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Research Article

Effect of Biochar Application and Re-Application on Soil Water Content, Temperature, Bulk Density: Insights from 2017 and 2018

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The study explores the impact of biochar application and re-application on soil properties such as water content, temperature, and bulk density over two years (2017 and 2018). The research was conducted at the Slovak Agricultural University of Nitra (Slovakia), where different treatments with biochar and nitrogen fertilizers were applied to the soil. The methods included measuring soil water content, temperature, and bulk density at regular intervals. Results indicated that biochar application significantly improved soil water content and temperature regulation, with higher biochar rates yielding better outcomes. Biochar also reduced soil bulk density, enhanced soil structure, and fertility. Re-application of biochar showed further improvements, underscoring its long-term benefits. It concludes that biochar is a promising amendment for sustainable agriculture, offering enhanced water retention, improved soil health, and reduced dependence on chemical fertilizers. These findings provide valuable insights for soil management practices aimed at mitigating soil degradation and promoting agricultural sustainability.

Keywords: biochar, soil water content, temperature, bulk density, nitrogen fertilizer

1 Introduction

Climate change is one of the major challenges of our time with far-reaching consequences on human health, the ecosystem, and the economy. The primary drivers of climate change are greenhouse gas (GHG) emissions, which trap heat from our planet's atmosphere and thus contribute to rising temperatures (IPCC, 2018).

According to studies, the agriculture sector is the largest consumer of water resources (Wallace, 2000). Global warming accelerates the global water cycle, which in turn affects soil water content (Schlesinger, 2005). As soil plays a pivotal role in the water cycle of nature, it is the primary regulator of hydrological changes. Soil acts as a connector between vegetation and the atmosphere (Kerr, 2007). The study of Qin et al. (2023) indicates a downward trend in soil water content over the past decade, with a rate of decrease of 2,251 kg.m^{-2}.

In arid and semi-arid regions, where rainfall is the primary source of moisture, it is necessary to implement strategies to enhance soil moisture retention. In such environments, soil physical properties play an important role in determining water retention and plant growth (Wang, 2021). To improve physical indicators such as aggregate stability, available water capacity, bulk density, infiltration, slaking, soil crusts, soil structure, macropores, etc. (Doran, 2015), various melioration techniques could be implemented. One such technique involves the addition of amendments to the soil (Chen et al., 2022).

There are several types of soil amendments that can be used for improving the soil water retention. Basically, they can be divided into three varieties. Unconventional organic matter sources are presented by biochar, woodchips, peat moss, coconut coir, etc. Usually, biochar is produced by burning organic materials in limited oxygen access. Each percentage increase in biochar

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could increase soil water-holding capacity by 1.7%, until biochar composition of the soil is around 10%, though its effectiveness is debated (Karhu et al., 2011).

However, the agricultural industry requires new reforms to achieve sustainable production. Soil additives must be versatile, and act not only as ameliorate but also affect soil productivity, act as fertilizers, and contribute to the mitigation of greenhouse gas emissions. Several studies have been conducted on this issue by research of Matheus et al., 2023; Sanz et al., 2022; Zheng, 2021. One recommended amendment option is biochar. It is a carbon-rich product obtained from the pyrolysis of organic materials, which has gained considerable attention in recent years for its potential benefits in agricultural practices. Studies have demonstrated that biochar can assist in neutralizing acidity and can be utilized for the remediation of contaminated sites. (Razzaghi, 2020; Vitkova et al., 2017).

Biochar's porous structure and capacity to accumulate moisture within its pores represent its primary attributes for enhancing soil water balance and fertility. Over time, the interaction of biochar with soil results in alterations to its wetting properties, which subsequently impact its water holding capacity. Following its ageing in soil for several years, biochar may develop a mineral-rich crust that improves its wettability without the need for fertilizers. The lateral surfaces of the material become porous layers filled with soil and clay particles, which enhance water retention. The higher nitrogen, oxygen, and hydrogen content of biochar enhances its water holding capacity by providing sites for hydrogen bonding with water molecules. Conversely, a high carbon content and surface area (indicating hydrophobic aromatic carbon) reduce the biochar's water binding ability. In essence, the evolving surface properties, porous structure, and chemical composition of biochar, which feature nitrogen/oxygen functional groups, are the main factors that allow it to improve soil water retention when applied as an amendment, especially over longer time periods (Zhang, 2024).

