Biochar, Manure, and Sawdust Alter Long-Term Water Retention Dynamics in Degraded Soil

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Biochars are porous but more recalcitrant than nonpyrolyzed organic materials, possibly causing more persistent alterations to soil water dynamics. In this 6-yr outdoor study, we amended an irrigated calcareous silt loam with a single 1 or 2% dry weight application of hardwood biochar, manure, sawdust, or acidified sawdust; 1% biochar + 2% manure; or a control. Soil water retention and plant-available water (PAW, g H_2O per g dry soil) were measured in spring. Across all years, 1% biochar + 2% manure produced the greatest PAW (0.262), with PAW in the order: 1% biochar + 2% manure > 2% rates > 1% rates > control (0.222). In most years, the 2% treatments increased PAW relative to the control. The PAW ratios (treatment PAW/mean annual control PAW) for the 2% rates varied with amendment and year ($P < 0.0001$): 2% manure peaked in Year 1, declining to a minimum in Year 3; the other 2% treatments were least in Year 1 and peaked between Years 3 and 5; 1% biochar + 2% manure consistently had a ratio near the maximum. Amendment effects on soil water retention were immediate but the peak benefits were delayed because of the differing hydrophobicity of the original materials and their particle sizes, where greater sizes slowed the removal of hydrophobic surface coatings. Biochar's effects on PAW were no more persistent than those of nonpyrolyzed amendments; however, adding biochar and manure had a mutually stabilizing effect, producing a large, more consistent retention increase over time.

Abbreviations: K_{fs}, field-saturated hydraulic conductivity; PAW, plant-available water; PR, penetration resistance; WDPT, water drop penetration time.

I n southern Idaho, decades of furrow irrigation applied to silt loam soils with slopes ranging from 1 to 4% have resulted in topsoil loss at the inflow-end of the irrigated fields. Leveling land to enlarge fields and reduce irrigation labor has contributed further to topsoil removal. In south-central Idaho alone, these processes are responsible for degrading 800,000 ha of otherwise highly productive soils (Robbins et al., 1997). The yield and quality of six out of the seven major crops grown in these degraded soils are significantly reduced relative to noneroded soils (Carter et al., 1985), and these degraded soils have lower soil quality as compared to areas containing appreciable topsoil (Ippolito et al., 2017). Relative to topsoil, the eroded soils are more alkaline, with threefold more free lime, one-half the organic C, and one-sixth to one-half the available nutrients (Robbins et al., 1997; Lentz et al., 2011).

The effect of erosion on the physical properties of south-central Idaho soils is not well documented but it is well known that decreases in total soil organic matter content typically decrease soil aggregate stability, water-holding capacity, and infiltration rate and increase bulk density (Khaleel et al., 1981; Larney and Angers, 2012; Ippolito et al., 2017). The physical properties of degraded soils, such as water holding capacity, penetration resistance (PR), and infiltration rate, can be improved by amending soils with organic materials (Khaleel et al., 1981; Martens and Frankenberger, 1992; Fierro et al., 1999; Kasongo et al., 2011). On the other hand, increased soil water-holding capacity from added or-

Core Ideas

- Biochar's long-term water retention effects on soil are poorly understood.

- The temporal effects of biochar, manure, and sawdust on water differed.

- Biochar and nonpyrolyzed organics all had long-lasting effects on water.

- Water retention dynamics were influenced by the repellency and particle size of the material.

- Water retention in the first or second years may not reflect the material's long-term potential.

ganic matter does not always result in an increase in PAW (Khaleel et al., 1981). The influence of organic amendments on soil hydraulic properties has been attributed to a decrease in soil bulk density and an increase in soil porosity and aggregate stability, although the effect is a function of the soil type, amendment material, and application rate (Mbagwu, 1989; Pagliai and Antisari, 1993; Kasongo et al., 2011; Larney and Angers, 2012). Enhancements derived from labile organic amendments such as manure initially can be greater but more transitory than those derived from more decomposed amendments, such as compost (Haynes and Naidu, 1998). In addition, manure application can have extended positive effects on above- and belowground crop biomass (Lentz et al., 2014), which could increase soil aggregate stability and porosity over time.

Biochar is another C source that may improve soil physical properties (Atkinson et al., 2010; Githinji, 2014). Biochar, a charcoal-like material produced by the pyrolysis of mainly photosynthetically fixed C biomass, is a recalcitrant soil additive that can potentially improve soil–water relationships (Novak et al., 2012) and reduce atmospheric CO_2 (Laird, 2008). Like their organic precursors, biochars commonly are porous low-density materials that interact with soil and mineral particles and soil organisms to increase soil aggregation, stability, and water relations (Obia et al., 2016; Burrell et al., 2016; Blanco-Canqui, 2017).

As early as 1950, Everson and Weaver (1950) reported that the addition of 0.6% carbon black increased a soil's saturated water content by 1.2-fold after 3 mo. Subsequent studies have determined that 1% or greater (w/w) biochar applied to soil increases available water capacity by 4 to 130% and decreases soil bulk density by 3 to 31% (Brockhoff et al., 2010; Devereux et al., 2012; Novak et al., 2012; Bruun et al., 2014; Ulyett et al., 2014; Obia et al., 2016; Burrell et al., 2016; Blanco-Canqui, 2017). Biochar's effects on medium to fine textured soils are less consistent than those on coarser soils, although the number of studies that specifically address silt loams are few (Sun and Lu, 2014; Mukherjee et al., 2014; Xiao et al., 2016; Blanco-Canqui, 2017). Biochar's influence on saturated hydraulic conductivity and infiltration in amended soils varies, depending on soil texture, though data on infiltration are limited (Omondi et al., 2016; Blanco-Canqui, 2017). Few, if any, biochar experiments have exceeded a 3-yr duration or described how the soil's physical properties change with time (Du et al., 2016; Blanco-Canqui, 2017). Further biochar research is needed to assess long-term (>3 yr) biochar impacts on the physical properties of degraded soils, particularly when exposed to field conditions (Omondi et al., 2016; Blanco-Canqui, 2017).

Our objective was to monitor soil water retention over six cropping seasons in an eroded soil treated with a one-time application of pyrolyzed or nonpyrolyzed organic amendments. We hypothesized that amended soils would produce an immediate increase in PAW, with biochar and two sawdust amendments producing moderate increases that would persist with time for biochar but decline moderately for sawdust treatments. Manure would produce a slightly smaller increase in PAW relative to others but, because of a progressive increase in microbial growth, biomass production, soil aggregation, and increasing porosity, would peak a year or two after application, followed by a steep decline.

