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Effect of Biochar Application and Re-Application on Soil Bulk Density, Porosity, Saturated Hydraulic Conductivity, Water Content and Soil Water Availability in a Silty Loam Haplic Luvisol

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Abstract: Due to climate change the productive agricultural sectors have started to face various challenges, such as soil drought. Biochar is studied as a promising soil amendment. We studied the effect of a former biochar application (in 2014) and re-application (in 2018) on bulk density, porosity, saturated hydraulic conductivity, soil water content and selected soil water constants at the experimental site in Dolná Malá (Slovakia) in 2019. Biochar was applied and re-applied at the rates of 0, 10 and 20 t ha^{−1}. Nitrogen fertilizer was applied annually at application levels N0, N1 and N2. In 2019, these levels were represented by the doses of 0, 108 and 162 kg N ha^{−1}, respectively. We found that biochar applied at 20 t ha^{−1} without fertilizer significantly reduced bulk density by 12% and increased porosity by 12%. During the dry period, a relative increase in soil water content was observed at all biochar treatments—the largest after re-application of biochar at a dose of 20 t ha^{−1} at all fertilization levels. The biochar application also significantly increased plant available water. We suppose that change in the soil structure following a biochar amendment was one of the main reasons of our observations.

Keywords: biochar; fertilization; bulk density; plant available water, porosity; saturated hydraulic conductivity; soil water constants; TDR measurement

1. Introduction

The threat of global climate change and its negative effects is currently a serious problem. As a result, an increase in potential evapotranspiration and a decrease in soil moisture can be expected in the south of Central Europe [1–3]. This means that the soils will gradually dry out [4,5] and at such soil moisture levels the plants will suffer from a lack of water, which may adversely affect the normal development of vegetation and crop yields [6,7].

Soil with good structure, bulk density, porosity and hydraulic conductivity provides a good environment for the better movement and retention of water and nutrients in the soil profile and greater growth of root systems, resulting in higher crop yields. One of the suitable alternatives in connection with the modification of the physical properties of soils appears to be the use of biochar.

Biochar is a stable, carbon-rich product that is obtained by thermal decomposition (pyrolysis) of organic material [8,9]. During the past decade, biochar has been considered a valuable product that provides the significant possibilities for soil improvement. The potential benefits of biochar as a soil amendment are well identified in the literature. These include a carbon sequestration, improved crop yields, and enhanced water retention [10]. According to several studies, an improvement in soil quality could be permanent after addition of biochar [11]. At the same time, biochar has the potential

to reduce global greenhouse gas emissions [12–14]. During the decomposition of organic materials, greenhouse gases such as carbon dioxide are released into the atmosphere. Because of pyrolysis, a lot of carbon is fixated in a more stable form and effectively sequestered after application into the soil [15]. The properties of biochar themselves depend in a large extent on the characteristics of the raw materials and on the conditions of pyrolysis [16]. Aslam et al. [17] attributed the improvement of physical properties of soil after introduction of biochar to the type of input material, pyrolysis conditions, application rate of biochar and the soil type into which biochar was applied and incorporated [18].

Various preceding studies reported a positive effect of biochar on the physical, hydro-physical and hydraulic properties of soil [8,19–21]. The application of biochar positively affected bulk density [22], soil porosity [23–25], soil water capacity [26] and soil hydraulic conductivity [27,28]. Due to the highly porous nature of biochar, its introduction into the soil can improve the soil physical properties by creating the new pores. Jones et al. [23] attributed the partial filling of large cavities in-between coarse sand particles to biochar application. Castellini et al. [29] stated that biochar has a potential impact on the soil physical properties and thus can affect the ecosystem water balance. The study of Sun and Lu [30] showed a positive effect of biochar application on soil porosity and available water capacity for plants resulting in an increase of crop yields.

It should be mentioned that many studies focused on the problematic soils (acidic, saline, with low soil organic carbon content) where the changes after biochar application can be expected to be robust [31–33]. However, in theory, a likelihood of biochar application is that it may have its greatest effect on the most fertile agricultural soils (Europe including Slovakia), where the greatest economic and practical potential is located. While there are many studies focusing on the short-term effects of biochar application on the soil properties, there has been only a limited amount of published studies tracing biochar's long-term effects (>5 years). These studies can be further divided into several groups. Some studies are focused on the effect of repeatable biochar application for a period of a few years. The other group of studies includes works with a single application of biochar at the beginning of the experiment establishment, followed by a monitoring period reaching up to 3–4 years [34]. The effect of biochar re-application on the soil properties is a new emerging topic and according to our knowledge, studies including biochar re-application are very rare [35].

The issue of the mid-term and long-term use of biochar in field conditions appears only a few times in the literature, and its positive impact on the soil properties, soil processes and functions has not been sufficiently demonstrated on the soil types in a temperate climatic zone (including Central Europe and Slovakia). Further research is therefore needed in this field.

The aim of this study was to examine the impact of biochar application in the fifth year after its application in combination with nitrogen fertilizer on bulk density, soil porosity, saturated hydraulic conductivity, soil water content and soil water constants. We assumed that the effect of biochar application will be noticeable even five years after its application because of biochar's stability. We also expected the effect to be bigger at the application dose of 20 t ha⁻¹. Another goal was to analyze the effect of biochar re-application on the above-mentioned soil characteristics one year after its additional application to the selected plots. We hypothesized that a bigger effect will be observed at treatments with biochar re-application in comparison to treatments with past biochar application.

