains, oxides, and other fine-size soil materials during wetting/drying cycles. This facilitates more physico-chemical bonding between soil materials resulting in formation of a dense, structureless layer (E horizon) with bulk densities (ρ_b) ranging between 1.41 and 1.82 g cm^{-1} (Long et al., 1969) and high penetration resistance (Ekwue and Stone, 1995).

Reduction in plant available water lowers crop yield, especially during periods of short-term drought (Reicosky et al., 1977; Busscher et al., 2010). Deep tillage is often used to fracture the

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compact subsoil layer (Busscher et al., 2002). However, deep tillage has a few issues such as requiring large tractors with significant horsepower to pull each shank (14–20 Kw), consumption of copious amounts of fuel (20–25 L ha^{-1}; Karlen et al., 1991), and deep tillage is usually needed annually to prevent re-setting of the dense soil layer (Threadgill, 1982; Porter and Khalilian, 1995).

Studies have investigated improving hydraulic characteristics of compacted horizons with the additions of composts (Parton et al., 1987; Wang et al., 2000), peat/manures (Ekwue and Stone, 1995), coal/fly ash (Chang et al., 1977), and crop residues (Busscher et al., 2011). Adding these degradable amendments stimulates microbial activity, particularly in the Southeastern USA because the warm and humid climate favors rapid decomposition (Parton et al., 1987; Wang et al., 2000), which results in the improved hydraulic properties dissipating within months (Schneider et al., 2009). It would be more desirable if the amendment, in addition to improving soil hydraulic properties, was recalcitrant.

Biochar is viewed as a potential long-term amendment improving soil chemical and physical conditions while sequestering carbon (Mukherjee and Lal, 2013; Lychuk et al., 2014). The feedstock used to create biochar has important soil nutrient and water quality implications, since manure-based biochars (e.g., poultry litter, swine solids) are nutrient rich (Novak et al., 2009; Cantrell et al., 2012), they can supply relatively large concentrations (≈60 mg/L) of water soluble P (Novak et al., 2014). Blending poultry litter with a nutrient-poor feedstock such as pine chips (*Pinus taeda*) has been reported to reduce P concentrations in the resultant biochar (Novak et al., 2014), thus reducing the negative environmental leaching potential.

Recently, researchers have found that biochar has the potential to increase soil water holding capacities (Laird et al., 2010; Basso et al., 2013) of sandy soils. But, studies of biochars impact on improving a soils saturated hydraulic conductivity have reported mixed results (Asai et al., 2009; Brockhoff et al., 2010; Githinji, 2014). These studies employed biochars pyrolyzed from a single feedstock and at high application rates (up to 100% v v^{-1}). Hence, there is a need to focus on the impact of variable feedstock composition and on lower application rates for their potential to remediate hydraulic properties of a compacted subsoil horizon.

In this investigation, we tested the hypothesis that biochars produced from two different feedstocks along with their blends can increase water infiltration through a compacted E horizon. Additionally, this study also examined whether applying blended biochars (poultry litter + pine chip) to soil reduces nutrient leaching, thus reducing potential water quality impairment.

2. Material and methods

2.1. Site description and soil characterization

The sample collection site was located at the Clemson University, Pee Dee Research and Education Center in Darlington, SC, USA (34°18′N, 79°44′W). The field has a long-term history (>30 yrs) of row crop production with corn (*Zea mays*), soybeans (*Glycine max*) and cotton (*Gossypium hirsutum*). At the time of soil sampling (2008), the field was under switchgrass (*Panicum virgatum*) for approximately 1 yr.

A Norfolk soil series was identified with a well-developed E horizon (Fig. 1A). The E horizon was exposed using a back hoe, and samples from the E horizon (20–40 cm depth) were collected using a shovel (Fig. 1B). The soil was then air-dried, sieved to <2-mm, and then analyzed for particle size (sedimentation method: Soil Characterization Laboratory, The Ohio State University, Columbus, OH, USA) and common soil fertility properties (Clemson University Soil Testing Laboratory, Clemson, South Carolina, USA). Its organic carbon (OC) content was determined by the loss of ignition method using 16 h of combustion at 575 °C (Jones, 2001). Total element concentrations in the Norfolk E horizon were determined using EPA digestion method 3052 (USEPA, 1996) and plant extractable nutrients were measured using Mehlich 1 reagent (Jones, 2001). The elements in acid digests were quantified using ICP–MS, and elements in the Mehlich 1 extracts quantified using ICP–OES.