MATERIALS AND METHODS
Site, Soils, and Amendments

The study soil was collected from the 0- to 15-cm depth in an artificially eroded Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids) in the early spring of 2009. The field source near Kimberly, ID (42°31'N, 114°22'W, 1190 m elevation) had been stripped of topsoil in the spring of 1991 to expose the calcareous Bk horizon, simulating erosion (Robbins et al., 1997). The soil, which had not previously been treated with organic amendments, contained 180 g kg^{-1} clay, 600 g kg^{-1} silt, 2.2 g kg^{-1} total organic C, and 28% calcium carbonate equivalent. Soil particle size analysis was determined via the hydrometer method, applied after the removal of organic matter. Soil total C and total N were determined on a freeze-dried sample with a Thermo-Finnigan FlashEA1112 CN analyzer (CE Elantech Inc., Lakewood, NJ), total inorganic C was determined via a pressure-calcimeter procedure (Sherrod et al., 2002), and total organic C by difference. The soil electrical conductivity and pH were determined on a saturated-paste extract (Table 1).

The chemical characteristics of the organic materials were determined in a previous study (Lentz and Ippolito, 2012) and are presented in Table 1. Solid manure from dairy cattle (*Bos* species), containing little to no straw bedding, was retrieved from an open pen at a local dairy where it had been stockpiled through summer 2008 in 1.7-m-high unconfined piles. The manure was air-dried, flail chopped, and sieved through an 8-mm screen. The biochar was manufactured from oak and hickory hardwood sawdust via fast pyrolysis at 500° C with a 5-s residence time (CQuest, Dynamotive Energy Systems Inc., McLean, VA). It had a 14% ash content, an O:C ratio of 0.22, and surface area of 0.75 m^2 g^{-1}. The pH of the CQuest biochar was near neutral (Table 1), which is at the low end of the pH range observed for biochars and was preferable to more alkaline amendments for this high-pH soil. Sawdust

Table 1. Selected chemical properties for manure and biochar [from Lentz and Ippolito (2012)], sawdust and acidified sawdust, bulk density, and water drop penetration time (WDPT) for amendments and soil.

Material	Volatile solids	EC†	pH†	C/N	C	N	Bulk density	WDPT
	g kg^{-1}	dS m^{-1}			——— g kg^{-1} ———		g cm^{-3}	sec
Manure	521	13.4	8.8	11.8	264	22.4	0.535	33
Biochar	707	0.7	6.8	208	662	3.2	0.524	>9000
Sawdust	968	0.39	4.8	560	560	1	0.393	500
Acidified sawdust	977	0.04	0.8	883	530	0.6	0.427	173
Subsoil	–	0.77	7.8	43.1	30.2	0.7	1.130	0.2

† Electrical conductivity (EC) of a saturated paste extract.

from lodgepole pine (*Pinus contorta* Douglas ex Louden) was obtained from a local sawmill and sieved through an 8-mm screen. The acidified sawdust amendment was produced by soaking the sawdust for 6 h in 12 M HCl (2.5 L HCl per 2 kg sawdust), pressing out the excess liquid, then drying the sawdust for 24 h under a ventilated hood. The acid degraded the wood structure by hydrolyzing cellulose components in the sawdust and increased the labile carbohydrate content (Hutomo et al., 2015).

The particle size distributions of the organic materials were determined via the procedure of Lim et al. (2016). The water repellency of the original, air-dried organic materials was assessed through the use of water drop penetration time (WDPT) to explore potential repellency effects on water retention dynamics. We measured WDPT for organic materials via the technique described by Lehrsch (2013). Previous research has indicated that WDPT values of <1 s, 1 to 60 s, 60 to 600 s, and >3600 s correspond to the nonrepellent, slightly repellent, strongly repellent, and extremely repellent classes (Leelamanie et al., 2008; Devereux et al., 2012).

Experimental Design

The experimental design was completely randomized with four replicates. The nine amendment treatments included manure, biochar, sawdust, and acidified sawdust, applied at 1% or 2% rates, and a combined 1% biochar + 2% manure treatment. An unamended control soil completed the treatment set. The 1% and 2% treatments were approximately equivalent to 22 and 42 Mg ha^{-1} (dry weight), respectively. Treatments were applied only once during the study.

Soil was collected from the field, air-dried, sieved through a screen (6 by 13 mm openings), and mixed to ensure uniformity. Enough soil for each treatment was added to the appropriate mass of air-dry amendment and mixed thoroughly in a cement mixer. Treated soils were prepared on 17 Apr 2009 for placement into 14-L planting pots 26 cm in diameter and 26 cm deep. Pots were prepared with a base layer of ~5 cm of wet sand. Next, 13.2 kg of air-dry treated soil mixture was packed into each pot by firmly tapping the vessel on the concrete floor five times. On 28 Apr. 2009, the pots were fertilized (Table 2) and planted to bean (*Phaseolus vulgaris* L.) for a short greenhouse experiment.

Soil pots were moved outdoors on 2 July 2009 to start the current study, where they remained except for 3–4 d each spring when they were moved under cover to perform leaching measurements (not reported here). All other sampling and measurements were conducted in the field. Pots were arranged in a shallow trench with straw packed around the pots' sidewalls to insulate them from surface heating and cooling effects. The straw was replaced by bark-chip mulch in subsequent years. A series of crops were grown in the pot soils from 2009 through 2015 (Table 2). Prior to planting each year, we sampled the pot soil with a probe 20 mm in diameter. Three samples to 15-cm depth were collected and composited, ~100 g was retained, and the excess was returned to the pot. The original pot soil volume was large enough that annual soil removal did not influence the soil measurements. After soil sampling each year, we inverted and mixed the pot soils to 15-cm depth with a tile spade, then seeded each pot with a selected crop. Crop planting density, harvest date, and soil sampling dates are given in Table 2. During the growing season, an automated flow-emitter system supplied irrigation water to all pots equally to meet estimated crop evapotranspiration requirements. At harvest, the entire aboveground crop tissue was collected from each pot.

