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Differences in soil physical properties caused by applying three organic amendments to loamy clay soil under field conditions

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Abstract

Purpose Organic amendment applications have been proposed as important agricultural management practices for the maintenance of soil health. Weathered coal (WC), biochar (BC), and grass peat (GP) have been used widely and globally for a long time. However, the differences in soil physical properties following the application of these amendments have rarely been evaluated under the same field conditions.

Methods In this study, the changes in the physical properties of loamy clay soil after applying WC, BC, and GP (3%, w:w) were investigated under field conditions after 375 days.

Results Relative to unamended soil, the WC, BC, and GP applications increased the total porosity and decreased the bulk density of amended soils ($P < 0.05$). The soil water content increased by 23.8% following the BC application, whereas it was decreased by 10.5% following the GP application ($P < 0.05$). The application of all the amendments increased the soil average temperature by 0.71 °C (GP), 0.41 °C (WC), and 0.18 °C (BC) ($P < 0.05$). Additionally, the WC application increased the fraction of aggregates of 1–2 mm in size (by 47.6%) and of 2–5 mm in size (by 65.8%), and the stability of soil aggregates ($P < 0.05$). All the amendments increased the soil pores (> 300 and 30–300 μm) of amended soils, but the saturated hydraulic conductivity of these soils was not significantly improved.

Conclusion The application of WC can improve the formation and stability of soil aggregates to reduce the risk of soil erosion. BC is suitable for use in drought-prone areas with low rainfall and strong evaporation because it can increase the retention capacity of soil water. GP should be applied with caution, considering that its decomposition after extraction leads to the severe loss of organic carbon to the atmosphere. Overall, the selection of organic amendments in agricultural management practices should take into account the local environmental conditions.

Keywords Weathered coal · Biochar · Grass peat · Soil physical properties · Field conditions

1 Introduction

The unsustainable management of croplands (including practices such as intensive land use and excessive use of chemical fertilizers), the most direct driver of land degradation, has resulted in the degradation of soils globally by 33%, which is mainly manifested as soil loss and soil quality decline (Amelung et al. 2020; Bonanomi et al. 2020). It is expected that by 2050 land degradation and climate change will lead to the reduction of global crop yields by an average of 10%, this percentage could be as high as 50% in some regions, which poses a serious threat to sustainable agricultural development and human food security (IPBES 2018). Thus, optimized agricultural management practices are required to prevent land degradation, promote soil health, and ensure food security.

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The application of organic amendments has been proposed as a potential alternative strategy for agricultural soil management practices (Amoah-Antwi et al. 2020; Bonanomi et al. 2020). Biochar, compost, animal manure, and organic wastes are commonly used organic materials in agricultural management practices owing to their potential to improve soil physical structure, maintain soil fertility, stimulate soil microbial activity, and ultimately enhance soil quality and crop productivity (Demisie et al. 2014; El-Naggar et al. 2019; Peng et al. 2019; Bonanomi et al. 2020). Many studies have reported the effects of these materials on soil properties, including soil aggregation (Li et al. 2012; Burrell et al. 2016), hydraulic properties (Herath et al. 2013; Barnes et al. 2014; Jačka et al. 2018), and soil organic matter (Li et al. 2012; Peng et al. 2019) in different soil types and experimental conditions, and the effects largely depend on the type of organic material used. Regretfully, there have been few studies comparing the effects of these organic amendments on soil properties side by side so far (Grunwald et al. 2016; Yazdanpanah et al. 2016; Egene et al. 2018). Additionally, most of the previous studies were carried out under laboratory conditions, which in turn the results are inconclusive and contradictory (Mukherjee and Lal 2014; Obia et al. 2016). Consequently, it is difficult to assess the differences among the soil property improvements incurred by different organic amendments based on previous inconsistent results observed in different soils and under experimental conditions. Thereby, the selection of suitable organic amendments in agricultural management practices is hindered.