The application of biochar has been demonstrated to result in a notable reduction in soil bulk density, primarily attributable to its lower particle density (1.5–1.7 g.cm^{-3}) in comparison to that of mineral soil particles (2.65 g.cm^{-3}), coupled with its highly porous structure. The clear evidence indicates that the application of biochar typically results in a reduction of soil bulk density by a range of 3–31%, contingent on the specific application rate and the prevailing soil texture. An application rate of 1–2% biochar by weight has been demonstrated to reduce bulk density by 12–15% in clayey soils and 7–10% in sandy soils (Zhang et al., 2013). Long-term studies have demonstrated that the reduction in bulk density persists over time, although the magnitude may undergo a slight decrease. Initial reductions of approximately 15% frequently stabilise at 10% after a few years as the biochar integrates into the soil matrix. The effect is most pronounced in medium-textured soils (loams) at application rates of 20–40 tons per hectare, while sandy soils demonstrate more variable responses due to limited particle interactions (Castellini et al., 2015).

It has been investigated that the application of biochar typically results in a reduction in soil temperature fluctuations, attributable to its influence on the thermal properties of the soil. The dark colour of biochar increases solar radiation absorption, while its porous structure and effects on soil water retention influence heat capacity and thermal conductivity (Gliniak et al., 2019). Indeed, studies demonstrated that soils amended with biochar exhibited a reduction in maximum temperature of between 1.0 and 2.5 °C compared to control soils during peak summer conditions. Hardie et al. (2014) observed that the addition of biochar at a rate of 47 t.ha^{-1} resulted in a 11% reduction in thermal conductivity in agricultural soils, thereby promoting more stable soil temperatures. The moderating effect on temperature is especially pronounced in surface soils (0–10 cm depth), where biochar can reduce daily temperature fluctuations by 20–30%. It was also indicated that the temperature-moderating effects of biochar may be more pronounced in coarse-textured soils than in clay soils, which is thought to be due to differences in water retention and heat transfer properties.

Objectives: to determine the effect of biochar application and its reapplication in combination with nitrogen on soil moisture, temperature and bulk density to make a comparative assessment.

2 Material and Methods

2.1 Study Site

The experimental field is located at the research site of the Slovak Agricultural University of Nitra, in the locality Malanta, Slovakia (lat. 48 19 00"; long. 18 09 00"). The allocation of the experimental field is presented in Fig. 1.

2.2 Climate Conditions

This area is characterized by a warm lowland climate with prolonged warmth, dry summers, short winters, and snow cover for only 14–30 days per year (Šiška et al., 2005). The average annual air temperature in 2017–2018 was in the range 9.8–10.2 °C. The level of precipitation based on the dataset of Nitra meteorological station, in 2017,

Figure 1 Experimental site in the locality Malanta (Slovakia)

is 489 mm, which is characterized as normal, corresponding to 30-year climatic normal from 1991 to 2020, and 0.624 m in 2018 classified as high. Based on the WBS classification, the soil is classified as Haplic Luvisol (FAO, 2015).

2.3 Experimental Layout

The field experiment was primarily established in 2014 to study the effects of biochar on soil properties, greenhouse gas emissions and crop yields (Table 1).

The entire area with 9 different treatments was separated into 27 plots with the measure of 6 × 4 m and isolated by 0.5 m groups. The exploration was performed within the arrangement: control – without biochar expansion, B10 with a dosage of 10 t.ha^{-1}, and B20 variation with a dosage of 20 t.ha^{-1} of biochar.

The test began in spring, earlier than sowing, when the exploratory range was furrowed by a harrow cultivator up to 10 cm profundity. After 4 years of experiment, the reapplication of biochar followed in 2018. Nitrogen fertilizer was also applied according to the experimental conditions. The required dose was calculated according to the needs of the plants using the balance method. Fertilizer is applied annually according to the crop in the rotation.

