Reducing Stormwater Runoff with Biochar Addition to Soils in Howard County, Maryland

Prepared for Howard EcoWorks

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09/01/2020

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1.

OBJECTIVES

The main objective of this project was to quantify the impact of biochar amendment to soil on stormwater infiltration for soils representing the dominant soil textures in Howard County and located within Tiber-Hudson watershed. Since soil saturated hydraulic conductivity is the most important soil hydraulic property controlling stormwater infiltration and runoff reduction, periodic field measurements of the hydraulic conductivity were performed to quantify the effect of amending soil with a commercially produced wood biochar at two different locations in Howard County. The data collected over the study period were used to evaluate the increase in annual rainfall infiltration for the unamended and biochar-amended soils.

2. STUDY AREAS

Based on review of Tiber-Hudson watershed and in consultation with Howard EcoWorks, two test sites located in Ellicott City were selected for the study. The first site (Site 1) is located adjacent to the parking lot at St. Peters Episcopal Church (39^{o}26' N, 76^{o}80' W). Site 1 receives stormwater runoff from 24.53 m^2 of impervious area. The second site (Site 2) is located adjacent to the parking lot of Slack Funeral Home (39^{o}27' N, 76^{o}81' W) and receives stormwater runoff from 117 m^2 of impervious area. At each site, side by side sections (5 ft by 5 ft) of tilled unamended soil and biochar amended soil were constructed for the study (Figure 2.1).

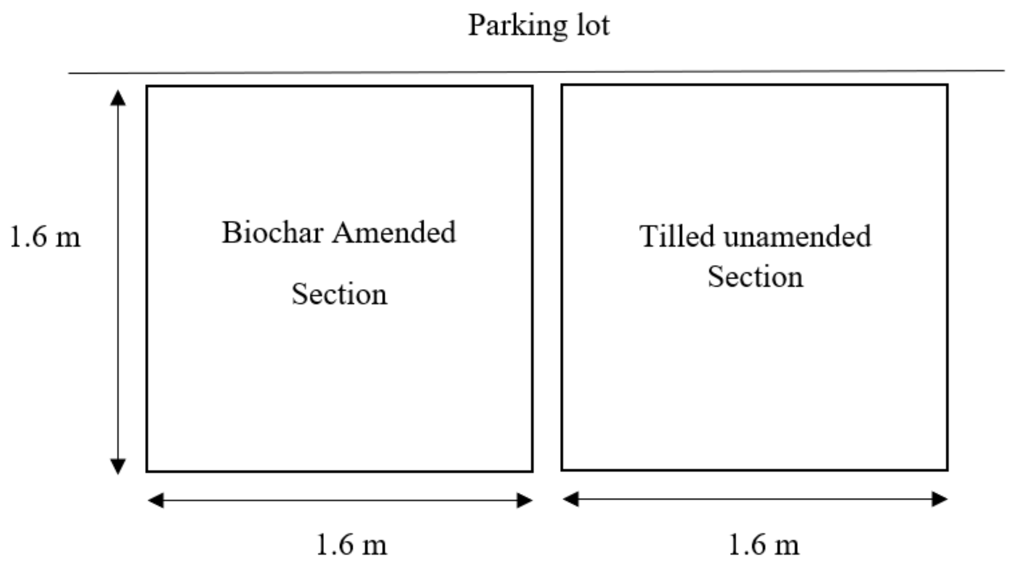


FIGURE 2.1: Plan view of biochar amended and unamended test sites

3. MATERIALS AND METHODS

3.1. Soil and Biochar Characterization

From each site bulk soil samples were collected to characterize the soil texture. To determine the soil particle size distribution, wet sieving (ASTM D 6913) and hydrometer tests (ASTM D 422) were performed using 500 g soil samples. 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 the soil fraction finer than 0.075mm, hydrometer tests were performed using a 152-H hydrometer. Data from sieve analyses and hydrometer tests for each sample were combined to produce a single particle size distribution (PSD) curve. Using the percentages of sand, silt and clay in a textural triangle, the USDA soil texture class was identified. The commercial biochar used for this project was made from tops and limbs of Douglas fir and ponderosa pine pyrolyzed at ~950^{0}C at high heating rate. The particle size distribution for Biochar was determined following ASTM D 2862.

