

*NCHRP IDEA Program*

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# **Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways**

Final Report for  
NCHRP IDEA Project 182

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*October 2017*

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- The NCHRP IDEA Program, which focuses on advances in the design, construction, and maintenance of highway systems, is funded by American Association of State Highway and Transportation Officials (AASHTO) as part of the National Cooperative Highway Research Program (NCHRP).
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## **IDEA Program Final Report**

**NCHRP-182**

Prepared for the IDEA Program

Transportation Research Board

The National Academies

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*University of Delaware*

*10/11/2017*

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## EXECUTIVE SUMMARY

### CONCEPT

To operate existing roadways and construct new ones, Departments of Transportation (DOTs) and other transportation agencies must meet increasingly stringent regulations for stormwater runoff. For example, to satisfy Chesapeake Bay water quality standards for nutrients and sediment, Maryland State Highway Administration must reduce their emission of nitrogen, phosphorus, and sediment by 75% by 2020. Achieving this milestone is estimated to cost in excess of \$720 million using standard technologies, assuming \$144k to treat one impervious acre and > 5000 acres to treat. Other states with roadways contributing to the Chesapeake Bay (DE, DC, NY, PA, VA, and WVA) must meet similar reduction goals. In other regions of the country, DOTs must satisfy increasingly stringent stormwater regulations for metals, bacteria, and other pollutants.

In this study the reduction of nutrient loading and stormwater runoff volume by biochar amendment to the soils of highway greenways was examined. Biochar is a charcoal-like material formed by combusting waste organic matter in an oxygen-limited environment and has high internal porosity and low particle density. Therefore, amending biochar to highways soils is expected to increase total porosity and water retention. Because biochar particles are often large and may enhance soil aggregation, biochar amendment may also increase soil hydraulic conductivity. Finally, based on other recently published findings, biochar amendment is expected to enhance sorption and transformation of nitrogen compounds. The objective of this Type 1 project was to test these hypotheses in controlled lab and pilot-scale experiments. While the focus of this work is on treatment of nitrogen and sediments in stormwater runoff, because biochar amendment reduces volume of stormwater runoff, it will also reduce loadings of other pollutants found in stormwater to surface water bodies.

### METHODOLOGY AND FINDINGS

Lab-Scale Experiments After screening several commercially available biochars, Soil Reef™ biochar (The Biochar Company, Berwyn, PA, USA) was selected. This biochar was amended to three representative soils in the MidAtlantic region: silt loam, sandy loam, and loamy sand. Biochar amended at 2 or 6% mass fraction to these soils increased available water content, a measure of a soil's ability to retain water, by 20-70% depending on the soil. Lab-scale tests also demonstrated that biochar amendment almost always increased unsaturated hydraulic conductivity, up to 500% for loamy sand. However, the impact of biochar amendment on saturated hydraulic conductivity was less significant, with conductivity only increasing by 20% with biochar amendment to loamy sand. These changes in soil hydraulic properties suggest that biochar amendment to a roadway soil may result in reductions in stormwater runoff, but will depend on the roadway soil and amount of biochar added.

Pilot-Scale Experiments To evaluate if biochar-induced changes in soil hydraulic properties determined in lab-scale experiments might reduce stormwater runoff, four  $0.6 \times 0.3 \times 0.3$  m (length  $\times$  width  $\times$  depth) greenways were constructed in the laboratory: two filled with sandy loam soil and two filled with the mixture of sandy loam and 4% biochar by mass. These experiments captured the three-dimensional water flow that will occur in the field with biochar-amended roadway soils, but allow more controlled evaluation of stormwater flow and nutrient transformation. Consistent



with lab-scale experiments, biochar amendment increased water retention and saturated hydraulic conductivity. These effects reduced stormwater runoff by 13% with respect to biochar-free soil, consistent with what was expected from lab-scale experiments. While data for stormwater runoff reduction were limited to one storm event, data collected over multiple wetting and drying cycles showed gradually increasing soil water retention, particularly in biochar-amended test cells. These data suggest time-dependent formation of soil aggregates that will enhance the soil's ability to retain and treat stormwater as biochar and soil age.

Field-Scale Experiments With support from the National Fish and Wildlife Foundation (NFWF), Delaware Department of Transportation, Maryland Transportation Authority, and City of Charlottesville, VA, biochar was amended at 4% to a sandy loam in a roadway filter strip along a four-lane divided highway in Delaware. Support from this Type 1 IDEA project was used to conduct lab and field measurements in support of the NFWF project. Over 74 storm events in 2016/2017, biochar amendment reduced average stormwater runoff volume and peak flow rate by 84 and 77%, respectively. In comparison, tillage alone of biochar-free soil reduced average stormwater runoff volume and peak flow rate by 54 and 51%, respectively. Thus, *biochar amendment increased the ability of the tilled roadway soil to reduce stormwater runoff and peak flow rate by ~ 50%*. This effect was 2 to 3 times more significant than what might be expected from lab and pilot-scale experiments in this soil/biochar mixture. The reason for the greater stormwater treatment in the field was macropores. Soil macropores in biochar-amended soils accounted for 84% of the flow under saturated conditions. Time-dependent formation of soil aggregates by microbial processes is believed to be the cause of macropore formation, which was enhanced by biochar.

In summary, biochar amendment to three representative roadway soils indicated that biochar amendment will improve soil hydraulic properties. Experiments at the pilot and field scale demonstrate that these effects enhance stormwater treatment, resulting in reductions in stormwater runoff volume and peak flow rate. Somewhat surprisingly, the benefits of biochar amendment were most pronounced at the field scale, which was attributed to time-dependent formation of soil aggregates that was not yet a significant process at the pilot scale. Future measurements in the pilot-scale experimental devices are expected to document this. Future work should evaluate performance of other commercially available biochars.

Cost Analysis Using costs determined from field-scale implementation, 0.12 acres of biochar-amendment is needed to treat 1-acre impervious with approximately 83% removal of nutrients and sediments at a cost of ~ \$31,700 per impervious acre treated, a standard metric for assessing BMP performance. A cost analysis comparing biochar-amendment to 23 BMPs, indicated that biochar is less expensive than 20 other BMPs – up to 10 times less. Biochar-amendment is more expensive than only three BMPs: erosion and sediment control, street sweeping, and urban grass buffers. However, utilization of these BMPs may be limited, for example, because of area of land needed and other constraints like existing slope and buffer width available for urban grass buffers. While biochar costs are similar to an urban grass buffer (\$26,600 per impervious acre), biochar-amendment requires a dramatically smaller footprint: 0.12 versus 3.7 acre per impervious acre for biochar and urban grass buffer, respectively. Thus, while these less expensive BMPs should be used where applicable, they are often insufficient to achieve necessary control of sediment and nutrients, in which case biochar-amendment could be used.

Future work should examine the longevity of biochar amendment; the utility of using less biochar, e.g., 2% application rate, to achieve the same benefit; and development of models to predict the effects of biochar amendment on stormwater treatment for a wide range of applications.

## **1. IDEA PRODUCT**

Stormwater discharge from roadways is a source of pollution for waterways that must be treated and controlled. Increasing stormwater regulations on nutrient loads are compelling state DOTs to undertake stormwater restoration to reduce nutrient loads and where possible stormwater volume. While existing stormwater technologies such as detention ponds and new Low Impact Development features can remove nutrients, the required increase in load removal and runoff volume reduction will be costly on a watershed-scale since more real estate is required for increased treatment using current technologies. We propose an entirely new approach that has the potential to dramatically increase nutrient removal efficiency and simultaneously reduce stormwater volume while avoiding new infrastructure – the addition of engineered biochar to highway greenways. Rather than capture stormwater for treatment in new treatments systems, existing highway greenways can be “enhanced” thus providing stormwater treatment without the cost of new infrastructure or purchase of additional right-of-way. Further, this stormwater treatment is achieved using a waste material, as biochars are often created from waste organic matter, e.g., sawdust.

## **2. CONCEPT AND INNOVATION**

Biochar is a charcoal-like material formed by combusting waste organic matter in an oxygen-limited environment. Biochars produced from almost all feedstocks have high internal porosity and low particle density. Therefore, adding biochar to roadway soils would result in increased total porosity that promotes increased capture of stormwater, and smaller soil bulk density that promotes deeper plant root growth and greater stormwater infiltration. Biochar amendment also promotes soil aggregation and the formation of soil macropores, which will increase infiltration and stormwater capture. In addition to these benefits to soil hydrology that should result in stormwater volume reduction, biochar has high surface area, significant cation exchange and adsorption capacity, and a stable carbon structure consisting of electroactive quinoid functional groups that serve as an efficient medium for electron transfer (wood biochars). These properties we believe important for increasing nutrient sorption and denitrification rate. Thus, a properly selected biochar amended to roadway soil is expected to increase stormwater capture, reduce stormwater runoff, and enhance retention and transformation of nutrients. These properties may prove a critical benefit for highway greenways: holding nutrient-laden water in the soil zone provides time for evapotranspiration, plant uptake, and microbial degradation of nutrients, while simultaneously reducing stormwater runoff volume.

It is also important to note that biochar amendment is expected to enhance the removal of other pollutants from stormwater runoff, including bacteria and metals, because of two factors: reduction in stormwater runoff volume that is reported in this study, and pollutant sorption. Thus, while the focus in this study was reduction of stormwater nutrient loads, biochar amendment will be beneficial to treatment of other stormwater pollutants.

### 3. INVESTIGATION

This project developed and demonstrated the application of a wood biochar (Soil Reef<sup>TM</sup>) to roadway soils for increasing stormwater retention and infiltration, and reducing stormwater runoff at three experimental scales: lab, pilot, and field. The influence of scale on biochar amendment was assessed by comparing data from these different scales.

#### 3.1. INFLUENCE OF BIOCHAR ON STORMWATER RETENTION AND INFILTRATION – LAB SCALE

##### 3.1.1. Biochar and Soil Samples

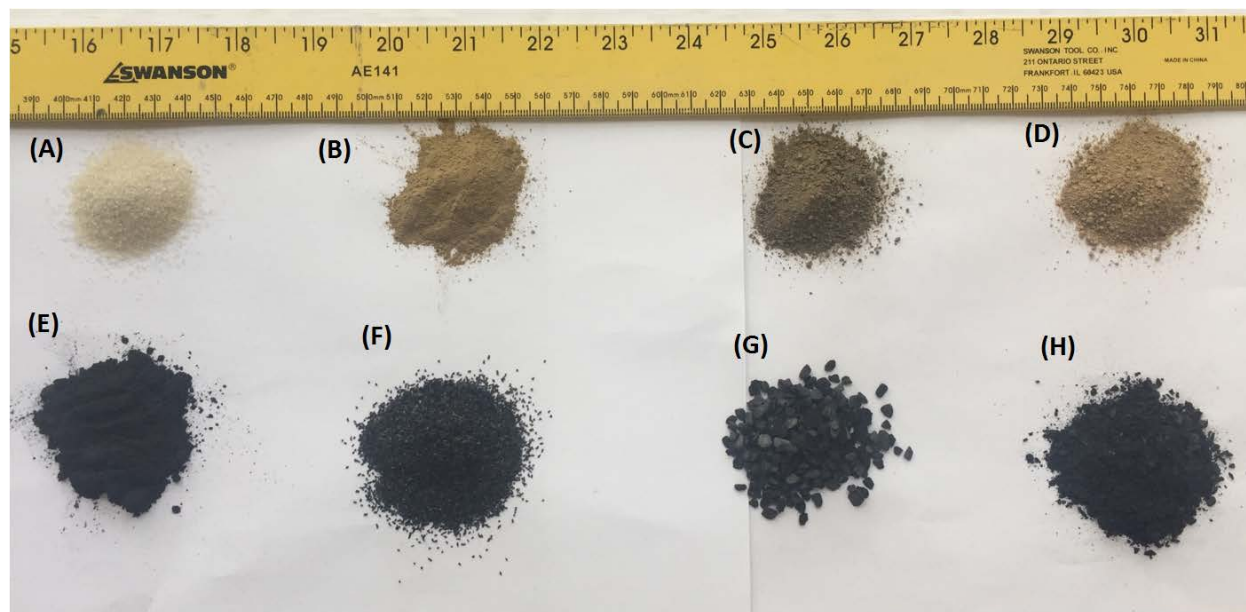
Commercially available Soil Reef<sup>TM</sup> biochar (The Biochar Company, Berwyn, PA, USA) was selected in this study based upon preliminary screening of commercially available biochars. Future work should examine other biochars and provide guidance for biochar selection based upon readily-measured biochar properties.

Soil Reef<sup>TM</sup> biochar is produced from carbonized Southern Yellow Pine by continuous pyrolysis at 550 °C for 10 min. This biochar has high specific surface area ( $350 \pm 30 \text{ m}^2 \text{ g}^{-1}$ ) and internal porosity ( $0.83 \pm 0.01 \text{ mL g}^{-1}$ ), and thus should have a significant effect on water retention and hydraulic conductivity. Because biochar properties may change after soil amendment due to leaching of readily soluble compounds, biochar was pre-rinsed before use in laboratory experiments. Biochar was added to de-ionized (DI) water at 1:50 ratio by mass (biochar to DI water), and the solution agitated at 50 rpm for 1 day. The rinsate was replaced with fresh DI water and the process repeated at least three times until the electrical conductivity of the rinsate was less than  $100 \mu\text{S cm}^{-1}$ . Rinsing biochar removed hydrophobic coatings on biochar surfaces that influence soil wettability (*I*) and aged the biochar, making it more representative for field conditions. The rinsed biochar was oven-dried at 105 °C for 24 h and then cooled to room temperature.

Natural soils were selected based on the United States Department of Agriculture (USDA) soil classification to have soil textures that span those found in the MidAtlantic region: silt loam, sandy loam, and loamy sand. These soil types are typical for many vegetated filter strips in the Coastal Plain region of the east coast (2). The loamy sand and silt loam were collected from 0 to 10 cm depth at the University of Delaware Farm Land at Newark, DE: 39°40'20.2"N 75°44'32.5"W and 39°40'11.5"N 75°45'07.9"W for loamy sand and silt loam, respectively. In order to have more diverse range of particle sizes between soil samples, small amounts of silt and clay were removed from the loamy sand sample using a sieve with 0.075 mm opening. The sandy loam was collected from 0 to 30 cm depth along Delaware State Route 896 located at Middletown, DE (39°31'52.0"N 75°44'12.8"W), which is the location of the field site where biochar was amended to a roadway soil (discussed below). All soils were oven-dried, crushed using a mortar and rubber-tipped pestle, sieved to less than 2 mm size, and stored at room temperature before use. In addition to these three natural soils, a uniform engineered sand (30/40 Accusand, Unimin Co., Le Sueur, MN, USA) was also used. This Accusand was further

sieved to a more uniform particle size (0.5-0.59 mm) using #30 and #35 sieves, then rinsed with DI water and finally oven-dried at 105 °C for 24 h.

Rinsed and unsieved biochar was added to natural soils at 2% and 6% (by mass). These application rates were selected based on minimum and maximum possible large-scale application rates. In addition, in order to better understand the mechanisms by which biochar alters soil hydraulic properties, biochar was sieved to different particle sizes: large (2-4.75 mm), medium (0.5-0.59 mm), and small (<0.075 mm). These biochar sizes were rinsed following the above-mentioned procedure, oven dried, and re-sieved. These different biochar sizes along with unsieved biochar were added to the uniform Accusand at 6% by mass. Photographs of soil and biochar samples are presented in Figure 1.

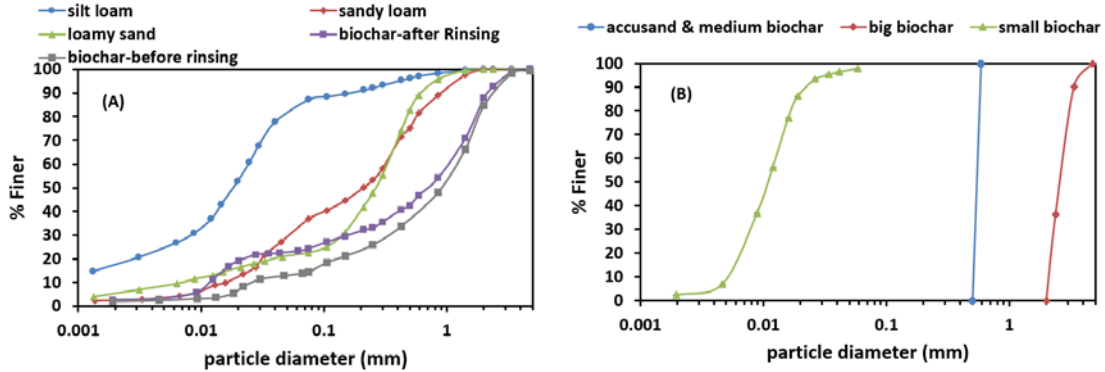


**FIGURE 1** Photograph of soil and biochar samples used in experiments: (A) Accusand, (B) silt loam, (C) sandy loam, (D) loamy sand, (E) small biochar, (F) medium biochar, (G) large biochar, and (H) unsieved biochar.

