



Can application of biochar improve the soil water characteristics of silty loam soil?

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Received: 10 January 2023 / Accepted: 21 March 2023 / Published online: 26 April 2023
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Abstract

Purpose This study investigates if a biochar application in 2014 and its reapplication in 2018 had affected the selected physical and hydrophysical soil properties of silty loam Haplic Luvisol at Dolná Malanta experimental site (Nitra, Slovakia) during the studied period of 2018–2020.

Materials and methods Biochar was produced from cereal husks and paper fiber sludge by pyrolysis at temperature of 550 °C for 30 min and was applied to the soil in doses of 0, 10, and 20 t ha⁻¹. The biochar treatments were combined with three levels of N fertilization (N0, N1, and N2).

Results Biochar significantly decreased the bulk density up to –12% and increased the soil porosity up to +22% even 4–6 years after the biochar application. We also observed an increase in saturated hydraulic conductivity, which was reflected in better precipitation retention and a higher average soil water content by 12–15% depending on the fertilization level. Depending on the level of N fertilization, the interval of plant available water enlarged by 8–51% (10 t ha⁻¹ of biochar), 18–21% (20 t ha⁻¹ of biochar) after single biochar application, and by 18–34% (10 t ha⁻¹ of biochar) and 19–31% (20 t ha⁻¹ of biochar) after reapplication of biochar, which has positive implications regarding providing soil water to plants.

Conclusions The results indicate that biochar amendments have the potential to substantially improve the soil water characteristics, and therefore, the quality status of silty loam agricultural soils.

Keywords Biochar application · Biochar reapplication · N fertilizer · Bulk density · Available water content

1 Introduction

Soil, with its water retention ability, plays an important role in influencing the natural water cycle. This important property can be best observed during extreme droughts under

the conditions of climate change. Agriculture soil drought occurs when soil moisture drops below the limiting value of the wilting point when the plants are unable to absorb water sufficiently from the soil profile. The soil water constants such as wilting point delineate the specific soil moisture conditions that are defined at certain water potential values (Scherer et al. 2022) and are used also at monitoring the long-term changes in the course of soil moisture to define the soil water regime.

Currently, the improvement of water retention in the landscape and within the soil profile is an often-discussed topic, especially in relation to climate change mitigation (Basso et al. 2013). Some studies suggest that biochar can improve the quality of degraded soils (Hseu et al. 2014; Ndor et al. 2015; Karim et al. 2020; Xing et al. 2021) and the soil water regime (Hardie et al. 2013; Yu et al. 2013; Mukherjee and Lal 2013; Arthur et al. 2015; Castellini et al. 2015; Ma et al. 2016; Salinas et al. 2018).

Biochar is a carbon-rich product made from biomass by pyrolysis process that takes place at high temperatures

Responsible editor: Lu Zhang

Highlights

- Biochar has the potential to retain water in loamy soil in Central Europe.
- Effects of biochar application on soil physical properties were observed even after 4–6 years.
- Better effect was observed at higher biochar application dose, after N fertilizer addition, and after reapplication of biochar.

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ranging from 300 up to 900 °C under low oxygen or no oxygen conditions (Spokas 2010; Ok et al. 2016; Lehmann and Stephen 2015; Antunes et al. 2017; Inyang et al. 2016). The properties of biochar, to a large extent depend on the characteristics of the input raw materials and on the conditions of pyrolysis (Antunes et al. 2017). The higher pyrolysis temperatures (> 500 °C) result with higher pH, porosity, specific surface area, carbon content and stability of the final product. The sorption capacity of the biochar increases at lower pyrolysis temperatures (≤ 400 °C) (Wu et al. 2012; Zhao et al. 2013). Initially, the contribution of biochar application was discussed in terms of carbon sequestration and the biochar potential to reduce greenhouse gas emissions into the atmosphere (Lehmann et al. 2011; Rizhiya et al. 2019; Kotuš and Horák 2021). It is within the interest of the scientific community to discuss the benefits of biochar application also in terms of its impact on other agro-environmental parameters of soils such as pH, organic carbon content, organic matter content, soil structure, and soil aggregate stability (Peng et al. 2011; Horák 2015; Šimanský et al. 2016; Ajayi and Horn 2016; Juriga and Šimanský 2019; Horák et al. 2020a, 2020b).

Biochar has the potential to increase the soil water retention (Karhu et al. 2011) and the amount of water available to plants (Baronti et al. 2014; Blanco-Canqui 2020; Medyńska-Juraszek et al. 2021). This means that the soils amended with biochar could potentially retain more water from precipitation, which could in turn lead to an increase of crop production in non-irrigated areas (Jeffery et al. 2011) and higher irrigation efficiency in irrigated areas. According to Wang et al. (2019) high dosage (≥ 10 t ha⁻¹) of high pore volume biochar with bulky particle size (≥ 1 mm) can improve water retention of coarse-textured soil with limited water storage capacity and may improve soil's resilience during hydrological extremes. Biochar has the potential to influence the physical and hydrophysical characteristics of soil (Castellini et al. 2015; Makó et al. 2020) and thereby alter water balance in the ecosystems (Spokas 2010; Jeffery et al. 2015; Lehmann and Stephen 2015; Shackley et al. 2016; Antunes et al. 2017; Alghamdi 2018; Yu et al. 2019). However, the effect of biochar application is evaluated for a wide range of soil textures from sandy (Wiersma et al. 2020) to clay soils (Wong et al. 2022). It is believed that in clay soils, biochar can reduce bulk density and increase soil porosity. Bulk density is one of the most important physical properties of the soil, which influences the infiltration of precipitation (Ueckert et al. 1978). A decrease in soil bulk density (Laird et al. 2010; Githinji 2014; Are et al. 2017; Karim et al. 2020) increases soil porosity and soil aeration (Verheijen et al. 2010; Sun and Lu 2014; Walters and White 2018) and may have a positive effect on root and microbial respiration (Rutigliano

et al. 2014). In addition, the effect of biochar on soil moisture (Novák et al. 2012), soil hydraulic conductivity (Lei and Zhang 2013; Esmaeelinejad et al. 2017), soil infiltration capacity (Abrol et al. 2016), field capacity (Jones et al. 2010), available soil water capacity (Brockhoff et al. 2010), and the relationship between soil water potential and soil moisture has been studied in the literature.

Most published works studying the effect of biochar on the physical and hydrophysical properties of soil are only short-term, especially the experiments that are carried out in laboratory conditions. There are only a limited number of studies that were conducted in field conditions over 5 years after biochar application in the soil. The impact of biochar reapplication on soil properties is an emerging topic, and to our knowledge, studies in this area are very rare (Nguyen et al. 2018). Therefore, this paper aims to analyze the impact of biochar application and reapplication in doses of 10 and 20 t ha⁻¹ without or with nitrogen fertilizer on selected physical soil properties (bulk density, soil porosity) and hydrophysical soil properties (saturated soil hydraulic conductivity, soil moisture, and water availability for plants) from the 4th up to 6th year after biochar application at the experimental site in Dolná Malanta (Slovakia). We hypothesized that biochar reapplication will increase soil porosity and soil water content and that biochar application will affect the evaluated soil hydrophysical properties even 6 years after its application.

2 Materials and methods

2.1 Study area

The experimental site in Dolná Malanta is located approximately 5 km north-east from the city of Nitra (Slovakia) (latitude 48°19'23.41", longitude 18°09'0.7") with an altitude of 175 m above sea level. The soil reference group at the site was characterized as Haplic Luvisol (IUSS Working Group WRB 2015). The soil on average contained 360.4 g kg⁻¹ of sand, 488.3 g kg⁻¹ of silt, and 151.3 g kg⁻¹ of clay and is classified as a silty loam texture (Soil Portal 2019). The climate is characterized as warm, slightly dry, with an average annual air temperature of 9.8 °C and an average annual precipitation of 540 mm (according to the 30-year climate normal 1960–1991) (Šiška et al. 2005). The average annual air temperature during the studied years 2018, 2019, and 2020 was 11.4 °C, 10.9 °C, and 8.8 °C, respectively. The total precipitation in 2018, 2019, and 2020 was 537.4 mm, 625.4 mm, and 669.4 mm, respectively.

Prior establishment of the field experiment, the site was used for conventional agricultural crop production. Before the initialization of the experiment with biochar, soil samples were taken at ten random locations from a depth of

0–10 cm in order to obtain the initial soil properties. The average soil organic carbon content, soil pH (KCl), and dry bulk density was 10.2 g kg^{-1} , 5.58 and 1.39 g cm^{-3} , respectively (Kondrlova et al. 2018). The field experiment was established in spring 2014 to study the impact of biochar on the greenhouse gas emissions (Horák 2017; Horák et al. 2017), soil hydrophysical properties and soil quality (Horák 2015; Igaz et al. 2018; Šimanský et al. 2018; Tarnik 2019; Vitková and Šurda 2019; Toková et al. 2020; Horák et al. 2020a,b) and finally crop yields (Kondrlova et al. 2018; Aydin et al. 2020). Since the establishment of the experiment, common field crops were grown at the site; namely spring barley (*Hordeum vulgare* L.), corn (*Zea mays* L.) and peas (*Pisum sativum* L.) in 2018, 2019 and 2020, respectively.