Soil Water Retention

We measured soil water retention on soil samples collected from each pot in each year from 2009 to 2011, and every other year from 2011 to 2015 (we assumed that changes in retention would decrease more slowly in later years). A pressure plate apparatus (models 1500 and1600, SoilMoisture Equipment Corp., Goleta, CA) was used to determine soil water retention at matric potentials of 0, –10, –20, –33, –50, –100, –300, –500, and –1500 kPa (Dane and Hopmans, 2002; Reynolds and Topp, 2008). Because the surface soil structure was disrupted substantially through tillage each year, we determined water retention on repacked soil samples, reasoning that this approach would be representative of agricultural surface soils at the start of each growing season. This technique also allowed the use of smaller sample volumes and shorter equilibration times, which was convenient, given the limited soil volume available in pots and the large number of samples to be processed in a given year (Klute, 1986). The air-dried soil samples were crushed, passed through a 2-mm sieve (Dane and Hopmans, 2002), and packed into brass rings (48 mm in diameter and 19 mm tall) to a bulk density of 1.16 g cm^{-3}. Soil rings were saturated with a deaerated 0.005 M CaSO$_4$ solution and sequentially equilibrated at the nine matric potentials. Water retention was measured in a constant temperature room to mini-

Table 2. The type and number of crop plants grown, fertilizer applied, and dates of planting, harvest, and soil sampling during each year of the study.

Year	Crop	N as NH$_4$NO$_3$	P as KH$_2$PO$_4$	K as KH$_2$PO$_4$, KCl	Planting date	Plants per pot†	Harvest date	Date sampled for soil water retention
		——(kg ha^{-1})——				n		
2009	Bean	100	22.4	59.6	6 July	2	30 Sept.	17 Apr. 2009
2010	Barley (*Hordeum vulgare* L.)	277‡	–	–	14 May	11	3 Aug.	19 Apr. 2010
2011	Pea (*Pisum sativum* L.)	–	–	–	17 May	2	2 Aug.	11 May 2011
2012	Bean	–	–	–	1 June	4	14 Sept.	–
2013	Sweet corn	200	22.4	37.2	31 May	1	22 Aug.	10 May 2013
2014	Barley	50	5.6	9.3	19 May	2	31 July	–
2015	Bean	–	–	–	19 May	4	21 Sept.	5 May 2015

† Surplus seeds were planted and the seedlings were later thinned to this target number.

‡ Included the N mineralized from manure during the growing season.

mize changing temperature effects on soil water characteristics (Bachmann et al., 2002). Plant-available water was estimated as the soil water retained between −10 and −1500 kPa.

Retention Fractions and Pore Size Interval Classes

The soil water retention measured at each soil matric potential was reported as g H_2O per g oven-dried soil. The "retention fraction" is the difference in water retained between two adjacent soil matric potential stages. It represents the water held in an equivalent pore-size range class (as determined by the capillary rise equation) and, when resolved across all the included matric potentials, provides a measure of soil pore size distribution (Flint and Flint, 2002). For example, the soil water retained at −1500 kPa was held in pores with an equivalent pore diameter of ≤0.19 mm. The equivalent pore diameter for other matric potential stages in the series from −500 to −10 kPa are: 0.58, 0.97, 2.92, 5.84, 8.85, 14.6, and 29.2 mm. Therefore, the retention fraction for the matric potential interval −1500 to −500 kPa represents the water held by the equivalent pores in the size interval from 0.19 to 0.58 mm in diameter, and so on. The matric interval from −10 to 0 kPa includes an equivalent pore size of >29.2 mm in diameter, but since the soil rings contained repacked soils, the upper limit of the pore size class was estimated to be <300 mm in diameter.

Soil Penetration Resistance

We assessed the strength of pot soils on 15 May 2013, 4 yr after amendments were applied. The PR(Lowery and Morrison, 2002) of pot soil that had been undisturbed since planting in May 2012 (except for irrigation) was measured with a Carter-type American Society of Agricultural Engineers standard recording cone penetrometer with a 13-mm diameter and a 30° solid angle cone-tipped probe (RIMIK penetrometer, model CP40, Rimik Pty. Ltd., Toowoomba, Qld, Australia). The hand-operated device, with a 600-mm measuring depth, electronic load cell, and distance sensor, measured the unconfined compressive strength of the soil as force per unit of area (kN m^{-2} = kPa). Pot soils were brought to field capacity and shielded from rainfall for 10 d prior to measurement. We measured the in situ PR of undisturbed soil three times in each pot by probing vertically downward from the soil surface to 150 mm at about 30 mm s^{-1}. The instrument integrated PR over 25-mm depth intervals. We used the arithmetic average of the three probings in a pot and individual depth intervals to give a mean PR for the 0- to 50-mm, 50- to 100-mm, and 100- to 150-mm depths.

Bulk Density, Infiltration, and Hydraulic Conductivity

The bulk density and water flow characteristics of pot surface soils were determined at the end of the study in mid-October of 2015, 6.5 y after amendment application. Thus measurements were made in pot soils that had not been disturbed since planting (5 mo) and reflect the treatment effects on soil structure at the season's end. Soil bulk density (*BD*) was determined with a core sampler (19 mm in diameter and 50 mm tall) from three soil samples collected outside the area occupied by the infiltrometer ring. Total porosity was calculated as 1 − (*BD* *PD*$^{-1}$), where *PD* is the

particle density. The quasisteady state infiltration rate (q_i) at two positive pressure heads (H_i, where H_1 = 5 cm and H_2 = 15 cm) and the field-saturated hydraulic conductivity (K_{fs}) were determined with a Marriot siphon-type supply reservoir and a single-ring constant-head infiltrometer; the ring height was 25 cm and inside radius was 7.46 cm (Reynolds, 2008). The sharpened ring was inserted 5 cm vertically into the soil surface. Except for clipping bean stems at the soil surface, removing loose plant residue, and lightly tamping soil within 8 mm of the interior ring wall (to prevent leakage around the cylinder), the soil surface was not disturbed. The quasisteady infiltration rates ($q_i = Q_i\pi a^2$) from the infiltrometer flow rates (Q_i) and H_i were inserted into Eq. [1] and coupled with Eq. [2] to calculate K_{fs} (cm s^{-1}) (Reynolds, 2008):

$$K_{fs} = \frac{T(q_2 - q_1)}{H_2 - H_1};\qquad\qquad [1]$$

$$T = C_1 d + C_2 a,\qquad\qquad [2]$$

where C_1 = 0.316π, C_2 = 0.184π, *d* is the ring insertion depth (cm), and *a* is the inside ring radius (cm).