Soil physical properties are important soil quality indicators and play a key role in the health of soil and the sustainability of agricultural production (Regelink et al. 2015; Rabot et al. 2018). Soil physical properties include soil texture, structure, pores, bulk density, water content, and temperature. These properties depend on the history of soil formation, but they can be substantially affected by natural forces and anthropogenic activities (Yu et al. 2019). Agricultural soils with poor physical structure (such as soil compaction and poor soil structural stability) are prone to degradation, which negatively affects crop yield and quality (Jia et al. 2020).

Among the different organic amendments, weathered coal, biochar, and grass peat are widely used worldwide (Klavins and Purmalis 2013; Gao et al. 2019; Amoah-Antwi et al. 2020). Weathered coal is the product of oxidized coal and usually exists on the coal seam surface or under a thin coal seam (Zhang et al. 2017). Weathered coal is particularly rich in organic matter (up to 80%), which is mostly regenerated to humic acid, an organic compound with colloidal properties (Zhang et al. 2017; Guo et al. 2020); thus, it can be used as a fertilizer and soil conditioner, and has a wide range of potential application prospects (Pei et al. 2017). Many studies have reported that weathered coal can increase water holding capacity and soil aggregate stability (SAS) in sandy soil by improving the soil microenvironment (Chen et al. 2002; Li et al. 2012; Liu et al. 2019). Biochar is a carbon-rich byproduct of the thermal decomposition of plant biomass waste in a zero- or low-oxygen environment (Cooper et al. 2020). Biochar has higher stability than common organic amendments and is highly resistant to soil microbial decomposition (Gul et al. 2015; Peng et al. 2019). In addition, biochar particles have a large surface area and high porosity (Villagra-Mendoza and Horn 2018). Several authors have reported improvements in SAS and soil hydraulic conductivity in fine loam following biochar application (Barnes et al. 2014; Demisie et al. 2014; Zhang et al. 2020). Peat is a biomass material derived from the partial decomposition of mosses and other bryophytes, grasses, and sedges under waterlogged conditions (Klavins and Purmalis 2013). Peat has been extensively used in agricultural production in the past because of its high porosity and large amounts of stored organic carbon (20–50%) (Rezanezhad et al. 2016; Berglund et al. 2019; Uddin et al. 2019). However, against the background of increasing use of amendments, studies on how soil physical properties respond to the application of these amendments under the same soil environments and at the field scale are still scarce.

To thoroughly understand the differences among the three amendments in terms of improving soil properties, we investigated the changes in soil physical properties 1 year after their application to loamy clay soil under field conditions. The objectives of this study were (1) to analyze the changes in physical properties of loamy clay soil following the application of weathered coal, biochar, and grass peat under field conditions after 375 days; (2) to discuss the applicability of the three amendments in field management.

2 Materials and methods

2.1 Study area

The research was conducted at the field experiment station of the Institute of Soil and Water Conservation, Chinese Academy of Sciences (108°04′ E, 34°16′ N, 439 m a.s.l.) in Yangling, Shaanxi, China. The study area is located in the Guanzhong Plain in Northern China and belongs to a semi-humid monsoon climatic zone. The average annual temperature is 12.9 °C, the annual precipitation is 637.6 mm, with nearly 60% falling from July to October, and the average annual pan evaporation is 1500 mm. The daily air temperature and precipitation during the experimental period were monitored using an automated weather station (Fig. 1). The main soil type in the region is genealogically classified as Eum-Orthic anthrosol (Li et al. 2016). The soil texture was loamy clay with 32% clay, 35% silt, and 33% sand (USDA standard).