2.2. Biochar preparation and characterization

Selection of manure and lignocellulosic feedstocks, blending ratios of poultry litter and pine chips, and pyrolysis conditions were outlined in Cantrell and Martin (2012) and Novak et al. (2014). The pine chip-, poultry litter- (50:50 and 80:20) blends were initially pelletized using a 6.4 mm dye plate, sieved to acquire >2-mm sized material, and then pyrolyzed at 500 °C for 2 h using a Lindburg oven equipped with an electric box + retort.

The major and minor dimensions for pelletized biochars (Table 2) were measured via light microscopy using an Epson Perfection V500 flatbed scanner and ImageJ software from the National Institute of Health (http://rsbweb.nih.gov/ij/). The images were smoothed using ImageJ software to prevent aliasing, and analyzed using the method outlined by Pordesimo et al. (2010). The pellets specific surface area (SSA) were measured based on N_2 adsorption at 77 K using a Quantachrome Nova 2200e (Boynton beach, FL, USA) as described in Rehrah et al. (2014). The BET (Brunauer, Emmett, and Teller) equation within the Nova 2200e automated software was used to determine their SSA. The %C, H, O and N contents in the biochars produced from poultry litter, pine chips, and their blends were previously reported (Novak et al., 2014). These values were determined on an oven dry-weight basis by Hazen Research, Inc. (Golden, CO, USA) following ASTM D 3172 and 3176 standard methods (ASTM, 2006). Total element contents (Ca–Zn) were determined using USEPA 3052 microwave assisted acid digestion method (USEPA, 1996) and were quantified using an ICP–OES. The pHs of the biochars were measured in 1:2 (v/v) biochar/Milli-Q water as previously outlined (Novak et al., 2014).

2.3. Treatments and column preparation

The treatments consisted of the Norfolk E horizon mixed with no biochar (control); 100% poultry litter biochar; 100% pine chip biochar; and 50:50 and 80:20 blends (w/w) of the pine chip:poultry litter biochars. Twenty g kg^{-1} of biochar (w/w) was added to the soil and soil moisture content was brought up to 10% (w/w) using Milli-Q water. These treatments were mixed into triplicate PVC columns (16 cm height × 10 cm diam.) that were open-topped, but had plastic screening attached to the bottom. Each column was gently tapped until a soil ρ_b of 1.5 g cm^{-3} was obtained. This ρ_b value is within range of soil ρ_b for E horizons in other sandy coastal plain soils (1.4–1.7 g cm^{-3}; Long et al., 1969).

2.4. Column incubation and water infiltration

The columns were set up in a randomized design on a laboratory bench and were incubated for 128 d. During the incubation, the soil moisture content of each column was gravimetrically monitored twice per week and sufficient Milli-Q water was added to maintain the 10% soil moisture content. Soil ρ_b was measured once per week and immediately before water leaching to monitor soil settling and provide an estimate of pore volume. On days 32, 67, 95 and 128 of incubation, each column was transferred to a wood rack/funnel system. Onto the top of each soil, 1.3 pore-volumes of Milli-Q water was poured using a plastic screen to distribute the water across the soil surface to minimize soil disturbance. The

