

ORIGINAL RESEARCH

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Impact of biochar on the water holding capacity of loamy sand soil

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Abstract

With the rise in global population and increased agricultural requirements comes an increasing need for freshwater. Currently, it is estimated that approximately 75% of fresh water consumption is for the growth of agricultural crops, and only 10% to 30% of this water is actually made available to plants. It is widely accepted that farming practices which rely heavily on chemical fertilizers and unsustainable land management practices have led in many regions to infertile sandy soils with reduced water holding capacity and insufficient amounts of organic matter. Combined with increasing global population, the need to better manage fresh water use, particularly agricultural usage, is paramount. The use of biochar as a soil amendment has been suggested as a way to increase water holding capacity, but only limited quantitative studies exist in terms of the effectiveness of biochar in increasing a soil's water holding capacity. The main purpose of this study was to determine the effect of woody biochar amendment (yellow pine from pyrolysis at 400°C) on the water holding capacity of loamy sand soil with different mixture rates. Results show a doubling in water holding capacity by mass using a 9% mixture of biochar (equivalent to 195 metric ton/ha), which is an agriculturally relevant concentration. High percentage mixtures of biochar increase water holding capacity dramatically. These results suggest the use of biochar has potential to mitigate drought and increase crop yields in loamy sand soil.

Keywords: Biochar; Water holding capacity; Loamy sand soil; Pyrolysis

Background

Agriculture is the single largest consumer of fresh water and accounts for about 75% of anthropogenic fresh water use [1]. According to Wallace [1], on average 63% of fresh water applied to agricultural lands is lost to evaporation and runoff. Rainwater and irrigation water that is not absorbed by soils is capable of transporting fertilizers and pesticides into watersheds creating non-point pollution. Due to the increased use of chemical fertilizers and the highly inefficient use of water, there has been an increase in non-point pollution in agricultural areas around the world [2]. With the world's population set to increase by 65% (i.e., 3.7 billion people) by 2050, the additional food required to feed future generations will put further pressure on freshwater resources [1].

The United States Department of Agriculture (USDA) reported that 8.7 million tons of commercial nitrogen fertilizer and an additional 1.1 million tons of animal

manure were added to agricultural lands in the USA [3]. Table 1 shows that over 500,000 tons of chemical nitrogen fertilizer and animal manure are annually distributed to agricultural lands in the southeastern USA, the highest areal rate in the country [3]. As seen in Table 2, nearly 50% of nitrogen fertilizer was lost through runoff and leaching [3]. Agricultural land in the southeastern USA is typically comprised of loamy sand soil, whose inability to hold water makes it more prone to fertilizer loss [3].

Biochar, or charcoal produced for agricultural usage, is produced from thermal decomposition of organic material under reduced oxygen conditions at temperatures above 700°C [4]. The microscopic structure of biochar is one of the primary determinants in its soil conditioning properties; the surface area of the pre-charred source material can be increased several thousand fold [5]. This increased surface area is the result of thermal decomposition of the organic material through which volatiles are driven off and the remaining structure is comprised of highly concentrated carbon chains. These chains can take on different organizational patterns based on the production

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Table 1 Sources of nitrogen inputs-by region and by crop [3]