2.2 Biochar application

Biochar used in this field experiment was made from paper fiber sludge mixed grain husks at a 1:1 ratio (according to their weight). The feedstock was processed by pyrolysis at 550 °C for 30 min in a Pyreg reactor (Pyreg GmbH, Görhe, Germany) and provided by Sonnenerde company (Austria) as a final commercial product. The size of biochar particles was under 5 mm (Šimanský et al. 2019a). Table 1 provides further detailed information on the biochar parameters. Biochar was applied manually to the soil surface at doses of 0, 10, and 20 t ha^{-1} in the spring 2014 (Table 2) and it was incorporated into the soil with rakes. The study was conducted on plots of $4 \times 6 \text{ m}$ with three repetitions per treatment. In the spring 2018, the biochar-amended plots were divided into two separate $4 \times 3 \text{ m}$ plots. While one half of the original plot had the initial amount of biochar applied (2014), the other half received additional biochar (biochar reapplication in 2018, abbreviated “reap”) at the same dose as when the field experiment was established in 2014 (Table 2).

2.3 N fertilizer application

An overview of the specific doses of N fertilizer in the studied years 2018, 2019, and 2020 is given in Table 2. Nitrogen industrial fertilizer (calcium ammonium nitrate LAD 27)

Table 1 The chemical and physical properties of biochar (Kondrlova et al. 2018; Šimanský et al. 2019a)

BD ^a (g cm^{-3})	SSA ^b ($\text{m}^2 \text{ g}^{-1}$)	Size fraction (mm)	pH (–)	Total C (g kg^{-1})	Total N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})
0.206	21.7	1–5	8.8	531	14	6.2	15	57

^aBD bulk density

^bSSA specific surface area

Table 2 Treatments in the field experiment and the amount of biochar and nitrogen fertilizer application doses

Treatment acronym	Biochar in 2014 (t ha^{-1})	Biochar in 2018 (t ha^{-1})	Fertilizer in 2018 (kg N ha^{-1})	Fertilizer in 2019 (kg N ha^{-1})	Fertilizer in 2020 (kg N ha^{-1})
Level N0 ^b					
B0 ^a +N0 ^b (control)	0	0	0	0	0
B10 ^a +N0 ^b	10	0	0	0	0
B10reap ^a +N0 ^b	10	10	0	0	0
B20 ^a +N0 ^b	20	0	0	0	0
B20reap ^a +N0 ^b	20	20	0	0	0
Level N1 ^b					
B0 ^a +N1 ^b	0	0	40	108	30
B10 ^a +N1 ^b	10	0	40	108	30
B10reap ^a +N1 ^b	10	10	40	108	30
B20 ^a +N1 ^b	20	0	40	108	30
B20reap ^a +N1 ^b	20	20	40	108	30
Level N2 ^b					
B0 ^a +N2 ^b	0	0	80	162	45
B10 ^a +N2 ^b	10	0	80	162	45
B10reap ^a +N2 ^b	10	10	80	162	45
B20 ^a +N2 ^b	20	0	80	162	45
B20reap ^a +N2 ^b	20	20	80	162	45

^aB0, B10, and B20 biochar application rate of 0, 10, and 20 t ha^{-1} , respectively, B10reap and B20reap treatments with biochar application in 2014 and biochar reapplication in 2018 at 10 and 20 t ha^{-1} , respectively

^bN0, N1, and N2 nitrogen fertilizer application rate in the specific year at Level N0, Level N1, and Level N2, respectively. Level N0 no application of fertilizer, Level N1 recommended amount of fertilizer for specific crop, Level N2 increased amount of fertilizer

was applied at the N1 and N2 application levels each year. The specific doses of N fertilizer at the N1 application level were calculated based on the requirements of grown crop each year using the balance method. An application dose at the N2 fertilization level was 50% higher than at the N1 level. An exception was made for spring barley in 2018, when the application dose at N2 fertilization level was doubled compared to the N1 fertilization level (Table 1).

2.4 Determination of the soil physical and hydrophysical properties

The basic soil physical properties (bulk density, particle density, porosity) and soil hydrophysical properties (hydraulic

conductivity, plant available water) were determined from undisturbed soil samples (100 cm³). In total, 4 soil sampling events were conducted in the autumn 2018, spring 2019, autumn 2019, and spring 2020. Each time, 3 undisturbed soil samples were taken from a depth of 0–10 cm from each individual plot, which means 9 representative soil samples per each treatment (a grand total of 135 soil samples per sampling event).

For more accurate statistical evaluation of data, one value with the biggest deviation from the data subset was excluded from further analysis ($n = 8$). Disturbed soil samples for determination of gravimetric water content were taken from a depth of 0–10 cm on biweekly intervals. A total of 13, 13, and 12 sampling events were performed in 2018, 2019, and 2020, respectively. At each sampling event, one representative soil sample was taken from each plot; therefore, there were 3 samples per treatment and total of 39, 39, and 36 samples per treatment in 2018, 2019, and 2020, respectively. The dry bulk density (BD) was calculated according to Eq. (1):

$$\text{SWC} = \frac{\text{weight of fresh soil (g)} - \text{weight of oven dry soil (g)}}{\text{weight of oven dry soil (g)}} \cdot 100 \quad (\% \text{ mass}) \quad (6)$$

$$\text{BD} = \frac{\text{mass weight of dry soil (g)}}{\text{total volume of undisturbed soil sample (cm}^3\text{)}} \quad (\text{g cm}^{-3}) \quad (1)$$

The particle density (PD) of the dried undisturbed soil samples was determined indirectly using the air pycnometer method. This method operates on the principle of utilizing the vacuum created by the mercury column after inserting the undisturbed soil sample into an air pycnometer (Eijkelkamp Soil and Water 2020). This procedure determines the volume of the solid phase of the soil. PD was calculated according to Eq. (2) (Igaz et al. 2017):

$$\text{PD} = \frac{\text{mass weight of dry soil (g)}}{\text{total volume of solid phase of the soil (cm}^3\text{)}} \quad (\text{g cm}^{-3}) \quad (2)$$

Total porosity (P) was calculated according to the Eq. (3):

$$\text{P} = \frac{\text{particle density (g cm}^{-3}\text{)} - \text{bulk density (g cm}^{-3}\text{)}}{\text{particle density (g cm}^{-3}\text{)}} \cdot 100 \quad (\% \text{ vol.}) \quad (3)$$

The saturated hydraulic conductivity (K_{sat}) of the soil was determined in the laboratory using an empty extension cylinder placed on the top of saturated undisturbed soil sample and filled with tap water creating a variable hydraulic slope. Using this setting, non-stationary flow was created in a saturated soil sample due to the changing hydraulic slope (Igaz et al. 2017; Mohsenipour and Shaid 2016). K_{sat} was calculated using Eq. (4):

$$K_{\text{sat}} = \frac{L}{t} \times \ln \frac{H_2}{H_1} \quad (\text{cm h}^{-1}) \quad (4)$$

where L is the height of the metal cylinder containing the soil sample (cm), t is time of water drop from the height H_2 to height H_1 (h), H_2 is the initial level of water in the extension cylinder (cm) and H_1 is the level of water in the extension cylinder after the water drop for time t (cm).

The pressure plate apparatus was used to determine water content at specific pressure potentials. Plant available water (θ_{PAW}) was then calculated as the difference between field capacity (θ_{FC}) measured at a pressure potential of -20 kPa and permanent wilting point (θ_{PWP}) measured at a pressure potential of -1500 kPa (Eq. 5).

$$\theta_{\text{PAW}} = \theta_{\text{FC}} - \theta_{\text{PWP}} \quad (\% \text{ vol.}) \quad (5)$$

Mass soil water content (SWC) was calculated gravimetrically from disturbed soil samples dried at 105 °C (Eq. 6):

2.5 Statistical analysis

The effect of biochar application and subsequent reapplication on the physical and hydrophysical properties of the soil was evaluated using a one-way analysis of variance (one-way ANOVA). Statistically significant effects at $p < 0.05$ were determined by the least significant difference (LSD) test. All analyses were performed in Statgraphics Centurion XVI software (Statpoint Technologies, Inc., Warrenton, VA, USA).