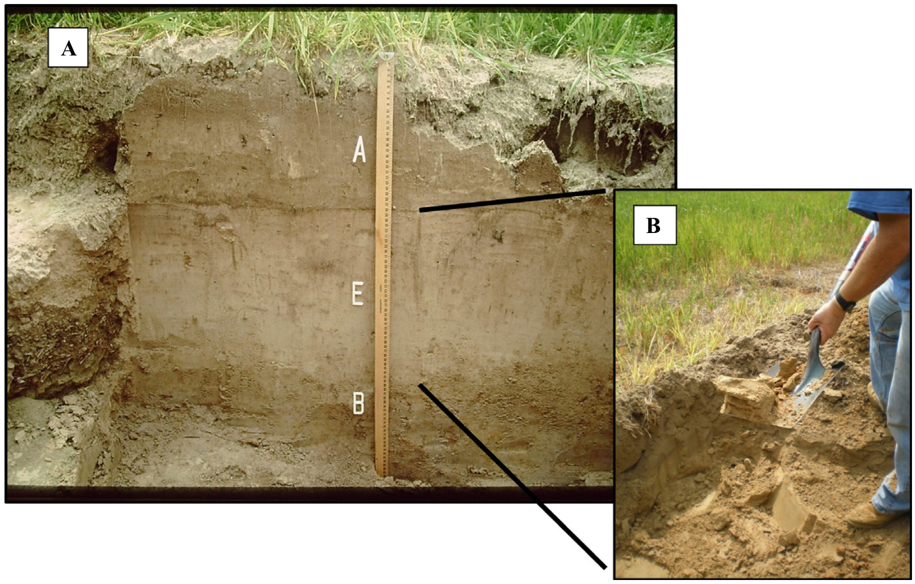

Fig. 1. Horizionation of a Norfolk soil series (A) with insert photo (B) focusing on platy structure of the compacted E horizon.

Milli-Q water was added to each column within a few minutes to keep the soil hydraulic heads similar in height above the soil surface. Thereafter, a plastic bottle was placed under each column and a leaching start time was recorded. Water and sediment collected in each bottle were weighed as a function of time at 1, 2, 4, 6, and 8 h after leaching commenced, thereafter; the bottles were weighed on a 4–12 h schedule. To minimize leachate evaporative losses, each bottle opening was wrapped with plastic wrap. Total water leachate and sediment collection was terminated when the bottle weights between two collection time periods (e.g., 64 vs. 69 h) were within 0.1 g difference. The earlier time period (e.g., 64 and not 69 h) was then selected as representing the final time period for water infiltration assessment.

Sediment was removed from the water leachate by filtration using 0.7 μm GF/F (Whatman™, Buckinghamshire, UK) filter paper. The filter paper plus sediment samples were dried at 105 °C and the sediment weight determined by difference. This provided an adjustment method to determine corrected water infiltration (as mL min^{-1}) since the water leachate mass at the final collection time period was separated from the sediment mass.

2.5. Water quality characterization

After sediment filtration, the pH and electrical conductivity (EC) of the water leachates were measured (Novak et al., 2014). Prior to anion and cation analysis, water leachates were pre-filtered through 0.2 μm nylon syringe filters (Environmental Express, Charleston, SC, USA). Following filtration, anion (Cl, NO_2–N, NO_3–N, SO_4–S, and PO_4–P) and cation (Na, NH_4–N, K) concentrations were quantified by chemically suppressed ion chromatography (IC) (ASTM, 2011; Standard D4327-11 and ASTM, 2009; D6919-09). Thermo Fisher™ Dionex™ ICS 2000 systems with automated potassium hydroxide and methanesulfonic acid eluent generation were used for anion and cation quantification respectively (Thermo Fisher™ Dionex™, Sunnyvale, CA, USA).

2.6. Statistical analyses

Corrected water infiltration values were pooled by treatment and leaching day and were analyzed using a two-way ANOVA with significant differences determined among treatment, leaching day, and treatment ∗ leaching day. Pooling the corrected mean water infiltration values by individual treatments allowed comparison using a Fisher Least Significant Difference (LSD) test. A two-way ANOVA was also employed to test for significant differences among corrected mean water infiltration values by individual leaching day and by treatment. Soil ρ_b were analyzed using a 1-way ANOVA by pooling treatments as a function of leaching day and by individual treatments. Linear regression was used to examine if Norfolk soil ρ_b influenced corrected mean infiltration values by pooling all results ($n = 80$) and on each leaching day ($n = 24$). Finally, a two-way ANOVA was used to identify water quality characteristics (i.e., pH, EC, anions, and cations) that were influenced by biochar treatment and in leachates collected on individual leaching days. All statistical tests were performed using SigmaStat v. 3.5 software (SSPS Corp., Chicago, IL, USA).