### 3.1.2. Particle Size Distribution

Sieve and hydrometer analyses were used to determine particle size distributions (PSD) of soil and biochar samples. The distribution of particles larger than 0.075 mm was determined by sieving, while the distribution of particles smaller than 0.075 mm was determined by a sedimentation using a hydrometer (3). All samples were oven-dried at 105 °C for 24 h before testing. A 500 g subsample of soils and a 200 g subsample of biochar were used for sieve analyses. Samples were wet sieved through 0.075 mm sieve. The coarse fraction retained on the 0.075 mm sieve was then oven-dried at 105 °C for 24 h, weighed, and then dry sieved using a wide range of sieve sizes. For hydrometer tests, 50-100 g of sample (either biochar or soil) were used. Hydrometer tests were performed according to ASTM D422-63, using 152-H hydrometer (3). Data from sieve analyses and hydrometer tests for each sample were combined to produce a single PSD.

The PSDs quantify the impact of biochar amendment on soil texture. PSD's of the three soil types and biochar (before and after rinsing) are shown in Figure 2. Rinsing the biochar in DI water changed the PSD of biochar: particles were weathered and stabilized, resulting in the breakup of very large particles. Because biochar particles can physically disintegrate, biochar particle size is not a static property and can change over time and as a function of environmental conditions (4). Soil Reef™ biochar has larger particle sizes than the three natural soils. This suggests that biochar-amended soil will create larger pores than the unamended soil, resulting in increased hydraulic conductivity.



**FIGURE 2** Particle size distribution of (A) natural soil and unsieved biochar (before and after rinsing), and (B) Accusand and different sieved biochar particle sizes.

### 3.1.3. Particle Density, Bulk Density, Porosity and Surface Area

The particle density for all soils was measured using the pycnometer method (5). Biochar is a very porous material with internal pores ranging from nanometer to micrometer (6). To characterize these pores and biochar density, mercury intrusion porosimetry (Micrometrics Analytical Services, Norcross, GA, USA) and N<sub>2</sub> and CO<sub>2</sub> sorption measurements were performed on unsieved biochar to determine internal biochar pore size distribution and specific surface area (7, 8). These data were used to determine biochar envelope and skeletal density. Biochar envelope density is mass of solid divided by the sum of solid and internal biochar pore volume, and biochar skeletal density is the mass of solid divided by the solid or skeletal volume. These parameters are needed to estimate the influence of biochar amendment on porosity and water retention of biochar/soil mixtures. Using these measurements, the average particle density of any biochar/soil mixture was calculated

$$\rho_p = \frac{100}{\frac{\% \text{ biochar}}{\rho_p} + \frac{\% \text{ soil}}{\rho_p}} \quad (1)$$

where % biochar and % soil are mass percentages, and  $\rho_p$  is particle density (soil) or skeletal density (biochar) (g cm<sup>-3</sup>).

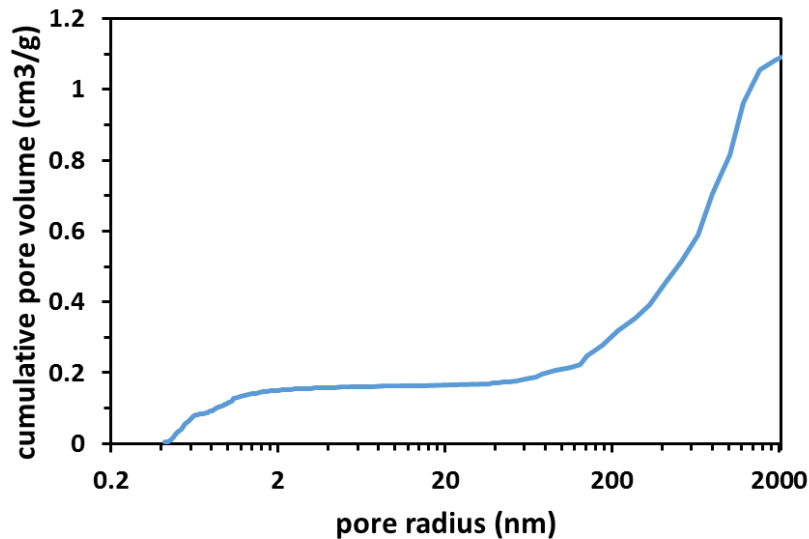
To determine dry bulk density, the oven dried soils or soil mixtures were gently repacked into a soil column (250 mL, inner diameter 80 mm, height 50 mm). To eliminate any voids and gaps, the cores were lightly tapped 50 times on the table during the packing. Excess particles were carefully removed using a margin trowel, and samples were weighed to

obtain dry solid mass. The dry bulk density is calculated by dividing total solid mass by total volume. The average particle density and the dry bulk density of all mixtures were used to obtain the total porosity ( $n$ ) of the sample mixtures.

$$n = 1 - \frac{\rho_b}{\rho_p} \quad (2)$$

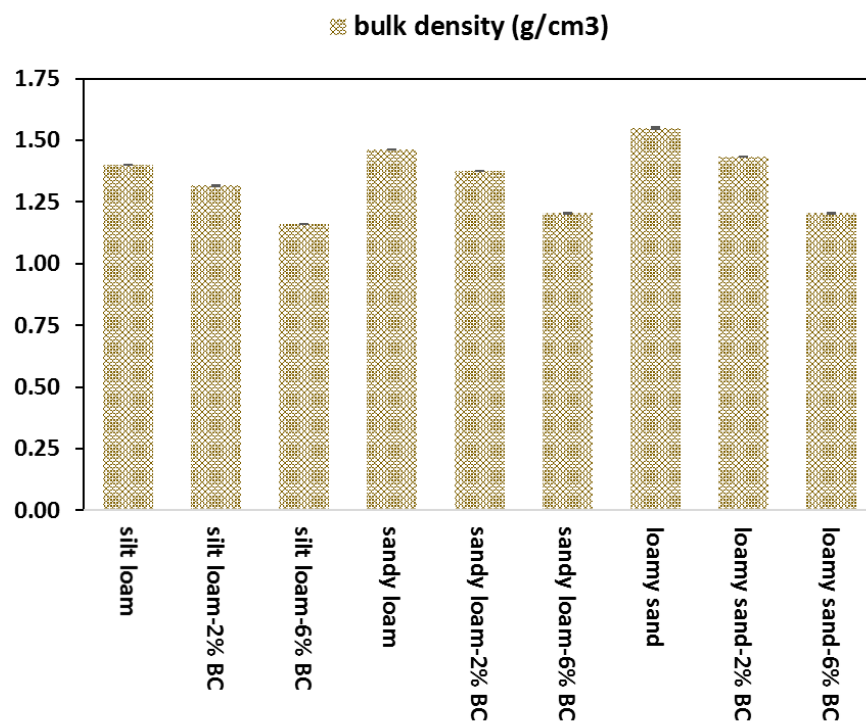
where  $\rho_b$  is dry bulk density density ( $\text{g cm}^{-3}$ ). If instead the biochar envelope density is used in equation (2), the porosity is the inter porosity (pores between individual biochar particles). The difference between total and inter porosity is intra porosity (pores inside biochar particles).

Soil Reef Biochar's specific surface area, envelope and skeletal density were determined to be  $438.6 \pm 1.1 \text{ m}^2 \text{ g}^{-1}$ ,  $0.524 \pm 0.009$  and  $1.23 \pm 0.12 \text{ g cm}^{-3}$ , respectively. The internal pores of this biochar range from 0.83 nm to  $4.13 \mu\text{m}$  (Figure 3), and the total internal pore volume is  $1.092 \pm 0.010 \text{ cm}^3 \text{ g}^{-1}$ . The biochar is less dense than natural soil ( $\sim 2.65 \text{ g cm}^{-3}$ ). Therefore, according to equation (1) adding biochar to soil will decrease the average particle density of soil-biochar mixtures. Furthermore, the incorporation of biochar will lower the dry bulk density, due to increasing total soil pore volume and/or lowering average particle density (9).

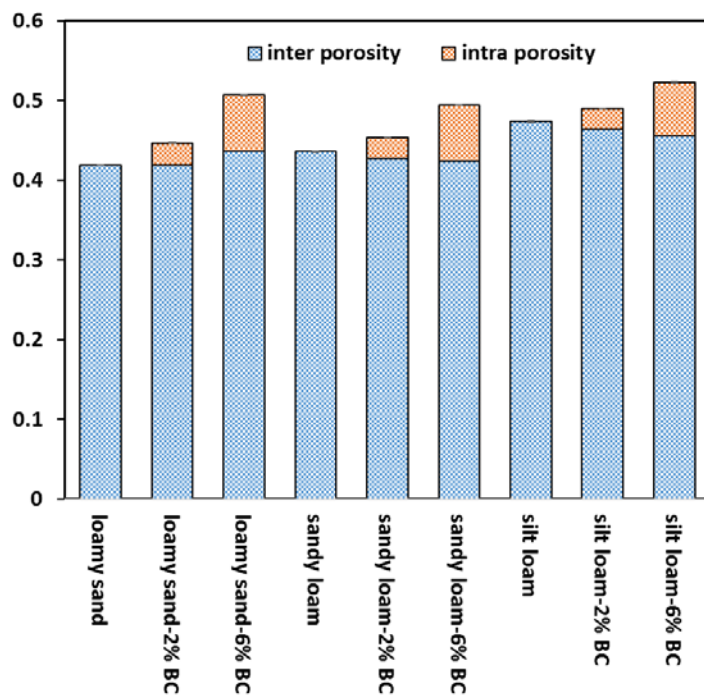


**FIGURE 3 Internal pore size distribution of Soil Reef™ biochar determined from mercury porosimetry.**

The dry bulk density and porosity of soil and soil/biochar mixtures tested in this work are shown in Figures 4 and 5, respectively. Amending the three soils with biochar at 2 or 6% decreased dry bulk density for all soils, which enhances plant root growth. Total porosities of each soil also increased, which should result in increased stormwater retention. For silt loam, for example, dry bulk density decreased by 5.9 and 16.9% and the total porosity increased by 4.6 and 13.7%, respectively, when 2 or 6% biochar was amended. Similar changes were found for sandy loam and loamy sand (see Figures 4 and 5). The increase in total porosity with biochar amendment is due primarily to the additional pore volume inside biochar particles – intra porosity (Figure 5).



**FIGURE 4** Bulk density of natural soils and their mixture with unsieved biochar (% values are biochar mass fraction in the samples).



**FIGURE 5** Total porosity, inter porosity, and intra porosity (pore volume within particles) of natural soils and their mixture with unsieved biochar (% values are biochar mass fraction in the samples).



#### 3.1.4. Water Retention – Dry Region

Retention of water for matric potentials between  $-10^4$  to  $-10^7$  cm  $H_2O$  was measured for soil/biochar mixtures using a WP4C water potential meter (Decagon Pullman, WA, USA, Figure 6). Samples were packed into small cups, and then DI water added to the cups to saturate samples. These saturated samples were placed in an oven for different periods to achieve a range of water contents. Then, samples were inserted into the WP4C where the total water potential was measured based on the chilled mirror dew point technique. Finally, the matric potential for each sample water content was determined by subtracting the osmotic potential, which was measured separately, from the total potential determined with the WP4C.



**FIGURE 6 Schematic of WP4C water potential meter for measuring water retention in dry region (taken from Decagon, Inc., WP4C operation manual).**

The gravimetric water content (mass of water/ dry mass of solid) is shown in Figure 7 as a function of matric potential for all biochars tested. Significant water is retained by biochar even when matric potentials are small, which is attributed to the water held in small micro and nano pores and/or sorption to biochar surface (10). Because data for different size fractions of biochar overlap, the internal micro and nano pore space as well as biochar surface area are independent of particle size. Similar water retention data for the three natural soils and Accusand are shown in Figure 8. Biochar holds significantly more water than natural soil and Accusand at high matric potentials, which corresponds to the data range shown in Figure 8. Soils with smaller particle size distribution and therefore higher surface area (e.g., silt loam versus loamy sand) exhibited higher water retention.



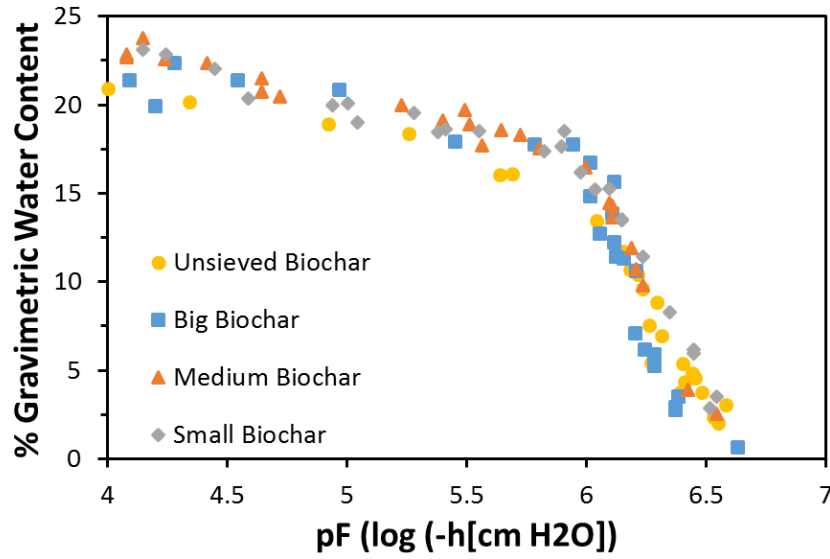


FIGURE 7 Water retention of different biochar particle sizes in the dry region ( $h = -10^4$  to  $-10^7$  cm H<sub>2</sub>O).

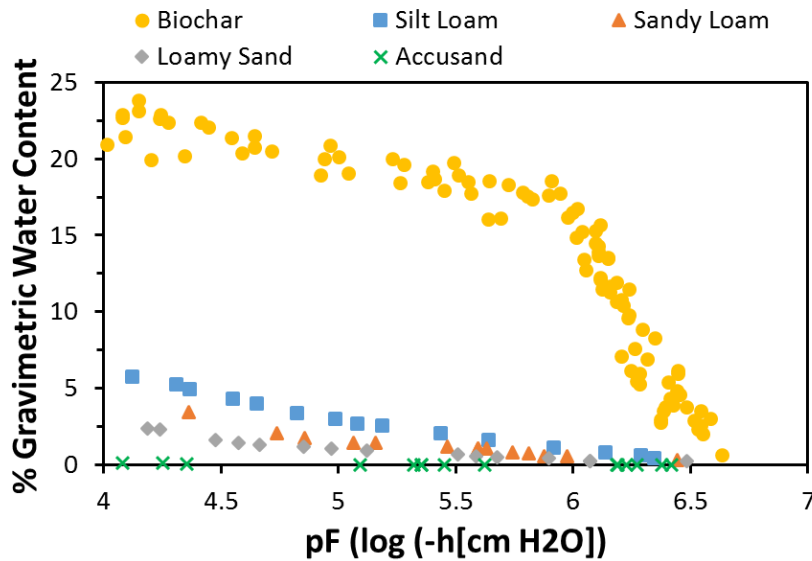


FIGURE 8 Comparison of water retention for biochar, natural soils, and Accusand in the dry region ( $h = -10^4$  to  $-10^7$  cm H<sub>2</sub>O).

The data shown in Figure 8 suggest that if biochar is mixed with soil, biochar-amended soil will retain significantly more water than soil without biochar. Water retained in soil amended with 2 or 6% biochar for all three natural soils tested is shown in Figure 9. Biochar amendment increased water retention for all soils, with the most dramatic increase shown for 6% biochar amendment to loamy sand.

While it is possible to experimentally measure the increase in water retention for any particular soil/biochar mixture, if models can predict this behavior then engineers and policy makers can screen different soil/biochar mixtures and

estimate how much biochar is required to achieve a desired increase in water retention. For water retention in the dry region, a simple model based upon the water retention behavior of the biochar and soil measured independently can be used to estimate the water retained in a soil/biochar mixture of specified biochar content:

$$MC_{mixture\ at\ h} = \frac{MC_{soil\ at\ h} \times \% \text{ soil} + MC_{biochar\ at\ h} \times \% \text{ biochar}}{100} \quad (3)$$

where MC is predicted gravimetric water content of biochar-solid mixture,  $h$  is matric potential in cm H<sub>2</sub>O, and % soil/biochar are mass percentage of soil and biochar, respectively. Model predictions using equation (3) are shown in Figure 9 and demonstrate excellent agreement with data. Similarly, this model was applied to mixtures of Accusand with various particle sizes of biochar with results shown in Figure 10. Here too equation (3) predicted the increase in water retention from biochar amendment very well. Results also demonstrate that water retention is not affected by biochar particle size in the dry region.