3 Results and discussion

3.1 Effect of applied and reapplied biochar on soil bulk density

When looking at non-fertilized treatments (N0 level of fertilization), biochar did not have any significant effect on BD

in the autumn 2018 (Table 3). A significant ($p < 0.05$) reduction of BD by 12 and 11% was observed in the treatments with a higher dose of biochar (B20 + N0 and B20reap + N0, respectively) in the spring 2019 (Table 4). In the autumn 2019, biochar application did not affect BD values, except for the treatment B10reap + N0 where BD increased significantly by 6% (Table 5). In the spring 2020, BD decreased

Table 3 Effect of biochar application and reapplication on soil properties in autumn 2018 (means \pm standard deviations) ($n=8$)

Treatment acronym	BD ^a (g cm ⁻³)	PD ^b (g cm ⁻³)	P ^c (% vol.)	K _{sat} ^d (cm h ⁻¹)	θ_{FC} ^e (% vol.)	θ_{PWP} ^f (% vol.)	θ_{PAW} ^g (% vol.)
Level N0 (0 kg N ha ⁻¹)							
B0+N0 (control)	1.42 \pm 0.15 a	2.45 \pm 0.08 a	43.02 \pm 4.82 ab	0.40 \pm 0.41 a	29.08 \pm 1.38 a	21.20 \pm 1.76 a	8.41 \pm 1.17 ab
B10+N0	1.50 \pm 0.13 a	2.51 \pm 0.07 ab	40.05 \pm 3.64 a	0.17 \pm 0.24 a	29.85 \pm 1.00 a	21.44 \pm 1.16 a	8.29 \pm 0.92 a
B10reap+N0	1.43 \pm 0.16 a	2.58 \pm 0.15 bc	44.73 \pm 7.62 ab	0.77 \pm 0.76 a	30.44 \pm 1.54 ab	20.74 \pm 2.37 a	9.70 \pm 1.41 bc
B20+N0	1.37 \pm 0.18 a	2.53 \pm 0.09 ab	42.50 \pm 6.43 a	0.42 \pm 0.75 a	30.02 \pm 1.72 a	21.61 \pm 1.20 a	8.40 \pm 1.13 ab
B20reap+N0	1.36 \pm 0.16 a	2.64 \pm 0.08 c	48.87 \pm 5.93 b	2.64 \pm 2.25 b	31.56 \pm 0.97 b	22.10 \pm 2.46 a	9.77 \pm 1.83 c
Level N1 (40 kg N ha ⁻¹)							
B0+N1	1.42 \pm 0.16 a	2.44 \pm 0.09 a	41.83 \pm 4.77 a	0.90 \pm 1.37 a	29.53 \pm 1.92 ab	–	–
B10+N1	1.46 \pm 0.08 a	2.51 \pm 0.04 bcd	41.75 \pm 2.32 a	0.96 \pm 0.97 a	31.30 \pm 1.07 c	21.95 \pm 1.50 a	9.02 \pm 1.84 a
B10reap+N1	1.41 \pm 0.16 a	2.49 \pm 0.10 abc	43.67 \pm 5.79 a	0.98 \pm 1.30 a	30.83 \pm 1.23 bc	21.94 \pm 1.60 a	8.49 \pm 1.11 a
B20+N1	1.45 \pm 0.13 a	2.56 \pm 0.04 cd	45.57 \pm 5.11 a	0.62 \pm 0.72 a	30.04 \pm 1.69 abc	20.57 \pm 1.23 a	8.36 \pm 1.20 a
B20reap+N1	1.42 \pm 0.07 a	2.58 \pm 0.07 d	45.01 \pm 2.70 a	0.76 \pm 0.96 a	30.36 \pm 0.83 abc	21.47 \pm 1.97 a	9.22 \pm 1.31 a
Level N2 (80 kg N ha ⁻¹)							
B0+N2	1.47 \pm 0.09 b	2.42 \pm 0.06 a	39.55 \pm 3.00 a	0.35 \pm 0.57 a	29.95 \pm 1.29 abc	–	–
B10+N2	1.46 \pm 0.12 b	2.49 \pm 0.04 ab	41.75 \pm 3.79 a	1.73 \pm 1.24 b	29.71 \pm 1.66 ab	22.01 \pm 1.20 a	8.86 \pm 1.72 ab
B10reap+N2	1.33 \pm 0.10 a	2.50 \pm 0.06 b	45.93 \pm 3.15 bc	0.77 \pm 0.82 a	29.96 \pm 0.84 abc	21.78 \pm 1.61 a	9.31 \pm 1.32 ab
B20+N2	1.34 \pm 0.12 a	2.50 \pm 0.06 b	45.83 \pm 3.96 b	0.64 \pm 0.59 a	30.46 \pm 1.20 bc	21.86 \pm 1.74 a	8.15 \pm 1.36 a
B20reap+N2	1.31 \pm 0.10 a	2.64 \pm 0.14 c	49.56 \pm 2.35 c	0.49 \pm 0.70 a	31.19 \pm 1.35 c	20.92 \pm 1.20 a	9.88 \pm 1.70 b

Different letters (a, b, c, d) indicate that treatment means are significantly different at $p < 0.05$ according to least significant difference test (one-way ANOVA). For explanation of treatment acronym see Table 2

^aBD bulk density

^bPD particle density

^cP soil porosity

^dK_{sat} saturated hydraulic conductivity

^e θ_{FC} field capacity

^f θ_{PWP} permanent wilting point

^g θ_{PAW} plant available water

significantly ($p < 0.05$) in all treatments with biochar by 4 up to 6% (Table 6).

In fertilized treatments at the first level of fertilization (N1), only insignificant changes were observed in autumn 2018 and BD decreased slightly in the treatment B10reap+N1 compared to the control B0+N0 (Table 3). In the spring 2019, there was a trend towards BD reduction in all treatments with biochar application, but a significant ($p < 0.05$) decrease by 8.5 and 9% was observed only in the treatments with a lower dose of biochar (B10+N1 and B10reap+N1 respectively) (Table 4). In the autumn 2019, BD generally increased slightly except a decrease in the B20+N1 treatment. However, significant change (+5%) was observed only in the treatment B10reap+N1 compared to the control B0+N0 (Table 5). In the spring 2020, BD decreased significantly ($p < 0.05$) in all treatments with biochar application in the range from 6 to 9% when compared to the control treatment B0+N0 (Table 6).

A general decreasing trend in BD was observed after biochar application at the second level of fertilization (N2)

during all three monitored years. In the autumn 2018, a significant decrease of BD was observed in the treatments B10reap+N2, B20+N2, and B20reap+N2 compared to the treatment without biochar with nitrogen fertilizer (B0+N2) (Table 3). However, BD in this control treatment (B0+N2) was slightly higher (but insignificant) compared to the unfertilized B0+N0 control (Table 3). In the spring 2019, there was a trend towards BD reduction in all treatments with biochar, but a significant decrease ($p < 0.05$) was only observed in the treatments B10reap+N2, B20+N2, and B20reap+N2 (Table 4). In the autumn 2019, lower BD was again observed in the treatments B10reap+N2, B20+N2, and B20reap+N2, but this reduction was significant ($p < 0.05$) only in comparison to fertilized control treatment (B0+N2) (Table 5).

In the case of B0+N2 treatment, BD increased slightly compared to the B0+N0 control (Table 5). A significant reduction ($p < 0.05$) of BD ranging from 4 to 10% was observed in all treatments with biochar addition in spring 2020 compared to the control B0+N0.

Table 4 Effect of biochar application and reapplication on soil properties in spring 2019 (means \pm standard deviations) ($n=8$)

Treatment acronym	BD ^a (g cm ⁻³)	PD ^b (g cm ⁻³)	P ^c (% vol.)	K _{sat} ^d (cm h ⁻¹)	θ_{FC} ^e (% vol.)	θ_{PWP} ^f (% vol.)	θ_{PAW} ^g (% vol.)
Level N0 (0 kg N ha ⁻¹)							
B0+N0 (control)	1.41 \pm 0.12 bc	2.54 \pm 0.09 b	44.19 \pm 3.95 ab	2.12 \pm 0.88 a	30.04 \pm 1.50 a	25.79 \pm 1.23 bc	4.03 \pm 1.38 a
B10+N0	1.39 \pm 0.11 b	2.51 \pm 0.04 a	45.73 \pm 3.35 a	2.24 \pm 2.35 a	30.37 \pm 1.05 ab	25.01 \pm 2.07 ab	5.02 \pm 1.63 ab
B10reap+N0	1.36 \pm 0.08 b	2.45 \pm 0.13 a	44.12 \pm 3.53 a	11.96 \pm 20.64 a	31.73 \pm 1.54 b	24.33 \pm 1.38 ab	7.11 \pm 0.83 d
B20+N0	1.24 \pm 0.08 a	2.45 \pm 0.11 a	49.98 \pm 1.97 b	10.73 \pm 7.42 a	29.29 \pm 1.49 a	24.14 \pm 1.49 a	5.52 \pm 1.49 bc
B20reap+N0	1.25 \pm 0.07 a	2.47 \pm 0.10 a	49.37 \pm 3.65 b	9.97 \pm 14.85 a	30.39 \pm 1.47 ab	23.74 \pm 1.57 a	6.65 \pm 1.71 cd
Level N1 (108 kg N ha ⁻¹)							
B0+N1	1.42 \pm 0.09 c	2.43 \pm 0.10 a	40.38 \pm 3.93 a	1.63 \pm 2.86 a	29.70 \pm 2.09 a	–	–
B10+N1	1.29 \pm 0.10 a	2.45 \pm 0.06 a	47.21 \pm 3.51 b	6.93 \pm 6.74 ab	30.76 \pm 2.06 a	25.17 \pm 2.05 ab	5.41 \pm 0.51 bc
B10reap+N1	1.28 \pm 0.10 a	2.40 \pm 0.09 a	46.25 \pm 5.47 b	2.55 \pm 1.84 a	30.16 \pm 1.39 a	23.94 \pm 1.61 a	6.52 \pm 1.26 c
B20+N1	1.33 \pm 0.11 abc	2.55 \pm 0.09 b	46.36 \pm 3.20 b	7.85 \pm 10.32 ab	31.23 \pm 1.76 a	27.11 \pm 2.16 c	4.76 \pm 1.42 ab
B20reap+N1	1.31 \pm 0.08 ab	2.38 \pm 0.05 a	45.26 \pm 3.99 b	9.55 \pm 10.43 b	31.25 \pm 1.46 a	24.90 \pm 1.52 ab	5.96 \pm 1.30 bc
Level N2 (162 kg N ha ⁻¹)							
B0+N2	1.38 \pm 0.10 bc	2.53 \pm 0.26 b	42.17 \pm 4.55 a	2.87 \pm 3.56 ab	30.48 \pm 1.12 a	–	–
B10+N2	1.37 \pm 0.07 abc	2.45 \pm 0.09 ab	46.39 \pm 4.17 b	4.23 \pm 4.94 ab	29.59 \pm 1.74 a	23.86 \pm 1.97 a	5.12 \pm 0.87 ab
B10reap+N2	1.28 \pm 0.07 a	2.39 \pm 0.08 a	47.11 \pm 3.59 b	5.74 \pm 3.78 ab	30.46 \pm 1.19 a	24.87 \pm 2.17 ab	5.48 \pm 1.35 b
B20+N2	1.31 \pm 0.06 ab	2.46 \pm 0.08 ab	47.04 \pm 2.73 b	8.46 \pm 7.37 b	30.76 \pm 1.92 ab	24.86 \pm 1.48 ab	4.74 \pm 1.12 ab
B20reap+N2	1.31 \pm 0.10 ab	2.45 \pm 0.09 ab	46.53 \pm 5.40 b	6.61 \pm 10.15 ab	32.03 \pm 1.20 b	24.37 \pm 1.85 ab	7.82 \pm 1.20 c