3. Results

3.1. Norfolk E horizon soil properties and biochar compositional characteristics

3.1.1. Soil properties

The Norfolk soil profile has a thick Ap horizon (0–28 cm), which is underlain by a well-developed E horizon (29–63 cm; Fig 1A). The E horizon is distinguishable from the bordering Ap and B horizons because the loss of SOM causes a higher matrix hue value (Fig. 1A) and exhibits a platy-like structural morphology (Fig. 1B), which, when dry, can impede both water infiltration and root penetration into the underlying subsoil layer (B horizon, Fig. 1A).

The E horizon has a sandy loam texture consisting of 71%, 24%, and 5%, respectively, of sand silt and clay. The pH is 5.4 with a cation exchange capacity of 1.5 $cmol_c\ kg^{-1}$. The Norfolk E horizon contains total and Mehlich 1 extractable nutrient concentrations in medium to low amounts, respectively, of macro-, and micro-nutrients (Table 1). Likewise, the E horizon has a low OC content (7.1 mg kg^{-1}) relative to the dark, colored Ap horizon.

3.1.2. Biochars

The major length for the 100% pine chip and poultry litter biochars were <6 mm while the minor length was between 2 and 4.5 mm (Table 2). Their specific surface areas ranged between 0.97 and 14.09 $m^2\ g^{-1}$. Biochars mixed with pine chips had higher SAA than biochar produced from poultry litter alone. Biochars

Table 1
Total and Mehlich 1 soil extractable nutrients from the untreated Norfolk E horizon.

	Nutrients (mg kg^{-1})	
	Total[†]	Mehlich 1
Macro-		
OC	7.1	nd
Ca	126	71
K	231	39
Mg	231	24
Na	30	3
P	50	5
Micro-		
Cu	1.4	0.2
Mn	39	3.3
Zn	11	1.2

[†] Using EPA method 3052.

produced from poultry litter had higher ash, S and N contents than pine chip biochars (Table 2). On the other hand, pine chip biochar had higher fixed carbon, and H contents. Blending of poultry litter with pine chips resulted in biochar blends containing intermediate amounts of almost all chemical and physical characteristics (Table 2).

The 100% pine chip biochar shows dissimilarity in its total contents of Ca, K, Mg, P, Mn and Zn compared to 100% poultry litter biochar (Table 3). The 100% poultry litter biochar was highest in K > Ca > P > Na > Mg and had greater concentrations of the micro-nutrients Cu, Mn, and Zn. Blending poultry litter manure with pine chips prior to pyrolysis resulted in micro-, and macro-nutrient dilution. For example, blending poultry litter feedstock with equal amounts of pine chips (50:50) resulted in almost a 50% decline in observed Cu, Mn and Zn concentrations. Further reductions were seen in the 80:20 poultry litter and pine chip blended biochar (Table 3).

3.2. Norfolk E horizon bulk densities and water infiltration

Soil ρ_b when pooled on individual leaching days were statistically equal, ranging from 1.503 to 1.525 g cm^{-3} (Table 4). There were subtle ρ_b differences when results were sorted by treatment. The lowest mean ρ_b calculated were <1.48 g cm^{-3} in soils treated with PC:PL 50:50; and PC:PL 80:20 (Table 4). The standard deviation (SD) are fairly tight around each treatment ρ_b mean ($\ll$0.1 g/cm^{-3}), indicating the four replicates had a similar pattern of settling.

There were significant differences in water infiltration when results were pooled by treatment and leaching day ($p < 0.001$; Table 5). On the other hand, the interaction of treatment × leaching was not significant. Water infiltration was enhanced by 1.5 to 2-times in the 80:20 PC:PL, 50:50 PC:PL, and 100% PC compared to the 100% poultry litter biochar and control (no biochar; Table 5).

However, when examining treatment results by leaching day the data revealed that statistically significant improvements were limited to the initial leaching on day 32 (Table 5). In subsequent leachings, water infiltration declined by almost 50% relative to the first leaching. This effect was further evident by examining water infiltration as a function of leaching day and for each treatment (Table 5). The highest initial water infiltration occurred with 50:50 PC:PL; 100% PC; and 80:20 PC:PL blend. By leaching 2 and 3 (day 67 and 95), only the 50:50 PC:PL and the 100% pine chip biochar treatments continued to show enhanced water infiltration. By the fourth leaching event (day 128), only the 50:50 PC:PL biochar treatment had a statistically significant increase in water infiltration (Table 5).

