https://doi.org/10.17221/15/2018-SWR

# Two types of biochars: one made from sugarcane bagasse, other one produced from paper fiber sludge and grain husks and their effects on water retention of a clay, a loamy soil and a silica sand

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**Citation**: Hlaváčiková H., Novák V., Kameyama K., Brezianska K., Rodný M., Vitková J. (2019): Two types of biochars: one made from sugarcane bagasse, other one produced from paper fiber sludge and grain husks and their effects on water retention of a clay, a loamy soil and a silica sand. Soil & Water Res., 14: 67–75.

**Abstract**: Biochar (BC) is used as a soil amendment to enhance plant growth by improving mainly soil chemical and hydrophysical properties. In this work the effects of two types of BCs on soil water retention properties were analysed. The first type of BC was made from sugarcane bagasse. It was added to a clay "Shimajiri Maji" soil at an application rate of 3 w%. The second type of BC was made from paper fiber sludge and grain husks. It was added into a loam soil at rates of 3.6, and 7.3 w%. It was assumed that the effect of BC amendment will be more pronounced in coarse-grained soil than in fine-grained one. Therefore, the second type of BC was applied additionally in the silica sand, in a textured contrast material compared with the loam soil. The BC amendment caused statistically significant increase of water content in the transmission pores of the clay soil, in the storage pores of the loam soil, and in the macropores and the storage pores in the silica sand. Despite of the positive effect on soil water retention, statistically significant increase of available water capacity (AWC) was identified only in the loam soil with the larger BC amendment rate. Possible reasons are discussed.

**Keywords**: available water capacity; pore categories

Biochar (BC) is a carbon-rich material produced during thermal decomposition of organic waste materials under a limited supply of oxygen (also known as pyrolysis) at relatively low temperatures (< 700°C) (Lehmann & Joseph 2009). Biochar is used as an alternative material in agriculture. It is defined as a co-product of thermochemical conversion of lignocellulosic materials and is used to enhance plant growth by improving soil chemical properties, e.g. nutrient retention and nutrient availability (Glaser *et al.* 2002); soil physical properties, e.g bulk density, water holding capacity and permeability (Laird *et al.* 2010; Kameyama *et al.* 2016), and soil biological properties (Ameloot *et al.* 2013), all contributing to an increased crop productivity (Bruun *et al.* 2014; Vitkova *et al.* 2017).

Supported by the Slovak Scientific Grant Agency VEGA Projects No. 2/0053/18 and 2/0189/17, by the Research & Development, Operational Program funded by the ERDF, the project implementation ITMS 26240120004 Centre of Excellence for Integrated Flood Protection of Land and partially supported by JSPS KAKENHI Grant No. 16K07952.

https://doi.org/10.17221/15/2018-SWR

The origin of biochar usage can be traced back to the early 19$^{th}$ century, as reviewed in Lehmann and Joseph (2009). The earliest research of biochar and its effects was conducted by Retan (1915) who investigated how biochar affects the growth of seedlings. Biochar research has advanced in many ways since then. Nowadays, biochar finds its application in four main environmental areas: soil improvement, energy production, mitigation of climate change, and waste management (Lehmann & Joseph 2009).

Biochar characteristics vary depending on production conditions and the type of biomass used. Laghari *et al.* (2016) point out that the agronomic benefits of biochar depend on the particular type of biochar and the application rates that have to be properly chosen for each type of soil. Several investigators report that biochar raises soil water retention especially within the range of available water capacity (AWC) (Laird *et al.* 2010; Abel *et al.* 2013). However, Tryon (1948) documented, that moisture available to plants was increased only in the sand, not affected in the loam, and decreased in the clay soil. Other recent studies consistently document an increase in AWC once biochar is incorporated into a soil. However, there is still not known how the properties of different kind of biochars can influence water retention characteristics of particular soil.

Besides the positive effect of BC on soil properties, some authors documented a negative impact on soil hydraulic conductivity (Moaragues-Saitua *et al.* 2017) or soil erosion (Wang *et al.* 2013). Time duration of BC amendment is also a crucial characteristic. Several authors (e.g. Madari *et al.* 2017) showed only a short time positive effect of BC amendment on the certain soil properties.