	Acres		Commercial fertilizer		Manure		Atmospheric deposition		Bio-fixation		Sum of inputs	
	1,000 s	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
By region												
Northeast	13,642	4.6	388,655	4.5	146,867	13.6	48,523	5.8	1,081,687	10.4	1,665,742	7.9
Northeast Great Plains	72,397	24.3	1,815,130	20.9	154,986	14.3	122,474	14.6	907,910	8.7	3,000,645	14.3
South Central	45,350	15.2	1,290,546	14.8	85,795	7.9	197,007	23.4	1,993,185	19.2	3,566,628	17.0
Southeast	13,394	4.5	423,992	4.9	82,103	7.6	55,854	6.6	468,580	4.5	1,030,529	4.9
Southern Great Plains	32,096	10.8	952,920	11.0	74,517	6.9	61,552	7.3	106,041	1.0	1,195,054	5.7
Upper Midwest	112,581	37.7	3,504,461	40.3	466,355	43.1	344,878	41.0	5,579,239	53.6	9,894,962	47.1
West	9,018	3.0	318,839	3.7	71,619	6.6	10,313	1.2	263,443	2.5	664,220	3.2
All regions	298,487	100.0	8,694,553	100.0	1,082,242	100.0	840,601	100.0	10,400,085	100.0	21,017,780	100
By crop												
Barley	4,635	1.6	171,683	2.0	2,244	0.2	7,313	0.9	0	0.0	181,242	0.9
Bom	78,219	26.2	4,369,865	50.3	552,495	51.1	231,507	27.5	0	0.0	5,153,867	24.5
Corn silage	5,197	1.7	186,760	2.1	298,616	27.6	14,971	1.8	0	0.0	500,345	2.4
Cotton	16,858	5.6	560,237	6.4	12,369	1.1	51,108	6.1	0	0.0	623,746	3.0
Legume hay	24,776	8.3	444,358	5.1	18,299	1.7	65,268	7.8	4,512,759	43.4	5,040,690	24.0
Oats	3,772	1.3	43,934	0.5	852	0.1	9,303	1.1	0	0.0	54,096	0.3
Peanuts	1,843	0.6	17,372	0.2	1,629	0.2	7,207	0.9	63,490	0.6	89,699	0.4
Potatoes	987	0.3	72,952	0.8	1,315	0.1	2,268	0.3	0	0.0	76,535	0.4
Rice	3,637	1.2	190,001	2.2	7	<0.1	15,522	1.8	0	0.0	205,541	1.0
Spring wheat	20,503	6.9	423,081	4.9	4,206	0.4	32,545	3.9	0	0.0	459,961	2.2
Sorghum	10,897	3.7	444,695	5.1	16,465	1.5	27,978	3.3	0	0.0	489,144	2.3
Soybeans	67,543	22.6	143,954	1.7	59,224	5.5	221,487	26.3	5,823,836	56.0	6,248,524	29.7
Winter wheat	45,014	15.1	1,179,798	13.6	26,822	2.5	106,697	12.7	0	0.0	1,313,400	6.2
All crops	298,478	100.0	8,694,553	100.0	1,082,242	100.0	840,601	100.0	10,400,085	100.0	21,017,780	100.0

temperature, with increased temperatures leading to increased organization [4].

The most famous example of agricultural biochar usage is the pre-Columbian Terra Preta soils of the Amazon River basin. The ancient Amazonian people built up the Terra Preta by adding large quantities of charcoal to the soil to amend the nutrient poor soils of the rainforest [6]. Terra Preta is found near large, well-established Amazon Indian villages, suggesting the causal relationship between agricultural stability and population expansion [6].

The practice of adding charcoal to degraded soils was deemed obsolete after the industrialization of chemical fertilizers. However, due to the negative effects of chemical fertilizers on modern agricultural soils and the environment, and the concern for increasing atmospheric carbon, there has been a renewed interest in charcoal-based soil amendment [7]. Much of this interest is focused on biochar. The claims for biochar are many: larger crop yields, decreased fertilizer requirements, greater microbial activity, reductions in greenhouse gas emissions

from fields, greater soil water holding capacity, drought mitigation, and increased soil organic carbon content (SOC), which can improve the physical properties of soil. Further, carbon sequestration benefits of biochar soil amendment have been heavily studied [8-11].

Sohi et al. [12] showed that soils with a high water holding capacity produce increased crop yields and a decreased need for irrigation. Singh et al. [13] suggested that the increased porosity of biochar increases water retention in soils, and the enhancement depends on biochar feedstock, soil type, and mixture rates. Nutrients dissolved in the water may also be retained in the soil so plants may be better able to access the nutrients [4]. To promote the use of biochar soil amendment, it is important to understand the mechanism of biochar-amended water retention, to characterize the effects of feedstock, biochar production, soil types, and mixtures, and to quantify these effects on plant growth.