Linear regression analysis revealed only in the first leaching (d 32), there was a moderate ability to predict water infiltration as a function of soil ρ_b (Table 6). The highest r^2 (0.597) and most significant relationship ($p < 0.001$) occurred with the initial leaching (day 32), which corroborates the statistically significant mean water infiltration value (Table 6). In subsequent leaching, our ability to predict water infiltration with respect to ρ_b was poor. Linear regression between soil ρ_b and water infiltration when sorted by individual treatments revealed a poor prediction relationship with r^2 ranging from 0.003 to 0.358, and p values of 0.029 to 0.821.

3.3. Water quality

There was a very significant effect ($p < 0.001$) for all water quality parameters measured in the leachates when results were grouped by treatment, across leaching day, and for treatment × leaching day event (Table 7). Sorting the biochars by treatment across leaching events revealed the water quality effects were a function of feedstock and blending ratio (Table 7). All biochar additions increased soil pH compared to the control ($p < 0.05$), while all but the 100% pine chip biochar significantly increased the EC (Table 7). Treatment with 100% poultry litter biochar caused the highest mean EC values measured (4.5 dS m^{-1})

Table 2
Biochar chemical and physical properties (VC = volatile C; FC = fixed C; PC = pine chip; PL = poultry litter; SSA = specific surface area).

Feedstock	pH	ash	VC	FC	C	H	N	O	S	H/C	O/C
	%										
Chemical											
Pure feedstock (100%)											
Poultry litter	na	41.89	17.65	41.46	48.26	1.50	3.98	4.61	0.76	0.37	0.07
Pine chip	na	2.61	22.39	75.00	88.83	3.14	0.45	4.97	0.002	0.43	0.04
Feedstock blends (w w^{-1})											
50:50 PC:PL	10.11	22.20	14.29	63.51	69.37	1.81	2.44	3.69	0.49	0.31	0.04
80:20 PC:PL	8.30	9.19	13.19	77.62	83.57	2.70	1.32	3.02	0.20	0.38	0.03

Physical	Length (mm)		SSA
	major	minor	m^2 g^{-1}
Pure feedstock (100%)			
Poultry litter	5.77	2.42	0.97
Pine chip	5.77	4.35	6.22
Feedstock blends (w w^{-1})			
50:50 PC:PL	nd	nd	9.78
80:20 PC:PL	nd	nd	14.09

Table 3
Total elemental analyses of pure feedstocks and manure-blended biochars (PC = pine chip and PL = poultry litter).

Feedstock	Ca	K	Mg	Na	P	Cu	Mn	Zn
	mg kg^{-1}							
Pure feedstock								
100% PC	5367	6141	614	164	286	29	181	14
100% PL	49,366	69,380	15,030	21,620	31,573	288	1072	1253
Manure-blended								
50:50 PC:PL	23,080	33,971	7680	10,414	17,074	147	559	563
80:20 PC:PL	13,829	14,434	3628	4117	6275	64	265	251

Table 4
Soil bulk densities (BD) when pooled by leaching day and sorted by treatment (PC = pine chips, PL = poultry litter, and SD = standard deviation).

Leaching day	*n*	Mean BD (g cm^{-3})†	Treatment	*n*	Mean BD (g cm^{-3})†	SD
32	20	1.527a	Control	4	1.565a	0.017
67	20	1.505a	50:50 PC:PL	4	1.472bc	0.033
95	20	1.511a	80:20 PC:PL	4	1.438bc	0.028
128	20	1.515a	100% PL	4	1.508bd	0.009
			100% PC	4	1.515bd	0.021

† Means followed by a different letter are significantly different using a one-way ANOVA at a $p \propto 0.05$.

compared to the control. Leachate from soil treated with 100% poultry litter and the two blends contained the highest concentrations of PO_4, SO_4, Cl, Na, and K (Table 7). However, blending the poultry litter feedstock with pine chips significantly reduced these water quality parameters. Grouping the results by leaching day revealed that, except for PO_4, the additional water leaching resulted in reductions of the effects from these biochars on the measured water quality parameters. Dissolved PO_4 concentrations were highest after the leaching on day 67, but also declined on days 95 and 128. Poultry litter in biochar seems to provide a persistent supply of soluble P.