Table 1 Treatments with dosing of biochar and nitrogen fertilizers applied on experimental site

Treatment	First application in 2017		Reapplication in 2018	
	biochar (t.ha^{-1})	nitrogen (kg.ha^{-1})	biochar (t.ha^{-1})	nitrogen (kg.ha^{-1})
B0N0	0	0	0	0
B10N0	10	0	0	0
B20N0	20	0	0	0
B10reap + N0	–	–	10	0
B20reap + N0	–	–	20	0
B0N1	0	160	0	40
B10N1	10	160	0	40
B20N1	20	160	0	40
B10reap + N1	–	–	10	40
B20reap + N1	–	–	20	40
B0N2	0	240	0	80
B10N2	10	240	0	80
B20N2	20	240	0	80
B10reap + N2	–	–	10	80
B20reap + N2	–	–	20	80

In April 2017, maize (*Zea mays* L.) was sown with the application of 0, 160, 240 kg of Nitrogen per hectare N0, N1, N2, respectively. After harvest, crop residues were left on the field. In 2018, spring barley (*Hordeum vulgare* L. var. Malr) was sown with a Nitrogen dose of 0, 40, 80 kg.ha^{-1} N0, N1, N2, respectively (Altdorff et al., 2019; Horák et al., 2017; Kondrlova et al., 2018). In 2018, reapplication of biochar at dosages of 10 and 20 t. ha^{-1} (B10reap + N0; B20reap + N0; B10reap + N1; B20reap + N1; B10reap + N2; B10reap + N2) was conducted for each level of fertilisation.

2.4 Characteristics of Biochar

The biochar utilized in the field experiment was manufactured by pyrolyzing a 1 : 1 weight ratio mixture of paper fibre sludge and grain husks, produced by the company Sonnenerde, based in Riedlingsdorf, Austria. The pyrolysis process was carried out at 550 °C for a duration of 30 min in a Pyreg reactor supplied by Pyreg GmbH, located in Dörth, Germany. The biochar particles ranged in size from 0 to 0.005 m. The main characteristics of the biochar are presented in Table 2.

Table 2 Properties of biochar

Parameters	Values
Total organic carbon (g.kg^{-1})	531
Total nitrogen (g.kg^{-1})	14
Ca (g.kg^{-1})	57
Mg (g.kg^{-1})	3.9
K (g.kg^{-1})	15
Na (g.kg^{-1})	0.77
Specific surface area (m^2.g^{-1})	21.7
Ash content (%)	38.3

2.5 Soil Sampling and Analysis

Soil sampling was carried out biweekly at a depth of 0–10 cm for estimating the soil water content (SWC) during the growing seasons of 2017 and 2018 across all treatment plots, with following analysing by gravimetric method. During the maize growing season in 2017 (38th to 43rd month after biochar application) and the spring barley season in 2018, soil samples were collected monthly from April to September. Soil temperature (T) was measured at 5 cm depth using a Volcraft DET3R thermometer concurrently with moisture sampling.

Bulk density (BD) was determined from undisturbed soil core samples (10 cm^3 volume) collected at 2–7 cm depth. For each plot (45 plots representing 15 treatments with 3 replicates), three samples were taken, resulting in 135 samples overall and 9 representative samples per treatment.

2.6 Statistical Analysis

Statistical analysis was carried out by a one-way analysis of variance (ANOVA) in the Statgraphics Centurion program (XV v.15.1.2) and the LSD test (α = 0.05) to compare the effects of biochar application and its reapplication.

3 Results and Discussion

One of the key benefits attributed to biochar is its ability to enhance soil water content (SWC). The data presented in Tables 3 and 4 illustrate the variations in SWC under different combinations of biochar (B) and nitrogen (N) treatments over two years, 2017 and 2018.

The application of biochar and its reapplication, either alone or in combination with nitrogen fertilizer, showed an overall increase in the average water content of the soil, with a range of 1.7–27.8% compared to the control plots (B0N0, B0N1, B0N2). The decrease in SWC observed on experimental plots B10N0, B10N2 and B10reapN0 was not statistically significant (p ≤0.05). A significant increase was observed in the case of biochar reapplication in dosage 20 t.ha^{-1} (B20reapN1 and B20reapN2 on 27.8 and 16.2%, respectively), in relation to the control plots (B0N1, B0N2). The soil water content increased with increased application rate of biochar, including reapplication, at both levels of fertilization. This suggests that the amendment affects soil moisture retention, as previously discussed by Toková et al. (2020). Furthermore, this finding is consistent with the existing literature on the subject (Taheri et al., 2024; Rasa et al., 2018; Vitkova et al., 2021), which indicates that biochar can enhance soil structure, thereby increasing its water-holding capacity. Additionally, nitrogen can stimulate plant growth, which can subsequently enhance soil moisture through enhanced root development and the provision of organic matter and its decomposition (Manea et al., 2023).

