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Augmenting soil water storage using uncharred switchgrass and pyrolyzed biochars

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Abstract

Biochar is an amendment that can augment soil water storage; however, its projected cost per ton could be financially limiting at field application scales. It may be more monetarily convenient if an alternate amendment was available that could deliver similar soil enhancements. We compared two switchgrass biochars pyrolyzed at 250 and 500 °C with raw switchgrass (uncharred) on moisture storage and bulk density changes in a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult). Amendments were mixed into triplicate pots at 20 g/kg along with untreated controls. Soils were laboratory incubated at 10% moisture content (w/w) for 118 days, and the pots were irrigated three times with 1.3 pore volumes of deionized water every 30 days. Soil bulk densities were recorded before each irrigation event. Assessment of alterations in soil water storage was examined through cumulative water evaporative losses from incubation day 0 to day 33 and by monitoring soil water contents for 13 consecutive days past each irrigation event. Rankings of soil water evaporative losses were as follows: uncharred switchgrass $\leq$ switchgrass (500 °C) $\leq$ switchgrass (250 °C) < control. After the first irrigation event, uncharred switchgrass amendment significantly increased moisture storage compared with soil treated with biochar and the control. While all amendments increased water storage relative to the control, uncharred switchgrass delivered equivalent, if not slightly better, moisture storage improvements compared with the two switchgrass biochars. Uncharred switchgrass would likely not be as effective over the long term (years to decades) as pyrolyzed biochars, due to greater degradation of uncharred material.

Keywords: Biochar, GRACEnet, soil water storage, switchgrass

Introduction

Biochar is a solid product obtained by pyrolysis of raw lignocellulosic feedstocks (Antal & Grønli, 2003). The literature has shown that biochar contains inorganic nutrients (Chan & Xu, 2009) along with a structural matrix composed of an assemblage of C structures, some of which are resistant to microbial oxidation (Lehmann *et al*., 2009). Consequently, it has gained widespread attention as an amendment to boost soil fertility (Chan *et al*., 2008; Novak *et al*., 2009a), enhance soil water storage (Brockhoff *et al*., 2010; Novak *et al*., 2012a) and soil C sequestration (Laird, 2008; Lee *et al*., 2010). Soil quality and physical property improvements have been linked to the biochars chemical and structural properties (Amonette & Joseph, 2009), the pyrolysis conditions (Novak *et al*., 2009b; Spokas *et al*., 2012) and the biochar application rate (Jeffrey *et al*., 2011).

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Rates of biochar application for soil C sequestration and fertility augmentation in field and lab evaluations can be quite variable (Spokas *et al*., 2012). On tropical and subtropical soils, biochar application rates, ranging from 0.5 to 50 t/ha, can be required to promote fertility and crop productivity enhancements (Blackwell *et al*., 2009). In a laboratory incubation experiment, Novak *et al*. (2012a) evaluated biochars produced from switchgrass (*Panicum virgatum*) and applied at 40 t/ha. They reported a significant increase in soil moisture storage.

When considering biochar application at the field scale, it could be argued that this management practice is financially unrealistic because the feedstock production acreage and estimated cost of applying biochar are high. Applying 40 t/ha of switchgrass biochar to a 1-ha field, as an example, would necessitate raw switchgrass biomass to be harvested from 6 to 12 ha of land. These projections are based on a switchgrass field in the Coastal Plain of SC yielding 13.4 t/ha (James R. Frederick, personal communication, 2012) and biochar mass recoveries ranging between 45 and 24% by wt., respectively, when pyrolyzed between 350 and 700 °C (Keri B. Cantrell, personal communication, 2012). In addition to the projected land area requirements for raw feedstock, an additional concern is the anticipated biochar costs that can range between US$ 150 and 300/t (De Gryze *et al*., 2010). Conservatively, it would cost over US$ 6000 per ha to apply this amount of biochar.