Different letters (a, b, c, d) indicate that treatment means are significantly different at $p < 0.05$ according to least significant difference test (one-way ANOVA). For explanation of treatment acronym see Table 2

^aBD bulk density

^bPD particle density

^cP soil porosity

^dK_{sat} saturated hydraulic conductivity

^e θ_{FC} field capacity

^f θ_{PWP} permanent wilting point

^g θ_{PAW} plant available water

Soil bulk density is an important indicator of soil compaction because it is directly affected by soil structure (Hillel 1998). A decrease in BD after biochar application could be caused by the lower BD of biochar (Table 1) compared to BD of silty loam soil at the experimental site. Biochar itself is a porous material (Adekiya et al. 2020), and when added to soil, it decreases bulk density and increases soil porosity (Nyambo et al. 2018). The change in porosity in soils treated with biochar is mainly due to the formation of macropores and rearrangement of soil particles (Hseu et al. 2014), aeration of the soil and reduced mechanical impedance of root growth in soils (Blanco-Canqui 2017). Biochar has the ability to form soil aggregates in combination with the soil particles. The improvement of structural properties of soil in this field experiment has already been observed in the past and it was published in other works (Šimanský 2016; Šimanský et al. 2019b). Some authors argue that the basic cations present in biochar can bond with clay and organic particles in soil

via cation bridges to form soil aggregates (Bronick and Lal 2005). Gradual oxidation of biochar in soil also increases the number of functionality groups on its surface (Obia et al. 2016), which can absorb soil particles and minerals, which in turn contributes to the formation of soil aggregates and to reduction of BD. In our work, however, we also observed an increase in BD in some treatments (autumn sampling) amended only with nitrogen fertilizer (B0+N1 and B0+N2). This phenomenon occurred because mineral nitrogen in the soil can accelerate the mineralization of organic matter in the soil, which can lead to an increase in BD (Šimanský et al. 2016). In contrast, biochar combined with nitrogen fertilizer generally resulted with a reduction of BD. This is because nitrogen has a beneficial effect on the incorporation of biochar into the soil. In our study, the use of a higher dosage of biochar (20 t ha⁻¹) in combination with a higher level of fertilization (N2) seemed to be more effective.

Table 5 Effect of biochar application and reapplication on soil properties in autumn 2019 (means \pm standard deviations) ($n=8$)

Treatment acronym	BD ^a (g cm ⁻³)	PD ^b (g cm ⁻³)	P ^c (% vol.)	K _{sat} ^d (cm h ⁻¹)	θ_{FC} ^e (% vol.)	θ_{PWP} ^f (% vol.)	θ_{PAW} ^g (% vol.)
Level N0 (0 kg N ha ⁻¹)							
B0+N0 (control)	1.46 \pm 0.08 a	2.47 \pm 0.04 ab	39.83 \pm 2.83 a	0.93 \pm 1.06 a	31.34 \pm 1.34 ab	26.85 \pm 1.50 b	4.50 \pm 0.69 a
B10+N0	1.52 \pm 0.08 ab	2.48 \pm 0.04 a	39.69 \pm 3.15 a	2.11 \pm 3.32 ab	30.75 \pm 1.42 a	25.44 \pm 1.21 a	5.73 \pm 0.89 c
B10reap+N0	1.55 \pm 0.08 b	2.50 \pm 0.07 a	39.87 \pm 3.92 a	0.73 \pm 0.72 a	31.38 \pm 1.08 a	26.67 \pm 1.42 a	5.25 \pm 0.58 bc
B20+N0	1.47 \pm 0.09 ab	2.51 \pm 0.09 a	40.73 \pm 2.64 a	2.93 \pm 2.5 ab	31.81 \pm 1.83 a	26.92 \pm 2.26 a	4.82 \pm 0.84 ab
B20reap+N0	1.46 \pm 0.07 a	2.52 \pm 0.05 a	42.30 \pm 1.86 a	3.57 \pm 3.35 b	31.97 \pm 1.41 a	26.21 \pm 1.12 a	5.25 \pm 0.28 bc
Level N1 (108 kg N ha ⁻¹)							
B0+N1	1.46 \pm 0.04 ab	2.46 \pm 0.03 a	40.63 \pm 1.55 a	4.10 \pm 1.71 b	30.14 \pm 1.74 a	24.66 \pm 2.73 a	5.24 \pm 0.71 a
B10+N1	1.51 \pm 0.06 ab	2.51 \pm 0.05 abc	39.15 \pm 1.80 a	1.23 \pm 1.37 a	32.13 \pm 1.01 b	27.62 \pm 0.85 bc	4.51 \pm 0.57 a
B10reap+N1	1.53 \pm 0.07 b	2.52 \pm 0.04 abc	40.89 \pm 2.20 a	1.08 \pm 1.35 a	31.65 \pm 1.67 ab	26.80 \pm 2.25 b	4.71 \pm 0.88 a
B20+N1	1.45 \pm 0.10 a	2.53 \pm 0.10 bc	40.79 \pm 5.11 a	0.87 \pm 1.11 a	34.18 \pm 3.13 c	29.51 \pm 2.65 c	4.67 \pm 1.22 a
B20reap+N1	1.49 \pm 0.06 ab	2.55 \pm 0.05 c	41.61 \pm 2.33 a	0.66 \pm 0.71 a	33.08 \pm 0.82 bc	27.86 \pm 1.26 bc	5.22 \pm 0.59 a
Level N2 (162 kg N ha ⁻¹)							
B0+N2	1.54 \pm 0.08 c	2.45 \pm 0.04 a	38.90 \pm 2.60 a	4.60 \pm 9.08 a	31.38 \pm 1.45 abc	27.26 \pm 1.24 b	4.75 \pm 0.93 ab
B10+N2	1.52 \pm 0.08 bc	2.51 \pm 0.05 bc	39.10 \pm 2.56 a	1.52 \pm 1.66 a	32.09 \pm 1.24 bc	26.87 \pm 1.60 b	4.78 \pm 0.54 ab
B10reap+N2	1.42 \pm 0.08 a	2.52 \pm 0.05 bc	43.93 \pm 3.04 c	2.05 \pm 1.60 a	30.78 \pm 1.42 ab	25.09 \pm 1.36 a	5.09 \pm 0.47 ab
B20+N2	1.42 \pm 0.09 a	2.46 \pm 0.03 a	42.48 \pm 3.57 bc	4.36 \pm 2.07 a	30.68 \pm 0.69 a	25.33 \pm 1.07 a	5.35 \pm 0.99 b
B20reap+N2	1.40 \pm 0.06 a	2.53 \pm 0.05 c	43.95 \pm 2.71 c	3.41 \pm 2.26 a	32.21 \pm 1.70 c	27.18 \pm 2.14 b	4.64 \pm 0.60 ab

Different letters (a, b, c, d) indicate that treatment means are significantly different at $p < 0.05$ according to least significant difference test (one-way ANOVA). For explanation of treatment acronym see Table 2

^aBD bulk density

^bPD particle density

^cP soil porosity

^dK_{sat} saturated hydraulic conductivity

^e θ_{FC} field capacity

^f θ_{PWP} permanent wilting point

^g θ_{PAW} plant available water

3.2 Effect of applied and reapplied biochar on soil porosity

In general, we observed a trend in a decrease of BD and an increase of PD during all three monitored years in the treatments with biochar that led to an increase of P (Tables 3, 4, 5, and 6).