3.2. Biochar Installation

In March 2019, biochar was incorporated in a 1.6 m ×1.6 m test section at each site to a depth of 30 cm. For the biochar amendment, the top 3 cm of the topsoil containing plant matter and grass roots were removed. Then, the remaining soil up to 30 cm depth was tilled and mixed combining both sections (tilled unamended and amended) to make a homogenous soil mixture for the entire test region. Based on in field bulk density measurement of soil, a soil volume equivalent to 4% (w/w) biochar was removed from the amended section. Then, biochar was added with shovels and mixed with a mechanical tiller up to 30 cm depth to construct the biochar-amended test section. Following biochar amendment, both sections was seeded with Tall fescue grass seed and stabilized with straw.

3.3. Field Saturated Hydraulic Conductivity Measurements

Periodic field testing was conducted after 5 (early September of 2019), 8 (late November of 2019) and 15 months (mid July of 2020) to quantify the field saturated hydraulic conductivity (K_{sat}) of biochar-amended and unamended soils. A Modified Phillip-Dunne (MPD) Infiltrometer (Upstream Technologies Inc, New Brighton, MN) was used to measure K_{sat} at multiple sampling points in each test region. Six sampling points on average were selected randomly for each test section for MPD measurement to estimate the K_{sat} of the entire test section. The MPD infiltrometer was inserted 5 cm into the surface of the soil and then filled to a specified height (usually 30 cm) of water (Figure 3.1). The change in water level in the MPD cylinder as it infiltrated into the ground was measured over time and recorded electronically

FIGURE 3.1: Field Saturated Hydraulic Conductivity Measurement with Modified Phillip Dune Infiltrometer. Three tests are ongoing in this photo.

with a wireless tablet. The data collected from each infiltrometer measurement were analyzed via a spreadsheet utilizing Visual Basic program to best-fit the water elevation versus time data according to procedures described elsewhere (Ahmed et al., 2015). For estimating K_{sat}, initial and final soil moisture content, the penetration depth of the infiltrometer and the water elevation (relative to the soil surface) versus time data were used. To measure the initial and final moisture content data, Time Domain Reflectometer (TDR) was used in the field.

Since biochar can affect the built-in calibration for determining the volumetric water content measurement of TDR, a unique calibration equation was developed following methods described in (Wanniarachchi et al., 2019) using TDR period and volumetric water content data of sand and sand plus 4%(w/w) biochar mixture. The calibration equation was used to estimate volumetric water content of biochar amended sections from field TDR data. Spatial variation of K_{sat} values based on the sampling points were mapped for each section at both sites using the Kriging correlation method.

3.4. Annual Infiltrated Rainfall Volume

To estimate the infiltration performance for unamended and amended soil, a model developed by (García-Serrana et al., 2018) was applied. With input of soil specific hydraulic conductivity (K_{sat}), width of the treated soil associated with K_{sat} (width of test section), width of the impervious surface (width of the parking lots at the site contributing to the runoff), and location's rainfall volume percentile curve, the percentage of annual infiltrated rainfall volume was calculated for each site considering minimum width of treatment section. While the ground slopes at all test sections were < 10%, the model developed by García-Serrana et al. (2018) assumed a 20% slope. Thus, the beneficial effects from enhanced infiltration because of biochar amendment will be underestimated with this simple modeling approach.

The rainfall percentile curve used in the model was developed analyzing the 10 year (1995-2004) rainfall data of MD CLARKSVILLE 3 NNE ($39^0$2553 N, $76^0$9286 W) weather station downloaded from National Oceanic and Atmospheric Administration (NOAA, USA).

3.5. Identification of Dominant Plant Species

Since soil macropores associated with plant root growth can contribute to the increased K_{sat} and stormwater infiltration rate, differences in plant species and their contributing percentage to plant cover was monitored following quadrat method (Weaver, 1918) in the study sites. Measurements were only conducted after the last set of K_{sat} measurements. A square frame (30 cm × 30 cm) divided into 10 ×10 grid (9.3 cm^2 per grid cell) was used for the estimation of percent plant cover by different species (Figure 3.2). The number of grids covered by a specific species divided by the total number of grids within the frame was used for the percent plant cover calculation. For both sites, 4-5 quadrats (depending on the variation of species) were used to extrapolate the plant cover estimation for the whole test section from quadrat measurements performed on August 11, 2020.

FIGURE 3.2: Plant cover estimation by different species using Quadrat method. Photo illustrates the square frame with a superimposed grid (red lines).