Alternatively, it may be economically prudent to simply use uncharred switchgrass as a substitute soil amendment because < 3 ha of land are required to produce biomass needed for an equivalent amendment application rate. There are no pyrolysis expenditure costs, and the price of uncharred switchgrass biomass is only US $42/t (Roberts *et al*., 2010). Thus, the cost of a 40 t/ha application of uncharred switchgrass would be less than US $1700, which would be a considerable saving over using biochar.

These calculations are only presented for discussion and do not consider the additional economics associated with biochar production (Brown *et al*., 2010), application methods (Williams & Arnott, 2010) nor the longevity differences between biochar and the uncharred switchgrass in soil. Biochar costs are expensive, and its use as a soil amendment for agricultural fields has been known to be economically unfavourable for a long time (Holbrook, 1849).

On the other hand, applying organic amendments (i.e. biosolids, organic wastes, manure, crop residues, etc.) to improve soil physical and chemical properties are well known in the literature (Busscher *et al*., 2011; Larney & Angers, 2012). Most soil properties were improved following organic amendment additions, but the impact of the enhancement varied greatly between amendment sources (Larney & Angers, 2012). Moreover, the longevity of easily decomposable organic amendments (i.e. biosolids and manure) raises the spectre of their long-term contribution to soil C sequestration and length of duration for the soil water storage benefits.

Boosting soil organic carbon (SOC) contents and water holding capacities are germane for agricultural production in the south-eastern USA Coastal Plain region because the area experiences erratic rainfall distribution and has agricultural soils with small SOC contents (Kern & Johnson, 1993) and poor water storage (i.e. coarse textures). In spite of the region receiving annual precipitation averaging 1300 mm (Busscher *et al*., 2010), the area frequently experiences short-term droughts during the summer period that can last up to 4 weeks (Sadler & Camp, 1986; Busscher *et al*., 2010). Crop moisture stress is common during these drought periods because the sandy-textured soils can store only about 20 mm H_2O/300 mm soil depth (Long *et al*., 1969), which is only sufficient for between 5 and 7 days water use by maize (Reicosky & Deaton, 1979). Augmenting SOC contents using organic amendments and biochar can increase soil aggregation and reduce bulk density, resulting in greater pore space for water storage (Busscher *et al*., 2011). Increasing soil moisture capacity is also a critical facet for improving agricultural resilience to climate variability (Bormann, 2012).

Here, it was hypothesized that uncharred switchgrass would deliver similar changes in soil water retention in coarse-textured soils as biochars pyrolyzed from switchgrass. The objective of this investigation was to evaluate modifications in moisture storage and bulk density in a Norfolk loamy sand treated with either uncharred switchgrass or two switchgrass biochars.

Materials and methods

Selection of soil and site description

The Norfolk soil chemical and physical properties, along with agricultural management history of the soil collection site, were reported by Novak *et al*. (2009b). Briefly, the parent material of the Norfolk loamy sand is marine sediments located in the middle Coastal Plain physiographic region of South Carolina, USA. Soil was collected from the 0- to 15-cm surface layer in a row-cropped field at the Clemson University Pee Dee Research and Education Centre (PDREC), Florence, South Carolina, USA. The soil was air-dried and sieved to < 2-mm. Its USDA textural class was a loamy sand and was largely composed of quartz and kaolinitic clays (Novak *et al*., 2009b). The Norfolk soil has a 16.8 g/kg SOC content and an acidic pH (4.8).

Feedstock selection and biochar pyrolysis conditions

The switchgrass feedstock used for this study was obtained by harvesting a crop at the PDREC. The raw feedstock was processed before pyrolysis by air-drying and grinding to pass a 6-mm sieve. The two switchgrass biochars were produced at North Carolina Agricultural and Technical State University as outlined by Novak *et al*. (2012a). The biochars were made using a slow pyrolysis procedure at 250 and 500 °C under a continual stream of N_2 gas. After recovery from the pyrolyzer, all biochars and the raw (uncharred) feedstock were ground to pass a 0.42-mm sieve using a Wiley Mini-Mill (Thomas Scientific, Swedesboro, NJ, USA). All samples were then further sieved to pass through a 0.25-mm sieve, placed in a sealable plastic bag and stored in a dessicator.