The aim of the paper was: (*i*) to quantify the retention properties of two types of biochars made from different organic materials at similar pyrolysis temperatures, and (*ii*) to quantify the short time effect of the biochar amendment on retention characteristics, and on the plant available water capacity of soils with different textures.

Materials (soils) with contrasting properties such as clay, loam and silica sand were used to support the hypothesis that the improvement of a soil's AWC by a BC amendment is identified more readily in coarse soils than in fine ones. One more reason for using the silica sand was that it is typical with the narrow pore and grain-size distribution. It was supposed that more pronounced effect of BC application could be found in the silica sand concerning the shape of the soil water retention curve as well.

## MATERIAL AND METHODS

Soil water retention curves (SWRC) measurements were provided in a laboratory on disturbed soil samples. Two main groups of samples were prepared. In the first group was used a biochar made from a sugarcane bagasse (BC (SB)) and a clay soil from the humid subtropical climate zone at the Miyako Island in Japan (Kameyama *et al.* 2016). The Miyako Island is a part of the Ryukyu Islands located between the southern border of the East China Sea and the north-western border of the Philippine Sea. In the second group was used a biochar made from a paper fiber sludge and grain husks (BC (FSGH)), applied in a loam soil in the temperate continental climate zone in Slovakia, Central Europe. In addition, silica sand was used for the BC (FSGH) amendment as the contrast material to a loam soil to test the hypothesis mentioned in previous. Benefits of laboratory experiments are that one can avoid uncertainties associated with the spatial variations of soil properties as well as the non-regular distribution of BC after soil amendment.

**Clay soil**. Soil was sampled from the surface layer of a sugarcane field at the study site on the Miyako Island (N 24°48'11'' E 125°16'52''). The predominant geologic feature is the highly permeable coral limestone. The land surface is covered with a shallow layer of calcaric dark red soil characterized by low AWC (Kubotera 2006). This soil, known as "Shimajiri Maji," is classified as Chromic Luvisol (IUSS Working Group WRB 2015). The soil texture was classified as clay soil with 7.7% of sand, 19% of silt, and 73.3% of clay. Although the area experiences high annual precipitation totals (larger than 2000 mm), rainfall patterns are poorly distributed, and long dry periods occur from June through September (Kameyama *et al.* 2016). The annual average temperature is 23.6°C; the highest elevation is 114.8 m a.s.l.

**Loam soil**. The loam soil was taken from the experimental station of the Slovak University of Agriculture in Nitra (N 48°19'00'' E 18°09'00'', the south-west of Slovakia), which is used for crop production and agricultural research. The soil type is classified as Haplic Luvisol (IUSS Working Group WRB 2015), moderate heavy soil, formed on loess Quaternary sediments. The soil texture is classified as loam with 36.0% of sand, 48.8% of silt, and 15.2% of clay. The annual average temperature is 9.8°C and the annual precipitation is 573 mm. The site is located at an altitude of 175 m a.s.l. More information on the experimental station and on the agricultural research can be found in Šimanský and Kováčik (2015).

**Silica sand**. Silica ST56 sand is the material with following characteristics: the mean particles diameter (d50) is 0.15 mm, the relative amount of particles with diameters < 63 μm is 2%, > 63 μm is 11%, > 100 μm is 62%, > 200 μm is 20%, > 315 μm is 3%, > 400 μm is 2%, and > 500 μm is 0.5%. The bulk density is 1.5 g per $cm^3$, the particle density is 2.65 $g/cm^3$, pH 8.

**Biochar from sugarcane bagasse**. Sugarcane bagasse is the main source of biomass on the Miyako Island. Sugarcane bagasse is the residue obtained from sugarcane stalks after juice extraction. In this study we used the biochar made from sugarcane bagasse which was air dried and heated in a batch-type pyrolysis furnace at 600°C for 2 h. The characteristics of the biochar determined by Kameyama *et al.* (2016) are listed in Table 1.