4. RESULTS

4.1. Soil and Biochar Properties

The particle size distribution (PSDs) of soils collected from Sites 1 and 2 are shown in Figure 4.1. Based on the percent sand, silt, and clay content, the USDA soil texture for the Church site was identified as loam (Table 4.1). Whereas for the Slack site the soil texture was identified as gravelly loam with high percentage of gravel.

Biochar used for this project contained 43.9%, 49.8%, 3.2% and 1.4% of 2-4 mm, 1-2 mm, 0.5-1 mm, and 0.5 mm particles sizes. The BET surface area and pore volume of the biochar were 553.78 m^2/g and 0.387 cm^3/g, respectively.

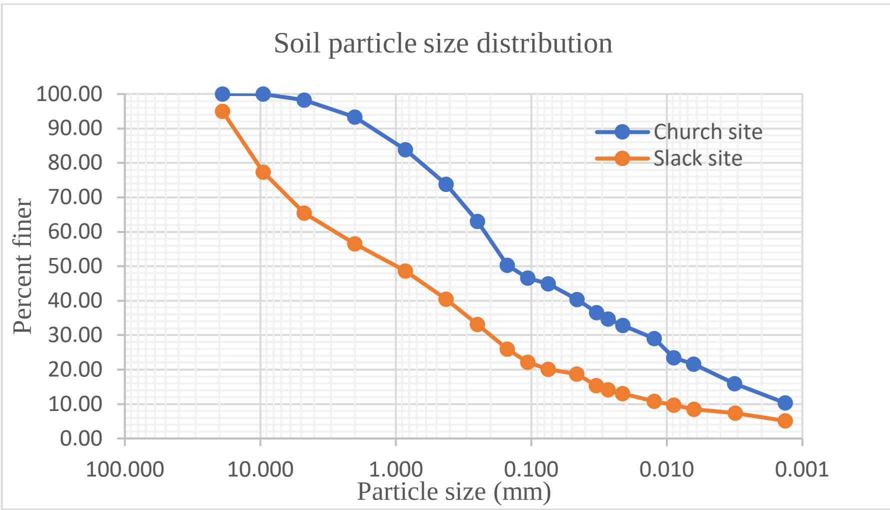


FIGURE 4.1: Particle size distributions of soil samples.

TABLE 4.1: Percent sand, sand silt content and soil texture of study sites

Site	% Sand	% Silt	% Clay	USDA Soil Class
Church Site	48.5	32.9	12	Loam
Slack Site	36.4	15.1	5	Loam (with gravel)

4.2. Field Saturated Hydraulic Conductivity

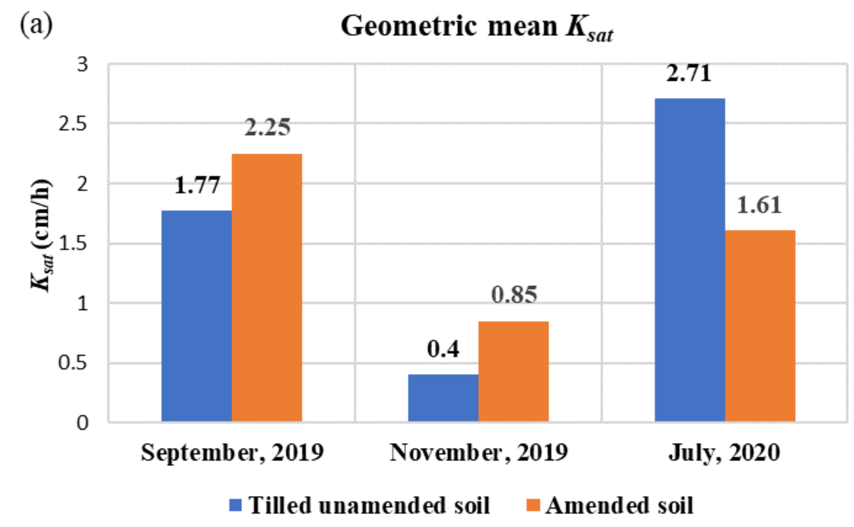
Field saturated hydraulic conductivity measurements are tabulated in Table 4.2, which includes the number of K_{sat} measurements at each measurement time, average percent initial and final volumetric water content (VWC), and geometric mean of K_{sat} (cm/h). For measurements at the Church site, the average initial moisture content for the biochar amended section was 48.6% greater compared to the tilled unamended section. The final moisture content for biochar amended section was on average 30% more than the unamended section. Similarly, at the Slack site, the initial VWC and final VWC for biochar amended soil were on average 46% and 24.6% higher than the unamended soil, respectively. Thus, biochar amendment increased the volume of water that could be stored in the soil at both sites.