Biochar characterization

The uncharred material and two switchgrass biochar samples were characterized for their physical and chemical properties that included pH, ash content and their elemental composition as outlined by Novak *et al*. (2009b). Chemical properties of the uncharred switchgrass and switchgrass biochars are shown in Table 1.

Table 1 Chemical properties of raw switchgrass and biochars (dry-weight basis)

		pH[a]	Ash[a]	C[a]	H[a]	O[a]	N[a]		
Sample	Pyrolysis (°C)	g/kg						O/C	H/C
Switchgrass	Uncharred	5.8	22	483	62	427	5.1	0.66	1.53
	250	6.4	26	553	60	356	4.3	0.49	1.29
	500	9.2	78	844	24	43	10.7	0.04	0.34

[a]Published in Bioenergy Research (Novak *et al*., 2012b).

Biochar incubation and water storage of Norfolk soil

The Norfolk soil and biochar incubation experiment consisted of triplicate treatments of a control (no amendments), the uncharred switchgrass and the two switchgrass biochars. The uncharred material and two biochars were mixed at 2% w/w (20 g/kg) into the Norfolk loamy sand, which represents a field application rate of 40 Mg/ha incorporated to a 15-cm soil depth. Each pot was laboratory incubated for 118 days total at a moisture content of 10% (w/w), and the soil moisture content was readjusted to 10% twice weekly. Between day 0 and day 33 of the incubation, the cumulative amount of water needed to restore each pot back to 10% was estimated to determine water evaporative losses from each soil treatment.

A total of three irrigation events were carried out on days 34, 63 and 98 of incubation. Prior to the first two irrigation events, the bulk density of all pots was determined. Soil bulk density values before the third irrigation event were inadvertently not recorded. On the day of irrigation, each pot was gravimetrically weighed for a baseline soil moisture content, then immediately irrigated with 1.3 pore volumes of deionized water. After 24–30 h, free drainage ceased, and the collected water's mass was recorded.

Each treatment's soil water storage capability was assessed through cumulative water evaporative losses from incubation day 0 to day 33 and monitoring soil water contents for 13 consecutive days past each irrigation event. The cumulative evaporative water losses were described above; in each pot, soil moisture content (% by weight) on days 3, 6, 9 and 13 after each irrigation event was used as comparison index between treatments. Changes in water storage for each treatment were also compared by estimating soil water storage as mm H_2O/150-mm soil depth using the estimated bulk density and the soil gravimetric moisture content on day 3 after the first and second irrigation events. Day 3 after the first two irrigation events was chosen as a convenient time period to compare soil water storage between treatments.

Statistics

Mean cumulative soil moisture evaporative losses for all four treatments were pair wise tested for significant differences using a multiple comparison procedure (Fisher LSD, $P = 0.05$). A similar statistical procedure was performed on the mean percentage of soil moisture contents (w/w) determined for each treatment on days 3, 6, 9 and 13 after all three irrigation events and for the first and second irrigation events when water contents were expressed on a v/v basis. All statistical tests were performed using SigmaStat v. 3.5 software (SSPS Corp., Chicago, IL, USA).

Results

Characteristics of uncharred switchgrass and biochars

The uncharred switchgrass and the 250 °C pyrolyzed biochar had acidic pH values, smaller C and N concentrations and contained relatively less ash than the 500 °C switchgrass biochar (Table 1). On the other hand, the 500 °C biochar had smaller O and H contents than the uncharred or 250 °C pyrolyzed material. This resulted in a decrease in the O/C and H/C atomic ratios in the 500 °C biochar (Table 1).