**Biochar from paper fiber sludge and grain husks**. This type of biochar was made from paper fiber sludge and grain husks in the weight ratio 1 : 1. The biochar was produced by pyrolysis at 550°C for 30 min in a Pyreg reactor (Pyreg GmbH, Dörth, Germany). The characteristics of the biochar were determined by the supplier (Sonnenerde Gerald Dunst Kulturerden GmbH, Austria), and are listed in Table 1.

**Preparation of samples**. Air-dried soils and BC (SB) were passed through a 2-mm sieve. BC (FSGH) was not sieved; it was applied in original fraction size. Non-amended soils, BC-amended soils, and BCs were packed in 0.5 cm layers gently tapping the cores with the volume of 100 $cm^3$ (Kopecky cylinders). Glass fiber or cloth filter was attached to the bottom of the samples. The pure soil samples were filled to prescribed bulk densities corresponding to field values. The BC-amended soils were prepared separately by adding particular percentage of mass fraction of BC to the soil and mixing for 5 min with a spoon in a plastic pot. They were packed then into the cores. Water retention curves of soil samples were measured immediately after BC amendment.

Three sets of samples were prepared for measurements on clay soil and its mixture with the BC (SB): a soil without biochar (control), a soil amended with biochar at 3 w%, corresponding to the field application rate of 30 t/ha at a depth 0 to 10 cm, and samples with a sole biochar made from sugarcane bagasse (Kameyama *et al.* 2016). Each treatment was performed with three replicates.

Four sets of samples were prepared to measure the retention properties of loam soil and silica sand and their mixtures with the BC (FSGH): a soil without biochar (control), a soil amended with biochar at 3.6 w%, and 7.3 w%, respectively, corresponding to the field application rate of 40 t/ha, and of 80 t/ha at a depth 0 to 10 cm, and samples with a sole biochar. Each treatment was performed with five replicates.

**Physical and chemical properties of both types of biochars measurement**. The mass fraction of O and the specific surface area were estimated for both BCs by the same methods. The mass fraction of O was estimated by calculation from known mass fractions of the measured elements (C, H, N, S and ash content) and according to DIN 51733:2008; the surface area was measured by the BET method (according to Brunauer *et al.* (1938) and ISO 9277:2010 (E)) from nitrogen gas adsorption isotherms. The physicochemical properties of the BC (SB) were measured as follows: the mass fractions of C, H, N and S were measured using a 2400 Series II CHNS/O Elemental Analyser (PerkinElmer, Inc., USA). For pH measurements the BC was diluted to 1 : 20 BC : deionized water (w/V) and equilibrated for 90 min on a shaker, as described in Rajkovich *et al.* (2012). The ash content was determined by weight loss after combustion in air at 750°C for 6 h (ASTM 2007); the particle density was measured by the liquid displacement method using 1-buthanol (JIS 1995). The physicochemical properties of the BC (FSGH) were measured as follows: the mass fractions of C, H, N were measured using a TruSpec CHN Analyser (Leco Corporation, USA); the pH was measured according to ISO 10390:2005 (E) using $CaCl_2$ solution; the ash content was estimated by using thermogravimetric analyser TGA (Leco Corporation, USA) by

Table 1. The physicochemical properties of two biochars (BC) used in the study

| BC | C | H | N | O | pH | Ash content | Surface | Bulk density | Particle density | Fraction |
|---|---|---|---|---|---|---|---|---|---|---|
| | (w%) | | | | (–) | (w%) | area ($m^2$/g) | ($g/cm^3$) | | size (mm) |
| BC (SB) | 75.3 | 1.7 | 0.7 | 3.8 | 9.2 | 9 | 218 | 0.16 | 1.6 | 0–2 |
| BC (FSGH) | 53.1 | 1.8 | 1.4 | 5.3 | 8.8 | 38 | 22 | 0.21 | – | 0–5 |

SB – sugarcane bagasse; FSGH – fiber sludge and grain husks

https://doi.org/10.17221/15/2018-SWR

rising the temperature to 550°C and holding until constant weight was reached.