TABLE 4.2 : Summary of Field Saturated Hydraulic Conductivity (K_{sat}) Measurements

Site	Section	Date of Measurements	Sampling Points	Mean Initial Volumetric Water Content (%)	Mean Final Volumetric Water Content (%)	Geometric Mean of K_{sat} (cm/h)
Church Site	Tilled unamended	September 2019	5	21.7±3.3	40.5±5.	1.8±1.0
		November 2019	5	29.8±2.3	40.3±0.8	0.4±0.1
		July 2020	6	34.9±2.8	48.2±2.5	2.71±2.6
	Biochar Amended	September 2019	5	34.1±4.7	53.6±5.8	2.25±2.4
		November 2019	6	44.4±4.5	54.9±1.7	0.85±0.81
		July 2020	6	48.8±2.8	59.1±3.1	1.61±1.32
Slack Site	Tilled unamended	August 2019	8	20.6±1.7	48.5±2.	8.84±6.32
		November 2019	5	24.2±1.2	39.1±1.8	6.16±10.29
		July 2020	6	21.8±2.4	44.4±6.7	0.83±3.14
	Biochar Amended	August 2019	10	35.5±6.1	55.2±3.5	56.75±83.08
		November 2019	6	36.1±1.6	53. 2±2.3	13.9±59.6
		July 2020	6	25.8±1.7	55.3±2.2	10.71±7.21

Temporal variation of the geometric mean K_{sat} is shown in Figure 4.2. For the Church site, the geometric mean of K_{sat} was 1.3 times higher in the biochar amended section after 5 months of amendment which increased to 2.2 times during November 2019 measurements. However, during the July 2020 measurements, the mean K_{sat} value for the tilled unamended section was 1.6 times higher than the biochar amended section.

For the Slack site soil, mean K_{sat} of the biochar amended soil was 6.4 times more than the unamended soil during first set of measurements. During the last set of measurements in July 2020, K_{sat} was 13 times higher for the amended soil in the Slack site. Thus, at both sites and over a two-year period, biochar amended soils had significantly larger mean K_{sat} than unamended regions. The only exception were measurements at the Church site in July 2020, which will be discussed further below. As will be shown below, larger K_{sat} results in significantly more stormwater infiltration.



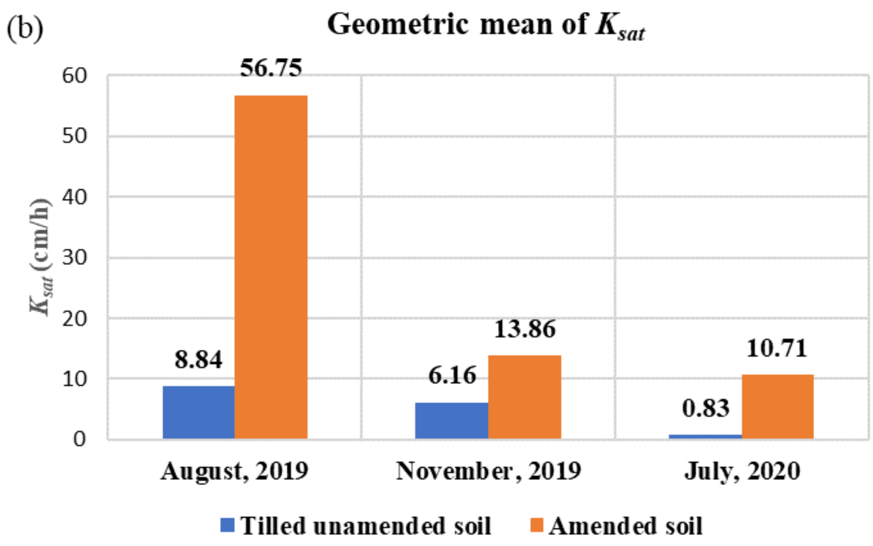


FIGURE 4.2: Temporal variation of geometric mean K_{sat} for (a) Church and (b) Slack sites.