4. Discussion

4.1. Biochar characteristics and their effect on soil bulk density

In this study, the biochars prepared from pine chip and poultry manure feedstocks have chemical and SSA values comparable to other biochars manufactured from similar feedstocks (Gaskin et al., 2008; Chan and Xu, 2009; Cantrell et al., 2012; Chia et al., 2015). We noted that blending pine chips into the poultry litter resulted in biochars with higher SSA. This is probably due to structural pores inherent with each feedstock's and the pelletization process that created surface fissures and other macro-pores (Chia et al., 2015). Higher SSA values would be associated with the ability of the N_2 gas to penetrate these fissures and macro-pores resulting in more surfaces for gas binding.

It is common for biochars produced from animal manures to contain high concentrations of plant macro-, and micro-nutrients due to unassimilated elements from their animal feed (Tsai et al., 2012; Novak et al., 2013). Since the pine chip feedstock has a relatively lower nutrient concentration, and is plentiful in the SE USA Coastal Plain region (Milesi et al., 2003), it is a desirable feedstock to blend with animal manures to achieve balanced soil nutrient levels (Novak et al., 2014). Blending the poultry litter with pine chips showed that the extracted nutrients are typically within the 10% of the predicted values based on the pure feedstock values. This exemplifies the fact that the nutrient content of biochars is predictable through careful feedstock selection (Novak and Busscher, 2013; Mukome et al., 2013; Joseph et al., 2013).

When this incubation experiment was terminated, soil ρ_b was examined as a function of both treatment and leaching day. Pooling individual treatment revealed that all mean soil ρ_b were significantly different than the control. This indicates biochar treatments created pore space, especially in the 100% pine chip biochar and the two biochar blend treatments. For example, although the relative ρ_b change is <10%, the pore volume increase is 4%. We speculate that pine chip biochar and the blends of pine chips and poultry litter biochar sorbed water and swelled resulting in a slight pore volume increase.

Conversely, when ρ_b were calculated by day of leaching, they were all similar (Table 3; 1.503–1.525 g cm^{-3}) suggesting that the overall impact of more pore volume formation was noticeable only when biochar treatments were analyzed by themselves. However, it is important to calculate the collective ρ_b by day of leaching to show how this variable remained unchanged while

Table 5
Statistical analyses of corrected mean water infiltration (PC = pine chip and PL = poultry litter).

Source of variation	*p*	Pooling individual treatments	Means (mL min^{-1})	Pooling individual leaching days	Mean (mL min^{-1})
Treatment	<0.001	50:50 PC:PL blend	0.219a	32	0.240a
Leaching day	<0.001	100% PC	0.202ab	67	0.154b
Treatment × leaching day	0.255	80:20 PC:PL blend	0.157b	95	0.117bc
		100% PL	0.099c	128	0.106c
		Control (no biochar)	0.095c		
		LSD ∝ 0.05	0.046	LSD ∝ 0.05	0.042
	Corrected mean water infiltration (mL min^{-1})†‡				
Leaching day	50:50 PC:PL	100% PC	80:20 PC:PL	100% PL	control
32	0.320a,a	0.269a,ab	0.296a,ab	0.191a,c	0.122a,c
67	0.209b,ac	0.250a,a	0.142b,bc	0.099a,b	0.071a,b
95	0.180b,a	0.168ab,a	0.077b,b	0.059b,b	0.100a,b
128	0.168b,a	0.119b,b	0.110b,b	0.047b,b	0.086a,b

† Means compared within a column followed by a different letter are significantly different at $p \propto 0.05$.
‡ Means compared between columns followed by a different letter are significantly different at $p \propto 0.05$.

Table 6
Linear regression relationship between Norfolk E soil bulk density and water infiltration (data pooled across all treatments by leaching day).

Leaching day	n	r^2	y_{int}	m	p
All data pooled	80	0.151	1.314	−0.776	<0.001
32	20	0.597	2.101	−1.219	<0.001
67	20	0.231	1.463	−0.870	0.032
95	20	0.189	1.204	−0.720	0.055
127	20	0.160	1.125	−0.670	0.081

water infiltration declined (Table 4) and discussed in the following section.