The main objective of this research was to study how different biochar mixture rates affect the water holding capacity of biochar-amended loamy sand soil. This sandy

Table 2 Nitrogen loss estimates-by region and by crop [3]

	Acres	Volatilized		Dissolved in surface water runoff		Dissolved in leachate		Dissolved in lateral subsurface flow		Lost with waterborne sediment		Lost with windborne sediment		Sum of all loss pathways	
	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
By region															
Northeast	4.6	78,711	2.9	45,275	7.9	46,457	4.7	4,604	7.0	91,141	7.2	1,060	0.4	267,281	4.5
Northern Great Plains	24.3	596,583	21.6	64,928	11.4	36,852	3.7	11,222	17.0	164,394	12.9	131,371	49.4	1,005,360	17.0
By crop															
Barley	1.6	52,993	1.9	12,562	2.2	1,765	0.2	1,235	1.9	11,585	0.9	6,659	2.5	86,798	1.5
Corn	26.2	956,074	34.7	124,161	21.8	389,473	39.0	25,796	39.1	562,179	44.3	92,247	34.7	2,149,929	36.3
Corn silage	1.7	46,467	1.7	15,244	2.7	20,805	2.1	2,448	3.7	56,684	4.5	5,058	1.9	146,705	2.5
Cotton	5.6	101,326	3.7	55,777	9.8	114,922	11.5	2,574	3.9	51,654	4.1	48,920	18.4	375,172	6.3
Grass hay	4.9	59,044	2.1	66,011	11.6	4,287	0.4	1,660	2.5	13,986	1.1	34	<0.1	145,023	2.4
Legume hay	8.3	152,594	5.5	67,735	11.9	5,340	0.5	2,555	3.9	781	0.1	13	<0.1	229,193	3.9
Oats	1.3	18,264	0.7	3,289	0.6	4,435	0.45	512	0.8	14,784	1.2	2,515	0.9	43,797	0.7
Peanuts	0.6	16,915	0.6	3,124	0.5	40,268	4.0	1,637	2.5	3,957	0.3	2,455	0.9	68,355	1.2
Potatoes	0.3	20,253	0.7	8,181	1.4	21,245	2.1	785	1.2	4,006	0.3	0,710	0.6	56,178	0.9
Rice	1.2	11,869	0.4	60,612	10.6	39,659	4.0	177	0.3	13,268	1.0	60	<0.1	125,643	2.1
Spring wheat	6.9	129,671	4.7	21,068	3.7	1,248	0.1	1,666	2.5	48,548	3.8	29,990	11.3	232,189	3.9
Sorghum	3.7	147,017	5.3	10,851	1.9	30,979	3.1	2,495	3.8	36,176	2.8	34,269	12.9	261,785	4.4
Soybeans	22.6	581,091	21.1	90,757	15.9	282,995	28.3	17,786	26.9	352,233	27.7	24,865	9.4	1,349,726	22.8
Winter wheat	15.1	462,504	16.8	30,973	5.4	41,217	4.1	4,733	7.2	99,679	7.9	17,133	6.4	656,238	11.1
All crops	100.0	2,756,079	100.0	570,341	100.0	988,637	100.0	66,055	100.0	1,269,517	100.0	265,924	100.0	5,926,729	100.0

soil is the dominate soil type of the southeastern USA and is recognized as having poor water holding capacity and limited growth potential for crops [3]. More information pertaining to the water holding capacity of biochar will allow for a better understanding of the other attributes which biochar is stated to possess. The use of biochar as a soil amendment in areas prone to drought may increase by better understanding the water holding capacity characteristics of biochar.

Relevant previous work in biochar

The potential benefits of biochar soil amendment are well identified in the literature. These include carbon sequestration, improved crop yields, and enhanced water retention.

The choices of feedstock for biochar production are dependent upon the most readily available biomass as well as the handling mechanism [6,14]. Any organic material can be used to make biochar, including wood, grass, leaves, and manure [4]. It was also suggested by Karhu et al. [15] that it may be possible to develop specialized biochars to meet different needs of the end user. The most important determining factor in regards to the actual affect of these custom tailored biochars would be the feedstock and the temperature used to produce the biochar.

The conversion of biomass carbon to biochar leads to sequestration of about 50% of the initial carbon compared to 3% sequestration from burning and less than 20% from biological decomposition [16]. Biochar is resistant to decomposition and remains in the soil for centuries or millennia. In summary, pyrolysis can transfer 50% of the carbon stored in plant tissue from the active to an inactive carbon pool. The remaining 50% of plant carbon can be used to produce energy in the form of food and fuel. This enables carbon negative energy production if renewable resources are used. Pyrolysis would facilitate bio-energy production and carbon sequestration if the biochar is redistributed to agricultural fields. Lehmann et al. [10] proposed biochar from farm wood-waste as a promising method for integrating carbon sequestration and renewable energy generation with conventional agricultural production. It is clear that biomass conversion sequestration projects have the potential to contribute significantly to climate change mitigation, although they may not be economically attractive at current output production and carbon prices [17].