The spatial variation of K_{sat} throughout the unamended and amended sections of Church site at different times is shown Figure 4.3. Here, warmer colors indicate higher K_{sat}. For the first measurements in September 2019, the biochar section had higher K_{sat} throughout the test section (Figure 4.3(b)). During the November 2019 testing, the site experienced smaller K_{sat} with less spatial variability in both sections. In July 2020, the tilled unamended section had higher K_{sat} than the amended section, which is hypothesized to be due to differences in sunlight that resulted in differences in plant species and thus root growth between the sections. From the spatial variation of K_{sat} in the biochar-amended section in July 2020 (Figure 4.3(b)), K_{sat} was higher in regions that were nearest to the tilled unamended section, which supports the hypothesis.

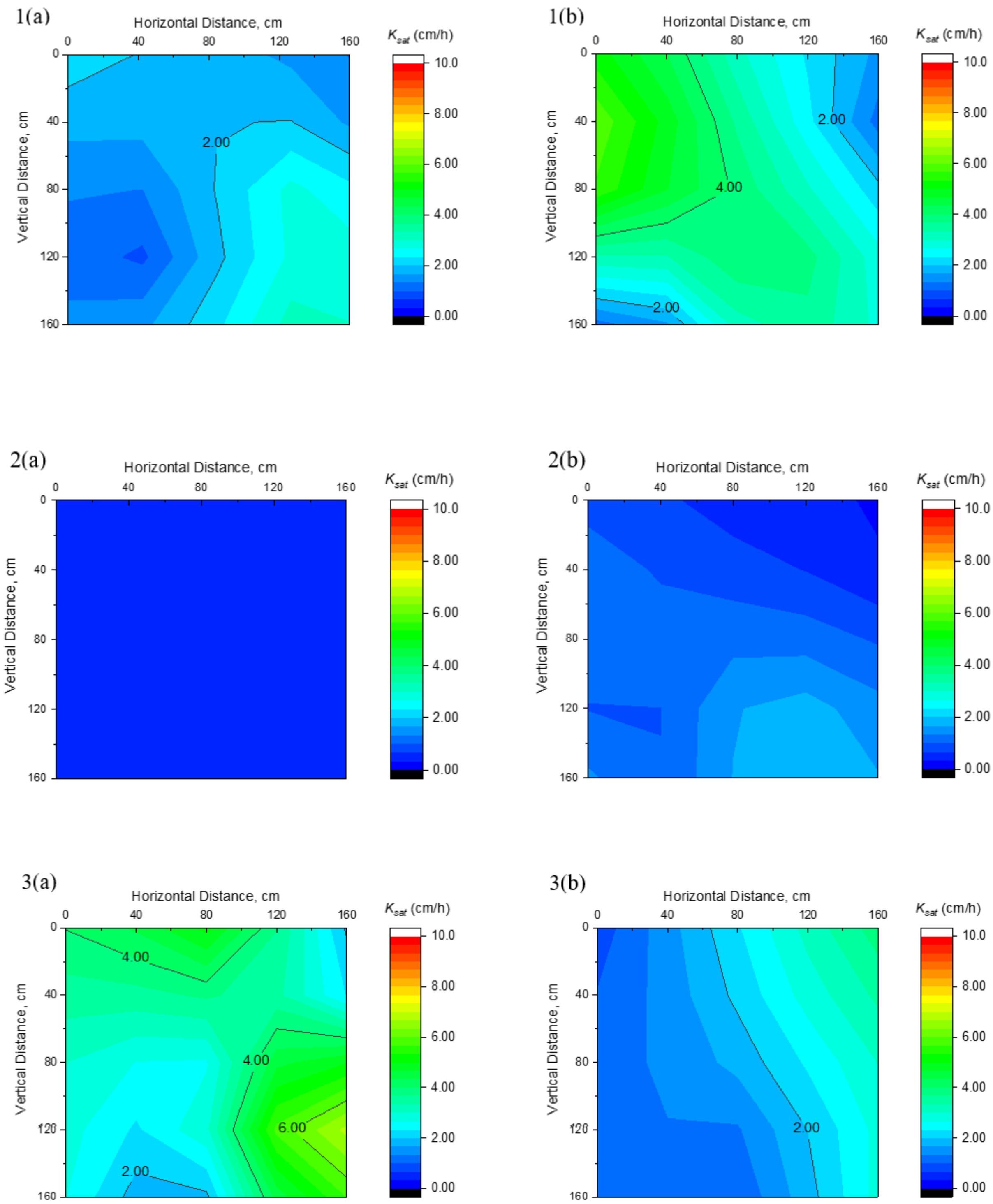


FIGURE 4.3: Spatial variation of K_{sat} for Church site: 1) September 2019, 2) November 2019, and 3) July 2020. (a) Tilled unamended section, and (b) Biochar amended section.