Calculations and Statistical Analysis

To simplify comparisons among amendments across years, a PAW ratio was computed by dividing the treatment PAW by the average control PAW values for the corresponding year. A PAW ratio greater than one indicated that the amendment increased soil PAW relative to the unamended soil. For the same reason, we also calculated a retention ratio for each pore size interval class. The calculation was identical to that for the PAW ratio, except that the retention fraction replaced the PAW value.

We examined soil water retention for each pore size interval, the PAW, and the PAW ratio via ANOVA via the PROC Mixed function in SAS (SAS Institute, Inc., 2012). The statistical model used a repeated measures statement (Repeated Yr/type = ARMA(1,1) subject = TRT*Rep;); included treatment, year, and their interaction as fixed effects; and block and year × block as the random effect. The influence of treatment rate (0, 1, and 2%) on PAW values each year was assessed via regression analysis with the PROC Reg function in SAS (SAS Institute, Inc., 2012). The PR responses were transformed via common logs prior to analysis and means were back-transformed to original units for reporting. Contrasts were included in ANOVAs to compare treatment classes with each other or with the control (e.g., manure vs. nonmanure; manure + biochar vs. sawdust and acid sawdust; etc.). Statistical analyses were conducted with a significance probability of 0.05.

RESULTS AND DISCUSSION
Particle size and WDPT

The two sawdust amendments had the coarsest particle size distribution, with 37% of the total particles being >0.5 mm (Fig. 1). Manure particles were slightly finer, with 27% of the total being >0.5 mm; biochar was even finer, with 6% of particles being >0.5 mm. Over time, the initial particle sizes of both biochar and
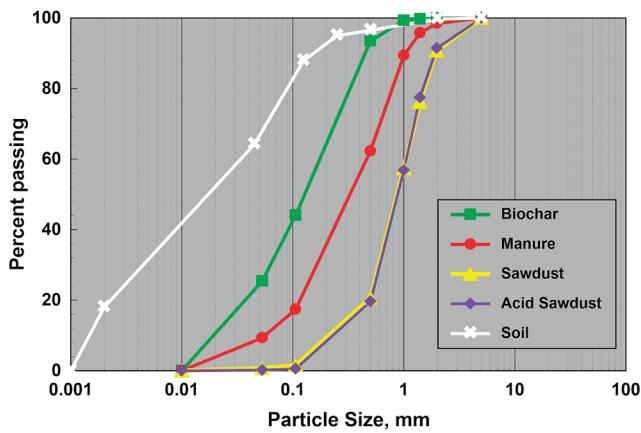
Fig. 1. The particle size distribution for the eroded Portneuf silt loam soil and four amendments.

sawdust were expected to change in the soil (Jackson et al., 2009; de la Rosa, 2018) via fragmentation caused by physical processes, such as freeze–thaw cycles and expansion of roots and fungal hyphae, which penetrate and grow in pores (Hammes and Schmidt, 2015). This increases the specifc surface of organic amendments and presumably increases water absorption (Dong et al., 2017).

Water drop penetration times for all amendments differed from each other and from the subsoil ($P < 0.0001$; Table 1). The biochar had extreme water repellency, the two sawdust materials exhibited strong repellency, manure was slightly water-repellent, and the subsoil was nonrepellent (Table 1). The extreme repellency of the biochar resulted from the short pyrolysis time and relatively low charring temperature used in its production, which increased the prevalence of aliphatic surface functional groups (Kinney et al., 2012; Das and Sarmah, 2015). Briggs et al. (2012) reported that leaching charcoal with water or other compounds reduced WDPT and hence the hydrophobicity of the organic amendments in the soil probably declined with time.

Plant-Available Water

Treatment, year, and their interaction all influenced soil PAW ($P < 0.001$). Across all years, the combined 1% biochar + 2% manure treatment produced the greatest PAW (0.262) and the PAW of other treatments followed in the order: 1% biochar + 2% manure > all 2% rates > all 1% rates > control (Table 3). Combining the 1% biochar and 2% manure produced a greater PAW value than when the two treatments were applied individually and, on average, the interaction was an additive one, particularly after 2010 (Table 3).

The regression analyses indicated that, for biochar, sawdust, and acid sawdust treatments, PAW increased linearly with amendment rate in each year measured (Fig. 2). For manure, a linear relationship between PAW and application rate was observed only in 2009. Thus in the years following 2009, the influence of manure on soil PAW was unaffected by the amount of manure applied to the soil. In contrast, the PAW of biochar-, sawdust-, or acid-sawdust-amended soils responded positively to the rate applied (Fig. 2). In the first year after application, manure produced a greater increase in PAW per unit rate applied (regression slope = 0.023) than the other treatments (biochar

Table 3. Treatment effects on the plant-available water PAW and PAW ratio averaged across the years measured (2009–2011, 2013, and 2015).

Treatment	Control	1% Biochar	2% Biochar	1% Manure	2% Manure	1% Sawdust	2% Sawdust	1% Acid sawdust	2% Acid Sawdust	1% Biochar + 2% Manure
PAW (g H₂O per g dry soil)	0.222 (0.003)‡	0.236 (0.004)	0.244 (0.003)	0.232 (0.004)	0.243 (0.007)	0.234 (0.006)	0.251 (0.003)	0.233 (0.005)	0.247 (0.003)	0.262 (0.004)
PAW ratio†	1.00 (0.006)	1.062 (0.006)	1.099 (0.010)	1.046 (0.010)	1.091 (0.017)	1.054 (0.015)	1.133 (0.010)	1.045 (0.007)	1.113 (0.009)	1.180 (0.0.11)

† The PAW ratio was computed as the treatment value divided by the mean control value in the corresponding year