**Measurement of soil water retention curves**. Desorption parts of water retention curves of the clay soil, BC (SB) and their mixtures were measured on the core samples by the sandbox method (Jamison 1958) for pressure heads between –10 and –30 cm and by the pressure plate extractor (Dane & Hopmans 2002) for pressure heads between –30 and –15 000 cm. Desorption parts of water retention curves of the loam soil, the silica sand and their mixtures with BC (FSGH) were measured by the pressure plate extractor (Dane & Hopmans 2002) for pressure heads between –10 and –10 000 cm. For pressure heads between –10 and –300 cm special ceramic plates for small pressures and manometer with very fine resolution were used. Adsorption parts of the water retention curves determined for the loam soil, the silica sand and the BC (FSGH) were estimated from adsorption isotherms measured in an exsiccator. The soil water retention functions were fitted by the van Genuchten soil water retention function (Van Genuchten 1980). As the goodness of fit (expressed by $r^2$) for the silica sand amended with the BC (FSGH) using the van Genuchten function was rather unsatisfactory ($r^2$ was 0.92 compared to other results in the range 0.97–0.99), the Durner's bimodal soil water retention functions were applied in this case (Durner 1994) (the goodness of fit was then improved to value 0.99).

**Estimation of water contents in different categories of pores**. There are various classification systems for soil pores, e.g. by Luxmoore (1981), Corey (1977), Greenland (1977). In this work we used a slightly modified Greenland (1977) concept classification of soil pores as follows: macropores or fissures with the equivalent pore diameters ($d$) larger than 300 μm, transmission pores with $d$ in the range from 10 μm to 300 μm, storage pores with $d$ in the range from 0.2 μm to 10 μm, and residual pores with $d$ smaller than 0.2 μm. Evidence from field experiments suggests that the threshold value of macropores, corresponding to water entry pressure of –10 to –6 cm, is typically accompanied with non-equilibrium preferential flow in many agricultural soils (Jarvis 2007). Transmission pores and fissures are pores which drain by gravity and allow free air and water movement and root development (Greenland 1977). The smallest transmission pores filled with water correspond to field capacity (FC). Storage pores typically allow capillary flow; in this range the water is available to plants (AWC). AWCs were estimated from the water contents in the range of storage pores, i. e. water contents in the range of pressure heads from –300 cm (FC) to –15 000 cm (wilting point – WP) using the capillary rise equation, relationship between the diameter of a pore that will fill up at a given negative pressure head. Water contents in different soil pore categories between different treatments were compared statistically using analysis of variance (ANOVA in MS Excel, 2010 data analysis tool). The null hypothesis of ANOVA was that the true difference of the means is equal to zero. The null hypotheses of the tests were rejected or accepted at a significance level of 0.05.

## RESULTS AND DISCUSSION

**Soil water retention properties of used materials and amended soils**. The physicochemical properties of both types of biochars (Table 1) show that the main differences between the two BCs are in their surface areas, the ash contents, and the fraction sizes. The soil water retention curves revealed the retention properties of the biochars, soils and the amended soils. Both biochars are characterized by a large retention capacity near saturation with mean values 0.756 $cm^3/cm^3$ and 0.682 $cm^3/cm^3$ for BC (SB), and BC (FSGH), respectively (Figure 1). At smaller pressure heads, the water contents of the BC (SB) exceeded the water contents of the BC (FSGH) and they are characterized with larger variability.

The clay "Shimajiri Maji" soil is characterized also with quite large water contents near saturation with the mean of 0.625 $cm^3/cm^3$, but they are rapidly reduced to the range of water contents between 0.35 and 0.49 $cm^3/cm^3$ at the pressure head of –40 cm. The water contents of the clay soil were even larger compared to the BC (SB) at the pressure heads below –250 cm. The soil water contents near saturation of the loam soils and the silica sands (Figure 1, on the right) were similar with the values around 0.45 $cm^3/cm^3$. The water contents of the silica sand rapidly decreased at the pressure head of –100 cm and reached the value of 0.074 $cm^3/cm^3$. The water contents of the loam soil at the pressure heads below –300 cm were similar to the water contents of the BC (FSGH) until pressure head –10 000 cm. From adsorption curves can be seen that water contents of BC (FSGH) were always smaller than those of the loam soil, but larger than of the silica sand.