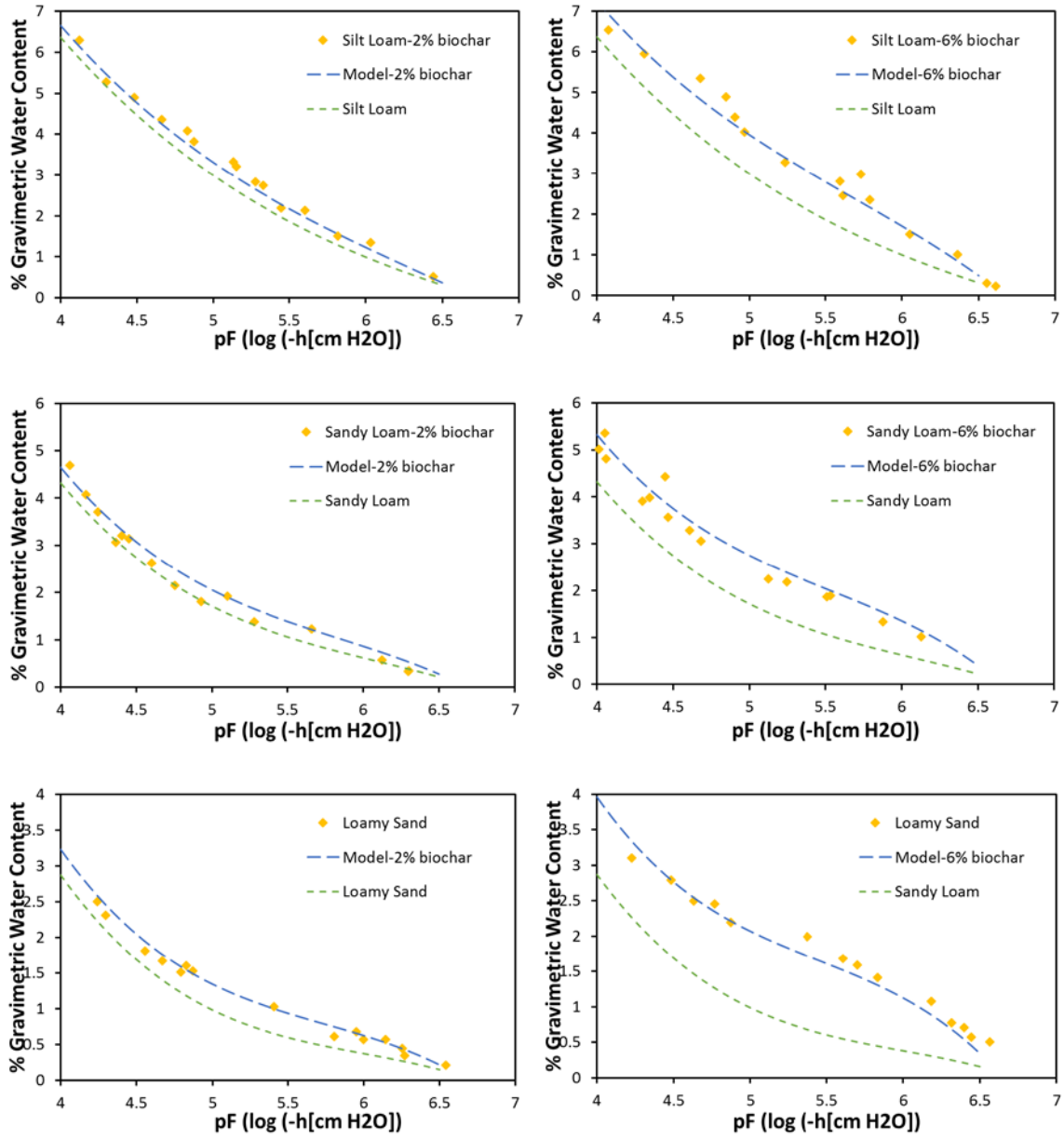
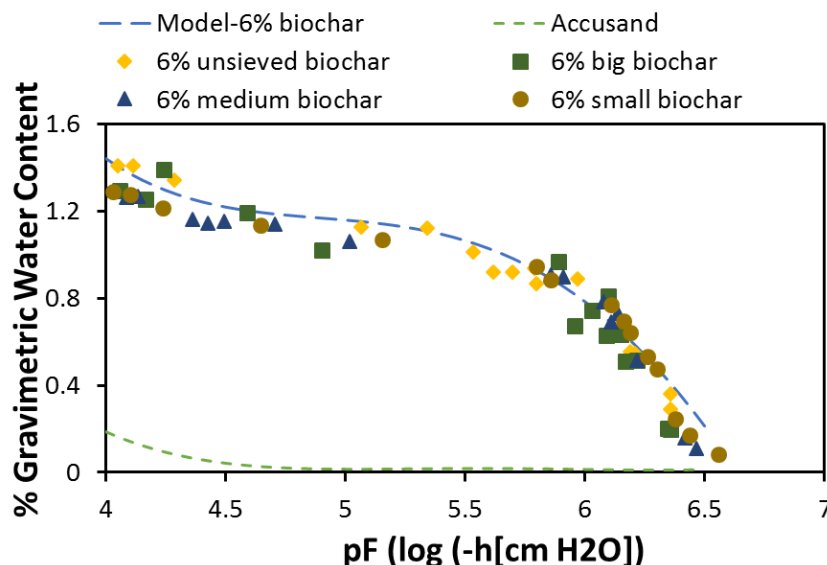


FIGURE 9 Measured and predicted water retention in the dry region ( $h = -10^4$  to  $-10^7$  cm H<sub>2</sub>O) for natural soil amended with unsieved biochar (% values are biochar mass fraction in the samples).

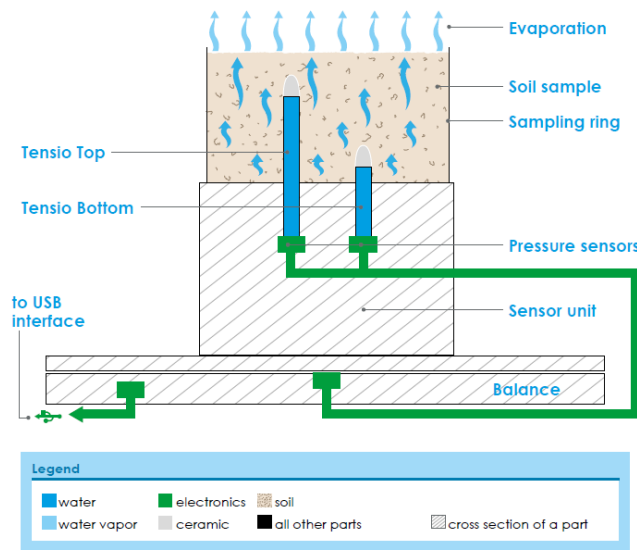


**FIGURE 10** Measured and predicted water retention data in the dry region ( $h = -10^4$  to  $-10^7$  cm H<sub>2</sub>O) for Accusand amended with different biochar particle sizes (% values are biochar mass fraction in the samples).

### 3.1.5. Water Retention – Wet and Dry Regions

To determine the influence of biochar on water retention in the wet region (0 to  $-10^4$  cm H<sub>2</sub>O), the soils and soil/biochar mixtures were gently packed into soil columns (250 mL, inner diameter 80 mm, height 50 mm), similar to the method for determining dry bulk density. Two independent replicates of each soil or soil/biochar mixture were prepared. The sample cores were placed in a metal bin and slowly saturated with de-aired DI water in 1-3 cm increments until the water level reached ~ 0-1 mm from the top of sample cores. To avoid soil swelling during the saturation process, a 2kg-weight was placed on top of each soil core. A metal screen was placed between each core and the weight to allow air transfer during saturation. Once water levels reached the top of each core, the bin was covered to minimize evaporation and cores allowed to slowly saturated over-night under atmospheric pressure.

Once water saturated, the soil water retention curve was measured for each soil/biochar mixture using HYPROP (Decagon Pullman, WA, USA). HYPROP is a fully automated measuring and evaluation system to determine the hydraulic properties of soil samples. HYPROP measures the water tension at two vertical locations in a sample using tensiometers. The soil water characteristic curve is calculated based on simultaneous measurement of sample weight and water tension, which are recorded continuously through time as water evaporates from the soil surface and the soil water content decreases. Figure 11 is a schematic diagram of this instrument. After completing the HYPROP measurements, soil samples are placed in an oven at 105°C for 24 h to determine the dry sample mass. Data from the HYPROP were then combined with water retention from the WP4C to obtain the soil water retention curve from saturation ( $h = 0$  cm H<sub>2</sub>O) to very dry conditions ( $h = -10^7$  cm H<sub>2</sub>O).



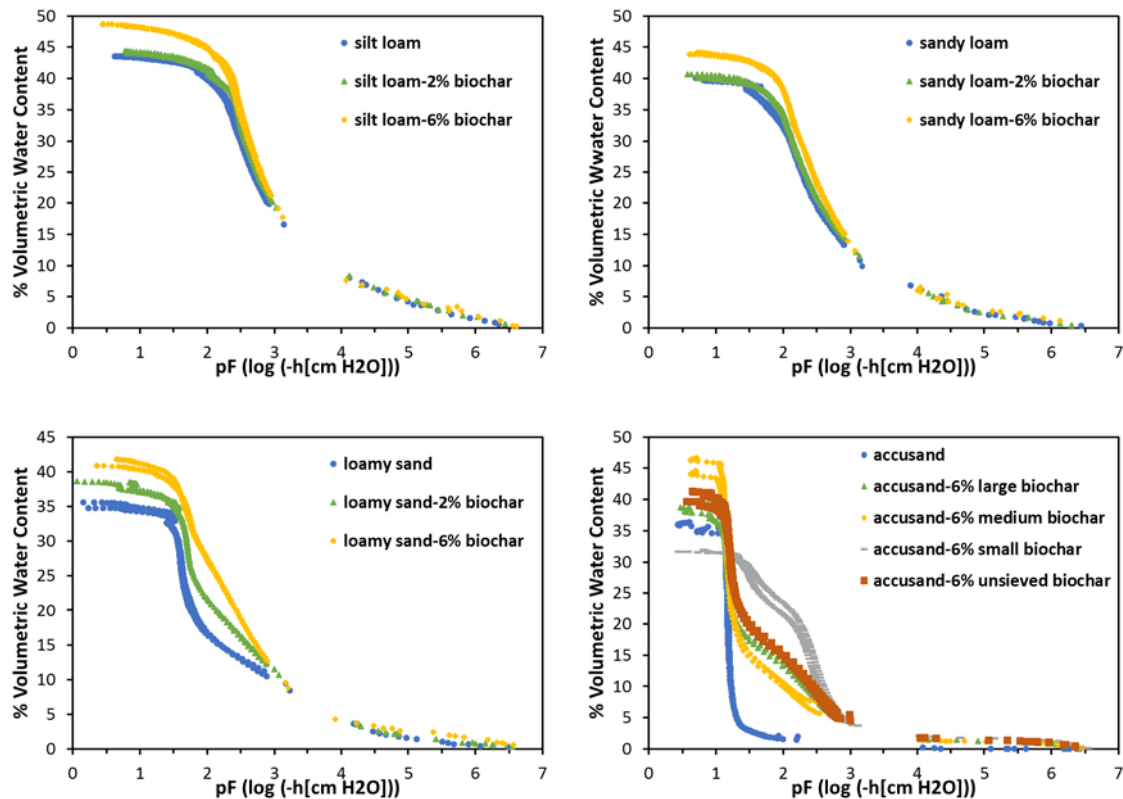
**FIGURE 11 Schematic diagram of HYPROP for measuring water retention and unsaturated hydraulic conductivity (taken from Decagon, Inc., HYPROP operation manual).**

Soil water retention data for all soils and soil-biochar mixtures using HYPROP and WP4C are shown in Figure 12 for the three natural soils with 2 and 6% biochar and for Accusand with 6% biochar and different types of biochar particles. In all treatments, biochar amendment increased water retention in the saturated region, with the most dramatic increases for loamy sand and Accusand. This increase is attributed to increasing total porosity with biochar amendment. However, saturated water contents were not equal to the total porosity, which is attributed to a small amount of air-entrapment before initiation of measurements with HYPROP (Figure 13). The highest residual air saturations were measured for biochar amendment to loamy sand. During the saturating process, air entrapment occurs when a thin film of water flows over rough interfaces resulting in one of two types of trapping processes: snap-off or bypass trapping. Air entrapment depends on the roughness of the pore-solid surfaces and solid wettability (11), both of which may be altered by biochar addition.

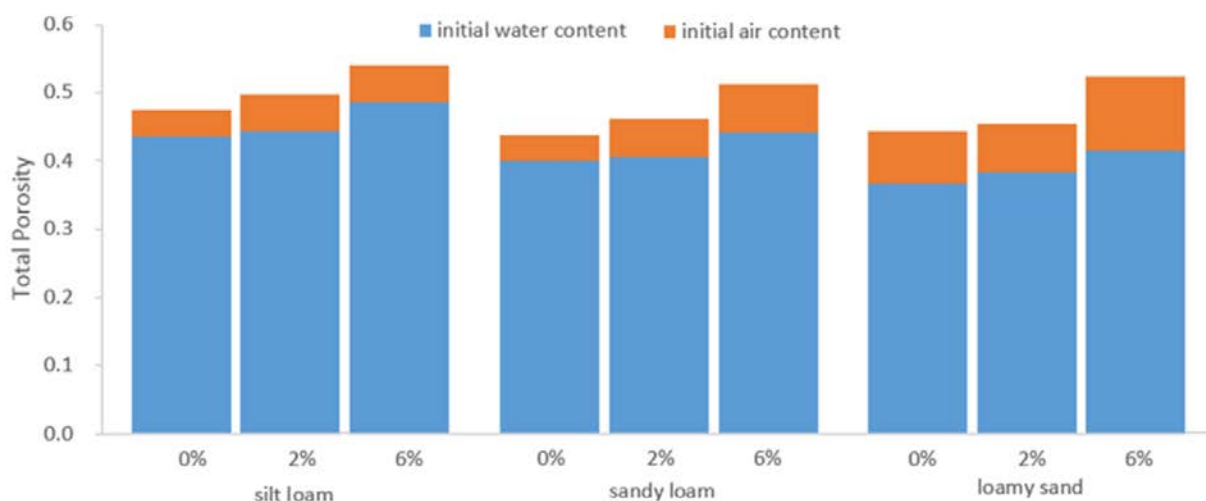
After air-entry into the soil ( $\sim h = -10^2$  cm H<sub>2</sub>O for silt loam, and  $\sim h = -10^{1.5}$  for sandy loam and loamy sand), the large pores and inter particle pore volume (pore volume between particles) of soil and soil/biochar mixtures began draining and water was retained only in smaller pores and biochar intra particle pore spaces (pore volume inside particles) (see Figure 12). Biochar is a porous medium with high surface area and internal porosity. Adding biochar improved water retention in the capillary region ( $h > -10^{1.5-2}$  cm H<sub>2</sub>O) and this improvement is higher for treatments with more biochar. Adding biochar to soil improves water retention due to the numerous micro and nano-scale pores within the biochar particles (12).

To assess the impact of changes in water retention on stormwater infiltration, it is convenient to determine field capacity, the volumetric water content retained by a soil after gravity drainage, and available water content, the water retained in a soil after gravity drainage that is available for plant uptake. The water retention data determined for the soil/biochar mixtures was used to calculate field capacity (water content at  $h = -10^{2.5}$  cm H<sub>2</sub>O) and water content at permanent wilting point ( $h = -10^{4.2}$  cm H<sub>2</sub>O). The available water content is defined as the amount of water held between

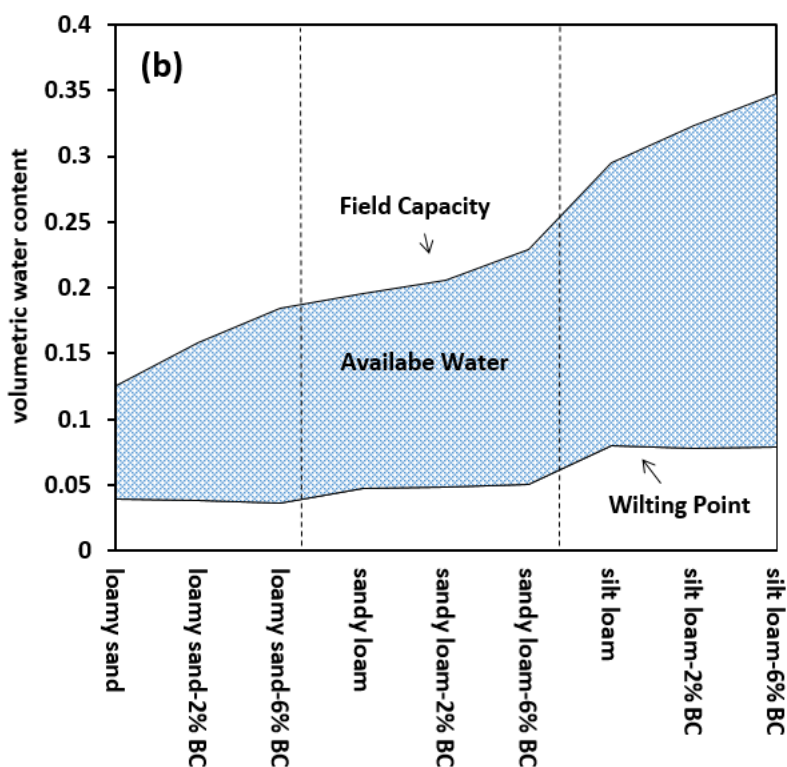
field capacity and permanent wilting point. Field capacity, permanent wilting point, and available water content are shown in Figure 14 for natural soils and their amendment with unsieved biochar. Adding biochar at the rate of 6% by mass increased available water content of silt loam, sandy loam, and loamy sand by 25, 20, and 70%, respectively. This result is consistent with the results for water retention: biochar addition had the most significant effect in improving water retention for the coarsest soils (see Figure 12). Thus, for the three soils selected to be representative for roadways in the MidAtlantic region, biochar significantly increased available water content. This suggests that biochar addition to roadway soils will have a significant effect in reducing stormwater runoff in all soils.