Cumulative water evaporative losses

Among the treatments, the control Norfolk loamy sand had the greatest cumulative evaporative moisture loss over the first 33 days of laboratory incubation (Table 2); the amount of evaporative loss was significantly different than that from

Table 2 Cumulative total water evaporative losses from treated and untreated Norfolk soil after 32 days of laboratory incubation (before first irrigation event; $n = 3$)

	Mean	Standard error
Norfolk soil + biochar (°C)	g H_2O	
Control (no biochar)	323.3a	2.9
Uncharred switchgrass	281.2b	1.3
Switchgrass (250 °C)	295.3c	4.6
Switchgrass (500 °C)	284.6bc	1.4

Means followed by a different letter are significantly different at $P < 0.05$ using a Fisher least significant difference multiple comparison procedure.

the amended Norfolk soils. Among the amended Norfolk soils, the cumulative amount of water loss was similar between uncharred switchgrass and switchgrass biochar pyrolyzed at 500 °C. Cumulative water losses between the two biochar-treated soils were similar, which can be explained by the higher standard error of the mean 250 °C biochar treatment.

Moisture content changes in the Norfolk soil

The mean gravimetric soil moisture content for all treatments was presented in two ways. First, the soil moisture contents on indexed days after all three irrigation events are shown in Table 3. On day 3 after the first irrigation event, the largest moisture content change relative to the control occurred in the Norfolk soil treated with uncharred switchgrass and the 500 °C biochar. Improvements in the ability of Norfolk soil to retain more water after treatment with uncharred switchgrass were most apparent on days 6, 9 and 13 after the first irrigation event. By the second irrigation event, mixed results occurred among the four treatments on days 3, 6 and 9. By day 13 after the second irrigation, the Norfolk soil treated with uncharred switchgrass had the highest moisture content. Similar results occurred after the third irrigation event, with the Norfolk soil treated with uncharred switchgrass on days 9 and 13 possessing significantly higher soil moisture contents.

In the second assessment, the daily mean and standard error (SE) of the soil moisture contents for all Norfolk soil treatments were presented (Figure 1). The plot showed that adding 2% (by wt) of uncharred switchgrass and both biochars raised soil moisture contents. On day 3, the control treatment had a mean soil moisture content of 15%; in comparison, the amended Norfolk soil had moisture contents > 25%. Ranking the percentage of soil moisture content over the 13 days past the first irrigation event was in order from largest to smallest: uncharred switchgrass > switchgrass 500 °C biochar > switchgrass 250 °C biochar > Norfolk control soil.

Mean soil bulk density values for each treatment were used to estimate the volumetric soil water content changes on day 3 for the first and second irrigation event (Table 4). Mean bulk density values for the Norfolk soil treated with uncharred switchgrass were significantly less than those of the other three treatments, implying less reconsolidation of soil particles. Correspondingly, more soil water was stored in the Norfolk soil treated with uncharred switchgrass than in the other treatments. Adding the uncharred switchgrass amendment to the Norfolk loamy sand increased net soil water storage by 21 mm H_2O/150 mm of soil compared with the control soil. Adding the 250 and 500 °C biochar also significantly improved soil water storage compared with the control but by reduced amounts of 12 and 19 mm H_2O/150 mm soil, respectively. After the second irrigation event, all three amendments showed a similar degree of water storage enhancement. Even after the second event, these three soil amendments increased water storage by > 11.9 mm H_2O/150 mm soil.

Table 3 Mean gravimetric moisture contents in treated and untreated Norfolk soils on selected days after irrigation events (n = 3; standard error inside parentheses)