Based on data from the meteorological station of Nitra (Slovakia), the average air temperature during the summer of 2017 was 18.7 °C. In 2018, the average air temperature for the summer period was about 18.4 °C. According to the soil laboratory analysis, the values presented in Table 3 for 2017, and Table 4 for 2018 years were obtained. Statistical analyses revealed no significant differences in temperature ratings. In 2017, temperatures ranged from 15.6 °C to 16.2 °C, while in 2018, they varied from 19.2 °C to 20.0 °C. On plots with biochar reapplication, the temperature range was slightly narrower, between 19.2 °C and 19.8 °C.

Moreover, the soil temperature increased with higher rates of biochar application, on average by 0.1–0.4 °C, the value reached in variant B20N2 (2018) was 20 °C.

Table 3 The effect of biochar, in 2017, on soil water content (SWC, % mass), soil temperature (T, °C), bulk density (BD, $g.cm^{-3}$) presented by means and standard errors. Lowercase letter within columns indicates the significant difference in means of treatments over the sampling dates ($p \leq 0.05$) according to LSD multiple-range test

Treatments	SWC (% mass) *n* = 3	Soil T (°C) *n* = 3	BD ($g.cm^{-3}$) *n* = 3
Not fertilized group – N0 level (0 kg.N.ha^{-1})			
B0N0	14.5 ±0.7 a	15.9 ±0.4 a	1.62 ±0.0 a
B10N0	14.0 ±0.6 a	15.9 ±0.4 a	1.53 ±0.0 a
B20N0	14.9 ±1.0 a	16.0 ±0.2 a	1.50 ±0.1 a
***p*-value**	0.5	1.0	0.5
Fertilized group – N1 level (160 kg.N.ha^{-1})			
B0N1	13.8 ±0.8 a	15.7 ±0.3 a	1.65 ±0.0 a
B10N1	14.5 ±0.7 a	15.6 ±0.4 a	1.64 ±0.0 a
B20N1	14.7 ±0.7 a	15.8 ±0.4 a	1.62 ±0.0 a
***p*-value**	0.4	1.0	0.8
Fertilized group – N2 level (240 kg.N.ha^{-1})			
B0N2	14.1 ±0.7a	15.6 ±0.4 a	1.63 ±0.1 a
B10N2	14.1 ±0.9 a	15.8 ±0.4 a	1.56 ±0.1 a
B20N2	14.6 ±0.9 a	16.2 ±0.3 a	1.52 ±0.0 a
***p*-value**	0.8	0.7	0.3

Table 4 The effect of biochar application and re-application, in 2018, on soil water content (SWC, % mass), soil temperature (T, °C), bulk density (BD, $g.cm^{-3}$), presented by means and standard errors. Lowercase letter within columns indicates the significant difference in means of treatments over the sampling dates ($p \leq 0.05$) according to the LSD multiple-range test

Treatments	SWC (% mass) *n* = 5	Soil T (°C) *n* = 5	BD ($g.cm^{-3}$) *n* = 3
Not fertilized group – N0 level (0 kg.N.ha^{-1})			
B0N0	12.4 ±1.0 a	19.6 ±0.5a	1.45 ±0.1 a
B10N0	11.9 ±1.1 a	19.8 ±0.4 a	1.50 ±0.1 a
B20N0	13.3 ±0.8 a	19.8 ±0.6 a	1.43 ±0.0 a
B10reap + N0	12.0 ±0.9 a	19.8 ±0.4 a	X
B20reap + N0	13.3 ±1.0 a	19.6 ±0.4 a	X
***p*-value**	0.6	0.9	0.7
Fertilized group – N1 level (40 kg.N.ha^{-1})			
B0N1	10.8 ±0.8 a	19.8 ±0.4 a	1.41 ±0.0 a
B10N1	11.7 ±3.2 a	19.5 ±0.5 a	1.40 ±0.0 a
B20N1	11.2 ±1.0 a	19.4 ±0.4 a	1.40 ±0.1 a
B10reap + N1	12.1 ±0.9 ab	19.2 ±0.3 a	X
B20reap + N1	13.8 ±1.1 b	19.2 ±0.5 a	X
***p*-value**	0.01	1.0	0.8
Fertilized group – N 2 level (80 kg.N.ha^{-1})			
B0N2	11.7 ±0.8 a	19.2 ±0.3 a	1.42 ±0.1 a
B10N2	11.3 ±0.9 a	19.5 ±0.3 a	1.41 ±0.1 a
B20N2	11.9 ±0.9 ab	20.0 ±0.4 a	1.41 ±0.1 a
B10reap + N2	12.5 ±1.1 ab	19.6 ±0.3 a	X
B20reap + N2	13.6 ±1.5 b	19.8 ±0.4 a	X
***p*-value**	0.1	1.0	0.6