**FIGURE 12** Soil water retention from full water saturation to dry region ( $h = 0$  to  $-10^7$  cm H<sub>2</sub>O) for natural soils and their mixture with unsieved biochar, and for Accusand and its mixture with different biochar particle sizes (% values are biochar mass fraction in the samples).



**FIGURE 13** Total sample porosity, initial water content and initial entrapped air content for natural soils and their mixture with unsieved biochar (% values are biochar mass fraction in the samples).



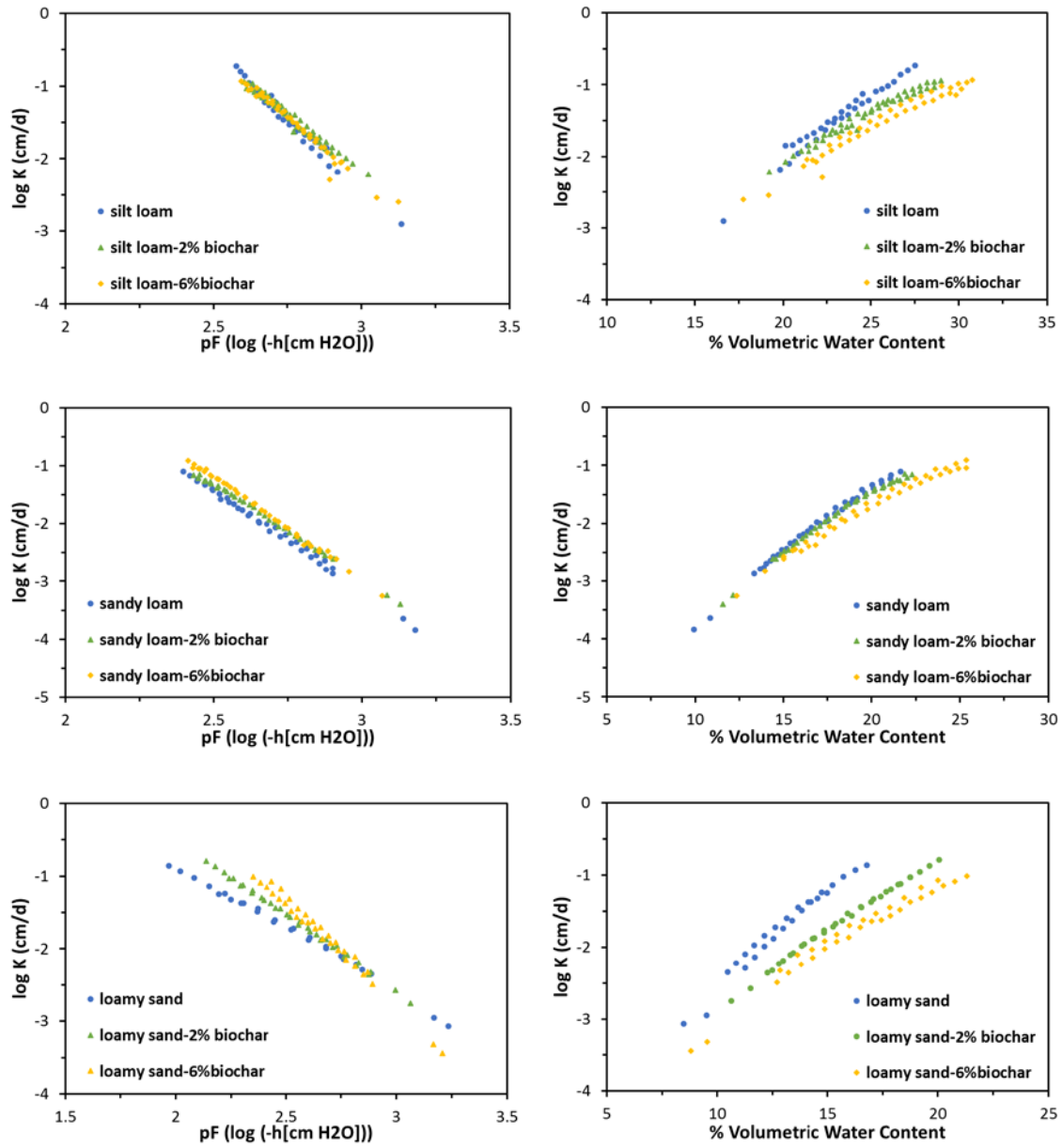
**FIGURE 14** Field capacity, permanent wilting point and available water content for natural soil samples with various % biochar content by mass. Dashed lines indicates border between different soil types.

### 3.1.6. Unsaturated Hydraulic Conductivity

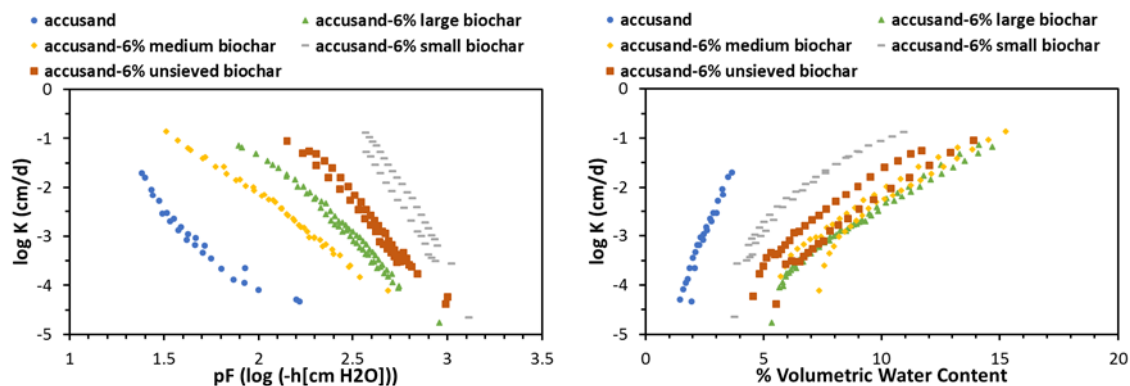
While water retention quantifies the volume of stormwater that is retained in soil and thus prevented from infiltrating to groundwater, the unsaturated hydraulic conductivity is a measure of the resistance to water flow before soil is fully water saturated. Unsaturated hydraulic conductivity was measured using HYPROP (Decagon Pullman, WA, USA) and is based upon the evaporation method (13). The unsaturated hydraulic conductivity for matric potential range of  $-10^{-2-4}$  cm H<sub>2</sub>O for natural soils and Accusand are shown in Figures 15 and 16, respectively.

As described above, the effect of biochar on water retention was most pronounced for coarse media: biochar amendment increased available water content most for loamy sand (70%) and least for sandy loam (20%). Similarly, the most significant effect of biochar amendment on unsaturated hydraulic conductivity occurred for the coarse textured soil – biochar at 6% increased unsaturated hydraulic conductivity of loamy sand by up to 500% (see Figure 15). In almost all biochar amendments, at a particular matric potential  $h$  adding biochar increased unsaturated conductivity. Note that the y-axes in Figure 15 are log scale. This suggests that biochar-amended roadway soil will infiltrate stormwater more quickly (higher unsaturated hydraulic conductivity) resulting in less stormwater runoff for all three natural soils, although the effect is most pronounced for loamy sand. The result is even more dramatic for Accusand (Figure 16), where biochar increases unsaturated hydraulic conductivity by a factor of 100 to 1000, depending on matric potential  $h$ .





**FIGURE 15** Unsaturated hydraulic conductivity of natural soils and their mixtures with unsieved biochar (% values are biochar mass fraction in the samples).



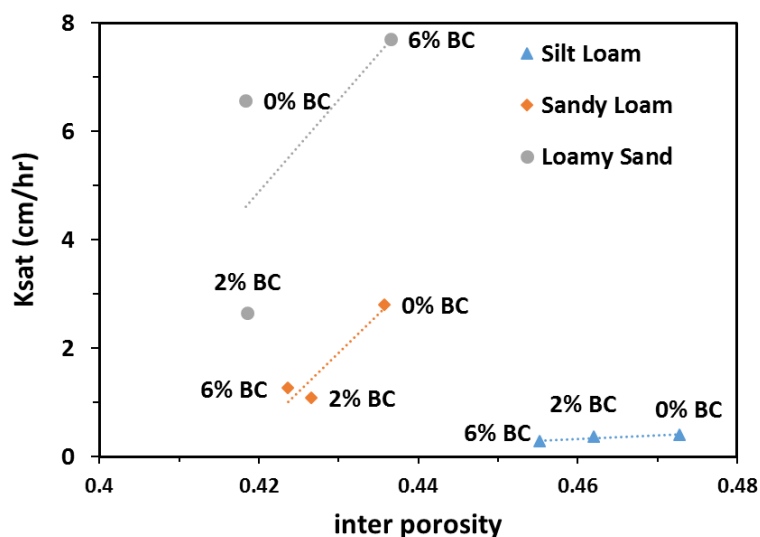
**FIGURE 16 Unsaturated hydraulic conductivity of Accusand and its mixtures with different biochar particle sizes (% values are biochar mass fraction in the samples).**

### 3.1.7. Saturated Hydraulic Conductivity

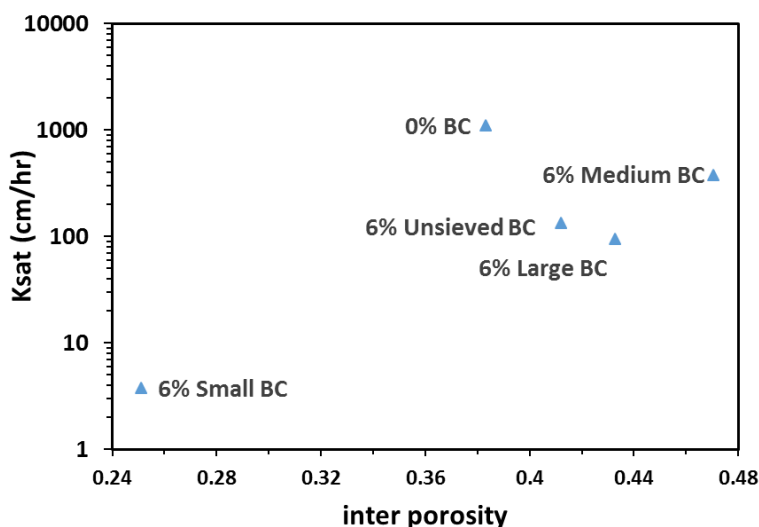
Saturated hydraulic conductivity ( $K_{sat}$ ) is a measure of the resistance to water flow when samples are water saturated. This condition will occur at the ground surface for roadway soils for large storm events. To measure  $K_{sat}$ , soil/biochar samples were packed in 5-cm diameter glass columns, 30-cm long. After packing, each column was flushed upward with  $\text{CO}_2$  gas for at least 30 minutes at a flow rate of approximately  $30 \text{ mL min}^{-1}$  to displace air, followed by four pore volume flushes of  $\text{CaSO}_4$  solution to achieve complete water saturation. For Accusand, a constant head method was employed and for natural soils a falling head method was used to measure saturated hydraulic conductivity.

While addition of biochar almost always resulted in increased unsaturated hydraulic conductivity at fixed matric potential  $h$  (Figure 15), saturated hydraulic conductivity of silt loam and sandy loam *decreased* 30% and 54%, respectively, when amended with 6% biochar (Figure 17). However, saturated hydraulic conductivity *increased* 17% for loamy sand with 6% biochar amendment. While the intra particle pore volume of biochar contributed significantly to higher water retention in all three soils, changes in saturated hydraulic conductivity were correlated instead with changes in inter pore volume – the large pores between biochar and soil particles. This is shown in Figure 17, where  $K_{sat}$  is plotted versus inter pore volume for the three soil/biochar mixtures. For any given soil type, biochar amendment decreased (silt loam and sandy loam) or increased (loamy sand) inter pore volume, with  $K_{sat}$  systematically increasing or decreasing according to biochar's effect on inter pore volume. Thus, for loamy sand biochar amendment increased  $K_{sat}$  and thus stormwater infiltration for water-saturated conditions, while for the other two soils biochar amendment decreased  $K_{sat}$ . Biochar amendment *decreased* saturated conductivity for Accusand in all cases (Figure 18). When small size biochar was added, it decreased inter porosity because small biochar particles filled the large pores between the sand particles; consequently saturated conductivity decreased. Although inter porosity increased when large, medium, and unsieved biochar were added in the Accusand,  $K_{sat}$  decreased. This unexpected result might be attributed to the surface roughness and irregular/elongated shape of biochar particles, which caused increased resistance to water flow and tortuosity in the very uniform Accusand.

These results for biochar influence on saturated hydraulic conductivity are important for assessing biochar's potential for reducing stormwater runoff. Ideally, biochar amendment should benefit all soil hydrologic function: increased water retention and increased unsaturated and saturated hydraulic conductivity. While biochar amendment always increased water retention and almost always unsaturated hydraulic conductivity (at specified  $h$ ) for the three natural soils, biochar only increased saturated hydraulic conductivity for loamy sand. When biochar is initially amended to roadway soils, soil aggregates have not yet developed and biochar amendment may in some cases result in minor changes or even increases in stormwater runoff. As will be shown below, though, biochar amendment favors the formation of macropores in soil, which form as soil ages and are expected to result in significant increases in saturated hydraulic conductivity that was not measured in the controlled laboratory experiments.



**FIGURE 17** Saturated hydraulic conductivity versus inter porosity for natural soils and their mixtures with unsieved biochar (% values are biochar mass fraction in the samples).



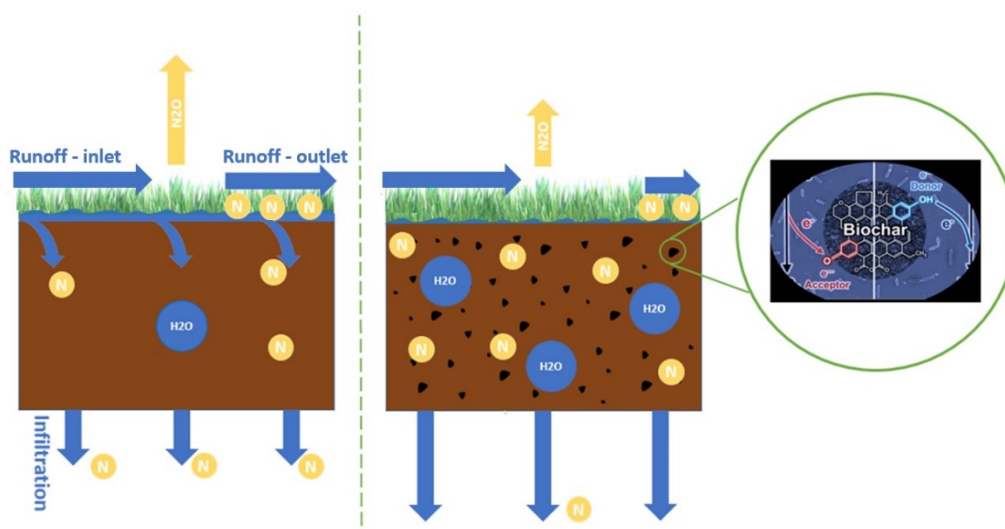
**FIGURE 18 Saturated hydraulic conductivity versus inter porosity for Accusand and its mixture with different biochar particle sizes (% values are biochar mass fraction in the samples).**

### **3.2. INFLUENCE OF BIOCHAR AMENDMENT ON STORMWATER RETENTION AND INFILTRATION – PILOT SCALE**

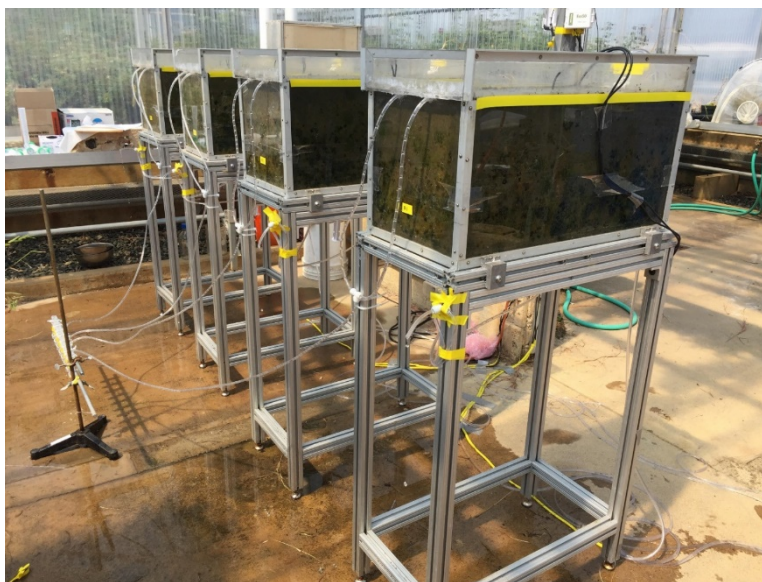
#### **3.2.1. Experimental Design**

The primary focus of this Type 1 project was to quantify the impact of biochar amendment on soil hydraulic properties at the lab scale, and these results are described above. A secondary objective was to conduct pilot-scale experiments to evaluate the impact of biochar amendment on stormwater runoff and infiltration. While lab-scale experiments quantified soil hydraulic properties, pilot-scale experiments quantified the influence of these changes in soil hydrology on stormwater runoff.