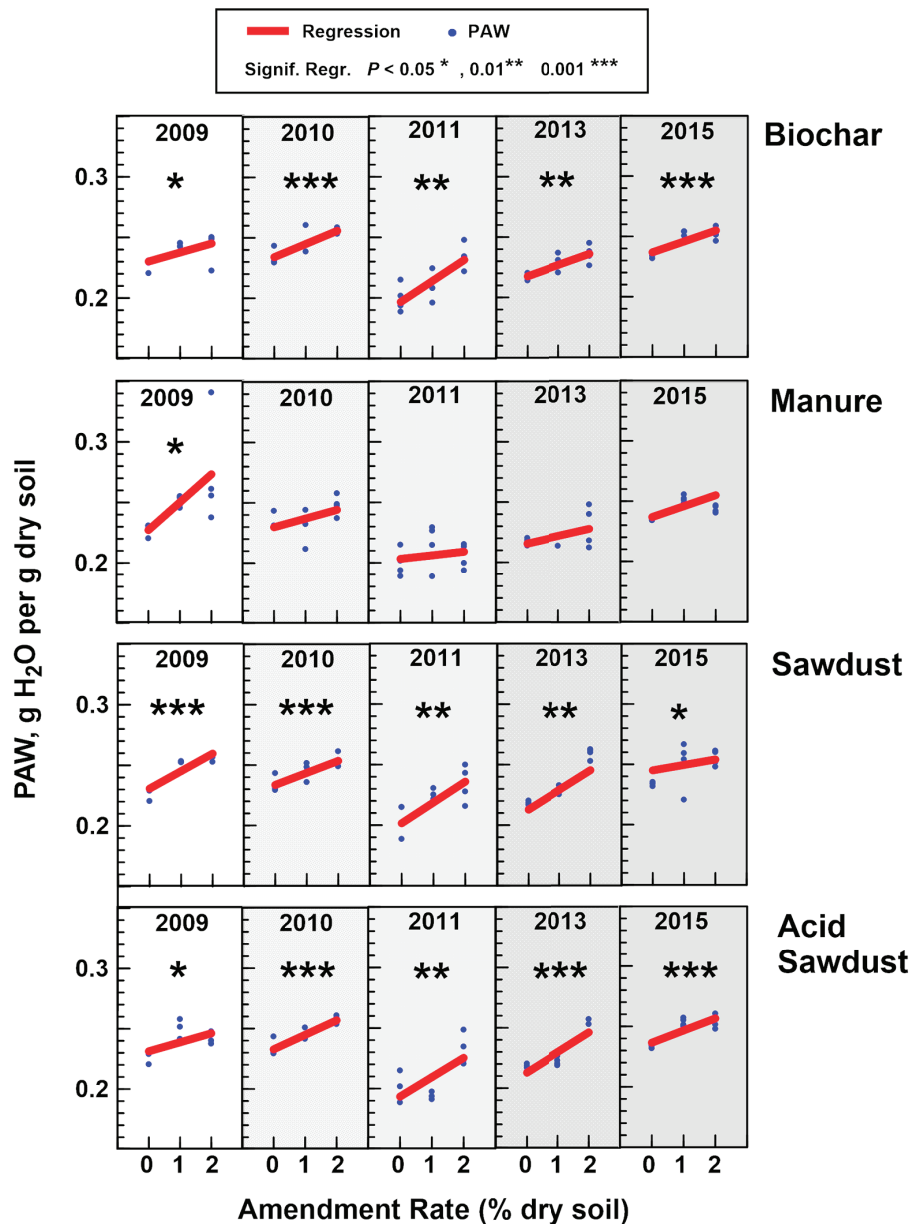‡ Values in parentheses are standard errors ($n = 20$).

Fig. 2. Plant-available water (PAW, the water retained between potentials of -10 and -1500 kPa) in soil as a function of year measured and amendment application rate for each amendment, where the control equals the 0 rate. The asterisks indicate the significance of the linear regression. (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$).

= 0.007; sawdust = 0.014; acid sawdust = 0.007), indicating that manure had the strongest and most immediate effect on soil PAW (Fig. 2). Conversely, the biochar, sawdust, and acid sawdust treatments produced the greatest PAW increases 3 to 5 yr after application, in 2011, 2011, and 2013, respectively. These materials required several years of incubation in the soil to develop maximum water retention benefits.

All treatments produced 6-yr mean PAW ratio values greater than unity, indicating that each amendment produced a long-term increase in soil PAW relative to the control (Table 3). Unlike PAW values, however, the effects on the PAW ratio were less distinct among treatments, with the nine amendment treatments falling into only two impact groups. The greatest PAW ratio was produced by the 1% biochar + 2% manure treatment, yielding a PAW 1.18 times that of the control. The PAW ratios of all other amendment treatments (not including the control) did not differ among themselves and, as a group, they produced

an average PAW ratio of 1.08 (Table 3), significantly greater than unity ($P < 0.0001$). On average, this group of treatments was 45% less effective than the 1% biochar + 2% manure treatment for increasing water availability in the soil.

The significant interaction of treatment and year was apparent when the PAW ratios of the 2% treatments were plotted against years (Fig. 3). The amendment effects on PAW ratios resulted in three basic temporal patterns: (i) the 2% manure PAW was 1.2-fold greater than the control initially, declined through to 2011, then gradually increased thereafter; (ii) the patterns for 2% biochar, 2% sawdust, and 2% acid sawdust were opposite to that of 2% manure: the three initially produced PAW values about 1.1 times that of the control, increased to a peak of 1.16 to 1.18 times the control in 2011 or 2013, then declined in later years; and (iii) the 1% biochar + 2% manure PAW ratio was consistently large during the 6-yr period and, unlike the other treatments, retained
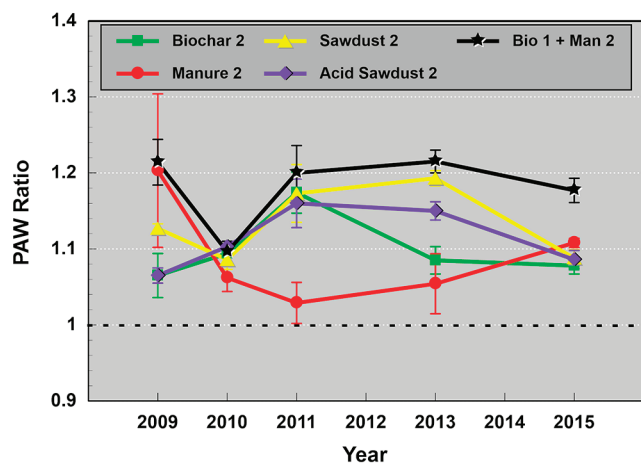
Fig. 3. The influence of amendment and year on the soil plant-available water (PAW) ratio. The PAW ratio was computed as the treatment value divided by the mean control value in the corresponding year. A PAW ratio greater than unity indicates greater PAW for the treatment than the control. Each leg of the error bars represents one SE of the mean ($n = 4$).

this large value through the entire experiment (Fig. 3). Except for a temporary decline in 2010, the combined biochar–manure treatment PAW ratio was about 1.2-times that of the control (Fig. 3).