Biochar has been also shown to reduce the amount of methane (CH₄) released from agricultural fields that utilize cover crops as a nutrient supply [15]. In addition, biochar has been shown to improve the environmental needs of Mycorrhizal bacteria in the soil; these microbes are fundamental aspects of a healthy soil bed [18]. It is currently speculated that the increased microbial activity

is actually one of the largest determining factors in the positive effects seen in plants after the introduction of biochar.

Since the time of the Amazonian Terra Preta soils, increased crop yield has been a recognized benefit from biochar soil amendment [6]. Biochar is capable of increasing the levels of calcium, potassium, and phosphorus in loamy sand soil [19]. Biochar also proved an adequate medium for immobilization and retention of soluble cadmium and zinc as well as increased pH levels in acidic soils [5]. Biochar's ability to manipulate different nutrients at different rates, as well as raise pH at different intervals was also studied. The results showed that different feedstocks at different temperatures could have these effects and that it may be possible to create biochar to do a very specific task [13].

Chan et al. [20] investigated the effect of biochar produced from green waste on the yield of radish crops. They applied three rates of biochar (10, 50, and 100 t/ha) with and without supplemental nitrogen application of 100 kg, N/ha. Biochar alone did not increase radish yield, but in the presence of supplemental nitrogen, higher rates of biochar application resulted in higher radish yields up to 266%. Major et al. [21] reviewed existing work on the magnitude and dynamics of biochar's effect on nutrient leaching and discussed possible mechanism and processes by which this effect is observed. They observed that nutrient leaching is generally greatest under fertilized row crops such as corn or horticultural crops, and targeting these cropping systems may yield the best results for reducing leaching.

While many articles report on carbon sequestration potential and nutrient trapping, there have been only a few studies on the effect of biochar on water holding capacity. Novak et al. [14] reported an increase in the water holding capacity of a loamy sand soil with 2% mixtures of biochar made from various switchgrass feedstocks. They were interested in understanding the different effects of temperature and feedstock on the water holding capacity of biochar but all values were calculated at a 2% mixture rate only. By varying retort temperature from 250°C to 750°C, increases in water holding capacity ranging from 7% to 16% were observed. Another finding was an 11% increase in water holding capacity reported as an additional observation and was not validated through the use of control techniques [15]. The ability of biochar to increase water holding capacity could have profound effects on areas prone to drought [15]. Sohi et al. [12] summarized the current state of biochar knowledge and concluded that soil water holding capacity was an area of significance that was lacking in research.

Methods

Methodology

The design of this experiment consists of sampling different mixtures of biochar and loamy sand soil by mass to see the effects on the water holding capacity at different mixture rates. Due to the thousands of soil combinations and the large discrepancy from one soil to another, this study focuses on the most common agricultural soil in North Carolina and the southeastern USA as a whole which is loamy sand. The defined name of the soil to be used in this study is outlined by Novak et al. [14] as a loamy sand. This soil is characterized as less than 35% of clay (i.e., particle size is smaller than 0.002 mm) and less than 50% of fine sand (i.e., particle size is between 0.05 and 2 mm) [22]. Loamy sand has limited water holding capacity resulting in increased leaching of nutrients [22]. The use of poor farming practices and degradation from chemical fertilizers is a known factor in the transformation of traditionally fertile soils to the sandy textures commonly found in the southeastern USA [7].

The particle size of the biochar typically used in experiments ranges from 0.25 to 20 mm uniformed sieved size [4,19]. It was also suggested by Lehmann [4] that 2 mm of biochar be the most suitable for application to the agricultural lands as well as transportation. The actual percentages of biochar mixed with sample soils ranged from 0.5 to 91 metric ton/ha, which is approximately up to 4.5% of biochar amendment [14,23]. It was also reported by Jha et al. [23] that negative effects on plant development began to occur in mixtures, greater than 9% biochar to loamy sand by mass (e.g., 90 g/kg).