Similarly, in 2017, the highest value was noted in variant B20N2, reaching 16.2 °C. In research conducted by Zhang et al. (2013), it was determined that the application of biochar mitigates fluctuations in seasonal and daily soil temperature and moderates extreme values. A reduction in the amplitude of soil temperature fluctuations after the addition of biochar was also reported by Liu et al. (2018). Zhang et al. (2012) also discovered a significant difference in soil temperature with changes in biochar application rate and albedo. It is suggested that the change in albedo was related to the structure and colour of the soil surface layer (Usowicz et al., 2016), since biochar has a dark shade, its application to dark soil reduces albedo and creates warmer conditions (Genesio et al., 2012). Another explanation, explored by He et al. (2016), is that the application of biochar increases the biomass of soil microorganisms, which in turn affects soil respiration and heat exchange in the soil.

Higher soil temperatures accelerate the evaporation of water from the soil surface, reducing soil water content, especially in the topsoil layers. Changes in soil temperature can alter the soil's physical properties, including its water retention capacity (Zhang et al., 2020). In warmer conditions, water rises through capillary action faster but can also evaporate more quickly once it reaches the surface. Based on these assumptions, a regression analysis was carried out. It indicates a significant positive relationship between temperature (T) and soil water content (W). The R Square value of 0.63314 suggests that approximately 63.31% of the variability in soil water content can be explained by the temperature. This high proportion indicates that temperature is a substantial predictor of soil water content.

Soil bulk density, as a vital physical property, was measured to evaluate its response to biochar application. Statistical analyses revealed no significant differences between treatments. However, as biochar dosage increased, soil bulk density decreased in samples B20N0, B20N1 and B20N2, with reductions ranging from 1.9% to 8.5% compared to samples without biochar application.

Despite the lack of statistical significance, BD values remained generally consistent across treatments, with slight reductions. This suggests that the effects of biochar on soil structure may become more pronounced over time as it integrates into the soil matrix (Ahmed et al., 2017). Blanco-Canqui (2017) reported a gradual decrease in BD in 19 out of 22 soils with increasing biochar application, supporting the idea that biochar can enhance soil aggregation and porosity over the long term. These improvements are likely due to the biochar's inherently porous nature and structural characteristics. Similar findings were observed by Li et al. (2023), Elangovan et al. (2014), and Peake et al. (2014).

The production temperature of biochar is a factor that affects its physicochemical properties. Higher production temperatures result in a decrease in aliphatic and soluble fractions and an increase in aromatic and insoluble portions (Keiluweit et al., 2010). Since aromatic carbon is more resistant to degradation, biochar produced at higher temperatures tends to be more stable than biochar produced at lower temperatures.

4 Conclusions

The results confirm that the application of biochar positively influenced soil water content, with significant increases observed in certain treatments. The findings align with numerous research, supporting biochar's ability to enhance soil structure and moisture-holding capacity. Also, nitrogen fertilization contributed to improved plant growth, indirectly affecting soil moisture dynamics through root development and organic matter decomposition. Biochar also influenced soil temperature, with higher application rates leading to slight increases in soil temperatures (0.1–0.4 °C). This effect is attributed to changes in soil albedo and microbial activity, which can influence soil respiration and heat exchange. While higher soil temperatures may enhance microbial activity and nutrient cycling, they can also accelerate water evaporation, potentially offsetting the benefits of increased moisture retention. Despite minor variations, soil bulk density (BD) showed a general decreasing trend with increased biochar application, supporting the idea that biochar contributes to improved soil porosity and aggregation over time. Although statistical significance was not observed in BD reductions, long-term integration of biochar into the soil matrix may enhance its structural stability.