In non-fertilized treatments (N0), porosity rose insignificantly in the autumn 2018 in the treatments with reapplied biochar (B10reap+N0 and B20reap+N0) (Table 3). In the spring 2019, the values of P increased in the treatments B10+N0, B20+N0, and B20reap+N0. In the last two treatments mentioned, this increase of 13 and 12% was significant ($p < 0.05$) compared to control B0+N0 (Table 4). In the autumn 2019, P increased in the treatments B10reap+N0, B20+N0, and B20reap+N0 (Table 5). In the spring 2020, we observed a significant increase ($p < 0.05$) of P in the treatments B10+N0, B10reap+N0, and B20reap+N0 by 11, 15, and 22%, respectively (Table 6).

At the first level of fertilization (N1), P increased insignificantly in the autumn 2018 in the treatments B10reap+N1,

B20+N1, and B20reap+N2 (Table 3). In the spring 2019, porosity values increased significantly ($p < 0.05$) in all treatments with biochar in the range from 12 to 17% compared to the control treatment at the fertilization level B0+N1. At the same time, however, P in B0+N1 was lower by 8.6% than in the non-amended control treatment B0+N0 (Table 4). Autumn samples in 2019 showed an insignificant slightly increasing trend in P in the treatments B10reap+N1, B20+N1, and B20reap+N1 compared to the control B0+N1 (Table 5). Spring samples in 2020 showed a significant increase ($p < 0.05$) of P in all biochar treatments ranging from 12 to 18% compared to B0+N0, except treatment B20reap+N1 (Table 6).

At the second level of fertilization (N2), we repeatedly observed a trend towards an increase of P in all monitored years. In the autumn 2018, P increased significantly ($p < 0.05$) by 16 up to 25% in the treatments B10reap+N2, B20+N2, and B20reap+N2 compared to the fertilized control B0+N2 (Table 3). At the same time, P in B0+N2 control treatment was lower by 8% than in the non-amended control treatment B0+N0 (Table 3).

Table 6 Effect of biochar application and reapplication on soil properties in spring 2020 (means \pm standard deviations) ($n = 8$)

Treatment acronym	BD ^a (g cm ⁻³)	PD ^b (g cm ⁻³)	P ^c (% vol.)	K _{sat} ^d (cm h ⁻¹)	θ_{FC} ^e (% vol.)	θ_{PWP} ^f (% vol.)	θ_{PAW} ^g (% vol.)
Level N0 (0 kg N ha ⁻¹)							
B0 + N0 (control)	1.67 \pm 0.06 b	2.46 \pm 0.07 a	33.04 \pm 3.37 a	0.90 \pm 1.07 ab	31.16 \pm 1.08 ab	27.61 \pm 1.01 bc	3.55 \pm 0.60 a
B10 + N0	1.58 \pm 0.06 a	2.51 \pm 0.06 abc	36.73 \pm 1.81 b	1.22 \pm 0.55 b	31.26 \pm 0.71 ab	26.65 \pm 1.14 ab	4.47 \pm 0.90 b
B10reap + N0	1.60 \pm 0.05 a	2.55 \pm 0.07 bc	37.88 \pm 1.58 bc	0.45 \pm 0.54 a	31.41 \pm 0.54 ab	26.56 \pm 0.95 ab	4.57 \pm 0.58 b
B20 + N0	1.60 \pm 0.05 a	2.50 \pm 0.06 ab	35.38 \pm 3.97 ab	0.43 \pm 0.61 a	30.67 \pm 0.69 a	25.75 \pm 1.02 a	4.19 \pm 0.67 ab
B20reap + N0	1.57 \pm 0.05 a	2.59 \pm 0.11 c	40.20 \pm 2.43 c	0.23 \pm 0.30 a	31.67 \pm 1.29 b	27.81 \pm 1.11 c	3.68 \pm 0.84 a
Level N1 (30 kg N ha ⁻¹)							
B0 + N1	1.65 \pm 0.08 cd	2.45 \pm 0.03 a	34.42 \pm 3.45 ab	0.87 \pm 0.90 a	30.30 \pm 1.20 a	26.90 \pm 1.07 abc	3.87 \pm 0.52 a
B10 + N1	1.52 \pm 0.06 a	2.47 \pm 0.07 a	38.76 \pm 2.24 c	1.40 \pm 0.93 a	30.94 \pm 0.72 a	26.30 \pm 0.94 ab	5.32 \pm 0.99 b
B10reap + N1	1.53 \pm 0.07 ab	2.51 \pm 0.03 a	38.86 \pm 1.96 c	1.67 \pm 1.73 a	30.50 \pm 0.93 a	26.13 \pm 1.08 a	4.20 \pm 0.85 a
B20 + N1	1.57 \pm 0.06 ab	2.50 \pm 0.05 a	37.45 \pm 3.53 c	2.11 \pm 3.28 a	30.74 \pm 1.25 a	27.18 \pm 1.18 bc	4.25 \pm 0.60 a
B20reap + N1	1.59 \pm 0.05 bc	2.49 \pm 0.12 a	37.12 \pm 1.65 bc	0.83 \pm 0.90 a	30.67 \pm 0.53 a	27.45 \pm 0.65 c	3.63 \pm 0.65 a
Level N2 (45 kg N ha ⁻¹)							
B0 + N2	1.54 \pm 0.04 ab	2.40 \pm 0.06 a	36.36 \pm 2.69 b	0.86 \pm 0.64 a	29.92 \pm 1.11 a	25.47 \pm 1.07 a	4.69 \pm 0.78 c
B10 + N2	1.51 \pm 0.05 a	2.49 \pm 0.06 bc	39.10 \pm 2.04 bc	1.99 \pm 0.84 b	31.15 \pm 0.96 bc	26.96 \pm 1.34 b	3.85 \pm 0.77 ab
B10reap + N2	1.53 \pm 0.06 ab	2.55 \pm 0.05 cd	39.04 \pm 2.41 bc	0.66 \pm 0.62 a	32.02 \pm 0.68 cd	27.95 \pm 0.65 bc	4.20 \pm 0.51 abc
B20 + N2	1.57 \pm 0.09 bc	2.55 \pm 0.05 cd	39.61 \pm 2.36 c	0.96 \pm 0.74 a	31.08 \pm 0.71 b	26.94 \pm 0.85 b	4.31 \pm 0.88 bc
B20reap + N2	1.60 \pm 0.05 c	2.56 \pm 0.09 d	37.42 \pm 3.48 bc	0.85 \pm 0.67 a	32.29 \pm 0.91 d	28.86 \pm 1.04 c	3.90 \pm 0.51 ab

Different letters (a, b, c, d) indicate that treatment means are significantly different at $p < 0.05$ according to least significant difference test (one-way ANOVA). For explanation of treatment acronym see Table 2

^aBD bulk density

^bPD particle density

^cP soil porosity

^dK_{sat} saturated hydraulic conductivity

^e θ_{FC} field capacity

^f θ_{PWP} permanent wilting point

^g θ_{PAW} plant available water

In the spring 2019, biochar amendment generally increased P in all treatments. The effect was insignificant when compared to B0 + N0 treatment; however, in comparison to B0 + N2, an increase of P was significant ranging from 10 to 12% (Table 4). Application of biochar showed positive effect also in the autumn 2019, as P increased in all treatments. In the case of B10reap + N2, B20 + N2, and B20reap + N2 treatments, the increase by 10, 6.7, and 10% was significant ($p < 0.05$) compared to the control B0 + N2 (Table 5). In the spring 2020, a significant increase ($p < 0.05$) of soil porosity ranging from 13 to 20% was observed in all biochar treatments compared to the treatment B0 + N0 (Table 6).

As mentioned above, biochar alone is a highly porous material with a low bulk density (Jones et al. 2010; Duarte et al. 2019; Adekiya et al. 2020), and therefore, its application to soil can increase soil porosity. In our work, we generally observed a decreasing trend in BD, especially in treatments with a higher dose of biochar and also increasing trend in P after application of biochar into the soil. Our observations are consistent with other studies (Chan et al. 2008; Githinji 2014; Mukherjee and Lal 2013; Nelissen

et al. 2015). Since P was calculated from BD and PD, its increase is mainly related to a decrease of BD and increase of PD. It is assumed that P increase may also be the result of improvements in soil structure after biochar application (Šimanský 2016).

3.3 Effect of applied and reapplied biochar on saturated hydraulic conductivity

Application of biochar alone or in combination with fertilizer slightly increased the values of K_{sat} almost in all treatments during the whole studied period, except for the spring 2020.