2. Materials and Methods

2.1. Field Experiment and Experimental Treatments

The research was conducted at the experimental site of the Slovak University of Agriculture in Nitra located in Dolná Malanta approximately 5 km north-east from the city of Nitra (Slovakia) (48°19'00" N; 18°09'00" E) (Figure 1). The continuous biochar field experiment was established in 2014 to examine the effect of biochar application on greenhouse gas emissions [13,36], soil quality [14,37–44] and crop yields [34,45,46]. The soil was classified as Haplic Luvisol according to World Reference Base [47] with the initial soil organic carbon content of 9.13 g kg⁻¹, pH of 5.71 (slightly acidic) and silty

loam soil texture. The site was used for conventional agricultural production prior to establishment of the experiment.



Figure 1. Experimental site location.

Fifteen treatments with three replicates were arranged on plots (4×6 m) in a randomized block design separated by 0.5 m wide protection strips in 2014. Biochar was manually applied at the doses of 0, 10 and 20 t ha^{-1} on the soil surface (Table 1). It was firstly manually spread by rakes and then incorporated by disking with a tractor cultivator into the depth of 0–10 cm. The biochar used in this experiment was produced from the mixture of paper fiber sludge and grain husks (in a 1:1 per weight ratio) by pyrolysis in a Pyreg reactor (Pyreg GmbH, Dörhe, Germany) at 550°C for 30 min. The biochar had a typical particle size of up to 5 mm [48]. Detailed information on its physical and chemical properties is provided in Table 2.

In 2018, the original plots with former biochar application were divided in halves (two subplots with dimensions 4×3 m) and the biochar was re-applied to one of these halves at the same doses as utilized in 2014 (Table 1, treatments with “reap” in their acronym). Nitrogen fertilizer was applied annually at the application levels of N0, N1 and N2 (Table 1). The crop rotation included spring barley (*Hordeum vulgare* L.) in 2014, maize (*Zea mays* L.) in 2015, spring wheat (*Triticum aestivum* L.) in 2016, maize in 2017 and spring barley in 2018. Fertilizer application doses in a period of 2014–2018 can be found in the published literature [34,49]. The specific doses of fertilizer at the application level N1 were calculated according to the requirements of each crop using the balance method. The dose in the fertilization level N2 was 50% higher than in the level N1 every year. The exception was done for spring barley, when the application level N2 was twofold in comparison to the level N1. Research observations presented in this study were carried out in 2019 during the vegetation season of maize when the N-fertilizer (calcium ammonium nitrate LAD 27) was applied at a dose of 108 kg N ha^{-1} in the fertilization level N1 (recommended dose for maize). The dose in the fertilization level N2 was 162 kg N ha^{-1} —50% higher than in N1.

Table 1. Treatments of the field experiment with a dose of biochar and a dose of nitrogen fertilizer.

Treatments	Biochar Application in 2014 (t ha ⁻¹)	Biochar Re-Application in 2018 (t ha ⁻¹)	N Fertilizer Application in 2019 (kg N ha ⁻¹)
Non-fertilized Group (0 kg N ha ⁻¹)			
B0 + N0 (control)	0	0	0
B10 + N0	10	0	0
B20 + N0	20	0	0
B10 reap + N0	10	10	0
B20 reap + N0	20	20	0
N1 Group—Fertilized (108 kg N ha ⁻¹)			
B0 + N0 (control)	0	0	0
B0 + N1	0	0	108
B10 + N1	10	0	108
B10 reap + N1	20	0	108
B20 + N1	10	10	108
B20 reap + N1	20	20	108
N2 Group—Fertilized (162 kg N ha ⁻¹)			
B0 + N0 (control)	0	0	0
B0 + N2	0	0	162
B10 + N2	10	0	162
B10 reap + N2	20	0	162
B20 + N2	10	10	162
B20 reap + N2	20	20	162

Table 2. Physical and chemical properties of biochar provided by Austrian company Sonnenerde [46,48].

Bulk Density (g cm ⁻³)	SSA (m ² g ⁻¹)	Size Fraction (mm)	SOC (g kg ⁻¹)	pH (–)	Total C (%)	Total N (%)	P (g kg ⁻¹)	K (g kg ⁻¹)	Ca (g kg ⁻¹)
0.206	21.7	1–5	10.2	8.8	53.1	14.0	6.2	15.0	57.0

SSA—specific surface area, SOC—soil organic carbon.

2.2. Climatic Conditions

The study area is located in a temperate region with a mean annual air temperature of 9.8 °C and total precipitation amount of 540 mm (according to 30-year climatic normal, 1961–1990) [50]. The mean air temperature was 10.9 °C and annual precipitation was 625.4 mm during the studied year 2019. Monthly data of the mean air temperature and precipitation amount in 2019 at the experimental site were compared to the climatic normal 1960–1991 [50] and evaluated according to Čimo et al. [51] (Table 3).

Table 3. Evaluation of monthly precipitation and mean air temperature normality in 2019 as compared to the climatic normal (CN) 1960–1991 [50].

Month	Precipitation			Mean Air Temperature		
	Total (mm)	% of Normal	Description	Mean (°C)	Deviation of Normal (°C)	Description
January	54.8	177	very wet	−2.2	−0.5	normal
February	27.4	86	normal	3.4	2.7	warm
March	22.4	75	normal	8.1	3.1	very warm
April	21.4	55	dry	9.7	−0.7	normal
May	134.8	232	extremely wet	9.3	−5.8	extremely cold
June	29.0	44	very dry	18.7	0.7	normal
July	52.2	100	normal	21.9	2.1	very warm
August	64.0	105	normal	22.3	3.0	very warm
September	52.8	132	wet	16.2	0.6	normal
October	17.8	49	very dry	12.0	1.6	warm
November	95.4	173	very wet	8.4	3.9	very warm
December	53.4	134	wet	3.3	3.2	very warm

2.3. Soil Sampling and Further Analyzes

To determine the selected physical, hydro-physical and hydraulic properties, soil sampling was conducted on trial plots in the spring 2019. Three undisturbed soil samples with a total volume of 100 cm³ were taken from each plot. In total, 135 samples were taken from 45 plots representing 15 treatments across 3 replicates. It means that for each treatment, 9 representative undisturbed soil samples were obtained. However, due to the high variability of soil properties within the treatment, one soil sample with the most extreme values was excluded from further statistical analyses. Bulk density (BD) was determined by the gravimetric method from oven-dried soil samples.