For this purpose, four  $0.6 \times 0.3 \times 0.3$  m (length  $\times$  width  $\times$  depth) pilot-sized highway greenways were designed, constructed and maintained at the University of Delaware greenhouse. A schematic of the experimental system is shown in Figure 19, while a photograph showing the four constructed boxes is in Figure 20. The expected benefits of biochar amendment are illustrated in Figure 19: reduced stormwater runoff, reduced nitrogen discharge (infiltration) to groundwater, and increased transformation of nitrogen pollutants to innocuous nitrogen gas that is discharged to the atmosphere. Each box was underlain by a perforated plate covered by a hydrophilic geomembrane to permit water drainage but inhibit sediment passage. Synthetic stormwater enters the box as “roadway runoff” on one side and then flows on top of and percolates through the 30-cm thick biochar-amended soil layer. Stormwater exits the system either as surface runoff or as soil water that infiltrates the full 30-cm thick soil. Two EC-5 moisture sensor (Decagon Pullman, WA, USA) were installed in each box to monitor soil water content at 0-15 cm and 15-30 cm depths. In addition, micro rhizon samplers (Soilmoisture Equipment Corp, CA, USA) were installed at 5 and 25 cm depth in each box to collect pore water samples.



**FIGURE 19** Schematic of pilot-scale experimental cells. Left box illustrates performance with biochar-free soil, and right box performance with biochar amendment.



**FIGURE 20** Pilot-scale experimental cells.

### 3.2.2. Soil and Biochar Properties

Four experimental systems were constructed. Two boxes were filled with a sandy loam soil collected from University of Delaware Farm Land at Newark, DE (39°40'07.2"N 75°44'21.6"W) and two were filled with the sandy loam amended with 4% Soil Reef™ biochar by mass. Sandy loam was selected as a typical roadway soil and is similar too but not identical with the sandy loam tested in the lab-scale experiments described above and found at the field test site described below. The soil was air-dried, crushed using a mortar and rubber-tipped pestle, sieved to less than 4.75 mm size, and stored at room temperature before use. Chemical properties of soil and biochar used in pilot-scale experiments are presented in Table 1. Physical properties of the biochar-free and biochar-amended soil are presented in Table 2. Similar to the results from lab-scale experiments, adding biochar decreased bulk density and increased total porosity of the soil.

**TABLE 1** Chemical Properties of Soil and Biochar Used in the Pilot-Scale Experiment.

Sample	Water pH	Est.	CEC	OM	by	Total	N	Total	C	C:N Ratio	NH4-N	NO3-N
		(meq/100g)		LOI (%)	(%)	(%)		(%)			(mg/kg)	(mg/kg)
Sandy	6.6 ± 0.0	6.9 ± 0.2		2.36	±	0.12	±	1.69	±	14.18	7 ± 2	5.4 ± 1.0
Loam				0.10		0.00		0.08		0.16		
Biochar	6.00 ± 0.0	10.3 ± 0.3		75 ± 2		0.26	±	19.4 ± 0.8		76 ± 2	9 ± 3	18.7 ± 1.9
						0.00						

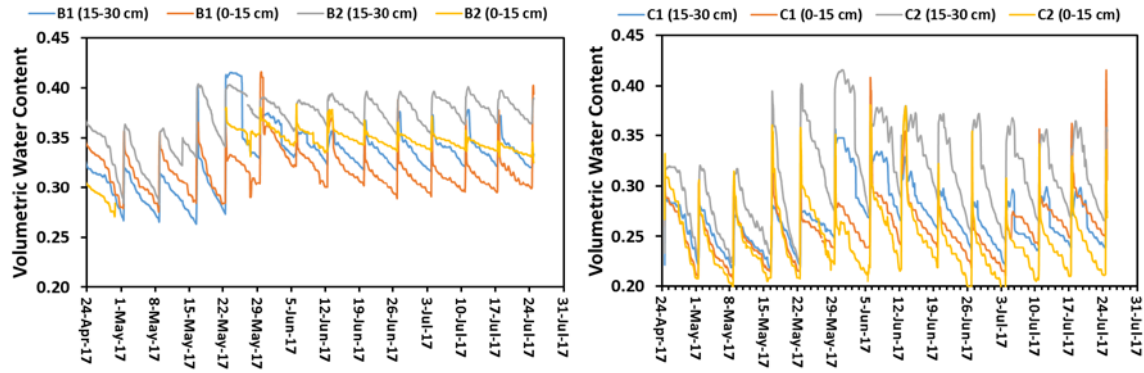
TABLE 2 Physical Properties of Biochar-Free and Biochar-Amended Sandy Loam in the Pilot-Scale Experiment.

Parameter	Biochar-free soil	Biochar-amended soil
bulk density (g/cm <sup>3</sup> )	1.46	1.20
envelope density (g/cm <sup>3</sup> )	2.65	2.28
skeletal density (g/cm <sup>3</sup> )	2.65	2.53
inter-porosity	0.45	0.48
intra-porosity	0.00	0.05
total porosity	0.45	0.53

### 3.2.3. Wetting Drying Cycles

In natural settings, during each stormwater event roadway soils become wet or even saturated, depending on the severity of the storm. Between storms, roadway runoff drains to deeper regions of the soil and/or evaporates. In order to mimic this natural wetting/drying behavior, the soil boxes were irrigated with de-chlorinated tap water at the start of each week, and then water was allowed to drain or evaporate during the week. Natural wetting/drying cycles may alter the soil structure and promote soil aggregate formation, which often influences the formation of large macropores that could transmit significant quantities of stormwater. These time-dependent changes in soil structure because of wetting/drying cycles are also influenced by the soil microbial community and composition (14).

Water content data for the biochar-free and biochar-amended soil over the course of 13 wetting/drying cycles are shown in Figure 21. Biochar-amended soil reached ~ 10% higher volumetric water content at saturated conditions: ~0.40 for biochar-amended soil versus ~0.36 for biochar-free soil. The most dramatic influence of biochar, though, is on water retained between wetting events, where the rate of drainage/evaporation is significantly less for biochar-amended versus biochar-free soil. Therefore, more water is retained in biochar-amended soil, providing greater time for evapotranspiration and microbial transformation of stormwater pollutants. Furthermore, an increasing trend in water content with wetting/drying cycle was observed in both treatments. These data strongly suggest formation of aggregates in this soil. Similar to field data reported below, biochar appears to enhance soil aggregation that results in more macropores, higher volumetric water contents during surface water ponding, and therefore increased rates of stormwater infiltration. Such an effect will result in less stormwater runoff volume, a key metric for evaluating the effectiveness if biochar amendment for stormwater treatment.



**FIGURE 21** Water retention of biochar-amended (left) and biochar-free soil (right) during 13 wetting/drying cycles.

### 3.2.4. Lab-Scale and Pilot-Scale Saturated Hydraulic Conductivity

Saturated hydraulic conductivity for biochar-free and biochar-amended soil (4% by mass) were measured in lab-scale column experiments using the constant head method described above. To measure saturated hydraulic conductivity and infiltration rate in pilot-scale experiments, a tension disk infiltrometer with diameter of 21 cm was used (Figure 22). Infiltration rates were measured at two locations for each box at four matric potential steps (-9, -6, -3, and 0 cm H<sub>2</sub>O) after the third and sixth wetting/drying cycle. The results of cumulative infiltration versus time data were used to obtain water retention, and saturated and unsaturated hydraulic conductivity of the near-surface soil in each box using DISK software (USDA).

Saturated hydraulic conductivity of biochar-free and biochar-amended soil in lab and pilot-scale experiments are shown in Figure 23. At both lab and pilot-scale, no significant difference in saturated conductivity was observed by adding biochar to this soil. At the lab-scale, columns were fully saturated using upward water flow and CO<sub>2</sub> flushing. However, in the soil boxes the saturation occurs with irrigation and imbibition of water from soil surface, which likely results in some air entrapment. Therefore, the smaller  $K_{sat}$  in pilot-scale boxes than lab-scale columns was expected and is likely due to air entrapment. The minimal impact of biochar amendment on  $K_{sat}$  for this soil in lab and pilot-scale experiments is in contrast with field-scale measurements, where we observed higher saturated conductivity than in the lab (discussed below).

In the pilot-scale experiments, while time-dependent changes in water retention were observed (Figure 21) similar changes in saturated hydraulic conductivity were not yet observed. We postulate that with additional wetting/drying cycles over longer time periods, soil aggregation will become more significant causing macropore formation and resulting in higher saturated conductivity and infiltration rate, particularly for biochar-amended soil. Our Type 2 proposal will test this hypothesis.



FIGURE 22 Photograph of infiltrometer used for measuring infiltration rate at different pressure steps.

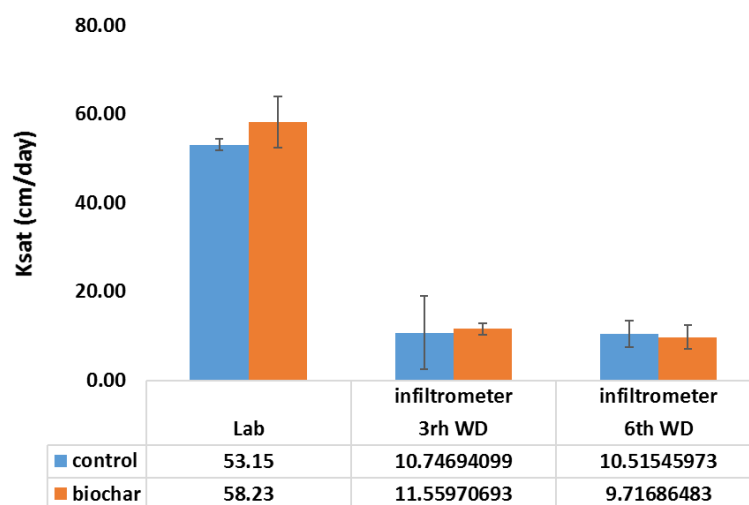


FIGURE 23 Saturated hydraulic conductivity of biochar-free (control) and biochar-amended soil in lab-scale and pilot-scale experiments.



### 3.2.5. Simulated Rainfall-Runoff Experiment

A simulated rainfall-runoff experiment was conducted to quantify the impact of biochar amendment on stormwater runoff and infiltration, including concentrations of organic and inorganic forms of nitrogenous compounds in runoff. Stormwater with a flowrate of  $143 \text{ mL min}^{-1}$  was applied to the upgradient edge of each soil box (see Figure 19) for a period of 24 h. This flowrate is equal to a rainfall intensity of  $10 \text{ mm h}^{-1}$ , assuming that the box collected stormwater runoff from a 2-lane roadway. During the first 6 h of the 24-h storm event, DI water with  $0.005 \text{ mol L}^{-1} \text{ CaSO}_4$  was pumped onto the soil box surfaces as roadway runoff. For the remaining 18 h, tap water with nitrate and bromide concentrations of  $5.3$  and  $8.4 \text{ mg L}^{-1}$ , respectively, was pumped onto the boxes as a step input at the same  $143 \text{ mL min}^{-1}$  flow rate. Bromide is an inert chemical and serves as a tracer to track water flow through the system. Nitrate was applied to the box as the sole nitrogen pollutant to investigate biochar-amended soils ability to enhance denitrification, which is believed to be the only way to completely remove nitrogen from stormwater (15). The flowrate of stormwater (inlet), runoff (surface outlet), and infiltration (outlet at soil bottom) were monitored during this 24-h event. In addition, samples were taken from each flow stream as well as rhizon pore water samplers to determine aqueous concentrations of total dissolved organic carbon (DOC), total nitrogen (TN), ammonium ( $\text{NH}_4^+$ ), nitrite ( $\text{NO}_2^-$ ) and nitrate ( $\text{NO}_3^-$ ).

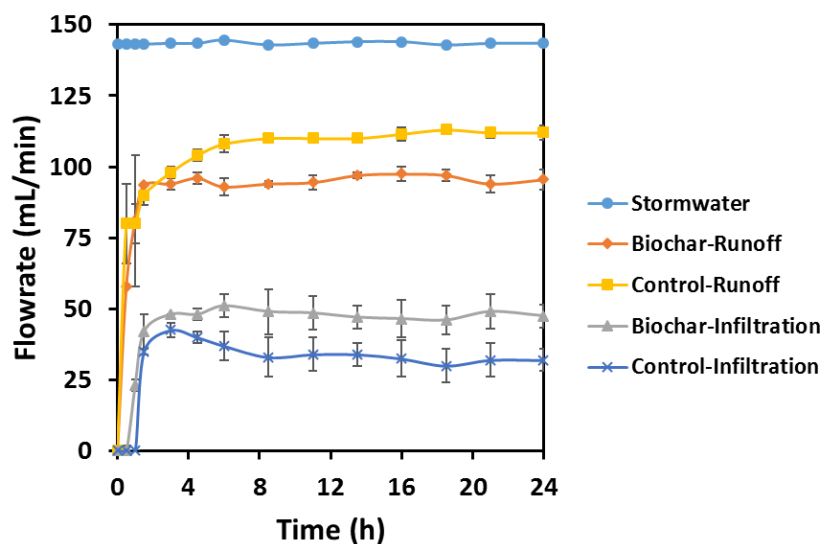
The flowrates of all flow paths for biochar-free and biochar-amended soil are presented in Figure 24. While 81% of the stormwater left the biochar-free soil as runoff, this was approximately 68% for biochar-amended soil. Thus, biochar amendment reduced stormwater runoff volume by 13% for this storm event. However, we expect significantly higher runoff reduction (comparing biochar-free and biochar-amended conditions) as the system ages, since aggregate and macropore formation are expected to be more extensive in biochar-amended soil.

Bromide ( $\text{Br}^-$ ), dissolved organic carbon, nitrate, and total nitrogen concentrations in all flow pathways during the test are presented in Figure 25. Concentrations of all pollutants in runoff, which exited the soil box surfaces, were similar to the inlet stormwater, which implies that mass transfer between soil and surface water was negligible with respect to transport across the soil surface. Biochar-free and biochar-amended soils showed similar trends for  $\text{Br}^-$  concentrations in the infiltration stream, the water that percolated through the soil boxes. Since the infiltration rate was higher in biochar-amended than biochar-free soil, the mean residence time might be expected to be larger in biochar-free soil. Nevertheless,  $\text{Br}^-$  passed the 30 cm soil depth sooner in biochar-free than biochar-amended soil. Thus, although biochar-amendment increased stormwater infiltration, actual water residence time in soil was larger with biochar amendment, which favors greater pollutant removal.