In this study, the samples were prepared using an unamended sample of loamy sand to establish a baseline measurement. The samples were first subjected to a characterization process where a sieve was used to insure a uniform size, less than 3 mm for the biochar and less than 2 mm for the loamy sand. Next, samples were mixed at different proportions between 0% and 100% of biochar to loamy sand by mass. In order to determine each sample weight, Howard's chart [24] was used. The use of Howard's chart will provide a relevant reference point for replication of the study and add validity to the experiment. Based on Howard's chart, a particle size, smaller than 2 mm, requires 20 g of saturated sample specimen [24].

The American Society for Testing and Materials (ASTM) standard D 2216-10, 'Laboratory determination of water (moisture) content of soil and rock by mass' states that soil samples be dried at (110°C) at relatively low humidity with a thermostatic control capable of maintaining 110°C ± 5°C. It also provides a

standard drying time of 12 to 16 h or until percent moisture readings over 1-h periods are less than 0.1%. Drying times may be reduced to 4 h if a forced-draft oven is used [25]. In addition, saturation procedures utilized by Péron et al. [26] present that a saturation period of 1 day will provide homogenization of water content throughout the sample.

Each mixture used in this study was saturated with water by following the procedure found in Péron et al. [26] to establish sample's water holding capacity. Water was slowly applied to each mixture container, while gently agitating, until excess water was observed. The mixtures were then allowed to sit for 24 h to assure homogeneity of water content throughout the sample. After that, the mixtures were drained by gravity for another 24 h through a coffee filter. Three 90-mL stainless steel containers were then tared, filled to two third full, and massed using a 0.01-g digital balance to determine wet mass. The samples were then dried at 110°C for 24 h using a convection oven and remassed to determine the dry mass. The results yielded the amount of water being held by each mixture.

Sample preparation

The biochar used for this experiment was produced by the research using a propane-fueled retort (i.e., pyrolysis). The vessel had an internal temperature sensor and the observer recorded the temperature as the reaction took place. Uncombusted gasses were flared off and the temperature reached 400°C toward the end of the reaction. The feedstock was mostly untreated yellow pine scrap lumber. The biochar (pyrolysis in 400°C for 3 h, C%: 71.2, N%: 0.2, surface area: 0.19 m²/g) was air dried, crushed by hand, and sieved to a 3-mm particle size. Representative feedstock and raw biochar are shown in Figure 1.



Figure 1 Representative raw yellow pine and resulting biochar from pyrolysis at 400°C.

The soil used in this study is loamy sand. A sample of loamy sand was acquired from the USDA-Agricultural Research Service (ARS) coastal plain soils, water, and plant research center in Florence, South Carolina. The USDA-ARS is a small research laboratory located on a historic tobacco farm and is designated as a creditable source for soil sampling [27]. The soil was air dried and sieved to a 2-mm particle size. Bulk mixtures with mass ratios between 0% and 100% biochar by mass were prepared. Representative samples are shown in Figure 2.

Results and discussion

Data collection and analysis

Collection of data occurred throughout the experiment. To determine the water holding capacity by mass, the following equation was used [25]:

$$\text{Water holding capacity (\%)} = \frac{(\text{mass}_{\text{wet}} - \text{mass}_{\text{dry}})}{\text{mass}_{\text{dry}}} \times 100\%$$

Statistical uncertainty (i.e., standard deviation) was determined in the way from the three replicate samples for each mixture. The average water holding capacities as a percentage of dry mass are shown in Table 3. It is noted that metric ton per hectare equivalent concentrations, calculated based on a soil density of 1,440 kg/m³ and a 15-cm treatment depth, are listed for agricultural comparison. Standard deviation at each proportion is also calculated, and it shows very low variance until 20% of biochar mixture. However, it is noticed that standard deviation gradually increases (up to 9.5%) as the mixture rate increases. Percent increase in water holding capacity from unamended soil is reported, along with the percent increase per percent biochar amendment. Note that unamended sandy loam soil has a water holding

capacity of 16%, while pure biochar can hold over 2.7 times (= 270%) its mass of water as shown in Figure 3.

Water holding capacities for biochar concentrations below 10% are shown in Figure 4. Notice that the error bar and the error ranges are also shown in the figure as the measurements repeated three times for each mixture. It was reported by Jha et al. [23] that mixture rates of less than 10% were safe for agricultural purposes to loamy sand soil (i.e., agriculturally meaningful biochar amendment). A clear positive correlation is shown in Figure 4 with doubled water holding capacity with around 9% of biochar amendment. An agriculturally relevant biochar amendment of 5% biochar (around 100 metric ton/ha) results in a water holding capacity of 24%, that is, a 50% increase over unamended soil. This is significant due to the tremendous amount of research, presenting that poor water holding capacity plays a major role in nutrient loss in the southeastern USA [12,13,19,21].