	Percentage of soil moisture content on day after leaching event (w/w)			
Norfolk soil + biochar (°C)	Day 3	Day 6	Day 9	Day 13
First irrigation (day 34)*				
Control (no biochar)	15.2 (0.43)a	5.6 (0.36)a	1.4 (0.35)a	0.3 (0.09)a
Uncharred switchgrass	28.3 (0.38)b	18.8 (0.32)b	9.6 (0.32)b	3.7 (0.12)b
Switchgrass (250 °C)	25.3 (0.95)c	15.4 (0.85)c	6.1 (0.85)c	1.8 (0.15)c
Switchgrass (500 °C)	26.5 (0.63)bc	16.6 (0.58)c	7.1 (0.58)c	2.1 (0.09)c
Second irrigation (day 63)				
Control (no biochar)	15.4 (0.18)a	10.4 (0.21)a	4.1 (0.26)a	1.0 (0.09)a
Uncharred switchgrass	25.9 (2.79)b	21.0 (2.82)b	14.7 (2.81)b	7.9 (2.54)b
Switchgrass (250 °C)	22.9 (0.52)b	17.8 (0.63)b	11.4 (0.79)b	4.2 (0.63)c
Switchgrass (500 °C)	21.7 (0.07)b	17.2 (0.76)b	9.8 (0.02)c	3.3 (0.06)c
Third irrigation (day 98)				
Control (no biochar)	16.3 (0.36)a	9.2 (0.43)a	3.5 (0.46)a	1.1 (0.16)a
Uncharred switchgrass	23.4 (0.60)b	16.4 (0.65)b	10.8 (0.67)b	5.4 (0.30)b
Switchgrass (250 °C)	22.7 (0.39)b	14.9 (0.44)c	9.1 (0.56)c	3.3 (0.30)c
Switchgrass (500 °C)	22.1 (0.34)b	14.7 (0.15)c	8.8 (0.16)c	3.3 (0.13)c

Means compared within a leaching event by day that are followed by a different letter are significantly different at $P < 0.05$ using a Fisher least significant difference multiple comparison procedure. *Irrigation event was conducted on this incubation day.

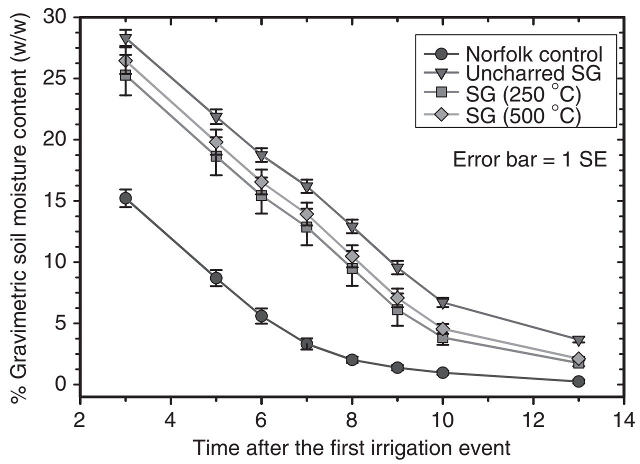

Figure 1 Daily mean soil moisture contents (w/w) measured after the first water irrigation event on a Norfolk loamy sand treated with uncharred switchgrass (SG) and two switchgrass biochars (error bar = 1 standard error, SE).

Table 4 Mean bulk density (BD), per cent gravimetric soil moisture contents (SMC) and estimated water storage in a treated and untreated Norfolk soil (on day 3 after first and second irrigation events; n = 3, standard error)

Norfolk + biochar	BD* g/cm^3	Percentage of SMC on day 3 (w/w)	Water storage mm H_2O/150 mm soil
First irrigation (day 34)			
Control (no biochar)	1.36 (0.01)a	15.2	31.0 (0.58)a
Uncharred switchgrass	1.23 (< 0.01)b	28.3	52.4 (0.81)b
Switchgrass (250 °C)	1.27 (0.01)c	25.3	42.97 (1.90)c
Switchgrass (500 °C)	1.25 (0.01)bc	26.5	49.72 (1.09)bc
Second irrigation (day 63)			
Control (no biochar)	1.35 (0.01)a	15.4	31.06 (0.07)a
Uncharred switchgrass	1.22 (< 0.01)b	25.9	47.51 (5.06)b
Switchgrass (250 °C)	1.28 (< 0.01)c	22.9	44.15 (0.75)b
Switchgrass (500 °C)	1.32 (0.01)a	21.7	42.98 (0.13)b

Means compared within a leaching event that are followed by a different letter are significantly different at $P < 0.05$ using a Fisher Least Significant Difference multiple comparison procedure. *Bulk density for the first and second leaching events was measured 24–120 hrs before water leaching. No bulk density measurements were collected before the third leaching event.