Retention curves of soils amended with BC are shown in Figure 2 along with the ranges of pres-

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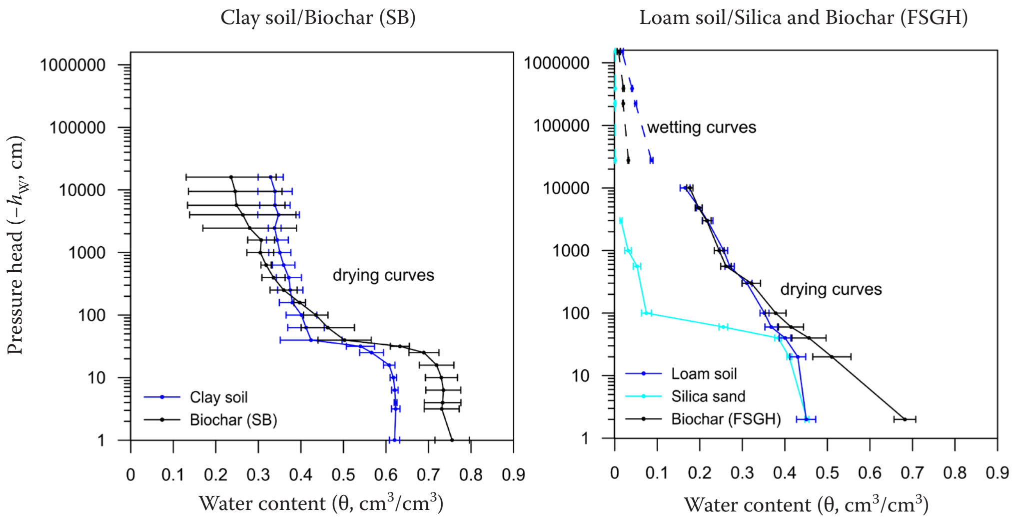


Figure 1. Soil water retention curves of materials used in the study

SB – sugarcane bagasse; FSGH – fiber sludge and grain husks; error bars represent 95% of confidence intervals

sure heads corresponding to different types of pores according to their equivalent pore diameter. The clay soil amended with the BC (SB) showed larger water contents at pressure heads near saturation (the threshold value was around –30 cm of pressure head), the opposite was true at smaller pressure heads compared to the control.

At first glance, retention curves of the loam soil amended with the BC (FSGH) looked like similar to the control, but by deeper analysis certain deviations were identified (shown later). Retention curves of the silica sand amended with the BC (FSGH) showed increase of the water contents in all scales of pressure heads.

**Water content in different kinds of pores**. The water contents in different pore categories, i.e. macropores, transmission, and storage pores, and the possible links between the biochars and the BC amended soils were analysed. The biochar (SB) contain more water in transmission pores compared with the BC (FSGH) (Table 2). Contrary, the biochar (FSGH) contain more water in macropores and storage pores. This affected the volume of water in particular soil pore categories in each amended soil. Adding the BC (SB) the water content increased in all pore classes in the clay "Shimajiri Maji" soil. This increase was even statistically significant in the category of all transmission pores (i.e, $d$ in the range of 10–300 μm). In the loam soils amended with the BC (FSGH), the water contents significantly increased in the storage and transmission pores only at higher amendment rate of 7.3 w%. In this type of soil the effect of relatively large water contents in the storage pores of the BC (FSGH) was more pronounced, than in macropores. In contrast, the effect of a relatively large content of macropores in the BC (FSGH) caused significant increase of the water contents in macropores in the silica sand amended with this type of biochar. However, in the case of transmission pores the water contents of the silica sand amended with the BC (FSGH) did not changed or even decreased. Statistically significant increase of the storage pores was identified only in the silica sand amended by the BC (FSGH) at amendment rate of 7.3 w%.