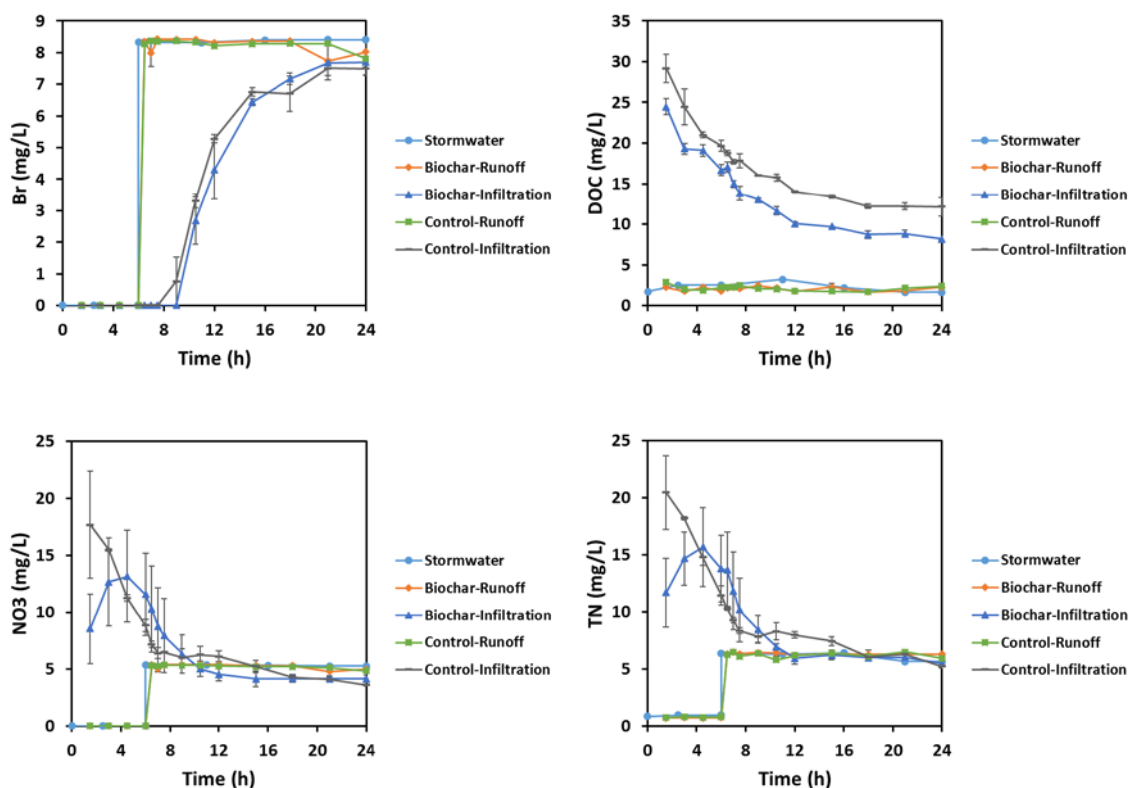
Dissolved organic carbon (DOC) in the infiltration stream from the biochar-free soil was significantly higher than soil amended with 4% biochar. Since there was 4% less soil in the soil/biochar mixtures, there was less DOC mass leaching from these soil boxes. Nitrogen also apparently leached from the sandy loam, which was expected since this was an agricultural soil that was likely fertilized in the past. Most of the total nitrogen (TN) leached in the infiltration stream from the bottom of each box was nitrate ( $\text{NO}_3^-$ ), thus trends for  $\text{NO}_3^-$  are similar to those for TN.  $\text{NH}_4^+$  was negligible in all streams. Since the soil was used for agricultural purpose before use in these experiments, it contained significant amounts of TN and organic carbon, possibly due to fertilization and plant residue. The soil C/N ratio was 14.8, leading to net mineralization of organic nitrogen to ammonium (16). Oxygen concentrations in top soils is typically high. Therefore,

ammonia can be oxidized to nitrate (via nitrification), which is an easily leachable nitrogen form in the soil. This is one possible explanation for high concentrations of  $\text{NO}_3^-$  and TN in infiltration water from the soil boxes. In this situation, it is difficult to draw strong conclusions about the effect of biochar amendment on denitrification of infiltrating stormwater: there is a significant mass of nitrate leached from the soil alone, which masks the treatment of infiltrating nitrate-laden stormwater.

If we are awarded a Type 2 project, these experiments will be continued and the original nitrogen in the soil will leach out after additional wetting/drying cycles, which are continuing. While this experiment confirmed biochar's impact on reducing stormwater runoff, we believe future experiments will demonstrate biochar's role in reducing pollutant concentrations, i.e., nitrogen – not only stormwater flow.



**FIGURE 24** Stormwater runoff and infiltration flowrates for biochar-free (control) and biochar-amended soil in the simulated rainfall runoff experiment. Biochar-amendment resulted in significant reduction in stormwater runoff and increase infiltration to groundwater.



**FIGURE 25** Br<sup>-</sup>, DOC, NO<sub>3</sub><sup>-</sup>, TN concentrations in stormwater (inlet), runoff (surface water outlet) and infiltration (bottom outlet) for biochar-free and biochar-amended soil in the simulated rainfall runoff experiment.

Based on the results of this research, other projects of our research group, and published data, we believe that biochar can enhance denitrification in roadway soil by three possible mechanisms. First, biochar increases water retention that increases anoxic conditions, especially between each storm event. Second, biochar enhances soil aggregate formation, which subsequently provides more anoxic micro habitats for bacteria within soil aggregates. Third, biochar provides electrons for microbial denitrification. Biochar has a stable carbon structure consisting of electroactive quinoid functional groups that serve as an electron donor and acceptor. It is reported that the bioavailable electron storage capacity of Soil Reef<sup>TM</sup> biochar is 0.87 mmol e<sup>-</sup> g<sup>-1</sup> (17). We found biochar amendment increased denitrification usually by a factor of two or more when added to bioretention media, and similar results may occur when incorporated into roadway greenway soil. Future experiments are needed to evaluate this hypothesis at the pilot-scale. Testing this hypothesis at the field scale is extremely difficult.

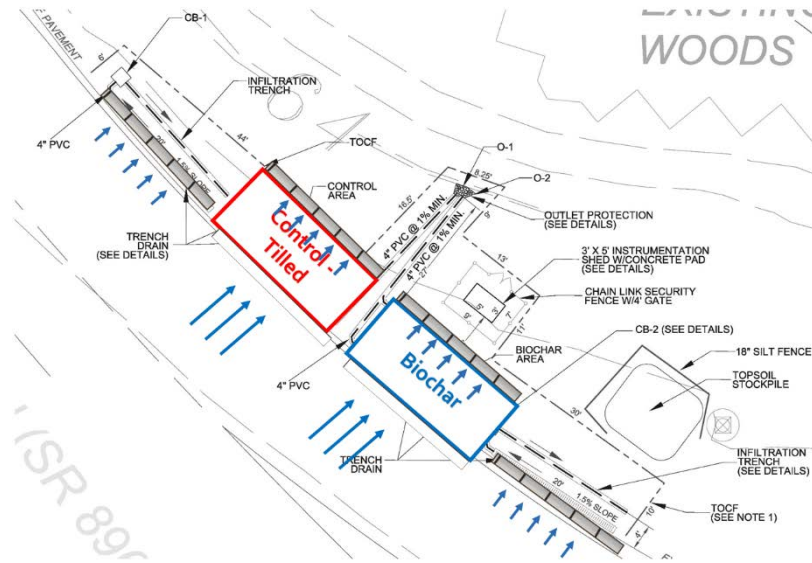
### 3.3. INFLUENCE OF BIOCHAR AMENDMENT ON STORMWATER RETENTION AND INFILTRATION – FIELD SCALE

Data from this Type 1 IDEA project were intended to test our hypotheses about the utility of biochar amendment to roadway soils at the lab and pilot scales, and provide a framework for a subsequent Type 2 proposal for field study. However, at approximately the same time this Type 1 project was initiated we received a grant to conduct a field test

supported by the National Fish and Wildlife Foundation (NFWF), Delaware Department of Transportation, Maryland Transportation Authority, and City of Charlottesville, VA. Both the IDEA and NFWF projects investigate the effect of biochar amendment to roadway greenways on stormwater runoff and nutrient load reduction. However, the focus of the IDEA project is on fundamental understanding of the influence of biochar amendment on soil hydraulic properties for a range of soils at the lab scale, and providing pilot-scale data demonstrating the impact on stormwater runoff. The IDEA project was intended to provide data to support a field study, while the NFWF project's focus is field performance metrics. Because of the synergy between the two projects and the Type I IDEA project's focus on fundamental mechanisms, significant effort from the IDEA project was expended on measurements at the field test site – measurements not planned for the NFWF project and which would not have been performed without IDEA project support. We briefly describe results from the field study that include the important field measurements supported by the IDEA grant.

### **3.3.1. Field Site Description**

The project site is located south of the Chesapeake and Delaware Canal in Delaware (USA) along the northbound lane of Rt. 896 at the Bethel Church Road on-ramp (Lat: 39° 31' 48.19" N, Long: 75° 44' 9.65" W). Two filter strips each  $6.1 \times 1.8 \times 0.3$  m (length  $\times$  width  $\times$  depth) abutting the roadway were modified to assess the impact of biochar amendment on stormwater runoff. The filter strips are shown with associated trench drains and piping for periodic collection of runoff samples in Figure 26. A photograph of filter strips is shown in Figure 27. One filter strip was tilled, while the other was tilled and amended with biochar at 4% mass fraction, identical to what was selected for the pilot-scale experiments described above. The two plots were separated from each other by 1-2 m. Stormwater runoff from a  $93 \text{ m}^2$  impervious roadway area was evenly distributed through the two filter strips during rainfall events. The soil in both filter strips is sandy loam, the same soil type used in the pilot-scale box experiments. Thus, the results from the pilot-scale experiments will aid interpretation of data from this field site.



**FIGURE 26** Filter strip layout with associated trench drains and piping for periodically collection of runoff samples from biochar-free (control) and biochar-amended greenways.

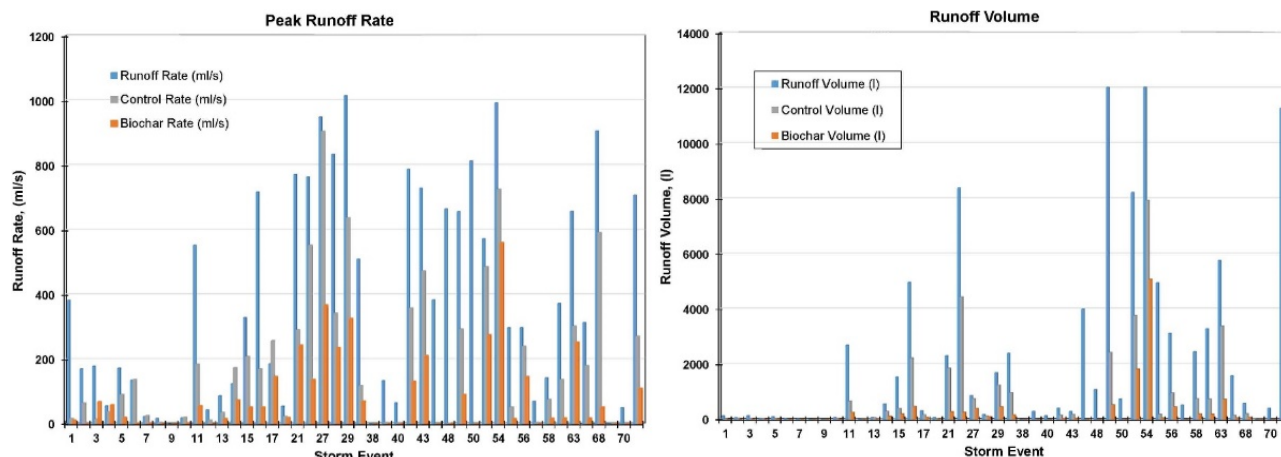


**FIGURE 27** Photograph of field site showing the filter strips and trenches: biochar-amended in foreground, and biochar-free (control, tilled) in background. Trench drains in white concrete are used to collect stormwater runoff.

### 3.3.2. Stormwater Runoff Results

The results from the two test sections constructed are shown in Figure 28 for 74 storms in 2016/2017, where peak runoff rate and total runoff volume are shown for each storm. For the 74 storm events, biochar reduced stormwater runoff volume by an average of 83% peak runoff flow rate by 77%. In comparison, tillage alone without biochar amendment

reduced stormwater runoff volume by an average of 54% and peak runoff flow rate by 51%. Assuming equal concentrations of pollutants in both effluents, biochar resulted in a dramatic reduction in nutrient load (total mass) discharged. While biochar's impact is less significant for large storm events, biochar-amended media provided significant treatment for small storms and “first-flush” of larger events.



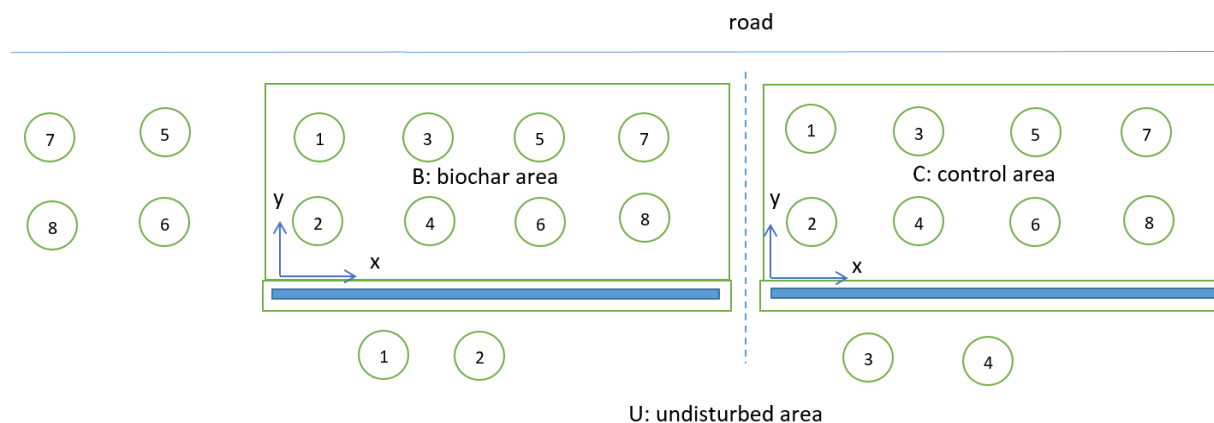
**FIGURE 28** Data from 1-yr operation of 4% biochar-amended and biochar-free (control, tilled) sections of roadway filter strips.

### 3.3.3. Field-Scale Saturated Hydraulic Conductivity

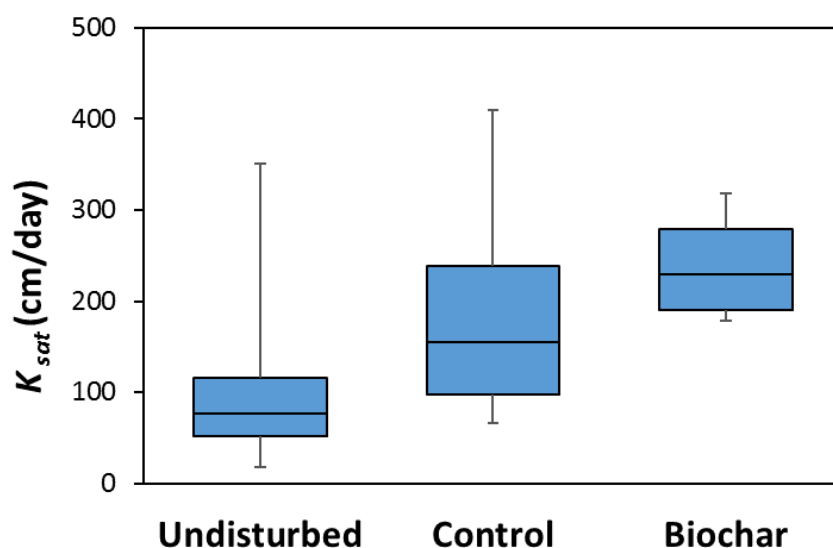
Biochar amendment resulted in a dramatic reduction in stormwater runoff at the site. To understand why this occurred, saturated hydraulic conductivity for biochar-free (control, tilled) and biochar-amended soil were measured using a tension disk infiltrometer, the same device used for measurements in the pilot-scale experiments. Infiltration rates were measured at 24 locations in the biochar amended, tilled, and undisturbed regions (Figure 29). Soil hydraulic properties were obtained by inverse modelling, similar to the pilot-scale experiment.

Saturated hydraulic conductivity of biochar-amended, tilled, and undisturbed soils are shown in Figure 30. Biochar amendment increased the geometric mean saturated hydraulic conductivity by ~ 50% over tilled (control), which is consistent with the 47% average reduction in runoff peak flow rate over control (tilled). Thus, the reduction in stormwater runoff peak flow rate with biochar amendment is primarily associated with biochar's influence on soil hydraulic properties. Figure 31 shows the hydraulic conductivity of biochar-amended, tilled, and undisturbed soil at  $h = 0$  cm  $H_2O$  (saturated condition) and  $h = -1$  cm  $H_2O$  (unsaturated condition). The difference between conductivity at these two pressure steps indicates the percentage of water moved through macropores (larger than 0.15 cm), which only become water filled and thus able to transmit water at  $h = 0$  cm  $H_2O$ . The percentage of water flowing in macropores for undisturbed, tilled and biochar-amended soils were 67, 78, and 84%. Thus, the increase in saturated hydraulic conductivity caused by biochar amendment to sandy loam at this site is due to biochar's significant influence on macropore formation.