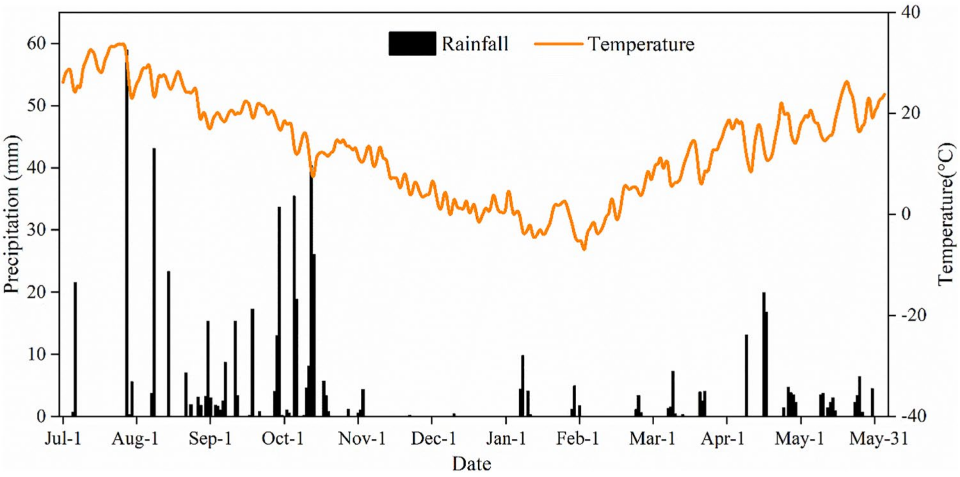


Fig. 1 The daily air temperature and precipitation from July 2017 to May 2018, Yangling, China

2.2 Amendment properties

The weathered coal was collected from the Minda Coal Mine in Ordos, Inner Mongolia, China. The grass peat was collected from the Mu Us Sandland in Yulin, Shaanxi, China. Biochar was provided by the Yixin Biological Energy Science and Technology Company in Shaanxi, China. The biochar was derived from apple branches pyrolyzed at 500 °C. All the amendment particles were ground and passed through a 2-mm sieve. The essential physical properties of the soil amendments are listed in Table 1. The specific surface area and pore size of amendments were determined using the Brunauer–Emmett–Teller (BET) N_2 method. In details, approximately 0.5 g amendment was dried in the oven at 105 °C for 3 days, then 0.02 g of the amendments was degassed for 3 h at 125 °C. The specific surface area and pore size were determined via a V-Sorb 2800P specific surface area and pore size analyzer (Gold APP Instrument Co., Ltd., Beijing, China) using N_2 as the adsorbate at 77 K under a relative pressure of 0.05–0.20. The pH of the soil was determined using a 1:2.5 (w:v) soil-water dilution. The pH of the amendments was determined using a 1:10 (w:v) amendment-water dilution. The organic carbon content of the soils and amendments was determined using the external heating $K_2Cr_2O_7$ method. The total nitrogen content was determined using the Kjeldahl method.

2.3 Experimental layout

In May 2017, the top layer of 0–20 cm of the soil in each plot was excavated using a shovel, and all the soils were sieved through a 10-mm mesh and divided into four equal parts. Taking 3% (w:w) as the addition rate, three amendments were uniformly mixed with the three parts of the soil using a large blender. Then, the three soil-amendment mixtures and control soil (no amendments) were placed back to the plots (2 m × 2 m). This process was performed in each plot in triplicate, with 12 plots placed in a randomized block design. All plots were kept in the open field at all times. Thus, four treatments were implemented in this study: soil control (SC), soil amended with weathered coal (WC), soil amended with biochar (BC), and soil amended with grass peat (GP). The soil surface was smoothed using a steel trowel after filling soil or soil-amendment mixtures to each plot. To avoid cross-contamination between plots, these were separated by cement slabs with an underground depth of 150 cm and aboveground height of 15 cm. To eliminate the influence of plant growth on soil water and soil structure, all plots were treated as bare land and were weeded regularly during the entire study period.