In the case of the unfertilized treatments (N0), an increase of K_{sat} in B10reap + N0, B20 + N0, and B20reap + N0 treatments ranged from 5 to 560% in the autumn 2018. In the case of B20reap + N0, the difference was significant ($p < 0.05$) compared to B0 + N0 (Table 3). In the spring 2019, an insignificant trend of increased K_{sat} was observed in all treatments with biochar in the range from 6 to 464% compared to the control (Table 4). In the autumn 2019, K_{sat} increased in treatments B10 + N0, B20 + N0, and B20reap + N0 in the range

from 127 to 284%. In the case of B20reap + N0, the difference was significant ($p < 0.05$) (Table 5). In the spring 2020, K_{sat} increased slightly only in the treatment B10 + N0 (Table 6); however, all observed changes were insignificant ($p > 0.05$).

At the first level of fertilization (N1), K_{sat} increased insignificantly in all treatments with biochar in the range from 55 to 145% in the autumn 2018 (Table 3) and in the range from 20 up to 350% in the spring 2019. Only in the case of B20reap + N1 treatment in spring 2019, the increase was significant ($p < 0.05$) (Table 4). In the autumn 2019, K_{sat} increased slightly only in the treatments B10 + N1 and B10reap + N1 compared to the control B0 + N0 (Table 5); however, all observed values for biochar treatments were significantly lower when compared to fertilized control B0 + N1. In the spring 2020, K_{sat} increased slightly only in the treatments B10reap + N1 and B20 + N1, however, all observed changes were insignificant (Table 6).

At the second level of fertilization (N2), we observed a slight increase of K_{sat} in the autumn 2018 in all treatments with biochar ranging from 23 to 333%. However, the difference was significant ($p < 0.05$) only in case of the treatment B10 + N2 compared to control treatment (Table 3). In the spring 2019, K_{sat} generally increased in the range from 100 to 299% but a significant increase ($p < 0.05$) was observed only in the treatment B20 + N2 compared to B0 + N0 (Table 4). In the autumn 2019, K_{sat} increased insignificantly in all treatments with biochar in the range from 63 to 369% compared to control B0 + N0 (Table 5). However, all observed values for biochar treatments were significantly lower when compared to fertilized control B0 + N2. In the spring 2020, the application of biochar did not generally affect K_{sat} . The only exception was B10 + N2 treatment where we observed a significant increase of 121% compared to the control B0 + N0.

Increasing the velocity at which water enters the soil is important for capturing rainfall, soil water retention, and overall soil management (Blaco-Canqui 2017). From this point of view, K_{sat} is an important soil property in solving the problems with soil water regime. In our study, we observed a trend of a K_{sat} increase in loamy soil in almost all cases with applied biochar, either in combination with N fertilizer or without N fertilizer. Some studies suggest that biochar can increase K_{sat} in clay soils and sandy-loam soils (Dan et al. 2015) by increasing the number of connected macropores. Another study suggests that biochar could effectively suppress water loss in coarse sandy soils (Uzoma et al. 2011) and thus reduce K_{sat} due to the absorption capacity of biochar. The changes in K_{sat} are associated with changes in soil porosity, aggregation, and water retention capacity (Nelissen et al. 2015). The size of the biochar particles itself and the particle size of the soil to which the biochar was applied also play an important role (Hardie et al. 2013; Jeffery et al. 2015; Lehmann and Stephen 2015; Esmaeelnejad et al. 2017). The

fact that the average K_{sat} values varied in such a wide range compared to the control is not surprising, since this value has a high variability. The standard deviation between the observed average values was rather large (Tables 3, 4, 5, and 6). K_{sat} depends on soil structure, which can vary in both space and time. According to Chirico et al. (2007), the relationship between K_{sat} and other soil properties, such as soil texture, soil bulk density, and organic matter, is not strong enough to permit accurate estimations of K_{sat} . Any change in the surface soil layer caused by natural factors, such as rainfall, growth and decay of plant roots, shrinking and swelling, or human interventions, such as cultivation treatments and wheel-traffic compaction can lead to changes in soil porosity. These changes can seriously affect K_{sat} and consequently soil water storage (Kargas et al. 2021). According to Alletto and Coquet (2009), K_{sat} of agricultural soil changes following a seasonal pattern. A decreasing tendency is expected from tillage to crop harvest due to soil compaction and progressive pore clogging.

Regardless of the determination method of K_{sat} in the field or laboratory, the measured value is representative for the specific place and time at which the measurement was carried out (Kargas et al. 2021). The measurements of K_{sat} can be affected by several factors. The first factor is the quality of the undisturbed soil sample and the content of the preferred water flow pathways in the soil sample. In one treatment of the field experiment, 9 soil samples were taken (8 used for further analysis), each of which could have a different composition (regarding the amount, size, and space distribution of pores). Another factor influencing the measurement could be the number of repetitions of the measurement. In our case, we performed two measurements per sample.

3.4 Effect of applied and reapplied biochar on plant available water

In the non-fertilized treatments (N0), we observed a trend towards an increase of the θ_{PAW} in the autumn 2018 in treatments with reapplied biochar compared to B0 + N0. In the case of treatment B20reap + N0, the difference was significant ($p < 0.05$) (+ 16%) compared to control B0 + N0. In both treatments with biochar reapplication the reason was a slight increase of θ_{FC} and in the case of treatment B10reap + N0 also a decrease of the θ_{PWP} (Table 3). In the spring 2019, θ_{PAW} increased significantly ($p < 0.05$) by 76, 37, and 65% in the treatments B10reap + N0, B20 + N0 and B20reap + N0 compared to the control treatment B0 + N0 (Table 4). This change was caused by a significant increase of θ_{FC} (+ 5.6% in the treatment B10reap + N0) and a significant decrease of θ_{PWP} (− 6.4 and − 8% in the treatments B20 + N0 and B20reap + N0, respectively). Although we did not observe any significant effect of biochar amendment on θ_{FC} and θ_{PWP} in the autumn 2019 compared to B0 + N0, θ_{PAW}

increased significantly ($p < 0.05$) in the treatments B10+N0, B10reap+N0, and B20reap+N0 in the range from 16.7 up to 27% compared to B0+N0 (Table 5). In the spring 2020, a general increase of θ_{PAW} was observed in all treatments with biochar compared to B0+N0. Significant ($p < 0.05$) changes of 26% and 29% were observed in the treatments B10+N0 and B10reap+N0 compared to control B0+N0 (Table 6).

At the first level of fertilization (N1), θ_{PAW} increased insignificantly in the treatments B10+N1, B10reap+N1, and B20reap+N1 in the autumn 2018 (Table 3). In the spring 2019, an increase of θ_{PAW} was observed in all treatments with biochar compared to B0+N0. Moreover, in most of the treatments the changes were significant ($p < 0.05$) (except for the treatment B20+N1) and ranged from 34 to 62% compared to control treatment B0+N0 (Table 4). At the same time, we observed an insignificant increase of θ_{FC} and general decrease of θ_{PWP} in all treatments with biochar (Table 4). The values of θ_{PAW} in the autumn 2019 increased only insignificantly in all treatments with biochar (Table 5). The same trend was observed also in the spring 2020, when θ_{PAW} increased after biochar application. Moreover, in the treatment B10+N1 the difference was significant ($p < 0.05$) compared to control B0+N0 (Table 6). At the same time, we did not observe any effect of biochar on θ_{FC} , while θ_{PWP} decreased significantly in the treatments B10+N1 and B10reap+N1 by 4.7 and 5.4%, respectively (Table 6).

At the second level of fertilization (N2), θ_{PAW} increased in the autumn 2018 in the treatments B10+N2, B10reap+N2, and B20reap+N2 in the range from 5 up to 17% (Table 3). In the spring 2019, an increase of θ_{PAW} in the range from 18 to 94% was observed in all treatments with biochar; however, the values were significantly different ($p < 0.05$) compared to the control B0+N2 only in the treatments with reapplied biochar B10reap+N2 and B20reap+N2 (Table 4). At the same time, θ_{FC} increased and θ_{PWP} decreased significantly only in the treatment B20reap+N2 (by +6.6%) and B10+N2 (by -7.5%) respectively compared to control treatment B0+N0, while the effect of biochar in other treatments was insignificant (Table 4). In the autumn 2019, θ_{PAW} increased in all treatments with biochar, but a significant increase of θ_{PAW} ($p < 0.05$) was observed only in the treatment B20+N2 (+19%) (Table 5). In the spring 2020, θ_{PAW} increased slightly in all treatments with biochar but the difference (+21%) was significant ($p < 0.05$) only in the treatment B20+N2 when compared to the control B0+N0 (Table 6).