The mean particle density was calculated from the same undisturbed soil samples as a ratio between the mass weight of dried soil sample to the volume of the solid phase of soil. The volume of the soil's solid phase was measured by an air pycnometer according to Langer (Eijkelkamp Soil & Water, Giesbeek, The Netherlands). This device measures the volume of objects placed in the vacuum bell by means of under-pressure created by the vertical movement of a mercury column [52]. Total porosity (P) was calculated from particle density and bulk density of the soil. Saturated hydraulic conductivity (K) was estimated in the laboratory from the saturated undisturbed soil samples using falling head method [53,54]. The principle of this method is a measurement of the flow rate per unit cross sectional area and unit hydraulic head gradient. The basic soil water constants—field capacity (FC), refill point (RP) and permanent wilting point (PWP) were determined by the pressure-plate apparatus at corresponding pressure potentials −20, −300 and −1500 kPa, respectively. Readily plant available water (RPAW) was calculated as a difference between measured values of FC and RP. Plant available water (PAW) was calculated as difference between FC and PWP.

2.4. Soil Water Content Measurements and Probe Calibration

Soil water content was measured by an electromagnetic-based soil water content probe with portable data logger—the HydroSense II portable system (hereafter HS2) (Campbell Scientific, Inc.[®], Logan, UT, USA) operating by time domain reflectometry (TDR) principle. The CS659 water content reflectometer sensor uses two parallel 12 cm long rods [55]. The manufacturer's specification of the sensing volume is a cylinder of ~30 mm diameter along the full length of the rods [56]. In order to achieve the accurate repeatable measurements, the sensor rods were fully inserted into the soil during the measurement. Soil water content was measured in % of volume [55]. The measurements were performed biweekly from the beginning of April to the end of September 2019 (vegetation season) in three repetitions per all 45 plots. In total, 1755 soil water content measurements were obtained for 13 sampling days in 2019. Calibration of measurements was performed according to our previously published findings [44]. Past calibration equations were derived for some treatments of the field experiment using the gravimetric method. This method generally serves as a standard method [57,58] for the calibration of soil moisture sensors. Using the calibration equations according to Toková et al. [44], further equations were calculated for remaining treatments of the field experiment. These equations are summarized in Table 4.

2.5. Statistical Analysis

The effect of biochar addition on the physical, hydro-physical and hydraulic soil properties was studied using one-way analysis of variance (ANOVA). The significant treatments at $p < 0.05$ were determined by the least significance difference (LSD) test. All analyses were performed in Statgraphics Centurion XVI software (Statpoint Technologies, Inc., Warrenton, VA, USA).

Table 4. Equations used to calibrate the measured values of soil water content.

Treatments	Calibration Equations	R ²
B0 + N0	$y = 0.8374x + 3.8489$	0.93
B10 + N0	$y = 0.8319x + 3.8984$	0.95
B20 + N0	$y = 0.8245x + 3.9869$	0.97
B10 reap + N0	$y = 0.8319x + 3.8984$	0.95
B20 reap + N0	$y = 0.8245x + 3.9869$	0.97
B0 + N1	$y = 0.7883x + 5.4387$	0.94
B10 + N1	$y = 0.8030x + 4.8839$	0.95
B20 + N1	$y = 0.7514x + 6.6475$	0.96
B10 reap + N1	$y = 0.8030x + 4.8839$	0.95
B20 reap + N1	$y = 0.7514x + 6.6475$	0.96
B0 + N2	$y = 0.7883x + 5.4387$	0.94
B10 + N2	$y = 0.8030x + 4.8839$	0.95
B20 + N2	$y = 0.7514x + 6.6475$	0.96
B10 reap + N2	$y = 0.8030x + 4.8839$	0.95
B20 reap + N2	$y = 0.7514x + 6.6475$	0.96

3. Results

3.1. Impact of Biochar Application and Re-Application on Bulk and Particle Density

When evaluating the effect of biochar application without nitrogen fertilizer (Table 5) on bulk density (BD), we found that a gradual increase in the biochar dose gradually decreased BD. However, a significant decrease ($p < 0.05$) of BD was found only when biochar was applied and re-applied at a dose of 20 t ha⁻¹ (B20 + N0 and B20 reap + N0) when compared to control (B0 + N0) (Table 5).

In the treatments with the fertilization level of N1 (108 kg N ha⁻¹) (Table 5), a decrease in BD was also observed after the addition of biochar, but not in the same trend as in the non-fertilized treatments. Bulk density significantly decreased ($p < 0.05$) after biochar application at a dose of 10 t ha⁻¹ in combination with the fertilization level N1 (B10 + N1), after re-application of biochar at a rate of 10 t ha⁻¹ (B10 reap + N1) and of 20 t ha⁻¹ (B20 reap + N1). The treatments were compared to the reference control treatment (B0 + N0), but also to the treatment only with fertilization at N1 (B0 + N1) (without biochar application).