4.2. Biochar effect on water infiltration

When averaged across all leaching events, biochar additions generally improved water infiltration (except for the 100% poultry litter biochar). Biochar additions increased water infiltration in the order: 50:50 PC:PL blend > 100% PC > 80:20 PC:PL blend. Mean water infiltration values were improved by 0.062–0.124 mL min^{-1} relative to the control in the three biochar treatments previously mentioned (Table 5; pooling individual treatments).

The multiple water leaching events revealed that water infiltration enhancement was transient. Water infiltration collectively declined between 30% and 50% after each additional water leaching event (Table 5). The decline in water infiltration was feedstock dependent with the 50:50 PC:PL blend, followed by the 100% pine chip, and the 80:20 PC:PL showing the most resistance to the rate decline. Although there was a reduction in water infiltration on day 32 and 67, the biochar amendments were still significantly different than the control at those times. This implies that some biochar feedstocks are better at improving initial water infiltration, but the enhancement dissipates after additional water leaching as a function of feedstock.

As noted in Table 5, pooling all water infiltration movement data by treatment and leaching day were strongly significant ($p < 0.001$), however, the interaction of treatment × leaching day was not significant. The lack of a significant interaction is related to the decline in water infiltration for all treatments with subsequent leachings.

Amending soils with biochar for the purpose of improving soil hydraulic conductivity has had mixed results. Ouyang et al. (2013) and Uzoma et al. (2011) reported improvements in soil hydraulic properties after biochar treatment using silt and sandy loam soils, respectively. On the other hand, Laird et al. (2010) and Major et al. (2012) reported no significant change in saturated hydraulic conductivity for biochar applied to a loam soil or water percolation in a biochar treated clay soil. The effect of biochar additions on soil hydraulic properties have been known to be a function of soil texture for some time (Tryon, 1948).

Based on these findings, we speculated that water infiltration in our biochar treated sandy loam soil should be affected by soil ρ_b changes, since formation of more pore space would enhance water flows (assuming pores are connected). We were able to predict water movement rates as a function of ρ_b fairly well during the first leaching event. Thereafter, the prediction relationship between water infiltration and soil ρ_b weakened with samples sorted by day of leaching and when results were examined collectively or by treatment. Our results show that in spite of the mean soil ρ_b values being statistically similar between leaching day, the mean water infiltration values declined from 0.25 to <0.12 mL min^{-1}. If we assume the pore space is initially increased after adding the biochar, the first water leaching was able to move through these additional soil voids or fissures on the biochar pellets resulting in enhanced water flows. But, the three additional water leaching caused some decrease in the ability of water to pass though the soil columns.

Declines in water infiltration could be related to biochar's pores essentially filling with water (Aharoni, 1997) or their physical disintegration (Verheijen et al., 2010). If the micro-pores and fissures of biochar become water-filled, its impact on water infiltration potentials would essentially be nil, leaving water infiltration as a function of gravity. This maybe why three of the four biochar treatments had similar water infiltration values as the control by the fourth leaching event (d 128; Table 5). Others have reported decreases in saturated hydraulic conductivity with increasing biochar addition to sandy loam textured soils (Brockhoff et al., 2010; Githinji, 2014).

On the other hand, Verheijen et al. (2010) suggested that soil compaction is possibly enhanced by biochar structurally degrading as a result of water flushing, heavy traffic during application, and soil tillage after application. The dislodged fragments were hypothesized to clog soil pores. Spokas et al. (2014) recently reported that pelletized lignocellulosic-based and manure-based biochars shaken in water physically broke down into flake-like fragments. The fragments were micro-meter to nano-meter in size, with some possessing jagged edges (see SEM images presented in Spokas et al., 2014). This lead us to speculate that the biochars could be suspended in percolating water and eventually move downward

Table 7
Statistical analyses of mean water leachate characteristics when sorted by biochar treatment and leaching day (PC = pine chip and PL = poultry litter, and EC = electrical conductivity).