According to Hardie *et al.* (2014) BC can affect porosity in an amended soil mainly in three ways: i/ by its own intrinsic porosity, ii/ by creation of packing or accommodation pores, and iii/ by improving aggregate stability. Positive effect of BC amendment on soil aggregate formation and stability was documented by several authors (Ouyang *et al.* 2013; Andrenelli *et al.* 2016; YU *et al.* 2016). However, to identify this mechanism is dependent on the incubation time (Andrenelli *et al.* 2016). Creation of packing pores, the new pores that are formed on the interface between the soil aggregates and the biochar particles, strongly depends on the soil texture and the biochar size (Hardie *et al.* 2014).

Larger water contents in macropores of the silica sand amended soil may result from the larger macroporosity of the BC (FSGH) but may be the result of sample preparation and specific properties of both materials. The silica sand contains soil particles with a narrow range of diameter (62% of all particles

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are of the diameter in the range 0.1–0.2 mm) and it showed also the narrow pore size distribution which can be seen from the soil water retention curves. As we evaluated the short time effect of BC application, it was not assumed that BC improved soil structure by formation of soil aggregates and thus increased macroporosity of the silica sand and the BC (FSGH) mixtures. On the contrary, no increase in the macropores was identified in the amended loam soil. The loam soil contains soil particles with wider range of