Plant available water in the soil is determined according to the range between the values of the soil water constants θ_{FC} and θ_{PWP} . The larger this interval is the more water can plants draw from the soil through their roots. In our work, we observed a general trend of an increase in θ_{FC} and a decrease of θ_{PWP} . This fact indicates that the interval between these two water constants has enlarged, which in turn has led to

an increase of θ_{PAW} . In summary, it can be concluded that in our observations, biochar increased the interval of available water for plants by up to tens of percent. Depending on the amount of applied biochar and the amount of nitrogen fertilizer, the average increase in the interval of plant available water ranged from +10 up to +34%. A more pronounced increase occurred in the treatments with biochar reapplication at 10 t ha⁻¹ (18–34%) and 20 t ha⁻¹ (19–31%). Another positive finding is that biochar application in 2014 still had a favorable effect on θ_{PAW} in 2020. An average increase in θ_{PAW} depending on the amount of applied nitrogen fertilizer ranged from 8 up to 51% (at 10 t ha⁻¹ of biochar) and from 18 up to 21% (at 20 t ha⁻¹ of biochar) when compared to the control.

The application of biochar to the soil also increases the organic matter in the soil (Shepherd et al. 2002), which increases the water capacity in the soil by increasing the specific surface area or soil aggregation. Changing the volume of mesopores and micropores in the soil also plays an important role (Lehmann and Stephen 2015; Liu et al. 2017). The high volume of mesopores in the soil can increase the area of water available to plants (Molliendo et al. 2015).

Table 7 Effect of biochar application and reapplication on soil water content (means \pm standard deviations) ($n = 39$)

Treatment acronym	SWC ^a (% mass)		
	2018	2019	2020
Level N0 (0 kg N ha ⁻¹ in 2018, 2019, and 2020)			
B0+N0 (control)	13.1 \pm 3.9 a	14.4 \pm 6.9 a	13.1 \pm 4.9 a
B10+N0	12.9 \pm 4.7 a	13.8 \pm 6.3 a	12.7 \pm 4.9 a
B10reap+N0	13.1 \pm 5.1 a	14.0 \pm 7.0 a	12.9 \pm 4.9 a
B20+N0	13.6 \pm 5.8 a	15.2 \pm 6.9 a	13.4 \pm 5.1 a
B20reap+N0	14.7 \pm 5.9 a	15.0 \pm 6.9 a	13.4 \pm 4.9 a
Level N1 (40 kg N ha ⁻¹ in 2018, 108 kg N ha ⁻¹ in 2019, and 30 kg N ha ⁻¹ in 2020)			
B0+N1	11.8 \pm 3.8 a	12.7 \pm 6.2 a	12.4 \pm 4.5 a
B10+N1	12.8 \pm 4.1 a	14.5 \pm 7.0 a	13.6 \pm 4.5 a
B10reap+N1	13.2 \pm 5.1 ab	14.0 \pm 6.4 a	12.4 \pm 4.9 a
B20+N1	12.1 \pm 4.8 a	14.4 \pm 6.9 a	13.8 \pm 4.9 a
B20reap+N1	15.1 \pm 4.9 b	14.9 \pm 7.2 a	13.7 \pm 4.6 a
Level N2 (80 kg N ha ⁻¹ in 2018, 162 kg N ha ⁻¹ in 2019, and 75 kg N ha ⁻¹ in 2020)			
B0+N2	12.9 \pm 3.9 ab	14.0 \pm 6.7 a	12.7 \pm 4.3 a
B10+N2	12.3 \pm 4.2 a	13.8 \pm 6.9 a	13.0 \pm 4.8 a
B10reap+N2	13.6 \pm 4.9 ab	14.3 \pm 6.9 a	12.9 \pm 4.9 a
B20+N2	12.8 \pm 4.2 a	14.7 \pm 6.7 a	13.1 \pm 4.7 a
B20reap+N2	14.9 \pm 6.1 b	15.3 \pm 6.5 a	14.0 \pm 4.3 a

Different letters (a, b, c, d) indicate that treatment means are significantly different at $p < 0.05$ according to least significant difference test (one-way ANOVA). For explanation of treatment acronym see Table 2
^aSWC soil water content

Table 8 Percentual change in soil water content (%) and number of events with higher and lower soil water content during 2018 when compared to the control treatment

Treatment acronym	2018													No. of events	
	10.4.	25.4.	7.5.	22.5.	5.6.	18.6.	4.7.	12.7.	31.7.	13.8.	30.8.	13.9.	28.9.	+	-
Level N0 (0 kg N ha ⁻¹)															
B10+N0	-3.70	-19.12	0.00	-4.69	-1.71	-23.28	-18.28	22.40	49.30	-1.06	-16.88	-4.17	8.74	3	9
B10reap+N0	12.35	0.74	-6.72	0.00	-4.27	-36.21	-1.08	20.83	-5.63	8.47	-8.13	3.33	-8.74	5	7
B20+N0	9.26	-13.97	-5.88	-10.16	-4.27	9.48	31.18	36.46	1.41	2.65	-3.75	-4.17	-16.50	6	7
B20reap+N0	32.10	18.38	-2.52	1.56	3.42	2.59	6.45	40.63	23.94	7.41	15.63	-1.67	-18.45	10	3
Level N1 (40 kg N ha ⁻¹)															
B0+N1	0.62	0.74	-16.81	-7.03	-8.55	-25.00	-15.05	-8.85	-8.45	-8.99	-15.63	-16.67	-10.68	2	11
B10+N1	6.17	-9.56	-9.24	9.37	-0.85	-9.48	7.53	5.21	30.99	4.76	-23.13	-18.33	-11.65	6	7
B10reap+N1	16.67	18.38	-16.81	-0.78	-9.40	-9.48	-2.15	16.15	0.00	8.99	-4.38	-5.00	-22.33	4	8
B20+N1	19.75	-13.97	-11.76	-8.59	-17.09	-21.55	7.53	6.25	-9.86	1.59	-19.38	-27.50	-19.42	4	9
B20reap+N1	34.57	-10.29	23.53	9.37	2.56	17.24	31.18	24.48	36.62	9.52	13.13	0.83	3.88	12	1
Level N2 (80 kg N ha ⁻¹)															
B0+N2	3.70	-18.38	-5.88	3.12	-17.09	16.38	1.08	6.25	32.39	-5.82	-3.75	-15.00	-3.88	6	7
B10+N2	2.47	2.21	-6.72	-7.81	-5.98	-12.93	-18.28	0.52	-5.63	-2.12	-19.38	-3.33	-20.39	3	10
B10reap+N2	17.90	9.56	12.61	-1.56	0.00	-12.93	18.28	16.15	7.04	4.76	-5.00	-25.00	-5.83	7	5
B20+N2	-2.47	-9.56	-21.01	-11.72	6.84	5.17	0.00	6.77	0.00	-0.53	-1.25	-9.17	-2.91	3	8
B20reap+N2	9.88	27.94	10.92	-7.81	16.24	5.17	54.84	48.96	19.72	13.76	-16.25	5.00	-15.53	10	3

The percentual difference in soil water content between the specific treatment and the control is accompanied by the color gradient from dark red (the lowest value in comparison to control) to dark blue (the highest value in comparison to control). + and - stands for the number of events with higher, respectively lower soil water content in comparison to the control treatment. For explanation of treatment acronym see Table 2

3.5 Effect of applied and reapplied biochar on soil water content

Soil water content (SWC) was determined at 13 sampling events in 2018 and 13 and 12 sampling events in 2019 and 2020, respectively. Table 7 presents the mean observed values of SWC during the whole studied period. Considering a trend that SWC took in the unfertilized treatments (N0) and treatments at the first level of fertilization (N1), biochar

application at 10 t ha⁻¹ less often increased SWC than at the application rate of 20 t ha⁻¹.

The most significant improvement was observed in the reapplication of biochar in a dose of 20 t ha⁻¹ at all fertilization levels (N0, N1, N2), while the average SWC for the entire “vegetation” period was higher by 12–15% in 2018, 3–6% in 2019, and 2–7% in 2020 when compared to the control. It seems that the positive impact of biochar on SWC decreases over time due to agrotechnical operations

Table 9 Percentual change in soil water content (%) and number of events with higher and lower soil water content during 2019 when compared to the control treatment