References

Ahmed, A., Gariepy, Y., & Raghavan, V. (2017). Influence of wood-derived biochar on the compatibility and strength of silt loam soil. *International Agrophysics*, 31(2). https://doi.org/10.1515/intag-2016-0044

Altdorff, D., Galagedara, L., Abedin, J., & Unc, A. (2019). Effect of biochar application rates on the hydraulic properties of an agricultural-use boreal podzol. *Soil Syst*, 3, 53. https://doi.org/10.3390/soilsystems3030053

Blanco-Canqui, H. (2017). Biochar and Soil Physical Properties. *Soil Science Society of America Journal*, 84, 687. DOI: 10.2136/sssaj2017.01.0017.

Castellini, M., Giglio, L., Niedda, M., Palumbo, A. D., & Ventrella, D. (2015). Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil and Tillage Research*, 154. https://doi.org/10.1016/j.still.2015.06.016

Chen, D., Wang, X., Carrión, V. J., Yin, S., Yue, Z., Liao, Y., Dong, Y., & Li, X. (2022). Acidic amelioration of soil amendments improves soil health by impacting rhizosphere microbial assemblies. *Soil Biology and Biochemistry*, 167. https://doi.org/10.1016/j.soilbio.2022.108599

Chen, J., Liu, X., Li, L., Zheng, J., Qu, J., Zheng, J., Zhang, X., & Pan, G. (2015). Consistent increase in abundance and diversity but variable change in community composition of bacteria in topsoil of rice paddy under short term biochar treatment across three sites from South China. *Applied Soil Ecology*, 91. https://doi.org/10.1016/j.apsoil.2015.02.012

Doran, J. W., & Parkin, T. B. (2015). Quantitative indicators of soil quality: A minimum data set. In *Methods for Assessing Soil Quality.*

Elangovan, R., & Sekaran, N. C. (2014). Effect of biochar application on soil properties and quality parameters in cotton. *Asian Journal of Soil Science*, 9(1).

FAO. (2015). World Reference Base for Soil Resources 2014: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps; FAO: Rome, Italy.

Genesio, L., Miglietta, F., Lugato, E., Baronti, S., Pieri, M., & Vaccari, F. P. (2012). Surface albedo following biochar application in durum wheat. *Environmental Research Letters*, 7(1). https://doi.org/10.1088/1748-9326/7/1/014025

Gliniak, M., Sikora, J., Sadowska, U., Klimek-Kopyra, A., Latawiec, A., & Kubon, M. (2019). Impact of Biochar on Soil Temperature. *IOP Conference Series: Earth and Environmental Science*, 362(1). https://doi.org/10.1088/1755-1315/362/1/012045

Hardie, M., Clothier, B., Bound, S., Oliver, G., & Close, D. (2014). Does biochar influence soil physical properties and soil water availability? *Plant and Soil*, 376(1–2). https://doi.org/10.1007/s11104-013-1980-x

He, X., Du, Z., Wang, Y., Lu, N., & Zhang, Q. (2016). Sensitivity of soil respiration to soil temperature decreased under deep biochar amended soils in temperate croplands. *Applied Soil Ecology*, 108. https://doi.org/10.1016/j.apsoil.2016.08.018

Horák, J., Kondrlová, E., Igaz, D., Šimanský, V., Felber, R., Lukac, M., Balashov, E. v., Buchkina, N. P., Rizhiya, E. Y., & Jankowski, M. (2017). Biochar and biochar with N-fertilizer affect soil N_2O emission in Haplic Luvisol. *Biologia* (Poland), 72(9). https://doi.org/10.1515/biolog-2017-0109

Horák, J., Šimanský, V., & Igaz, D. (2019). Biochar and biochar with N fertilizer impact on soil physical properties in a silty loam Haplic Luvisol. *Journal of Ecological Engineering*, 20(7). https://doi.org/10.12911/22998993/109857

IPCC. (2018). Global Warming of 1.5 °C. Intergovernmental Panel on Climate Change. Retrieved June 07, 2024. http://www.ipcc.ch/sr15/

Karhu, K., Mattila, T., Bergström, I., & Regina, K. (2011). Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity – Results from a short-term pilot field study. *Agriculture, Ecosystems and Environment*, 140(1–2). https://doi.org/10.1016/j.agee.2010.12.005

Keiluweit, M., Nico, P. S., Johnson, M. G., & Kleber, M. (2010). Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental science & technology*, 44(4), 1247–1253.