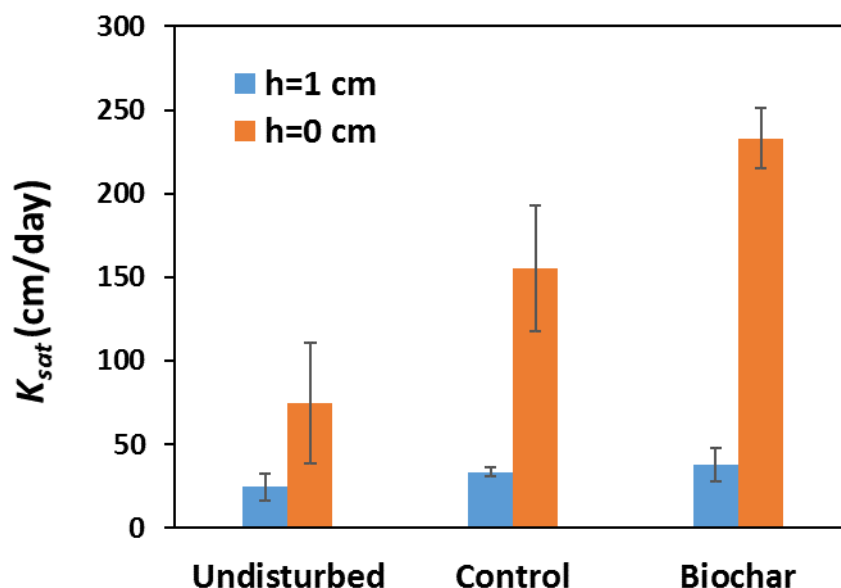
Macropores are often created by soil aggregation, which is influenced by soil microbial activity. The lab-scale experiments were conducted over short time periods and did not include soil aggregate formation. These lab data quantify biochar's influence on soil hydraulic properties without soil aggregation and macropores and are useful for predicting biochar effects during the period after initial amendment to a field soil. At the field site, saturated hydraulic conductivity measurements were made eight months after biochar amendment, which allowed time for soil aggregation and macropore formation. Pilot-scale experiments show changes in soil hydrology (Figure 21) with time, and thus we anticipate pilot-scale experiments will capture this time-dependent soil aggregation and macropore formation when continued in a Phase 2 project.



**FIGURE 29 Plan view showing the location of infiltration measurements in biochar-amended, biochar-free (control, tilled), and undisturbed soils.**



**FIGURE 30 Saturated hydraulic conductivity of biochar-amended, biochar-free (control, tilled), and undisturbed roadway soil. Horizontal lines for each treatment are the geometric mean, upper and lower ranges of the boxes are upper and lower quartiles, and the top and bottom whiskers represent the maximum and minimum data values.**



**FIGURE 31 Comparison of hydraulic conductivity of biochar-amended, biochar-free (control, tilled), and undisturbed roadway soil at saturated ( $h = 0$ ) and unsaturated ( $h = -1$  cm) conditions. The more significant the difference in conductivity between  $h = 0$  and  $h = -1$  cm, the greater water flow in macropores for saturated conditions.**

### 3.4. ENGINEERING AND CONSTRUCTION COST ANALYSIS

Based on the data presented above, biochar amendment to roadway soils has the potential to be an industry-altering technology for stormwater runoff and pollution reduction within the Chesapeake Bay watershed and beyond. Data from one year of biochar testing of 74 storm events in the field study supported by NFWF show that biochar amendment at 4% (mass content) may reduce stormwater runoff by 83% - using a treatment area 8.3 times smaller than the contributing impervious roadway. Thus, *only 0.12 acres of biochar-amendment is needed to treat 1-acre impervious with approximately 83% removal of nutrients and sediments.* Using cost data for construction at this site, design plus construction costs would be approximately \$31,700 per impervious acre treated. While these costs are similar to an urban grass buffer (\$26,600 per impervious acre), biochar-amendment requires a dramatically smaller footprint: 0.12 versus 3.7 acre per impervious acre for biochar and urban grass buffer (18), respectively. Thus, biochar amendment is possible in many greenways and open spaces where urban grass buffers are not.



A cost analysis comparing biochar-amendment to 23 BMPs, including bioretention, wet ponds, and street sweeping was conducted and results are shown in Table 3. For the same treatment for 1-acre impervious, biochar is less expensive than 20 other BMPs – up to a factor of 10 less. Biochar-amendment is more expensive than only three BMPs: erosion and sediment control, street sweeping, and urban grass buffers. However, utilization of these BMPs may be limited, for example, because of area of land needed and other constraints like existing slope and buffer width available for urban grass buffer. Not accounted for in this analysis is the enhanced denitrification that biochar-amendment is expected to promote: we found biochar amendment increased denitrification usually by a factor of two or more when added to bioretention media, and similar results may occur when incorporated into soil. Thus, use of biochar-amended soils will significantly reduce design, installation, and operation and maintenance costs, all while using existing open space.

TABLE 3 Summary Unit Planning Level Stormwater Cost Estimates per Impervious Acre Treated

Summary Unit Planning Level Stormwater Cost Estimates Per Impervious Acre Treated (Revised 2017) (1)										
Stormwater Management Practice	Pre-Construction Costs	Construction Costs	Land Costs	Total Initial Costs	Total Post Construction Costs	Total Post Construction Costs (+20 years)	Total Costs (+20 years)	Average Annual Cost (+20 years)	Land Area Required (acres)	
	Indexed for Inflation (2011-2017) @ 8.4% (2)					Estimated for Inflation based on 1997 to 2017 assuming 17.4% (3)				
Biochar Amended Soils @ 4%	\$ 2,331	\$ 29,346	\$ -	\$ 31,677	\$ 943	\$ 20,462	\$ 52,139	\$ 2,607	0.12	
Erosion & Sediment Control	\$ -	\$ 21,680	\$ -	\$ 21,680	\$ 11	\$ 235	\$ 21,915	\$ 1,096		
Street Sweeping	\$ 10,163	\$ 6,557	\$ -	\$ 16,720	\$ 489	\$ 10,608	\$ 27,327	\$ 1,366		
Urban Grass Buffers	\$ 2,331	\$ 23,306	\$ -	\$ 25,637	\$ 943	\$ 20,462	\$ 46,099	\$ 2,305	3.7	
Wet Ponds & Wetlands (New)	\$ 6,032	\$ 20,108	\$ 2,168	\$ 28,309	\$ 827	\$ 17,946	\$ 46,254	\$ 2,313		
Vegetated Open Channels	\$ 23,610	\$ 21,680	\$ 2,168	\$ 47,458	\$ 661	\$ 14,347	\$ 61,805	\$ 3,090		
Urban Forest Buffers	\$ 3,252	\$ 32,520	\$ -	\$ 35,772	\$ 1,312	\$ 28,459	\$ 64,231	\$ 3,212		
Bioswales (New)	\$ 13,008	\$ 32,520	\$ 2,168	\$ 47,696	\$ 1,009	\$ 21,897	\$ 69,593	\$ 3,480		
Dry Detention Ponds (New)	\$ 9,756	\$ 32,520	\$ 5,420	\$ 47,696	\$ 1,334	\$ 28,953	\$ 76,649	\$ 3,832		
Filtering Practices (Sand, below ground)	\$ -	\$ 43,360	\$ -	\$ 43,360	\$ 1,768	\$ 38,361	\$ 81,721	\$ 4,086		
Filtering Practices (Sand, above ground)	\$ 6,504	\$ 38,482	\$ 5,420	\$ 50,406	\$ 1,551	\$ 33,657	\$ 84,063	\$ 4,203		
Bioretention (New - Suburban)	\$ 4,336	\$ 40,650	\$ 3,252	\$ 48,238	\$ 1,660	\$ 36,009	\$ 84,247	\$ 4,212		
Dry Extended Detention Ponds (New)	\$ 18,103	\$ 32,520	\$ 5,420	\$ 56,043	\$ 1,334	\$ 28,953	\$ 84,996	\$ 4,250		
Infiltration Practices w/o Sand, Veg. (New)	\$ 15,176	\$ 45,257	\$ 5,420	\$ 65,853	\$ 939	\$ 20,368	\$ 86,221	\$ 4,311		
Wet Ponds & Wetlands (Retrofit)	\$ 23,125	\$ 46,249	\$ 2,168	\$ 71,542	\$ 827	\$ 17,946	\$ 89,488	\$ 4,474		
Urban Nutrient Management	\$ 23,306	\$ 66,124	\$ -	\$ 89,430	\$ 34	\$ 729	\$ 90,159	\$ 4,508		
Infiltration Practices w/ Sand, Veg. (New)	\$ 17,344	\$ 47,425	\$ 5,420	\$ 70,189	\$ 982	\$ 21,309	\$ 91,498	\$ 4,575		
Dry Extended Detention Ponds (Retrofit)	\$ 18,970	\$ 48,780	\$ 5,420	\$ 73,170	\$ 1,334	\$ 28,953	\$ 102,123	\$ 5,106		
Urban Stream Restoration	\$ 56,910	\$ 46,612	\$ -	\$ 103,522	\$ 966	\$ 20,956	\$ 124,478	\$ 6,224		
Hydrodynamic Structures (New)	\$ 24,390	\$ 37,940	\$ -	\$ 62,330	\$ 3,828	\$ 83,049	\$ 145,379	\$ 7,269		
Impervious Urban Surface Reduction	\$ 9,484	\$ 94,850	\$ 54,200	\$ 158,534	\$ 959	\$ 20,815	\$ 179,349	\$ 8,967		
Bioretention (Retrofit - Highly Urban)	\$ 13,008	\$ 142,275	\$ 3,252	\$ 158,535	\$ 1,660	\$ 36,009	\$ 194,544	\$ 9,727		
Urban Tree Planting	\$ 3,252	\$ 3,252	\$ 162,600	\$ 169,104	\$ 1,312	\$ 28,459	\$ 197,563	\$ 9,878		
Permeable Pavement w/o Sand, Veg (New)	\$ 23,610	\$ 236,095	\$ -	\$ 259,705	\$ 2,372	\$ 51,462	\$ 311,166	\$ 15,558		
Permeable Pavement w/ Sand, Veg (New)	\$ 33,053	\$ 330,533	\$ -	\$ 363,587	\$ 3,317	\$ 71,971	\$ 435,558	\$ 21,778		
Cost data doe (1) taken from Costs of Stormwater Management Practices in Maryland Counties (King and Hogan, 2011) and corrected for inflation to 2017 dollars										
Source of information for (2) and (3) - US Inflation Calculator. <a href="http://www.usinflationcalculator.com/">http://www.usinflationcalculator.com/</a>										

### 3.5. REGULATORY ANALYSIS

While the National Pollution Discharge Elimination Standard (NPDES) and the Total Maximum Daily Load (TMDL) regulations have been in place for many years, due to a number of legal actions and lawsuits by prominent environmental groups there is an ever-expanding number of court consent decrees, penalties and in the case of the Chesapeake Bay watershed a TMDL Presidential Executive Order that has been challenged and upheld by the US Supreme Court. These actions have resulted in the US EPA stepping up their oversight of the nation's water quality regulations, standards and enforcement activities as it strives to gain control of the ever-growing eutrophication impacts and expanding hypoxic zones.

For many communities throughout the nation, the NPDES Municipal Separate Storm Sewer System (MS4) permit and TMDL program have become major operational programs with additional tax burden. For many older communities that are already dealing with crumbling and aging infrastructure, the additional cost of meeting new and unfinanced stormwater treatment regulations is quite significant. Under the NPDES and TMDL programs, many communities seek BMPs that are cost effective and provide low operational and maintenance costs. Within the NPDES program, depending on permit conditions communities must reduce runoff from their impervious areas anywhere from 10% to 20%, either through runoff infiltration or storage (quantity control). For other communities like those in the Chesapeake Bay watershed, they also have the added burden on achieving water quality targets through a variety of specialized BMPs focused on treating water (quality control) from all sources, including urban and agriculture.

The potential economic impact and financial cost for NPDES/TMDL implementation, operation and maintenance has not been lost on businesses, the general tax paying public, and many levels of government, including transportation agencies. For transportation departments and authorities, the challenges to achieve greater quantity and quality treatment of stormwater runoff are complex and pronounced. These challenges include

- confined and limited right-of-way;
- high percentage of impervious surface to treat;
- older legacy systems lacking stormwater management and requiring retrofitting to meet new standards;
- complex engineering to balance between safety and long term environmental requirements;
- property acquisition for new stormwater treatment technologies, which may be complex and expensive;
- complex and time consuming environmental studies (NEPA), compliance and permitting; and
- influences of land use and drainage beyond right-of-way.

To meet NPDES regulations for stormwater and the TMDL regulations for nutrients, sediment, bacteria and in some cases heavy metals, cost effective, innovative and simple-to-implement-and-maintain designs are necessary. More importantly, a solution that can be completed within most transportation agencies limited right-of-ways while having limited impact on traffic and minimal to no permitting is critical.

Current technologies involve the development of “green” infrastructure and Environmental Site Design (ESD). The objective of these systems is to mimic natural hydrologic runoff characteristics (groundwater recharge and surface flow) as closely as possible while simultaneously maximizing disconnected impervious areas. It is generally envisioned that much of this would be accomplished by using numerous small-scale, nonstructural stormwater best management practices (BMPs) to reduce nutrient loading and runoff control.

While current “green” technologies are a step in the right direction and may be applicable in many situations, the findings of the research presented in this report demonstrates that an enormous opportunity is being overlooked – the modification of existing highway greenways using biochar. Based on the research results, implementation using a broad-scale soil restoration BMP method would significantly improve infiltration, water retention and nutrient removal through the inclusion of recalcitrant carbon (biochar). This approach would take advantage of the under-utilized “green” real estate often owned and maintained by most transportation agencies. It is possible that NPDES/TMDL permit

requirements could be met using this method thereby considerably reducing design, installation and operation and maintenance costs, both present and future.

Demonstrating the significance of the research presented here is the December 2016 report by the Chesapeake Bay Program, *“Recommendations of the Expert Panel to Define Removal Rates for Disconnecting Runoff from Impervious Areas onto Amended Soils or Treatment in the Stormwater Conveyance System”*. The purpose of the modified/enhanced soils protocol developed by this expert panel is to direct stormwater runoff from impervious cover of existing development to an acceptable area of pervious cover where it may be effectively infiltrated and stored. The protocols represent an entirely new set of practices for treating urban runoff that involves changing the existing hydrologic properties (Hydrologic Soil Group (HSG) shifting) of the soils receiving and generating runoff. The panel sees soil modifications as needed because most urban soils have likely lost their original capacity to infiltrate runoff due to the mass grading and engineered soil compaction that has historically accompanied land development.

While the NPDES/MS4 and TMDL implementation programs nationwide are complex and expensive, there is nothing preventing the use of broad-scale soil restoration techniques or the utilization of biochar as an amendment or in combination with other amendments. Soil restoration is considered an acceptable BMP for the NPDES program. For the TMDL program in the Chesapeake Bay region, soil restoration using compost has been accepted as a BMP measure as outlined in the December 2016 expert panel document mentioned above. Biochar use and crediting in place of or in combination with compost has not been directly approved. However, biochar has entered the conversation of many agencies including the US EPA for its potential for soil restoration and as an amendment in engineered soil media for use in other approved BMPs. It is highly likely that detailed lab and field measurements of the biochar-amended roadway soils would be accepted by the regulatory agencies for crediting to the TMDL or NPDES program. For the rest of the nation outside of the Chesapeake Bay watershed, there are no road blocks to begin to apply the findings of this research to highway greenways as part of any NPDES program.

#### **4. PLANS FOR IMPLEMENTATION**

As described above, through support from the National Fish and Wildlife Foundation (NFWF), Delaware Department of Transportation, Maryland Transportation Authority, and City of Charlottesville, VA, the project team initiated a field-scale test site of biochar amendment of roadway soil along Rt. 896 in Delaware in December/January 2016. While not a large implementation, this site is of sufficient size to evaluate the performance of biochar amendment on reduction of stormwater runoff in the field. The results from 1.5 years of testing are presented above and demonstrate that biochar amendment at 4% (mass content) may reduce stormwater runoff by 83% - using a treatment area 8.3 times smaller than the contributing impervious roadway. Cost of biochar application is approximately \$31,700 per impervious acre treated, a standard metric for assessing BMP performance, making it one of most cost effective BMP options that has the additional benefit of using existing transportation agency right-of-way. Purchase of additional land for stormwater treatment with this BMP is not needed.