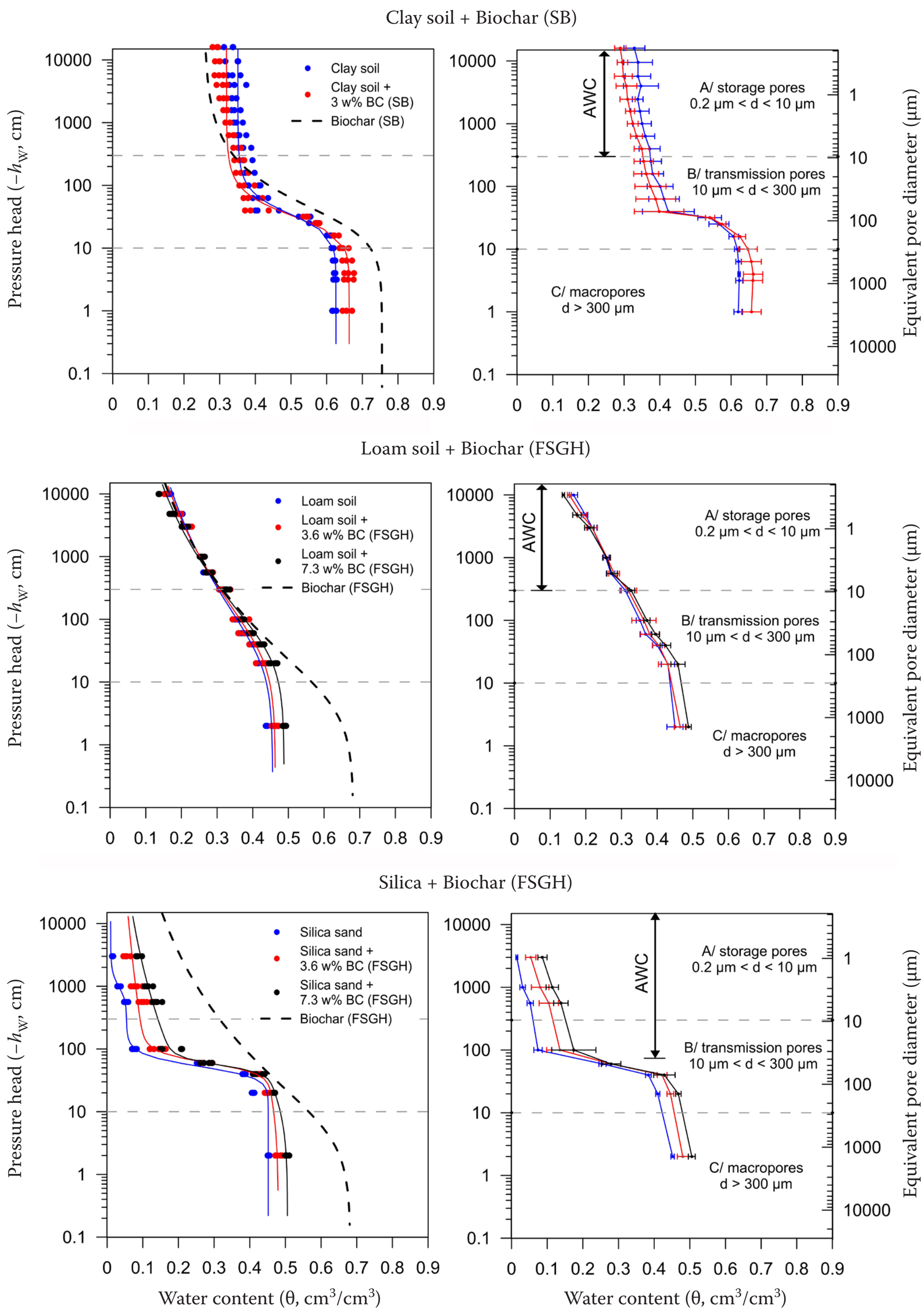


Figure 2. Soil water retention curves (points) and best fits (on the left), mean values and error bars (corresponding to 95% of confidence intervals) of the soil water contents at given pressure heads (on the right)

SB – sugarcane bagasse; FSGH – fiber sludge and grain husks; AWC – available water capacity

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diameter (64% of particles are with diameter smaller than 0.05 mm (silt and clay), 36% of particles are with the diameter in the range 0.05–2 mm). We assume that the voids in the BC (FSGH) loam soil mixtures were probably easier filled up with the finer loam soil particles.

The hypothesis that the improvement of a soil's AWC by amendment with BC is identified more readily in coarse soils than in fine ones was not fully proved in this study. The available water capacity of the clay soil amended with the BC (SB) increased by 0.02 cm$^3$/cm$^3$, but this increase was found statistically not significant (see water content in storage pores, Table 2). However, Kameyama *et al.* (2016) showed larger effect of BC amendment on AWC in the clay "Shimajiri Maji" soil amended with the BC (SB) that was pyrolysed at higher temperature of 800°C and at larger BC application rates of 5 w%, and of 10 w%. Very similar increase of AWC as in the clay amended soil was found in the loam soil amended with the BC (FSGH) (by 0.018 cm$^3$/cm$^3$) at similar BC amendment rate (3.6 w%). Contrary, AWC of the loam soil amended with the BC (FSGH) at higher BC amendment rate of 7.3 w% increased significantly by 0.046 cm$^3$/cm$^3$. Abel *et al.* (2013) documented that biochar (from feedstock maize) can increase AWC of up to 0.16 and 0.12 volumetric water contents in sandy soils with low organic content, and loamy sand. The increase of the AWC caused by the BC (FSGH) amendment was not clearly found

Table 2. The volumetric water content in macropores, transmission, and storage pores for three different treatment sets and for two biochars

| | Macropores | Transmission pores | | Storage pores |
|---|---|---|---|---|
| Negative pressure head ($-h_w$, cm) | 0–10 | 10–60 | 60–300 | 300–15 000 |
| Equivalent pore diameter (μm) | > 300 | 50–300 | 10–50 | 0.2–10 |
| **Treatment set 1** | | | | |
| Clay soil | $0.008^a$ *0.007* | $0.205^a$ *0.025* | $0.038^a$ *0.011* | $0.043^a$ *0.014* |
| Clay soil + 3 w% BC (SB) | $0.014^a$ *0.005* | $0.258^a$ *0.041* | $0.037^a$ *0.017* | $0.063^a$ *0.006* |
| **Treatment set 2** | | | | |
| Loam soil | $0.016^a$ *0.005* | $0.073^a$ *0.011* | $0.057^a$ *0.005* | $0.151^a$ *0.006* |
| Loam + 3.6 w% BC (FSGH) | $0.015^a$ *0.008* | $0.070^a$ *0.014* | $0.060^a$ *0.004* | $0.169^a$ *0.012* |
| Loam + 7.3 w% BC (FSGH) | $0.015^a$ *0.003* | $0.079^a$ *0.002* | $0.068^b$ *0.006* | $0.197^b$ *0.005* |
| **Treatment set 3** | | | | |
| Silica sand | $0.000^a$ *0.000* | $0.208^a$ *0.006* | $0.198^a$ *0.005* | $0.044^a$ *0.001* |
| Silica sand + 3.6 w% BC (FSGH) | $0.013^b$ *0.008* | $0.187^b$ *0.012* | $0.216^b$ *0.015* | $0.035^b$ *0.002* |
| Silica sand + 7.3 w% BC (FSGH) | $0.021^b$ *0.012* | $0.206^a$ *0.011* | $0.135^c$ *0.010* | $0.077^c$ *0.014* |
| **Biochar** | | | | |
| Biochar (SB) | 0.030 *0.002* | 0.262 *0.030* | 0.117 *0.017* | 0.114 *0.068* |
| Biochar (FSGH) | 0.117 *0.010* | 0.142 *0.004* | 0.109 *0.005* | 0.162 *0.006* |