Kerr, Y. H. (2007). Soil moisture from space: Where are we? *Hydrogeology Journal*, 15(1). https://doi.org/10.1007/s10040-006-0095-3

Kondrlova, E., Horak, J., Igaz, D. (2018). Effect of biochar and nutrient amendment on vegetative growth of spring barley (*Hordeum vulgare* L. var. Malz). *Australian Journal of Crop Science*, 12(2). https://doi.org/10.21475/ajcs.18.12.02.pne476

Li, Y. Q., Li, L. J., Zhao, B. W., Zhao, Y., Zhang, X., & Dong, X. (2023). Effects of Corn Straw Biochar, Soil Bulk Density and Soil Water Content on Thermal Properties of a Light Sierozem Soil. *Nature Environment and Pollution Technology*, 22(2). https://doi.org/10.46488/NEPT.2023.v22i02.032

Liu, Z., Xu, J., Li, X., & Wang, J. (2018). Mechanisms of biochar effects on thermal properties of red soil in south China. *Geoderma*, 323. https://doi.org/10.1016/j.geoderma.2018.02.045

Lu, N., Liu, X. R., Du, Z. L., Wang, Y. D., & Zhang, Q. Z. (2014). Effect of biochar on soil respiration in the maize growing season after 5 years of consecutive application. *Soil Research*, 52(5). https://doi.org/10.1071/SR13239

Ma, R., Wu, X., Liu, Z., Yi, Q., Xu, M., Zheng, J., Bian, R., Zhang, X., & Pan, G. (2023). Biochar improves soil organic carbon stability by shaping the microbial community structures at different soil depths four years after an incorporation in a farmland soil. *Current Research in Environmental Sustainability,* 5. https://doi.org/10.1016/j.crsust.2023.100214

Manea, A., Tabassum, S., Lambert, M., Cinantya, A., Ossola, A., & Leishman, M. R. (2023). Biochar, but not soil microbial additives, increase the resilience of urban plant species to low water availability. *Urban Ecosystems*, 26(5). https://doi.org/10.1007/s11252-023-01382-4

Matheus, R., Kantur, D., & Salli, M. K. (2023). Utilization of organic soil amendments and phosphorus fertilizer to improve chemical properties of degraded dry land Vertisol and maize yield. *Journal of Degraded and Mining Lands Management*, 10(2). https://doi.org/10.15243/jdmlm.2023.102.4297

Peake, L. R., Reid, B. J., & Tang, X. (2014). Quantifying the influence of biochar on the physical and hydrological properties of dissimilar soils. *Geoderma*, 235–236. https://doi.org/10.1016/j.geoderma.2014.07.002

Qin, T., Feng, J., Zhang, X., Li, C., Fan, J., Zhang, C., Dong, B., Wang, H., & Yan, D. (2023). Continued decline of global soil moisture content, with obvious soil stratification and regional difference. *Science of the Total Environment*, 864. https://doi.org/10.1016/j.scitotenv.2022.160982

Rasa, K., Heikkinen, J., Hannula, M., Arstila, K., Kulju, S., & Hyväluoma, J. (2018). How and why does willow biochar increase a clay soil water retention capacity? *Biomass and Bioenergy*, 119. https://doi.org/10.1016/j.biombioe.2018.10.004

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma,* 361. https://doi.org/10.1016/j.geoderma.2019.114055

Sanz, C., Casadoi, M., Tadic, Đ., Pastor-López, E. J., Navarro-Martin, L., Parera, J., Tugues, J., Ortiz, C. A., Bayona, J. M., & Piña, B. (2022). Impact of organic soil amendments in antibiotic levels, antibiotic resistance gene loads, and microbiome composition in corn fields and crops. *Environmental Research*, 214. https://doi.org/10.1016/j.envres.2022.113760

Schlesinger, W. H. (Ed.). (2005). Biogeochemistry. *Treatise on Geochemistry*, Elsevier.