In the treatments with the higher level of fertilization (162 kg N ha⁻¹), the trend of decreasing BD by gradual increase of the biochar dose was again observed. In that case, BD significantly decreased ($p < 0.05$) after biochar application at a dose of 20 t ha⁻¹ re-application at a dose of 10 t ha⁻¹ and of 20 t ha⁻¹ (B20 + N2, B10 reap + N2 and B20 reap + N2, respectively) (Table 5) when compared to the control treatment (B0 + N0).

Biochar addition in general caused a decrease in particle density (except treatment B20 + N1) when compared to control B0 + N0, however not all results were significant ($p < 0.05$). At the first fertilization level N1, a significant decrease was observed in the majority of treatments, even in the case of the fertilized treatment without biochar application (B0 + N1). At the second fertilization level N2, no significant ($p < 0.05$) effect of biochar application was observed except for the treatment B10 reap + N2 where particle density significantly decreased by 6%.

3.2. Impact of Biochar Application and Re-Application on Porosity

In the non-fertilized treatments, a significant increase ($p < 0.05$) in porosity (P) was observed in the treatments with a biochar dose of 20 t ha⁻¹ (B20 + N0 or B20 reap + N0) (Table 5). The highest P was observed in the treatment B20 + N0 (49.98% vol.) which represents a significant increase by 13% when compared to the control (B0 + N0).

In the case of fertilized treatments (N1 and N2 level of fertilization), biochar application did not have any significant effect in comparison to control treatment B0 + N0. However, a significant increase

($p < 0.05$) in P was recorded when the treatments with biochar application were compared to only fertilized treatments at the first and second level of fertilization (B0 + N1 and B0 + N2, respectively).

Table 5. Effect of biochar application and re-application on bulk density, particle density, porosity, and saturated hydraulic conductivity (means \pm standard deviations). Different letters indicate that treatment means are significantly different at $p < 0.05$ according to least significance difference test.

Treatments	BD	PD	P	K
	g cm^{-3} n = 8	g cm^{-3} n = 8	% vol. n = 8	cm h^{-1} n = 8
Non-fertilized Group (0 kg N ha $^{-1}$)				
B0 + N0 (control)	1.41 \pm 0.12 b	2.54 \pm 0.09 a	44.19 \pm 3.95 a	2.12 \pm 0.88 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
B20 + 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
B10 reap + 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
B20 reap + 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
N1 Group—Fertilized (108 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
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
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
B10 reap + 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
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
B20 reap + 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
N2 Group—Fertilized (162 kg N ha $^{-1}$)				
B0 + N0 (control)	1.41 \pm 0.12 c	2.54 \pm 0.09 b	44.19 \pm 3.95 ab	2.12 \pm 0.88 a
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
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
B10 reap + N2	1.28 \pm 0.07 a	2.39 \pm 0.08 a	47.11 \pm 3.59 b	5.47 \pm 3.78 ab
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
B20 reap + 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

BD—bulk density, PD—particle density, P—porosity, K—saturated hydraulic conductivity.

3.3. Impact of Biochar Application and Re-Application on Saturated Hydraulic Conductivity

Generally, the values of saturated hydraulic conductivity (K) increased with an increasing application rate of biochar in most of the treatments with or without fertilization (N0, N1 and N2) (Table 5). However, a significant increase ($p < 0.05$) of K in the first level of fertilization (N1) was found only in treatment B20 reap + N1, when biochar was re-applied at a dose of 20 t ha $^{-1}$. A significant increase ($p < 0.05$) was also found at treatment B20 + N2, when 20 t ha $^{-1}$ of biochar was combined with fertilization level of N2 as compared to control treatment without biochar and fertilizer application (B0 + N0).

3.4. Impact of Biochar Application and Re-Application on Soil Water Content Dynamics

The dynamics of soil water content (SWC) at all biochar treatments and fertilization levels during the studied period (April–September 2019) is shown in Figures 2–4. Generally, the highest values of SWC were observed in all 15 treatments after a rain event with high precipitation (37.8 mm) at the end of May (22 May 2019) (Figures 2a, 3a and 4a).

In the case of non-fertilized treatments, the relative percentage change in comparison to control treatment (B0 + N0) showed that the treatment B20 reap + N0 increased the soil moisture in a range from 1.8–10% (10 of 13 measurements events) (Figure 2b). This positive effect was also found in other biochar treatments. However, it was not so evident and in some cases a decrease in SWC relative to control treatment (B0 + N0) was observed. During the dry period of experiment from 24. June up to 6.

July, all biochar treatments showed higher SWC in the range from 4.76–13.67% when compared to control (B0 + N0).