Biochar treatment[†]	pH	EC (dS m^{-1})	Anions (mg L^{-1})				Cations (mg L^{-1})	
			NO_3	PO_4	SO_4	Cl	Na	K
Control	5.9a	0.1a	6a	0.1a	2a	6a	4a	9a
50:50 PC:PL	8.0bg	2.3b	5a	54b	55b	385b	163b	599b
80:20 PC:PL	7.3c	0.8c	5a	10c	20c	110c	53c	159c
100% PL	8.0dg	4.5d	4b	63d	160d	799d	246d	1132d
100% PC	6.5e	0.2a	5a	0.1a	3a	8a	5.0a	18a
Leaching day[†]								
32	6.8a	4.3a	2a	16a	160a	970a	265a	1059a
67	7.3b	0.9b	8b	33b	18b	55b	62b	228b
95	7.1c	0.6c	7c	28c	7c	13c	36c	140c
128	7.4d	0.4c	3d	24d	6c	8c	28d	107c
Source of variation	p Value							
Treatment	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Leaching day	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Treatment × leaching day	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[†] Biochar treatment means and leaching day means within the same column that are followed by a different letter are significantly different at p α 0.05.

through the soil profile. Given the size of the primary biochar particles and the jagged-edge morphology of these biochar particles, it is conceivable that soil micro-pores could eventually become physically clogged, thus reducing water infiltration. This hypothesis has merit considering that Joseph et al. (2013) also reported formation of nano-scale fragments from pyrolyzed black carbon material. Biochar's structural stability in soils in still a relatively new area of scientific exploration, and will require more scrutiny to ensure that biochars do not promote cementation processes in soils and slow down water infiltration. If biochar fragments are capable of clogging soil pores, more research will be needed on determining what chemical (e.g. binding agents, ash) or physical (e.g., pressing pellets under high pressure) measures are necessary to keep biochar pellets intact.

4.3. Biochars and water quality

Water quality characteristics of the soil leachates were grossly modified after treatment of the Norfolk E horizon with 100% poultry litter biochar and to a lesser extent with the 100% pine chip and blended biochars. While all biochars influenced leachate pH, the most striking modification after applying the 100% poultry litter biochar were to the EC value and concentration of PO_4, SO_4, Cl, Na and K. Water leachate EC values of 4.5 $dS\,m^{-1}$ is a concern because water having EC values > 3 $dS\,m^{-1}$ may reduce crop growth due to its high salt content (Sparks, 1995). Likewise, PO_4 concentration ($\approx$60 $mg\,L^{-1}$) is detrimental to water quality if the water reached ground or surface waters. It is well documented, that elevated PO_4 concentrations contributes to excessive algae growth and eventually water eutrophication (Mallin et al., 1997; Peierls et al., 2003).

On the other hand, the additional water leaching events sufficiently diluted PO_4, EC, and other anion and cations to lower concentrations. Therefore, blending the poultry litter feedstock with pine chips in 50:50 and 80:20 (w/w) ratios prior to pyrolysis was sufficient to significantly lower the impact of the biochars influence on excessive water pH, EC, and anion and cations concentrations that could reduce plant growth and degrade water quality.

5. Conclusions

In this study, we hypothesized that biochars added to a compact Norfolk E horizon could improve water infiltration. We also examined if the employed biochars had an impact on water quality. We proved our hypothesis by showing that application of most biochars to the Norfolk E horizon (all except biochar produced from poultry litter), resulted in significant increases in the initial water infiltration (0.157–0.219 $mL\,min^{-1}$; $p < 0.05$) compared to the control (0.095 $mL\,min^{-1}$). However, water infiltration declined significantly with additional water leaching. Reduction in water infiltration rates may be due to water occupying biochar pores and fissures and/or clogging of pores due to biochar physical disintegration. Biochars produced using pure pine chips and blends with poultry litter showed the highest mean water infiltration during the 1st leaching (d 32). Water leachates were enriched in PO_4, SO_4, Cl, Na, and K after addition of the poultry litter biochar, however, concentrations of these elements declined through blending with pine chips biochar and multiple water leaching. Our results show that adding pine chip and the blended biochars to a compacted subsoil layer can initially increase water infiltration, but infiltration declined for three of the biochar treatments with subsequent leaching events. The 50:50 blend of pine chip:poultry litter was the most resilient biochar treatment in the compact soil, since after multiple water leachings, it still had a water infiltrations value of 0.168 $mL\,min^{-1}$.

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