The spatial variation of K_{sat} at the Slack site is shown in Figure 4.4. Since both the biochar and gravel content impact K_{sat} measurements, higher standard deviations for K_{sat} in the biochar amended section were observed for all three measurement periods.

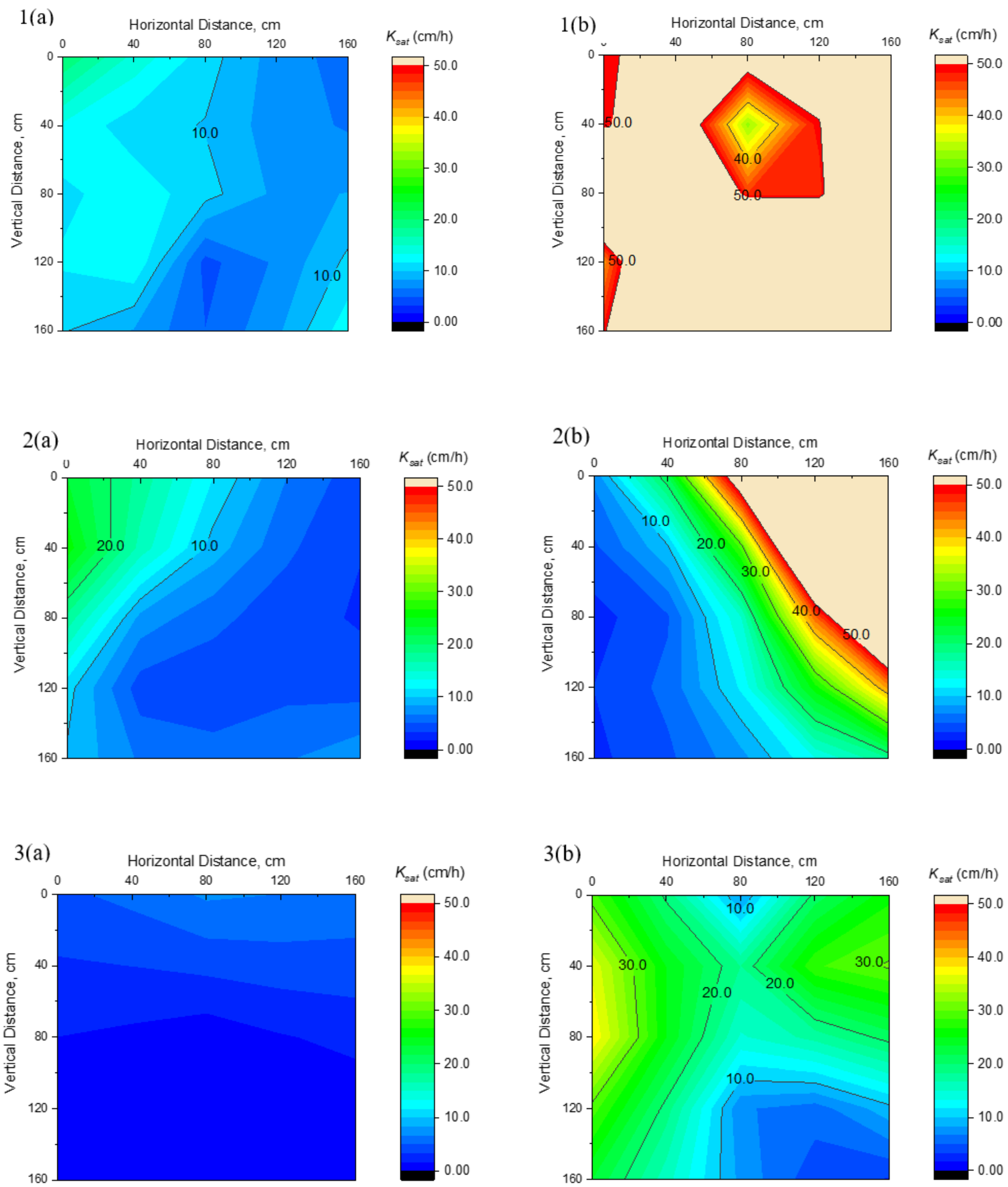


FIGURE 4.4: Spatial variation of K_{sat} for Slack site: 1) August 2019, 2) November 2019, and 3) July 2020. (a) Tilled unamended section, and (b) biochar amended section.