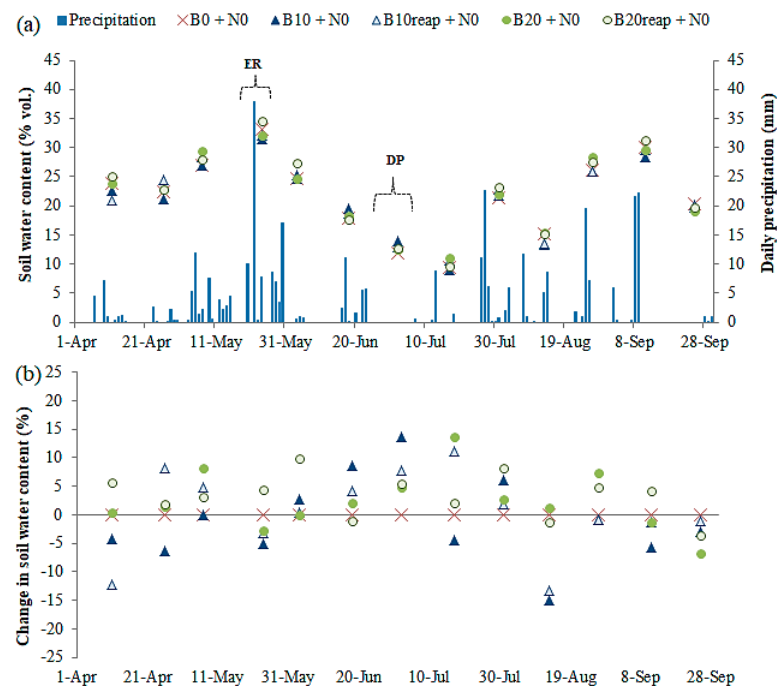


Figure 2. Soil water content dynamics in unfertilized treatments during the studied period in 2019: (a) soil water content with indication of daily precipitation, ER—extreme rainfall, DP—dry period; (b) percentage change in soil water content relative to control treatment B0 + N0 (without biochar and N-fertilizer application).

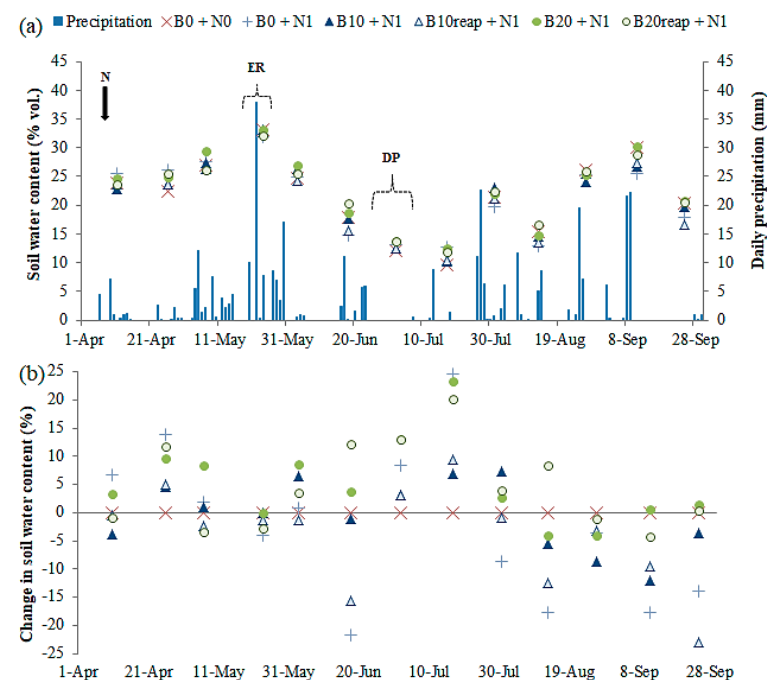


Figure 3. Soil water content dynamics in fertilized treatments N1 during the studied period in 2019: (a) soil water content with indication of daily precipitation, N—nitrogen fertilizer application, ER—extreme rainfall, DP—dry period; (b) percentage change in soil water content relative to control treatment B0 + N0 (without biochar and N-fertilizer application).

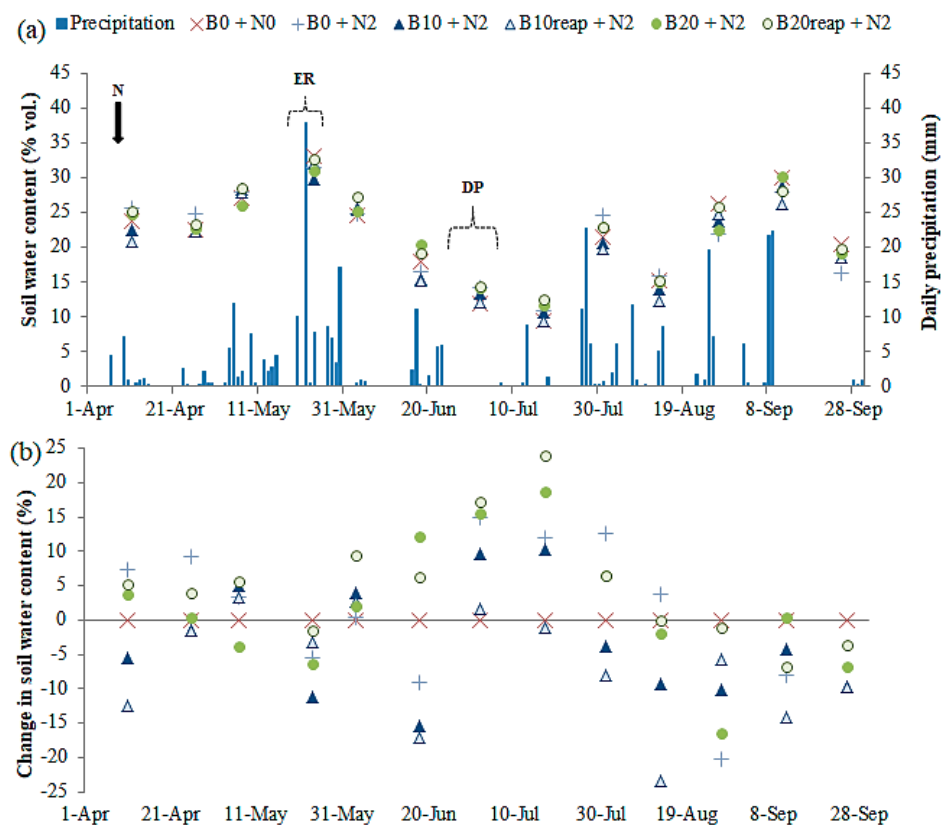


Figure 4. Soil water content dynamics in fertilized treatments N2 during the studied period in 2019: (a) soil water content with indication of daily precipitation, N—nitrogen fertilizer application, ER—extreme rainfall, DP—dry period; (b) percentage change in soil water content relative to control treatment B0 + N0 (without biochar and N-fertilizer application).