Treatment acronym	2019													No. of events	
	11.4.	26.4.	7.5.	24.5.	3.6.	18.6.	2.7.	17.7.	31.7.	13.8.	27.8.	11.9.	25.9.	+	-
Level N0 (0 kg N ha ⁻¹)															
B10+N0	-5.63	-15.38	-7.26	-0.86	-10.14	5.38	14.63	11.90	-11.73	-4.55	-10.24	-2.21	4.04	4	9
B10reap+N0	-13.75	-43.96	-7.26	0.00	-4.73	-2.31	-19.51	28.57	-3.35	11.36	4.88	4.42	1.01	5	7
B20+N0	11.25	-10.99	-1.28	9.44	0.68	10.00	12.20	21.43	1.68	22.73	2.44	0.00	11.11	10	2
B20reap+N0	4.38	-8.79	-2.14	4.29	-5.41	3.08	7.32	71.43	5.59	1.14	5.37	5.31	5.05	10	3
Level N1 (108 kg N ha ⁻¹)															
B0+N1	6.25	-19.78	-4.70	-2.58	-15.54	-17.69	-19.51	21.43	-26.82	-6.82	-27.32	-15.93	-11.11	2	11
B10+N1	11.88	-6.59	-6.84	2.15	-2.70	25.38	-7.32	40.48	0.00	-25.00	-4.88	-0.88	3.03	5	8
B10reap+N1	5.00	-7.69	-5.13	1.29	4.73	14.62	-19.51	11.90	-5.03	1.14	-22.44	-6.64	-5.05	6	7
B20+N1	18.13	8.79	0.00	6.01	-4.05	6.92	2.44	14.29	-2.23	-15.91	-13.17	-3.54	-12.12	6	6
B20reap+N1	7.50	-7.69	0.85	2.58	0.68	11.54	0.00	23.81	6.15	5.68	-9.27	11.95	1.01	10	2
Level N2 (162 kg N ha ⁻¹)															
B0+N2	-1.25	-14.29	-7.69	2.58	-7.43	-3.08	-19.51	28.57	4.47	12.50	-8.78	-9.73	9.09	5	7
B10+N2	7.50	-20.88	-5.13	0.43	-10.81	-0.77	-9.76	14.29	-8.94	-10.23	-18.54	2.65	15.15	5	8
B10reap+N2	12.50	-12.09	0.43	3.86	2.03	-12.31	-14.63	30.95	-16.20	7.95	-13.17	3.10	7.07	8	5
B20+N2	6.25	-4.40	-0.43	2.58	-8.11	9.23	-12.20	45.24	-1.68	1.14	-5.37	2.21	18.18	7	6
B20reap+N2	10.00	10.99	7.26	7.30	6.76	12.31	-2.44	119.05	-11.17	12.50	-14.15	3.10	13.13	10	3

The percentual difference in soil water content between the specific treatment and the control is accompanied by the color gradient from dark red (the lowest value in comparison to control) to dark blue (the highest value in comparison to control). + and - stands for the number of events with higher, respectively lower soil water content in comparison to the control treatment. For explanation of treatment acronym see Table 2

Table 10 Percentual change in soil water content (%) and number of events with higher and lower soil water content during 2020 when compared to the control treatment

Treatment acronym	2020												No. of events	
	21.4.	6.5.	21.5.	2.6.	22.6.	9.7.	17.7.	31.7.	12.8.	25.8.	9.9.	21.9.	+	–
Level N0 (0 kg N ha ⁻¹)														
B10+N0	-10.08	21.69	0.71	8.07	-4.02	-4.26	-10.00	0.81	-2.81	-16.49	-4.40	-12.90	4	8
B10reap+N0	-1.55	9.64	0.71	6.21	-2.23	9.57	-6.67	1.63	-6.74	3.09	-0.55	-23.66	6	6
B20+N0	-4.65	14.46	14.18	6.83	1.79	18.09	-16.67	0.81	-2.25	-3.09	2.75	-8.60	7	5
B20reap+N0	12.40	0.00	8.51	5.59	-3.13	4.26	0.00	-0.81	4.49	-2.06	2.75	4.30	7	3
Level N1 (30 kg N ha ⁻¹)														
B0+N1	-2.33	22.89	-9.22	-4.35	-1.34	-3.19	-20.00	-5.69	-12.36	0.00	-9.34	-8.60	1	9
B10+N1	13.95	56.63	6.38	9.32	-3.13	8.51	-8.33	3.25	-9.55	5.15	-4.40	-6.45	7	5
B10reap+N1	1.55	15.66	-14.18	-1.24	-8.04	-2.13	-18.33	-3.25	-8.99	-27.84	-1.65	-19.35	2	10
B20+N1	15.50	12.05	10.64	13.66	2.23	6.38	0.00	0.81	-5.06	16.49	2.75	4.30	10	1
B20reap+N1	-0.78	-13.25	2.84	9.32	-4.91	12.77	13.33	7.32	2.81	27.84	2.20	20.43	9	3
Level N2 (75 kg N ha ⁻¹)														
B0+N2	-2.33	25.30	0.71	-6.83	-3.57	-1.06	-10.00	-4.88	-11.80	6.19	-5.49	-3.23	3	9
B10+N2	-9.30	34.94	0.71	6.83	-3.13	-3.19	-13.33	0.00	-0.56	-1.03	-2.75	-3.23	3	8
B10reap+N2	6.98	2.41	0.71	0.00	2.23	1.06	-3.33	-0.81	-11.80	2.06	-2.75	-7.53	6	5
B20+N2	-8.53	18.07	6.38	0.00	-2.23	8.51	-6.67	6.50	-2.81	-3.09	-2.75	1.08	5	6
B20reap+N2	3.10	48.19	-4.26	7.45	0.45	7.45	18.33	3.25	0.00	22.68	2.75	9.68	10	1

The percentual difference in soil water content between the specific treatment and the control is accompanied by the color gradient from dark red (the lowest value in comparison to control) to dark blue (the highest value in comparison to control). + and – stands for the number of events with higher, respectively lower soil water content in comparison to the control treatment. For explanation of treatment acronym see Table 2

and admixing of biochar into deeper layers. However, we assume that the positive effect of biochar on SWC increases in the deeper layers of the soil profile where biochar gradually reaches over time.

The positive effect of a higher dose of reapplied biochar on SWC is confirmed when analyzing individual terms of soil moisture measurement. Overall biochar amendment did not significantly affect SWC at any fertilization level, except for reapplication of biochar in a dose of 20 t ha⁻¹ for all fertilization levels (N0, N1, N2).

Overall, SWC was not significantly affected by biochar application at any fertilization level, except for reapplication of biochar at a dose of 20 t ha⁻¹ at all fertilization levels (N0, N1, N2). Biochar reapplication at that rate (B20reap) had the highest potential to generally increase SWC as it was observed during the individual sampling events (Tables 8, 9, and 10). In the treatment B20reap + N0, a trend to increase SWC was observed at 10, 10, and 7 sampling events in 2018, 2019, and 2020, respectively. At the first level of fertilization the same application dose of biochar (B20reap + N1) tended to increase SWC at 12, 10, and 9 sampling events in 2018, 2019, and 2020, respectively. In the treatment B20reap + N2, a trend to increase SWC was observed at 10, 10, and 10 sampling events in 2018, 2019, and 2020, respectively.

One of the main advantages of applying biochar into soil is its ability to retain water by its natural internal porosity (Yu et al. 2013; Rasa et al. 2018) or its ability to aggregate soil (Herath et al. 2013; Laird et al. 2010), which is indirectly related to soil water content (Rasa et al. 2018). Our findings on the positive effect of biochar on soil water content are consistent with the work of Leelamanie (2014) and Agegnehu et al. (2015).

4 Conclusions

Based on the results observed in our field experiment with biochar at the experimental site in Dolná Malanta (Nitra, Slovakia) we can conclude that the application of biochar in 2014 and its subsequent reapplication in 2018 resulted in positive trends in changes of studied soil hydrophysical characteristics and storage of available water for cultivated plants. The results showed that biochar can reduce bulk density in silty loam Haplic Luvisols and possibly in similar soil types with loamy texture.

The most significant trend towards a reduction of bulk density was observed in the treatments with biochar application and reapplication at dose of 20 t ha⁻¹ in combination with all levels of fertilization. At the same time, depending on the amount, the application of biochar increased soil porosity in the range from + 10 up to + 20%. Subsequent reapplication of biochar after 4 years supported this positive trend of increasing porosity in loamy soil. Increasing soil porosity by the biochar application results in an improvement of the soil structure, the quality of the soil pores, and their interconnection. This has a positive effect on the observed increase in saturated hydraulic conductivity of the soil. The increase in hydraulic conductivity was reflected in better retention of precipitation, increased soil water content and in overall improved hydrological soil balance. The highest average increase in soil water content was observed in the treatments with reapplied biochar at a dose of 20 t ha⁻¹ (12–15%) in combination with all levels of fertilization (N0, N1, and N2). We assume, that the repeated biochar application influenced soil pore size redistribution towards an

increase of the proportion of capillary pores in the soil. Biochar directly led to an enlargement of the interval of plant available water by decreasing the value of permanent wilting point and increasing the field capacity and therefore had a favorable effect on providing sufficient amount of water to plants. Depending on the level of N fertilization, the interval of plant available water increased by 8–51% (biochar application dose of 10 t ha⁻¹), 18–21% (biochar application dose of 20 t ha⁻¹), 18–34% (biochar reapplication dose of 10 t ha⁻¹) and 19–31% (biochar reapplication dose of 20 t ha⁻¹).

Acknowledgements This study was financed by the Operational Program Integrated Infrastructure within the project: Sustainable smart farming systems taking into account the future challenges 313011W112, cofinanced by the European Regional Development Fund and by the Scientific Grant Agency VEGA Project No. 1/0021/22 and VEGA Project No. 1/0747/20.

Author contribution All authors contributed to the study conception and design. LT: conceptualization, methodology, data collection, data curation, data analysis, investigation, resources, original draft preparation. DI: conceptualization, methodology, supervision, project administrator, manuscript editing, funding acquisition. JH: methodology, manuscript editing. EA: writing review and comments, manuscript editing, language editing, funding acquisition. All authors have read and approved the final manuscript.

Data availability The datasets analyzed in the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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