4.3. Annual Average Infiltrated Rainfall Volume

The annual infiltrated rainfall volume as a percentage of the total rainfall on the impervious parking lot was computed for each site at different measurement times and is summarized in Table 4.3. Because the ratio of impervious pavement to pervious treatment section width was smallest at the Church site, the higher increase in infiltrated volume was observed for the Slack site across all seasons compared to the Church site. For the Church site, except for the July 2020 measurement there was a 12.9% to 61.5 % increase in infiltrated rainfall volume in the biochar amended medium compared to the tilled section for September 2019 and November 2019, respectively. At the Slack site, similar large increases in annual average infiltrated rainfall volume occurred for the biochar amended soil (58.7%, 35.7%, and 223.8%). For the Slack site, the increase in infiltrated volume increased dramatically from 58.7% to 223.8% after 15 months of biochar amendment (July 2020).

TABLE 4.3 : Summary of Annual Infiltrated Raifall Volume from Model

				Tilled unamended section		**Biochar amended section**		
Site	**Width of impervious area (m)**	**Minimum width of test section (m)**	**Timeline**	**Mean K_{sat} (cm/h)**	**Annual Infiltrated rainfall volume (%)**	**Mean K_{sat} (cm/h)**	**Annual Infiltrated rainfall volume (%)**	**Percent increase in Infiltrated volume**
Church site	18.3	1.83	September 2019	1.77	31	2.25	35	12.9
			November, 2019	0.4	13	0.85	21	61.5
			July, 2020	2.71	38	1.61	29	(-) 23.7
Slack site	27.5	2.75	August, 2019	8.84	63	56.75	100	58.7
			November, 2019	6.16	56	13.86	76	35.7
			July, 2020	0.83	21	10.71	68	223.8

4.4. Plant Species Identification

For the Church site, in August 2020 the biochar amended section was covered mostly with Tall fescue (80%) and white clover (7%), with remaining ground surface uncovered with plants. The tilled unamended section, though, was covered with Ground Ivy (34%), which is a cool season perennial grass with fibrous root system, along with White clover (12%) and the remainder covered with Tall Fescue grass. No bare ground was observed in the tilled section. We attribute the higher density of plant growth and the presence of Ground Ivy in the tilled unamended section to smaller solar radiation.

In the Slack site, Tall fescue grass was observed to be dominant species with 85 to 90% plant coverage for both sections and no observable differences.

5. DISCUSSION

The variation of K_{sat} was observed seasonally and can be attributed to gradual soil compaction, and reductions in plant growth and plant evapotranspiration before winter. Higher K_{sat} measurements in summer may be due to enhanced soil pore system after winter due to freeze thaw cycles. For both sites, all measurements in the biochar amended section had higher K_{sat} than the tilled unamended section, except for the July 2020 measurements at the Church site. This anomaly is believed due to differences in sunlight in the biochar amended and unamended regions, which caused differences in growth of different plant species (Figure 5.1).

Figure 5.1: Tilled unamended section (left) and biochar amended section (right) at Church site in July 2020.

For the biochar amended sections at the study sites, an increase in infiltration volume and decrease in runoff volume was computed for both sites. Such decreases in runoff volume will also contribute to reductions in nutrient loading to surface water bodies by stormwater runoff. Depending on the site specific K_{sat} and desired runoff reduction, the simple model applied in the study might be used for preliminary design of required biochar amended sections in critical areas of Tiber-Hudson watershed.

6. CONCLUSIONS

A commercially produced wood derived biochar was amended to soil at two locations in Elicott City, Howard County with an objective of increasing infiltration and reducing stormwater runoff. Periodic field observation of soil saturated hydraulic conductivity indicated that biochar has the potential to dramatically increase the saturated hydraulic conductivity, the controlling parameter of soil infiltration rate, for typical soils in the Tiber Hudson watershed. The increased saturated hydraulic conductivity because of biochar amendment was predicted to cause significant increases in annual average infiltrated rainfall volume at both the Church and Slack sites, which corresponds to significant reductions in stormwater runoff. If the amendment of existing soils with biochar is implemented at other impervious/pervious points of disconnection in the Tiber-Hudson watershed, the effect on runoff and pollutant loading to the surface water bodies could be significant. However, large scale watershed scale modeling is required to verify the reduction.

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