Regarding the fertilization level N1, treatments B20 + N1 and B20 reap + N1 increased SWC in a range from 0.7–23.4% (10 of 13 measurements events) and 0.49–20.17% (8 of 13 measurements events) respectively when compared to control B0 + N0 (Figure 3b). An increase in SWC was observed also for all other biochar treatments when compared to control treatment (B0 + N0) during the dry period. However, it should be noted that higher SWC was observed also at the treatment without biochar application at first fertilization level (B0 + N1) when compared to B0 + N0 control treatment.

The treatment B20 reap + N2 also showed the largest increase in SWC in a range from 3.9–24.0% (8 of 13 measurements events) between fertilized treatments at N2 level (Figure 4b). Similarly, an increase in SWC was observed at all other biochar treatments during the dry period. However, higher SWC was again observed also at treatment without biochar application (B0 + N2) when compared to B0 + N0 treatment.

3.5. Impact of Biochar Application and Re-Application on Plant Available Water and Readily Plant Available Water

Plant available water (PAW) specifies what proportion of the soil pores can be filled by water accessible to plants, bound in the soil in a range of pressure potential from -1500 kPa (PWP = 4.18 pF) up to 20 kPa (FC = 2.3 pF). The higher the PAW value for given soil, the greater the capacity of soil pores for water to be available to plants. In general, an increase in PAW was observed in all treatments with biochar applied with or without N-fertilizer (levels N0, N1, N2). All biochar treatments increased the PAW in a range from 20 up to 49% (0.99 up to 3.79% vol.) (Table 6).

A significant increase ($p < 0.05$) in PAW was found in all unfertilized treatments with biochar application (B10 reap + N0, B20 + N0, B20 reap + N0) when compared to the control (B0 + N0), except for the treatment B10 + N0. In case of the fertilized treatments at the N1 level, a significant increase ($p < 0.05$) in PAW was found at the treatments with a biochar dose of 10 t ha⁻¹ (B10 + N1 and B10 reap + N1) and at the treatment with re-applied biochar at a dose of 20 t ha⁻¹ (B20 reap + N1) (Table 6). In the fertilized treatments at the N2 level, a significant increase ($p < 0.05$) in PAW was only recorded in the case of the treatments with re-applied biochar (B10 reap + N2 and B20 reap + N2).

Table 6. Effect of biochar application and re-application on basic water limits (means \pm standard deviations). Different letters indicate that treatment means are significantly different at $p < 0.05$ according to least significance difference test.

Treatments	FC % vol. n = 8	RP % vol. n = 8	PWP % vol. n = 8	RPAW % vol. n = 8	PAW % vol. n = 8
Non-fertilized Group (0 kg N ha ⁻¹)					
B0 + N0 (control)	30.04 \pm 1.50 a	25.98 \pm 1.20 b	25.79 \pm 1.23 b	3.84 \pm 1.32 a	4.03 \pm 1.38 a
B10 + N0	30.37 \pm 1.05 ab	25.42 \pm 2.05 ab	25.01 \pm 2.07 ab	4.61 \pm 1.43 ab	5.02 \pm 1.63 ab
B20 + N0	31.73 \pm 1.54 b	26.22 \pm 1.33 b	24.33 \pm 1.38 ab	5.29 \pm 0.56 b	7.11 \pm 0.83 d
B10 reap + N0	29.29 \pm 1.49 a	24.23 \pm 1.17 a	24.14 \pm 1.49 a	4.86 \pm 1.15 ab	5.52 \pm 1.49 bc
B20 reap + N0	30.39 \pm 1.47 ab	25.35 \pm 1.61 ab	23.74 \pm 1.57 a	5.04 \pm 1.38 ab	6.65 \pm 1.71 cd
N1 Group—Fertilized (108 kg N ha ⁻¹)					
B0 + N0 (control)	30.04 \pm 1.50 a	25.98 \pm 1.20 ab	25.79 \pm 1.23 bc	3.84 \pm 1.32 a	4.03 \pm 1.38 a
B0 + N1	29.70 \pm 2.09 a	24.64 \pm 1.94 a	-	5.15 \pm 0.53 b	-
B10 + N1	30.76 \pm 2.06 a	26.16 \pm 2.08 ab	25.17 \pm 2.05 ab	4.44 \pm 0.58 ab	5.41 \pm 0.51 bc
B10 reap + N1	30.16 \pm 1.39 a	26.23 \pm 1.78 ab	23.94 \pm 1.61 a	4.80 \pm 1.05 ab	6.52 \pm 1.26 c
B20 + N1	31.23 \pm 1.76 a	26.54 \pm 1.35 b	27.11 \pm 2.16 c	4.38 \pm 1.36 ab	4.76 \pm 1.42 ab
B20 reap + N1	31.25 \pm 1.46 a	26.21 \pm 1.39 ab	24.90 \pm 1.52 ab	5.05 \pm 1.11 b	5.96 \pm 1.30 bc
N2 Group—Fertilized (162 kg N ha ⁻¹)					
B0 + N0 (control)	30.04 \pm 1.50 a	25.98 \pm 1.20 ab	25.79 \pm 1.23 b	3.84 \pm 1.32 a	4.03 \pm 1.38 a
B0 + N2	30.48 \pm 1.12 a	26.69 \pm 1.60 b	-	4.26 \pm 1.05 a	-
B10 + N2	29.59 \pm 1.74 a	24.43 \pm 1.89 a	23.86 \pm 1.97 a	4.68 \pm 0.64 ab	5.12 \pm 0.87 ab
B10 reap + N2	30.46 \pm 1.19 a	26.23 \pm 1.78 b	24.87 \pm 2.17 ab	4.55 \pm 0.77 ab	5.48 \pm 1.35 b
B20 + N2	30.76 \pm 1.92 ab	25.51 \pm 1.48 ab	24.86 \pm 1.48 ab	4.65 \pm 1.11 ab	4.74 \pm 1.12 ab
B20 reap + N2	32.03 \pm 1.20 b	25.47 \pm 1.70 ab	24.37 \pm 1.85 ab	5.36 \pm 1.06 b	7.82 \pm 1.20 c