Šiška, B., Špánik, F., Repa, Š., & Gálik, M. (2005). *Practical Biometeorology* (*Praktická Biometeorológia*). SUA. (In Slovak)

Su, J., Zeng, Q., Li, S., Wang, R., & Hu, Y. (2024). Comparison of organic and synthetic amendments for poplar phytomanagement in copper and lead-contaminated calcareous soil. *Journal of Environmental Management*, 355. https://doi.org/10.1016/j.jenvman.2024.120553

Taheri, M. al R., Astaraei, A. R., Lakzian, A., & Emami, H. (2024). The role of biochar and sulfur-modified biochar on soil water content, biochemical properties and millet crop under saline-sodic and calcareous soil. *Plant and Soil*, 499(1–2). https://doi.org/10.1007/s11104-023-05912-z

Toková, L., Igaz, D., Horák, J., & Aydin, E. (2020). 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. *Agronomy*, 10(7). https://doi.org/10.3390/agronomy10071005

Usowicz, B., Lipiec, J., Łukowski, M., Marczewski, W., & Usowicz, J. (2016). The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow. *Soil and Tillage Research*, 164. https://doi.org/10.1016/j.still.2016.03.009

Vitkova, J., Kondrlova, E., Rodny, M., Surda, P., & Horak, J. (2017). Analysis of soil water content and crop yield after biochar application in field conditions. *Plant, Soil and Environment*, 63(12). https://doi.org/10.17221/564/2017-PSE

Vitková, J., Šurda, P., Rončák, P., Botková, N., & Zvala, A. (2021). Statistical analysis of soil water content differences after biochar application and its repeated application during 2020 growing season. *Acta Hydrologica Slovaca*, 22(2). https://doi.org/10.31577/ahs-2021-0022.02.0036

Wallace, J. S. (2000). Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems and Environment*, 82(1–3), 105–119. https://doi.org/10.1016/S0167-8809(00)00220-6

Wang, G., Zhang, X., Yinglan, A., Duan, L., Xue, B., & Liu, T. (2021). A spatio-temporal cross comparison framework for the accuracies of remotely sensed soil moisture products in a climate-sensitive grassland region. *Journal of Hydrology*, 597. https://doi.org/10.1016/j.jhydrol.2021.126089

Wang, X., Li, Y., Wang, H., Wang, Y., Biswas, A., Wai Chau, H., Liang, J., Zhang, F., Bai, Y., Wu, S., Chen, J., Liu, H., Yang, G., & Pulatov, A. (2022). Targeted biochar application alters physical, chemical, hydrological and thermal properties of salt-affected soils under cotton-sugarbeet intercropping. *Catena*, 216. https://doi.org/10.1016/j.catena.2022.106414

Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., Li, Y., He, T., & Wang, Z. (2023). Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis. *Geoderma*, 437. https://doi.org/10.1016/j.geoderma.2023.116591

Zhang, H., Cheng, Y., Zhong, Y., Ni, J., Wei, R., & Chen, W. (2024). Roles of biochars' properties in their water-holding capacity and bound water evaporation: quantitative importance and controlling mechanism. *Biochar*, 6(1). https://doi.org/10.1007/s42773-024-00317-2

Zhang, Q., Wang, Y., Wu, Y., Wang, X., Du, Z., Liu, X., & Song, J. (2013). Effects of Biochar Amendment on Soil Thermal Conductivity, Reflectance, and Temperature. *Soil Science Society of America Journal*, 77(5). https://doi.org/10.2136/sssaj2012.0180

Zhang, Z., Pan, Z., Pan, F., Zhang, J., Han, G., Huang, N., Wang, J., Pan, Y., Wang, Z., & Peng, R. (2020). The change characteristics and interactions of soil moisture and temperature in the farmland in Wuchuan County, Inner Mongolia, China. *Atmosphere*, 11(5). https://doi.org/10.3390/ATMOS11050503

Zheng, H., Ma, W., & Li, G. (2021). Adoption of organic soil amendments and its impact on farm performance: evidence from wheat farmers in China. *Australian Journal of Agricultural and Resource Economics*, 65(2). https://doi.org/10.1111/1467-8489.12406