Discussion

The biochar's chemical properties conform to the general literature findings that high temperature pyrolysis (> 350 °C) causes an increase in pH, C, ash content, but, smaller O and H contents. This is due to the loss of volatile compounds through thermal degradation of ligno-cellulosic structures (Antal & Grønli, 2003; Amonette & Joseph, 2009).

Water retention increases in sandy soils treated with organic amendments has been reported previously (Tyron, 1948; Brockhoff *et al*., 2010). Our results corroborate these previous findings; incubation of the uncharred and two biochar amendments resulted in less evaporative water loss and significant augmentation in water storage for the Norfolk soil. It is plausible that the uncharred material and both biochars made from switchgrass reduced water evaporative losses due to water storage in biochar's pores (Kinney *et al*., 2012) or due to potential water adhering forces from organic and inorganic surfaces (Novak *et al*., 2012a).

Here, uncharred switchgrass caused the longest lasting (by day 13) significant enhancement of soil moisture storage. The Norfolk soil moisture contents by day 13 in the control were $\leq$ 1%. In contrast, soil treated with uncharred switchgrass had a 5- to 7-fold higher moisture content. Soil moisture contents were also promoted after adding the two switchgrass biochars, with no clear statistical distinction of which biochar was superior at raising soil moisture storage. These conclusions have potential agronomic management ramifications by lowering crop moisture stress in sandy soils because the amended Norfolk soil would potentially have more water stored for crop uptake. This finding is in agreement with soil moisture tension results previously reported (Novak *et al*., 2012a).

A numerical impact of these amendments for soil moisture storage changes was demonstrated by estimating v/v moisture storage. All three amendments generally promoted soil water storage estimates greater than the control. Soil water storage after the first irrigation event was increased by almost 40% after adding the uncharred switchgrass. Similar soil moisture content enhancements occurred after adding the two biochars, but the degree of improvement was less (28–37%).

This finding could be an inclusion into soil water management programs for crop production in agricultural fields containing sandy soils. Inclusion of uncharred switchgrass should reduce the theoretical cost of improving sandy soils compared with applying biochars pyrolyzed from switchgrass. Smaller amounts of biomass feedstocks and land area are also needed to produce that biomass tonnage, and there are no thermal energy expenditures for producing biochars. Despite a potential drawback of having to repeat applications of uncharred switchgrass due to mineralization losses, the cost per ha to treat sandy soil could be less. However, the duration of the biochar impact also needs to be considered because the biochar effect could be longer lasting due to assumed slower mineralization of the biochar C, thereby improving economic realities. Even though uncharred switchgrass showed equal if not slightly better improvements in water storage, biochar remains a viable amendment to improve sandy soils where crop productivity is limited and may be more beneficial than adding biochar to highly productive soils (Ippolito *et al*., 2012).

Repeated irrigation revealed that the significant water storage alteration still occurred after 63 days of incubation, but the relative increase in water storage declined. This finding is similar to results in Novak *et al*., (2012a) and was suspect to be related to the sand particles reconsolidating, thus lowering pore space or by plugging of biochar pores (Kinney *et al*., 2012).

Conclusions

All three amendments applied to the Norfolk soil increased moisture storage relative to the control, but the uncharred switchgrass provided higher water storage amounts and the effect was longer lasting than the two biochars. Both the high and low temperature switchgrass biochars also boosted water storage in the Norfolk soil, but the degree of improvement was, at times in this experiment, not as great as the uncharred material. Uncharred switchgrass compared with biochars, therefore, offers an alternate remedy to increase soil water storage in sandy soils. Uncharred switchgrass may be less likely retained in the sandy soil over long periods of time and may contribute little to long-term soil C sequestration. Repeated application of uncharred switchgrass may be a component of a soil water management plan to compensate for mineralization and erosion losses. This study highlights the need to understand the temporal duration of soil moisture storage benefits before initiating a field scale soil amendment strategy.

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Disclaimer

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