The analysis of treatment class relationships confirmed the significance of the PAW ratio patterns shown in Fig. 3. The PAW ratio of the biochar, sawdust, and acid sawdust 2% treatments, as a group, differed from 2% manure in all years except 2015 ($P < 0.04$) and differed from 1% biochar + 2% manure in 2013 and 2014 ($P < 0.006$). Finally, the effect of all amendments on soil water retention was long-lasting and, out of the 2%-biochar, 2% sawdust, and 2% acid sawdust treatments, the two sawdust amendments produced the more persistent rise in PAW ratio during 2011 to 2013 ($P = 0.002$) (Fig. 3).

Underlying Factors Affecting PAW Dynamics

We hypothesize that the delayed peaking of PAW ratios for the biochar, sawdust, and acid sawdust amendments (Fig. 3) was at least partially caused by the strongly to extremely water-repellent character of the original material. This repellency produced contact angles of >90° at the pore surface–water interface and prevented water from entering pores via capillarity (Poiseuille's law) (Leelamanie et al., 2008). If water was inhibited from entering biochar and sawdust pores, the full benefit of the added porosity could not be achieved in amended soils (Gray et al., 2014). With time, however, leaching and microbial action would remove the hydrophobic compounds coating pore surfaces in amendment particles, first on those near the exterior and then those on the interior (Briggs et al., 2012; Das and Sarmah, 2015). In contrast, the slightly water-repellent manure material would provide little resistance to water absorption and hence the added porosity in manure was more immediately available to increase soil water retention. Manure's immediate influence on PAW relative to the control and other amendments (Fig. 3) may also be caused by the relatively short-term manure-induced increased persistence of soil macroaggregates (≥2 mm), which can occur within 15 d of application and persist for 7 mo (Wortmann and Shapiro, 2008). The slight increase in the manure PAW ratio near the end of the study (2015) suggests that a long-term process may also influence water retention in manured soils, perhaps through the accumu-
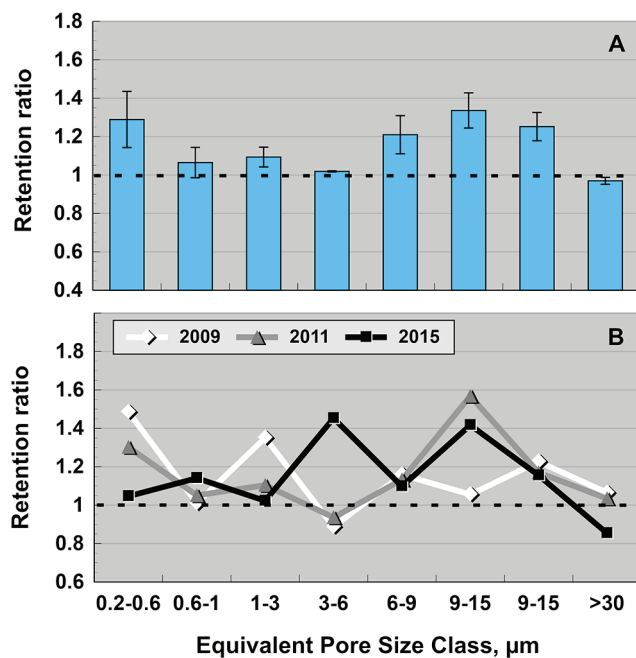
Fig. 4. The mean retention ratio (A) averaged across 2% amendment treatments and all years (2009–2011, 2013, and 2015) as a function of pore size class and (B) averaged across all 2% amendment treatments, including the combined biochar + manure as a function of pore size class in 2009, 2011, and 2015. The retention ratio is the difference in water retained between two adjacent soil matric potentials (and hence a pore size class), divided by the mean control value. Each leg of the error bars represents one SE of the mean ($n = 5$).

lated effects of increased root biomass caused by manure over the long term (Lentz et al., 2014).

The sawdust and acid sawdust responded similarly to biochar in the first 3 yr after application (Fig. 3), even though these materials were not as strongly water-repellent as biochar (Table 1). The average particle sizes of the two original sawdust materials were about four times larger than that of biochar (Fig. 1), suggesting that particle size influenced the soil's water retention dynamics. Since the physical forces that fragment amendments attack both nonpyrolized and biochar materials alike (Hammes and Schmidt, 2015; Jackson et al., 2009; de la Rosa, 2018), we expect that the relative particle size differences among the amendment types would tend to persist over time, even though the average particle sizes for each would decline. The comparatively smaller biochar particles had greater surface areas and smaller interior volumes than the larger sawdust particles; hence biochar pores were more accessible to soil water and microorganisms and more rapidly cleansed of their hydrophobic coatings. We conclude that the effect of the sawdusts' lower water repellency (relative to biochar) on water retention was offset by the sawdusts' greater particle size, which effectively slowed the dissipation of native hydrophobic pore coatings. The particle-size differential may also explain why the water retention increased in sawdust amendments were more extended in time and/or peaked later than those for biochar (Fig. 3).

Soil Water Retention Fractions

When averaged across all 2% treatments and years (2009–2011, 2013, and 2015) for each pore size class, the mean retention ratios revealed that the amendments increased retained water in the 0.2- to 0.6-μm and 6- to 30-μm pore size classes (Fig. 4A).

Table 4. The mean soil penetrometer resistance for three depths in potted soils, measured in 2013, 4 yr after the experiment was initiated. Mean separations were determined among individual treatment means and among treatment classes.

Treatment	Control	1% biochar	2% biochar	1% manure	2% manure	1% sawdust	2% sawdust	1% acid sawdust	2% acid sawdust	1% biochar + 2% manure
					——— MPa ———					
Soil depth										
0–50 mm	1.36 a†	1.35 a	1.21 a	1.35 a	1.22 a	1.48 a	1.29 a	1.30 a	0.91 b	1.25 a
50–100 mm	2.14 a	1.98 ab	1.79 b	1.88 abc	1.75 bc	1.62 bc	1.77 bc	1.91 abc	1.32 d	1.64 c
100–150 mm	2.00 a	1.82 a	1.75 a	1.85 a	1.65 b	1.31 bc	1.50 bc	1.63 bc	1.23 d	1.41 cd

Class	Control	Biochar, manure	Sawdust, acid sawdust	1% biochar + 2% manure
			——— MPa ———	
Soil depth				
0–50 mm	1.36 a†	1.28 a	1.24 a	1.25 a
50–100 mm	2.14 a	1.85 b	1.66 c	1.64 bc
100–150 mm	2.00 a	1.77 a	1.42 b	1.41 b

† For each soil depth increment, means followed by the same letter are not significantly different (P < 0.05).