Given our results both in the lab and from this field site, the following steps are planned to advance implementation of biochar amendment to roadway soils:

- Publish results in peer-reviewed journals and present them to USEPA and other governmental bodies. We have started this process, and in 2016 and 2017 have made technical presentations to USEPA Region 3, Delaware Department of Transportation, Delaware Department of Natural Resources and Environmental Control, Maryland Transportation Authority, and at the 8<sup>th</sup> Annual Chesapeake Bay Stormwater Retreat (invited presentation). We were recently invited to present our results at the 2018 Annual TRB Annual Meeting. Results should also be presented at webinars for transportation agencies.
- Continue field-scale study. We are seeking additional financial support to continue the study at our existing field site for at least 2-3 years. Such data will allow us to answer the question, “How frequently must biochar be replaced?” We postulate that biochar will last for long periods and that this BMP will require minimal maintenance. This new field work will address questions about required maintenance and service life of biochar amendment, as well as quantify biochar impact on first-flush of pollutants.
- Because formation of macropores appears to be key with biochar amendment, additional lab and field measurements should be made to understand and quantify this process.
- Since there are many commercial biochars produced locally across the US, it is important to quantify the actual biochar properties that cause the increased water retention, macropore formation, and water infiltration. Once these properties are determined, different biochars can be tested based upon these readily-measured properties. This task will require careful laboratory experiments with a number of different biochars.
- Conduct side-by-side tests with competing soil amendments, e.g., compost, which also has been suggested as an amendment that would improve soil hydrology.
- Scale-up field test 10-fold and apply biochar to other, more challenging locations. We are seeking additional financial support for work at a new field sites that will include sections of roadway on the I-95 corridor. Demonstrating that biochar amendment will be beneficial in other roadway soils at the field scale is important. These new tests should also quantify the effect of soil fertilization and plant residues from roadway maintenance activities on biochar performance.
- Conduct field tests for conditions with brackish water and freeze/thaw cycles.
- After successful completion of field trials, develop specifications, guidelines, and marketing plans for biochar amendment.
- Engage the regulatory community and other stake holders, presenting data from our work and advocating for any additional work needed to allow full-scale implementation. We will meet with Chesapeake Stormwater Network in August 2017, and will continue to seek audience with stake holders and regulators.
- The project team will host the US Biochar Initiative's 2018 Symposium in Wilmington, DE, August 20-23, 2018. This national conference will bring together 300-400 attendees including engineers, remediation specialists, restoration scientists, DOTs, biochar producers and users, entrepreneurs, research and development scientists, students, policy and regulatory agencies, investors, waste managers, and biomass and renewable energy industry professionals.

## 5. CONCLUSIONS

Biochar amendment to roadway soils and its ability to treat stormwater runoff was studied. Commercially available Soil Reef™ biochar (The Biochar Company in Berwyn, PA, USA) was selected because of its expected beneficial properties on soil hydraulics and nutrient retention and transformation, and this biochar was amended to three representative soils in lab-scale experiments. These experiments demonstrated that biochar amendment (2-6% mass fraction) increased available water content, a measure of a soil's ability to retain water, by 20-70%, depending on soil. Thus, biochar amendment is expected to enhance retention of stormwater in soil, reducing stormwater runoff. Further, lab-scale tests showed that biochar amendment almost always increased unsaturated hydraulic conductivity, up to 500% for loamy sand. However, the impact on saturated hydraulic conductivity was less significant, with biochar amendment only increasing conductivity when amended to loamy sand and there by ~ 20%.

Biochar was amended to sandy loam in pilot-scale experiments at 4% application rate. Consistent with lab-scale experiments, biochar amendment did not cause a significant increase in saturated hydraulic conductivity. However, biochar increased water retention which when coupled with other effects reduced stormwater runoff by 13% with respect to biochar-free soil, consistent with what might be expected from lab-scale measurements. Pilot-scale data indicated slow changes in soil structure, which gradually increased soil water retention through wetting/drying periods. These data suggest time-dependent formation of soil aggregates that will enhance the soil's ability to retain and treat stormwater as biochar and soil age.

With support from the National Fish and Wildlife Foundation (NFWF), biochar was amended at 4% to a sandy loam in a roadway filter strip along a four-lane divided highway in Delaware. Over 74 storm events in 2016/2017, biochar amendment resulted in an average reduction of stormwater runoff volume and peak flow rate by 84 and 77%, respectively. In comparison, tillage alone without biochar amendment reduced stormwater runoff volume by an average of 54% and peak runoff flow rate by 51%. *Thus, biochar amendment increased the ability of the tilled roadway soil to reduce stormwater runoff volume and peak flow rate by ~ 50%.* This is 2 to 3 times more significant than what might be expected from lab and pilot-scale experiments. Field measurements of soil hydraulic properties indicated that the reason for the greater stormwater treatment in biochar-amended soils in the field was the formation of soil macropores. Time-dependent formation of soil aggregates by microbial processes is believed to be the cause of soil macropore formation.

In summary, biochar amendment to three representative roadway soils indicated that biochar amendment will have beneficial effects on soil hydraulic properties. Experiments at the pilot and field scale demonstrate that these effects enhance stormwater treatment, resulting in reductions in stormwater runoff volume and peak flow rate. Somewhat surprisingly, the benefits of biochar amendment were most pronounced at the field scale, which was attributed to time-dependent formation of soil aggregates that was not yet a significant process at the pilot scale. Using costs determined from field-scale implementation, 0.12 acres of biochar-amendment is needed to treat 1-acre impervious with approximately 83% removal of nutrients and sediments at a cost of ~ \$31,700 per impervious acre treated. While these costs are similar to an urban grass buffer (\$26,600 per impervious acre), biochar-amendment requires a dramatically smaller footprint: 0.12 versus 3.7 acre per impervious acre for biochar and urban grass buffer, respectively. Thus, biochar amendment is possible in many roadway soils and open spaces where urban grass buffers are not. Future work should

examine the longevity of biochar amendment; the utility of using less biochar, e.g., 2% application rate, to achieve the same benefit; and development of models to predict the effects of biochar amendment on stormwater treatment for a wide range of applications.

## **6. INVESTIGATOR PROFILE**

Dr. Paul Imhoff is a Professor in the Department of Civil and Environmental Engineering at the University of Delaware, Newark, DE, USA. Dr. Imhoff has BS, MS, and PhD degrees in Civil and Environmental Engineering, from the Univ. of Cincinnati, Univ. of Wisconsin-Madison, and Princeton Univ., respectively. Dr. Imhoff is a recipient of the National Science Foundation Career Award. Dr. Imhoff's teaching and research interests focus on the movement of fluids and mass transfer processes in porous media, with a particular emphasis on model development and application. In the last five years he has employed laboratory and field techniques to understand the influence of biochar soil amendment on soil hydraulic properties, phosphorus leaching, and the retention and transformation of nitrogen compounds. Dr. Imhoff's research is supported by the National Science Foundation (NSF), National Fish and Wildlife Foundation (NFWF/USEPA), Department of Energy (DOE), California Department of Resources Recycling and Recovery, Environmental Research and Education Foundation (EREF), and the Delaware Department of Transportation (DelDOT).

Mr. Hegberg, from the inception Chesapeake Bay Restoration Program in 1987, has been involved in a breadth of ecological restoration and water resources related projects. His experience has given him the opportunity to participate on projects that have spanned the entire life cycle (planning/design/construction/monitoring) using various delivery methods (traditional, design/build, full delivery). Over the years, Mr. Hegberg has developed a strong reputation for being a visionary entrepreneurial leader working to bring innovative market-based solutions to some of the most complex environmental and community redevelopment projects. Part of this vision has been in real world applications of broad scale soil restoration techniques that more naturally mimic natural hydrologic process through subsoiling, microbial inoculation, biochar and other soil amendments. Currently, he is actively involved in the development of the next generation of smart enhanced BMPs through a number pilot projects and Research & Development BMPs studies using recalcitrant carbon (biochar) as an enhanced media and/or soil amendment to improve BMP efficiencies and restoration of disturbed restoration in partnership with the University of Delaware. Mr. Hegberg is also involved in the development of Waste2Energy gasification projects in the United States and Internationally with a goal of producing commercial volumes of biochar for restoration and remediation.

## **GLOSSARY AND REFERENCES**

- (1) Yi, Susan, Brandon Witt, Pei Chiu, Mingxin Guo, and Paul Imhoff. "The origin and reversible nature of poultry litter biochar hydrophobicity." *Journal of environmental quality* 44, no. 3 (2015): 963-971.

- (2) Knight, E. M. P., W. F. Hunt, and R. J. Winston. "Side-by-side evaluation of four level spreader-vegetated filter strips and a swale in eastern North Carolina." *Journal of Soil and Water Conservation* 68, no. 1 (2013): 60-72.
- (3) ASTM Standard D422-63, Standard Test Method for Particle-Size Analysis of Soils, ASTM International (2007), West Conshohocken, PA.
- (4) Spokas, K. A., J. M. Novak, C. A. Masiello, M. G. Johnson, E. C. Colosky, J. A. Ippolito, and Carmen Trigo. "Physical disintegration of biochar: an overlooked process." *Environmental Science & Technology Letters* 1, no. 8 (2014): 326-332.
- (5) ASTM Standard D854-06e1, Standard test methods for specific gravity of soil solids by water pycnometer, ASTM International (2006), West Conshohocken, PA.
- (6) Brewer, Catherine E., Victoria J. Chuang, Caroline A. Masiello, Helge Gonnermann, Xiaodong Gao, Brandon Dugan, Laura E. Driver, Pietro Panzacchi, Kyriacos Zygourakis, and Christian A. Davies. "New approaches to measuring biochar density and porosity." *Biomass and Bioenergy* 66 (2014): 176-185.
- (7) ASTM Standard D4404-10, Standard test method for determination of pore volume and pore volume distribution of soil and rock by mercury intrusion porosimetry, ASTM International (2010), West Conshohocken, PA.
- (8) Ravikovitch, Peter I., Aleksey Vishnyakov, Ron Russo, and Alexander V. Neimark. "Unified approach to pore size characterization of microporous carbonaceous materials from N<sub>2</sub>, Ar, and CO<sub>2</sub> adsorption isotherms." *Langmuir* 16, no. 5 (2000): 2311-2320.
- (9) Rogovska, Natalia, David A. Laird, Samuel J. Rathke, and Douglas L. Karlen. "Biochar impact on Midwestern Mollisols and maize nutrient availability." *Geoderma* 230 (2014): 340-347.
- (10) Tuller, Markus, and Dani Or. "Water films and scaling of soil characteristic curves at low water contents." *Water Resources Research* 41, no. 9 (2005).
- (11) Geistlinger, Helmut, Iman Ataei-Dadavi, Sadjad Mohammadian, and Hans-Jörg Vogel. "The impact of pore structure and surface roughness on capillary trapping for 2-D and 3-D porous media: Comparison with percolation theory." *Water Resources Research* 51, no. 11 (2015): 9094-9111.
- (12) Lim, T. J., K. A. Spokas, Gary Feyereisen, and J. M. Novak. "Predicting the impact of biochar additions on soil hydraulic properties." *Chemosphere* 142 (2016): 136-144.
- (13) Schindler, Uwe, and Lothar Müller. "Simplifying the evaporation method for quantifying soil hydraulic properties." *Journal of Plant Nutrition and Soil Science* 169, no. 5 (2006): 623-629.
- (14) Wick, Abbey F., Lachlan J. Ingram, and Peter D. Stahl. "Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes." *Soil Biology and Biochemistry* 41, no. 2 (2009): 201-209.
- (15) Morse, Natalie R., Lauren Elyse McPhillips, James P. Shapleigh, and Michael Todd Walter. "The role of denitrification in stormwater detention basin treatment of nitrogen." *Environmental Science & Technology* (2017).

- (16) Sylvia, David M., Jeffrey J. Fuhrmann, Peter G. Hartel, and David A. Zuberer, eds. Principles and applications of soil microbiology. No. QR111 S674 2005. Upper Saddle River, NJ:: Pearson Prentice Hall, 2005.
- (17) Saquing, Jovita M., Yu-Han Yu, and Pei C. Chiu. "Wood-derived black carbon (biochar) as a microbial electron donor and acceptor." *Environmental Science & Technology Letters* 3, no. 2 (2016): 62-66.
- (18) King, Dennis, and Patrick Hagan. "Costs of stormwater management practices in Maryland counties." Prepared for Maryland Department of the Environment Science Services Administration. Reference Number UMCES CBL (2011): 11-043.



## **APPENDIX**

NCHRP Program Committee: William van Peeters, Federal Highway Administration; Marcel Tchaou, Federal Highway Administration Office of Project Development & Environmental Review; Peter Mattejat, Maryland Transportation Authority; and Charles Hegberg, reGENESIS Consulting Services, LLC

August, 2017

Project Number: NCHRP-182

Start Date: August 6, 2015

Completion Date: August 5, 2017

Product Category: NCHRP Highway IDEA

Principal Investigator: Paul T. Imhoff, Professor Department of Civil and Environmental Engineering

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**TITLE:** Reducing Stormwater Runoff and Pollutants with Biochar

Biochar was amended to roadway soils and evaluated for its ability to reduce stormwater and pollutant runoff.

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### **WHAT WAS THE NEED?**

To operate existing roadways and construct new ones, Departments of Transportation (DOTs) and other transportation agencies must meet increasingly stringent regulations for stormwater runoff. While existing stormwater best management practices (BMPs) are effective for removing many pollutants, they are costly and usually require the purchase of additional real estate. DOTs might achieve significant treatment by altering the properties of roadway soils, which would reduce costs and the need to purchase additional land for stormwater treatment.

### **WHAT WAS THE GOAL?**

The objective was to reduce nutrient loading and stormwater runoff volume by biochar amendment to roadway soils. Biochar is a charcoal-like material formed by combusting waste organic matter in an oxygen-limited environment and has high internal porosity and low particle density. Therefore, amending biochar to highways soils is expected to increase total porosity and water retention. Because biochar particles are often large and may enhance soil aggregation, biochar amendment may also increase soil hydraulic conductivity. Biochar amendment is also expected to enhance sorption and transformation of nitrogen compounds. These hypotheses were tested in controlled experiments. While the focus of this work was on treatment of nitrogen and sediments in stormwater runoff, because biochar amendment reduces volume of stormwater runoff, it will also reduce loadings of other stormwater pollutants to surface water bodies.

### **WHAT DID WE DO?**

- Lab-scale experiments evaluated the influence of biochar amendment on the hydraulic properties of three representative soils from the MidAtlantic region: silt loam, sandy loam, and loamy sand. Porosity, dry bulk density, water retention, and unsaturated and saturated hydraulic conductivity were measured for biochar amendment of 2 and 6% by mass.

- Pilot-scale experiments were completed in four,  $0.6 \times 0.3 \times 0.3$  m (length  $\times$  width  $\times$  depth) greenways conducted in the laboratory: two filled with sandy loam soil and two filled with the mixture of sandy loam and 4% biochar by mass. Experiments captured the three-dimensional water flow that will occur in the field with biochar-amended roadway soils, but allowed more controlled evaluation of stormwater flow and nutrient transformation.
- Field-scale experiments were conducted with support from the National Fish and Wildlife Foundation, Delaware Department of Transportation, Maryland Transportation Authority, and City of Charlottesville, VA. Biochar was amended at 4% mass fraction to a sandy loam in a roadway filter strip along a four-lane divided highway in Delaware, and reductions in stormwater runoff were quantified for 74 storm events in 2016/2017.
- Using data from the field-scale implementation, costs for biochar amendment to achieve specified stormwater treatment objectives were estimated and compared to other traditional BMPs.

### WHAT WAS THE OUTCOME?

Biochar amendment improved hydraulic properties of all amended soils. Because of biochar's influence on soil hydraulics, biochar amendment reduced stormwater runoff volume and peak flow rate by 84 and 77%, respectively, over 74 storm events in 2016/2017. At this field site, 0.12 acres of biochar-amendment was needed to treat 1-acre impervious with approximately 83% removal of nutrients and sediments at a cost of ~ \$31,700 per impervious acre treated. While these costs are similar to an urban grass buffer, biochar-amendment required a dramatically smaller footprint: 0.12 versus 3.7 acre per impervious acre for biochar and urban grass buffer, respectively. Results were disseminated to state agencies in Delaware and Maryland, Chesapeake Bay stormwater practitioners, and USEPA Region 3. New support is sought for longer duration field tests (2-3 years) and applications with smaller quantities of biochar, which would reduce implementation costs.

### WHAT WAS THE BENEFIT?

Biochar amendment of roadway soils dramatically reduced stormwater runoff volume and peak flow rate, requiring only 0.12 acres of biochar-amended soil to treat 1-acre impervious roadway at ~\$31,700 per impervious acre treated. Data suggest similar benefits might be achieved for different roadway soils in other locations.

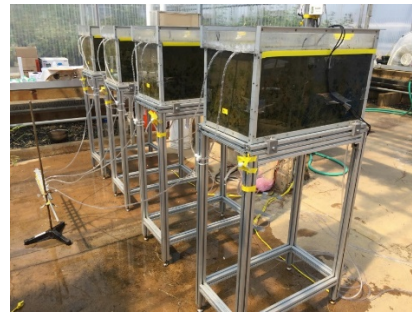
### LEARN MORE

Additional information can be found from the final report (insert link) or by contacting Paul T. Imhoff ([imhoff@udel.edu](mailto:imhoff@udel.edu)).

### IMAGES



Field site with biochar amendment



Pilot-scale experimental cells