To quantify the *value* of biochar amendment, the increase in water holding capacity per unit of biochar amendment is shown in Figure 5. For biochar concentrations below 10%, higher biochar concentrations provide an increasingly greater enhancement of water holding capacity per unit amendment, suggesting a better value from higher concentrations. Above 10% biochar concentration, however, the increase in water holding capacity per unit of biochar amendment remains constant at around 12%, suggesting no further increase in value above 10% amendment. A possible interpretation is that 10% amendment maximizes the water holding value of biochar.

Conclusions

While previous research suggests that biochar is well suited for increasing the water holding capacity of soils, there have been few quantitative studies on the effect of



Figure 2 Representative prepared samples after sieving and mixing.

Table 3 Experiment results

% biochar by mass	Metric ton/ha equivalent	Average water holding capacity (%)	Standard deviation (%)	% increase	% increase/ % amendment
0	0	16	0.7	-	0
1	21.6	16.8	0.7	5.1	5.1
2	43.2	19	0.1	18.9	9.4
3	64.8	19.3	0.2	20.7	6.9
4	86.4	21.4	0.2	33.9	8.5
5	108	23.5	0.3	47.3	9.5
6	129.6	27.2	0.5	70.4	11.7
7	151.2	24.8	0.3	55.2	7.9
8	172.8	29.5	1.7	84.8	10.6
9	194.4	30.2	1.8	89.1	9.9
10	216	32.3	1.4	102.1	10.2
15	324	44.4	0.6	178	11.9
20	432	50.4	1.3	215.5	10.8
25	540	60.1	3	276.6	11.1
30	648	78.3	8.7	390.2	13
35	756	81	3.5	407.4	11.6
40	864	91.2	2	470.8	11.8
45	972	92.4	1.9	478.8	10.6
50	1,080	124.9	9.3	681.7	13.6
75	1,620	209.6	7.8	1,212.6	16.2
100	2,160	274.1	9.5	1,616.1	16.2

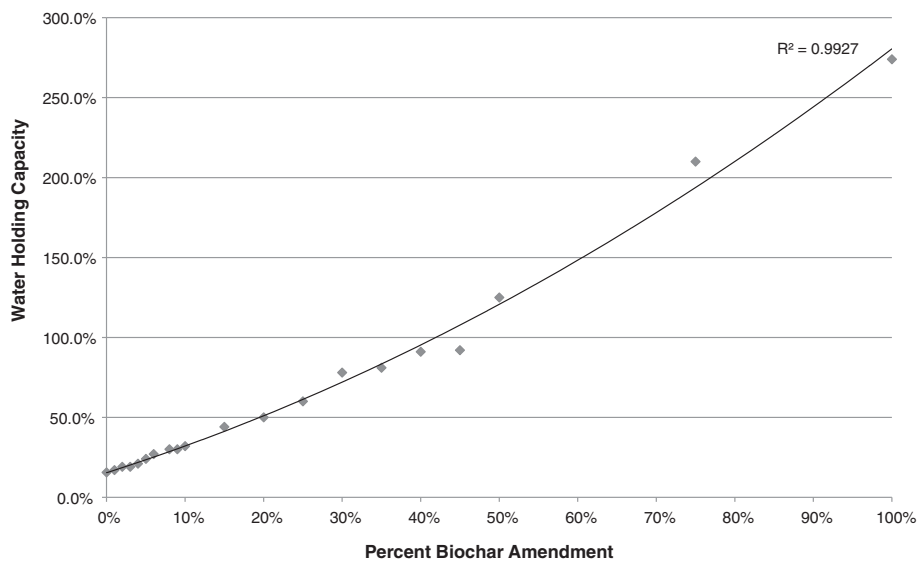


Figure 3 Water holding capacity at different mixture rates varied from 0% to 100%.