For a given pore size class, a retention ratio of >1 indicates that more water is retained in the amended soil relative to the control and, equivalently, that the number of pores in the amended soil is greater than that of the control. The amendments increased the number of pores in 0.2- to 0.6-µm and 6- to 30-µm pore size classes by 1.27-fold on average relative to unamended soils.

An interaction between treatment and year influenced the retention fractions ($P < 0.001$, except for the 0.6- to 1-µm size class), indicating that the soil pore size distribution in amended soils changed with time. The interaction was seen most clearly when the mean retention ratios for the five 2% amendment treatments were plotted against the soil pore size class for 2009, 2010, and 2015 (Fig. 4B). In 2009, water held in amounts exceeding that of the control generally occurred in the relatively smaller pore size classes (i.e., 0.2–3 µm) (Fig. 4B). Over time, however, the water exceeding control levels shifted from the smaller pores to medium pore size classes (i.e., 6–30 µm) (Fig. 4B).

The pore size distributions shown in Fig. 4 were produced by the relatively large 2% application rates; therefore, the porosity of the amendments themselves probably had a substantial effect on the soil mixture's porosity. The structures of sawdust and biochar particles are very similar because the wood-derived biochar commonly retains the xylem and phloem structure of the original material, albeit slightly shrunken because of the expunging of volatile materials during heating (Chia et al., 2015). The trend toward larger pores could result from the thinning of cell (now pore) walls through fungal or microbial degradation, leading to the breaching and opening up of the interior structure. This has been observed in wood (Flournoy et al., 1991; Lee et al., 2004).

Penetration Resistance

The experimental conditions mimic those occurring in a field after amended soils have been irrigated and hence provides a measure of the soil resistance that growing roots would encounter in the field. Four years after the amendments were applied (2013), treatment effects on PR were found at each soil depth interval ($P < 0.0001$), although the influence of treatment was greatest in the 50- to 100- and 100- to 150-mm soil layers (Table 4). In the two deeper soil layers, the control soils produced the largest PR; the sawdust, acid sawdust, and 1% biochar + 2% manure produced the least (26% < control); and biochar and manure amendments were intermediate (12.6% < control) (Table 4). These results differ from those of short-term (<2 yr) biochar studies, which generally found no significant effect of biochar addition on PR (Blanco-Canqui, 2017). However, the relative effects of manure and sawdust on the reduction of PR after 4 yr (this study) and after 8 mo (Gülser and Candemir, 2012) were similar in that the amendments with large C/N ratios (sawdust and hazelnut husk, respectively) produced twice the reduction of manure (Table 4). Changes in PR in soils have been correlated with changes in soil organic C, silt and clay content, mean weight diameter, total porosity, bulk density, and water content (Pabin et al., 1998; Sojka et al., 2001; Gülser and Candmir, 2012). Gülser and Candmir (2012) attributed the decrease in soil PR primarily to amendment-

induced increases in the soil's total porosity. In the current study, soil PR was not correlated with total porosity or bulk density ($P > 0.07$) and silt and clay content was constant among pot soils. This suggests that PR responses resulted primarily from treatment effects on mean weight diameter, water content, or both.

Bulk Density, Infiltration, and Saturated Hydraulic Conductivity

Six years after application, all biochar and sawdust treatments except the 2% acid sawdust had reduced the soil bulk density relative to the control by 11% on average (Fig. 5A). This reduction is comparable to that observed: (i) after 3 yr in a silt loam soil amended with 3% (w/w) mixed woodchip biochar (Burrell et al., 2016); (ii) after 2 yr in a loam soil amended with 1% corn (*Zea mays* L.) straw biochar (Xiao et al., 2016); and (iii) after 2 yr in a silty clay loam soil amended with 2% farmyard manure (Shirani et al., 2002). Notably, the soil bulk density increased with an increasing application rate ($P = 0.003$) from an overall average of 0.99 g cm^{-3} for 1% to 1.05 g cm^{-3} for 2% rates (Fig. 5A). This suggests that increased amendment application rates resulted in slightly greater soil packing over time. The reverse relationship was reported for pyrolyzed and nonpyrolyzed amendments when bulk density was measured shortly after application (3 mo); in other words, soil bulk density decreased with an increasing addition rate (Spokas et al., 2016).