FC—field capacity, RP—refill point, PWP—permanent wilting point, RPAW—readily plant available water, PAW—plant available water.

In our study we also evaluated the impact of biochar on readily plant available water (RPAW). When soil moisture drops to the RP value, it is necessary to supply water to the plants in the form of irrigation in the field conditions. Generally, RPAW increased in all treatments with biochar combined at all fertilization levels (N0, N1, N2) in the range from 13 up to 29% (0.54–1.52 % vol.) (Table 6).

A significant increase ($p < 0.05$) of RPAW was observed in the unfertilized treatment with re-applied biochar at a dose of 10 t ha⁻¹ (B10 reap + N0) and in the case of both levels of fertilization in treatments with re-applied biochar at a dose of 20 t ha⁻¹ (B20 reap + N1 and B20 reap + N2) in comparison to control (B0 + N0) (Table 6). In the case of the treatment with re-applied biochar with nitrogen at the N2 level (B20 reap + N2), we observed an increase in RPAW of up to 28% (1.52% vol.).

4. Discussion

In the case of non-fertilized treatments, a significant decrease in bulk density (BD) was only observed for application and re-application at a dose of 20 t ha⁻¹ of biochar. Biochar application

at the dose of 10 t ha^{-1} had no significant effect on BD (Table 5). The observed decrease in BD could have several reasons, which may be related to the biochar properties such as particle size, active surface area, porosity as well as properties of the soil. Further, the ability of biochar to form the soil aggregates in combination with soil particles leading to a decrease in BD could also play a role. This was confirmed in the research of Šimanský [59]. He found that the structural condition of the soil significantly improved after biochar application at a dose of 20 t ha^{-1} (B20 + N0) when compared to control (B0 + N0). The lower biochar application dose (10 t ha^{-1}) had no effect on the improvement of the soil structure. Biochar can improve the physical condition of the soil [37,60,61] through the supplied organic matter [62]. The surface of biochar particles after oxidation may contain the hydroxyl and carboxyl groups that are able to associate with the mineral and other organic soil particles to form soil aggregates [31]. Biochar supplied to the soil is a substrate for soil fauna. Its particles can be mixed with the soil particles in a digestive tract of the earthworms creating coprolites that are agronomically valuable soil aggregates. These products contribute to more favorable soil structure [18] with consequently lower BD values.

Due to its inert nature, biochar is often combined with other organic and mineral fertilizers to improve its effect in the soil [63,64]. Fertilization—especially with nitrogen—is a significant factor influencing BD. Mineral nitrogen applied to the soil can act as an accelerator speeding up the mineralization of organic matter [62], which can result in an increase of BD values. However, application of biochar in combination with N fertilization has a positive effect on the incorporation of biochar—especially into larger aggregates [62]—which helps to improve the soil structure [65] and ultimately reduce the BD values as was also confirmed in the results obtained by Šrank and Šimanský [64]. In our case, a significant decrease in BD was observed for biochar application and re-application at the dose of 10 t ha^{-1} in combination with 108 kg N ha^{-1} (B10 + N1 and B10 reap + N1) and at the second fertilization level (162 kg N ha^{-1}) for biochar application at a dose of 20 t ha^{-1} (B20 + N2) and re-application at both doses (B10 reap + N2 and B20 reap + N2) (Table 5). The explanation of these observations may be the specific combination of biochar with N fertilization. The addition of N fertilizer to the soil improves the microbial activity [66] which in turn can intensify the mineralization of biochar in the soil leading to a subsequent increase in biochar's active surface and cation exchange capacity [67], resulting in increased soil aggregation capacity [68] and lower BD.

Porosity (P) increased significantly only in the case of biochar application and re-application at a higher dose (20 t ha^{-1}) without fertilization (Table 5). This fact strictly corresponds to the observed BD values in these treatments. Some authors attributed the increase in P to biochar porosity as documented by several studies [23,24,30,69,70]. The pore size itself also plays an important role. Biochar is a porous material [23,71] whose micropores can be rapidly clogged by clay particles when water infiltrates the soil, reducing their total volume [72]. This is probably the reason why the effect was only observed with the application and re-application of a higher dose of biochar when compared to a dose of 10 t ha^{-1} of biochar. However, we also suppose that this effect (an increase in P due to application of a higher dose of biochar) can also be the result of an improvement in the soil structure [59]. One of the most important mechanisms of the soil structure formation that has significantly increased total P in the treatments B20 + N0 and B20 reap + N0 may be the ability of biochar itself to associate with the soil mineral particles directly [65] or through Ca bridges [73,74]. As reported by Rajkovich et al. [75], carbonates precipitate on the biochar surface during its production. Biochar also contains basic cations, including Ca^{2+} which improves the soil aggregation. The biochar used in our study contained 57 g kg^{-1} of Ca^{2+} (Table 2). No other significant differences in P were observed between the unfertilized control and the treatments with biochar in combination with N fertilization (Table 5). However, differences were found in both groups with N fertilization (N1 and N2) between the treatments with N fertilization only (B0 + N1 and B0 + N2, respectively) and the combinations of biochar with N fertilization (for biochar application and re-application). This means that P in B0 + N1 and B0 + N2 was reduced due to N fertilization, which accelerated the mineralization of the soil organic matter as has already been documented at this experimental site in the year 2015 [37]. On the other hand, the combinations of