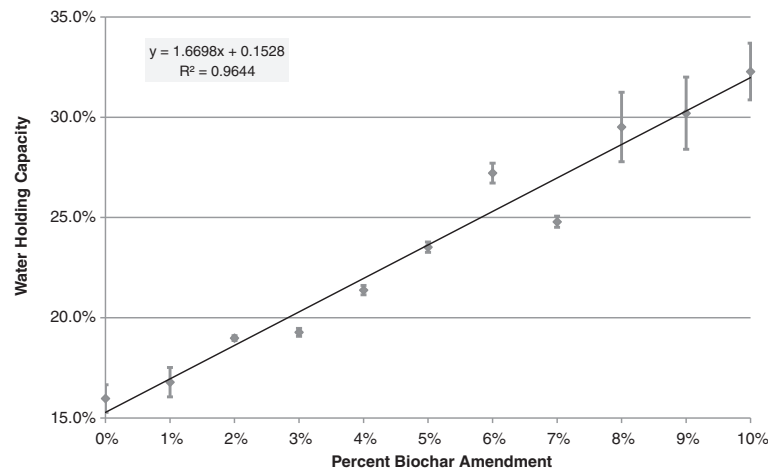


Figure 4 Water holding capacity at different mixture rates varied from 0% to 10%.

biochar on water holding capacity. This research found that the biochar used in this study increases water holding capacity of a loamy sand soil by around 1.7% by mass for each 1% of added biochar over the agriculturally relevant range up to 10% biochar concentrations. These lower end mixture values are representative of the allowable amounts of biochar that can be added without causing damage to plants. Water holding capacity of un-amended sandy loam soil, 16%, is doubled by the addition of 9% by mass of biochar. This finding is important because it establishes biochar as an effective medium for increasing irrigation effectiveness, runoff mitigation, and reducing non-point source agricultural pollution.

Biochar's effects on water when mixed with soils are important to understand because it may be the most influential aspect of biochar in regards to microbial activity, plant growth, and nutrient usage. The current practices of irrigation are awaiting a revolution in order to more efficiently provide soils with water, but it will be important to understand the possible impact

of preparing soils with amendments such as biochar. The significance of such information may allow for a shift in the conventional wisdoms associated with irrigation as well as fertilization practices.

This study only considered one type of biochar (yellow pine from pyrolysis at 400°C) mixed with one type of soil (loamy sand), and thus further research is clearly indicated. Additional research should address the effects of biochar feedstock and production methods, soil types, particle size, and saturation/drying cycles. The creation of a water release curve for biochar-amended soils would be a logical next step.

To promote the practice of agricultural biochar soil amendment, the full life cycle costs and benefits to biochar soil amendment must be estimated. The effect of water holding capacity on crop growth due to water holding capacity, nutrient retention, and microbial growth must be understood, in addition to the benefits of the likely reduced need for irrigation and fertilizer and pesticide usage. Inclusion of traditionally externalized costs associated with

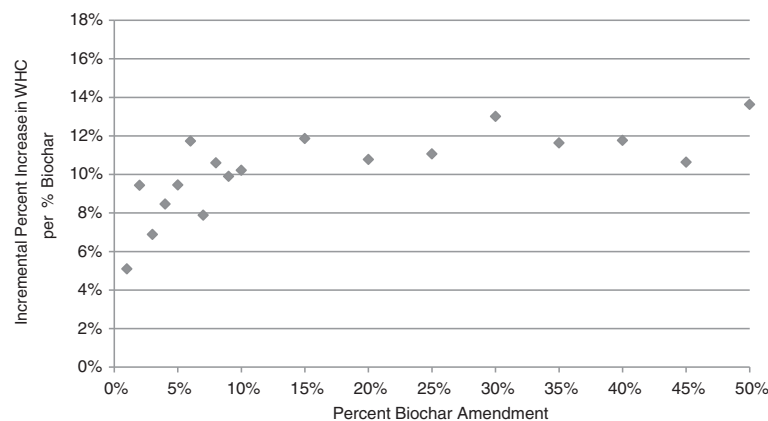


Figure 5 Incremental increase in percent water holding capacity normalized to percent biochar amendment.

carbon and environmental degradation, a side effect of current farming techniques, will further improve the cost/benefit analysis of agricultural biochar usage.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

OY supervised SS's Master of Science research regarding the biochar experiment and drafted the manuscript. BR participated in the design of the study and drafted the manuscript. SS conducted the biochar experiment for this research and helped to write the manuscript. All authors read and approved the final manuscript.

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