After 6 yr, infiltration rates under 5- and 15-cm pressure heads produced nearly identical relationships among treatments, except that infiltrations rates were approximately 28% greater at the larger head. Therefore, data for the 5-cm head only are shown. The 1% and 2% sawdust, 2% acid sawdust, and combined 1% biochar + 2% manure treatments generated similarly large infiltration rates, averaging 21.5 cm hr^{-1}, double the rate measured for the control (Fig. 5B). The 1% biochar and 2% manure treatments failed to increase the infiltration rate when applied singly but when combined, they increased the infiltration rate twofold relative to the control, at both the 5- and 15-cm head. Martens and Frankenberger (1992) attributed infiltration increases in organic-amended soil to the amendment's stimulation of microbial activity and the accompanying increase in aggregate stability as well as a decrease in soil bulk density. In the current experiment, we noted a strong negative correspondence between infiltration rate and soil PR ($r^2 = -0.38$ to -0.60; $P < 0.01$). Given that soil mean weight diameter increases with decreasing PR (Gülser and Candmir, 2012), this suggests that amendments increased infiltration rates by increasing aggregate stability and hence the soil's mean weight diameter. Treatments may have influenced infiltration via effects on root biomass and hence the prevalence of soil macropores. Lentz et al. (2014) reported that out of the control, biochar, manure, and combined biochar + manure treatments, biochar alone had no effect or decreased corn root biomass, whereas biochar + manure produced the greatest corn root biomass of the four treatments. This might explain why, in the current study, the infiltration rates of the combined 1% biochar + 2% manure treatment exceeded that of the amendments applied alone (Fig. 5B).
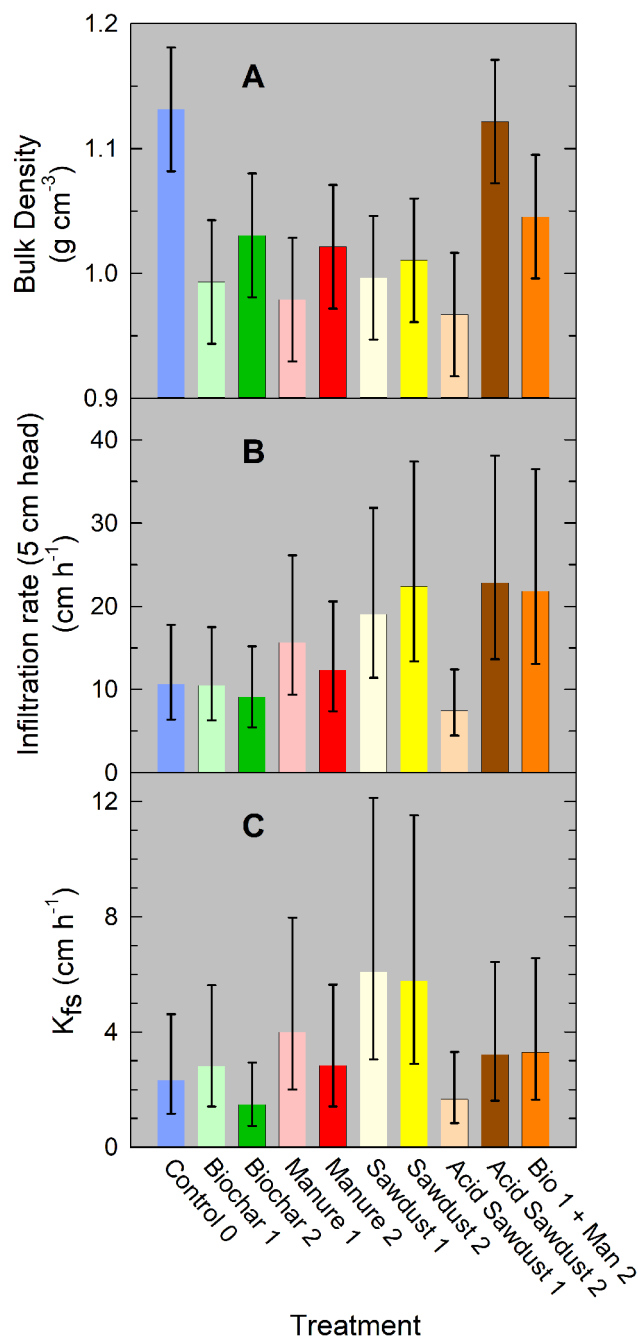

Fig. 5. Treatments effects on (A) soil bulk density, (B) infiltration rate under a 5-cm head, and (C) field-saturated hydraulic conductivity (K_{fs}), all measured 6 yr after amendments were applied. Numbers in treatment labels indicate the application rate (%). Error bars are the 95% confidence limits on the means ($n = 4$).

By the sixth year, the 1 and 2% sawdust treatments as a class exhibited an average 2.6-fold greater ($P = 0.02$) soil K_{fs} than the control (Fig. 5C). The K_{fs} for the soils of the other treatments did not differ from that of the control. These findings are similar to those of Mbagwu (1989) obtained at 90 d after applying amendments to a sandy clay loam, showing that partially decomposed sawdust amendments were decisively more effective than manure for increasing K_{fs}. In the current study, a stepwise regression analyzing only biochar, manure, and sawdust data showed that K_{fs} was inversely related to soil bulk density and

positively related to amendment particle size (K_{fs} = 29.9 + 37.3 × size − 30.6 × bulk density; $P < 0.0001$). Sixty-nine percent of the variation in K_{fs} was explained by the two variables. These factor relationships with K_{fs} differed from those reported for loamy sand amended with pyrolyzed or nonpyrolyzed pine chips after 3 mo of incubation: In that case, K_{sat} decreased both with decreasing soil bulk density and decreasing particle size (Spokas et al., 2016).

CONCLUSIONS

Our hypotheses concerning the temporal effects of organic amendments on PAW were not supported by the results. Specifically, (i) the major impact of biochar and the two sawdust treatments on PAW was not immediate, (ii) manure's effect on PAW achieved a maximum early in the study and did not progressively increase to a maximum in the second or third year after application, and (iii) biochar's effects on PAW were no more persistent than those of nonpyrolyzed amendments during the 6-yr study. We conclude that other factors influence soil PAW development, in addition to the quantity of highly porous amendment added. Our results suggest that: (i) the water-repellent properties of the added organic material may temporarily impede water from filling open pores in added materials, until leaching processes or microbial action have dissipated the hydrophobic coatings on pore walls and (ii) increasing amendment particle size inhibits the clearing of water-repellent pore coatings and delays the time to reach maximum PAW.

Manure, which was the least water-repellent of the treatments, produced an immediate increase in PAW, which may at least partially reflect short-term increases in soil macroaggregates in response to organic matter and nutrient addition, microbial growth, and soil stabilization. The slight increase in the manure PAW ratio between 2011 and 2015 suggests the possibility of long-term manure effects on PAW, caused, for example, by persistent increases in root biomass. These effects may have compounded with time.

In general, amendment-induced effects on soil PAW varied with time. Therefore, PAW measurements made on soil samples collected in the first year or two after application are not likely to accurately reflect the true long-term potential of biochar, manure, and organic residues for increasing soil water availability.

All amendments produced long-term increases in PAW when averaged across all 6 yr. The combined 1% biochar + 2% manure treatment proved to be the most effective, presumably because of the greater total quantity of material applied (i.e., the effects of the two amendments were additive). However, evidence suggests that the combined treatment was longer-lasting than single amendments. Further experimentation is needed to better understand how biochar and manure may interact to prolong PAW enhancements in soils.

Finally, the shift toward larger pore sizes with time in amended soils may have ramifications related to soil N turnover. Soil oxygen status controls nitrification and denitrification processes, and larger soil pores are more likely to be air-filled, which increases gas diffusion and oxygen availability in soil (Butterbach-Bahl et al., 2013).

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