different doses of biochar with different levels of N fertilization had a positive effect on increasing total P. The most significant difference was observed in the case of treatments B10 + N1 and B10 reap + N2.

An increase in soil saturated hydraulic conductivity (K) in the treatments with biochar can be explained by the fact that the particle size of the ingested biochar (1–5 mm) was larger than the particle size of the silty loam soil at the experimental site. Lehmann and Stephen [8] stated that the hydraulic conductivity of the soil enriched with biochar was mainly influenced by the size of biochar and soil particles. The hydraulic conductivity of the soil may increase after the application of biochar with larger particles than the soil particles, and may decrease after application of biochar with smaller particles than the soil particles. This statement was confirmed by Esmaeelnejad et al. [76] and Lim et al. [77]. The study by Lim et al. [77] showed an increase in hydraulic conductivity of soil after application of biochar with the particles larger than the original soil particles. Improved (increased) hydraulic conductivity may also be the result of an improvement in the soil structure through the applied biochar, as mentioned in more detail above. However, it should be mentioned, that the measurement of K could be influenced by several factors (e.g., the size of cavities in the tested soil sample, soil air trapped during saturation of the sample, occurrence of preferential flow, etc.). The samples taken in one treatment could therefore have a significant disparity in the values. In some cases, a large variance was recorded between the measured K values, which also affected the average value of K and the standard deviation.

Our results showed that re-application of biochar generally increased the soil water content at all fertilization levels during the studied period April–September 2019 (Figures 2–4). This trend was more visible in re-application at a dose of 20 t ha⁻¹. At the same time, it turns out that the impact of biochar application (in 2014) decreased over 5 years [37], which may be caused by the incorporation (mixing) of biochar into the deeper layers of the soil profile. Previous studies in the same field experiment showed a positive effect of biochar application at a dose of 20 t ha⁻¹. For example, a significant effect of biochar application at this dose was demonstrated in 2014 [13,36], 2015 [37] and 2018 [42]. Vitková and Šurda [78] stated that, SWC in the treatment with biochar at the rate of 20 t ha⁻¹ was higher by 3–8% vol. when compared to the control treatment B0 + N0 during the monitoring period June–July 2018. The beneficial effect of biochar on soil moisture can be caused by its porous character and the influence on soil water constants: FC, RP and PWP. Rasa et al. [79] stated, that the addition of biochar to the soil can change the texture and structure of the soil and that these changes indirectly modify the characteristics affecting soil moisture. At the same time, they stated that biochar, as a highly porous material, can directly affect the soil's ability to retain water through biochar's internal porosity. Biochar application also influences the redistribution of soil pore categories (semi-capillary, capillary and non-capillary pores). Moreover, with an increasing application dose of biochar the volume of capillary pores also increases [18], since the biochar is a porous material containing also the micropores.

As defined by PAW (a difference between FC and PWP), the higher the resulting PAW value, the more water the soil can provide to the growing plants. In our experiment, we observed an interesting finding—that the added biochar generally decreased PWP and slightly increased the FC value in most of the treatments, thus created a larger interval for plant available water. We suppose that the main reason for the increase in RPAW and PAW is probably the change in the structural state of the soil and the proportion of interaggregate and aggregate pores in the soil. An increase in the range of PAW was caused by a decrease in PWP values (at 4.18 pF). This fact clearly states that the proportion of capillary pores in the soil has increased. Our findings on the positive effect of biochar application on PAW are consistent with the work of Igaz et al. [37], Liu et al. [80] and Abel et al. [81].

5. Conclusions

Five years after biochar application, significant differences were observed in 2019 for all evaluated soil quality parameters, however not for all treatments. Biochar application at a dose of 10 t ha⁻¹ in combination with 108 kg N ha⁻¹ significantly decreased bulk density and increased plant available water. When the same dose of biochar was combined with 162 kg N ha⁻¹, a significant decrease in permanent wilting point was observed. The significant effect of biochar amendment was more visible

at the application rate of 20 t ha⁻¹. In the case of non-fertilized treatments, bulk density and permanent wilting point significantly decreased and porosity and plant available water significantly increased.

Considering the soil water content (SWC) dynamics over the studied period in 2019, various trends (a decrease, increase, no effect) were observed. However, during the dry period, a relative increase in SWC was observed in all biochar treatments when compared to the control treatment without biochar and fertilizer addition. This trend was observed at all fertilization levels.

Most of the significant differences after biochar re-application were observed in bulk density (a decrease), permanent wilting point (a decrease) and plant available water (an increase). Higher values were observed after biochar-reapplication (at the both rates and all fertilization levels) in plant available water.

Biochar and biochar combined with nitrogen fertilization appears to be a promising practice to improve sustainability of intensive agriculture by improving soil physical and hydro-physical characteristics through positively affecting the soil structure. However, more research is needed on different soil types and different agro-ecosystems beyond one year before this practice can be widely recommended to farmers.

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