BC (SB) – biochar made from sugarcane bagasse; BC (FSGH) – biochar made from fiber sludge and grain husks; standard deviations are indicated by italics; values in the same column with the same letter are not significantly different at $P < 0.05$; statistical differences were evaluated for the particular treatment set separately

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in the case of the silica sand. The AWC of the silica sand amended with a biochar (at amendment rate of 3.6 w%) was even slightly decreased. At a higher rate of amendment (7.3 w%), the AWC increased by 0.03 $cm^3/cm^3$. One of the reasons of this result is that lower boundary pressure head value in the AWC is usually set arbitrarily ($h_w$ = –300 cm). This can be true for finer materials, but not for sands. Therefore, the AWCs of the silica sand and the silica sand mixtures were recalculated with larger value of lower boundary (e.g. $h_w$ = –60 cm). Then, the AWC increased by 0.009 $cm^3/cm^3$ (at amendment rate of 3.6 w%) and even decreased by 0.03 $cm^3/cm^3$ (at amendment rate of 7.3 w%). As it was shown in Figure 2 retention curves of the silica sand amended with the BC (FSGH) showed increase of the water contents in all scale of pressure heads, i.e. at FC as well as at WP. This is the possible reason why the increase of AWC was not found in this soil. AWC estimated as the difference between water contents at FC and WP is widely used, it greatly depends on the choice of matric potential for FC (Eden *et al.* 2017). It can differ if it is measured under field conditions compared to static condition in the laboratory.

## CONCLUSIONS

This work presents results of the research how retention properties of two types of biochars can affect the properties of amended soils. Overall short time positive effect of BC amendment on retention properties of amended soils was clearly identified. The BC (SB) was characterized by the large volume of transmission pores with corresponding water capacity of 37.9% of volumetric water content (VWC). Contrary, the BC (FSGH) showed larger water capacity of macropores (11.7% of VWC) and storage pores (16.2% of VWC). Biochar properties affected water contents in particular soil pore categories of amended soils. In the clay soil amended with the BC (SB) (at amendment rate of 3 w%) significantly increased the volume of transmission pores (by 5% of VWC), in the loam soil amended with the BC (FSGH) increased the volume of storage pores (by 1.8% and 4.6% of VWC at amendment rates of 3.6, and 7.3 w%, respectively). In the silica sand amended with the BC (FSGH) significantly increased the volume of water in macropores (by 1.3% and 2.3% at amendment rates of 3.6, and 7.3 w%, respectively), and storage pores (by 3.3% at amendment rate of 7.3 w%). Storage pores in the soil greatly contribute to the available water capacity, whereas macropores and transmission pores enhance soil structure and soil aeration. According to our laboratory results larger BC amendment rates are needed to be applied to expect more significant increase of AWC of amended soils. Appropriate amendment rates are around 7.3 w%, corresponding to relatively large field application rates approximately of 80 t/ha applied into the soil depth of 0 to 10 cm. This should be taken into account and examined under the field conditions. The BCs' effect on hydraulic conductivities of amended soils was not studied in this work as well as the long-term influence of the BC amendment on soil water characteristics. They should be a subject of further examination.

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Received for publication January 19, 2018
Accepted after corrections August 3, 2018
Published online December 10, 2018