2.4 Indicator measurement

On day 375, two intact soil samples were randomly taken from a depth of 0–10 cm in each plot using soil cutting rings

Table 1 Essential physicochemical properties of three amendments and soil

	pH	Bulk density (g cm^{-3})	Surface area (m^2 g^{-1})	Average pore size (nm)	Organic carbon (g kg^{-1})	Total nitrogen (g kg^{-1})
Biochar	11.27	1.11	6.66	19.21	398.56	12.35
Grass peat	8.06	0.80	0.15	36.01	125.00	6.17
Weathered coal	6.86	1.15	1.57	55.93	310.11	5.24
Soil	8.67	1.47	–	–	5.60	0.60

(100 cm^3 in volume) to determine the bulk density (BD), total porosity (TP), saturated hydraulic conductivity (Ks), and pore size distribution (PSD) of unamended and amended soils, totaling six repetitions in total from all replicates. In addition, two intact soil samples were randomly taken from a depth of 0–10 cm in each plot using a shovel for aggregate separation.

2.4.1 Soil water content and temperature

To observe the soil temperature (ST) and water content (SWC) from June 2017 to May 2018, we monitored a 0–10 cm soil layer for SWC and ST in each plot using a remote wireless data acquisition system with temperature sensors and moisture sensors made in Handan South Jinan New Area Shengyan Electronic Technology Co., Ltd, China. The monitoring frequency was used to output data per 6 min.

2.4.2 Soil saturated hydraulic conductivity

Ks was determined by the constant head method and calculated using Darcy's equation (Jačka et al. 2018). All intact soil cores collected using cutting rings were first gradually saturated from the bottom. The Marsh bottle was then used to supply water with a constant head. The beaker was accurately weighed every 30 min to determine the amount of water that flowed out during this time until the water supply had been stabilized for a period of time. When the discharged water amount was substantially the same in three consecutive measurements, the experiment was completed, and the temperature and water level were measured simultaneously.

2.4.3 Soil pore size distribution and total porosity

The PSD was determined from soil water retention curves, and the soil water retention curve was measured by the centrifugation method (Hitachi CR21GII centrifuge; 20 °C).

After determining Ks, all the samples (kept saturated) were used to determine the soil water retention curves. The soil samples were centrifuged at suctions of 0.01, 0.10, 0.20, 0.40, 0.60, 0.80, 1.00, 2.00, 4.00, 6.00, 8.00, and 10.0 bar. After centrifugation at each suction, the weight of the sample was recorded. The pore size distribution was estimated using the Young–Laplace equation (Liu et al. 2018b):

$$d = 3/h \tag{1}$$

where d is the equivalent diameter of the cylindrical pores (mm) and h is the corresponding matric potential (cm H_2O). Four pore size classes were obtained in the experiment: macropores (> 300 μm), mesopores (30–300 μm), micropores (5–30 μm), and ultra-micropores (< 5 μm).

TP was calculated by measuring the saturated SWC (when the suction was 0):

$$TP = \theta/V_b \tag{2}$$

where TP is the total porosity (%), θ is the total volume of water in the soil at saturation (equal to the mass of water at saturation, assuming the density of soil water is 1.00 g cm^{-3}; cm^3), and V_b is the bulk volume of the soil (equal to the volume of the core; cm^3).

2.4.4 Soil bulk density

After determining the soil water retention curves, the soil in the cutting rings was dried in an oven at 105 °C and weighed after 24 h to determine the soil BD.

2.4.5 Aggregate separation and stability

The samples collected using a shovel were physically fractionated using a wet sieving method after dry sieving. Air-dried soil samples (500 g) were placed on top of a stack of sieves (10, 7, 5, 3, 2, 1, 0.5, and 0.25 mm), which were shaken for 10 min using a motorized sieving device. The soil retained by each sieve was weighed, and the percentage of the total weight was calculated. Then, 50 g subsamples (precise to 0.01 g) for wet sieving were prepared based on the percentage of aggregates at all levels in dry sieving. The subsample was placed in deionized water for 20 min and then placed on the top of a stack of sieves (5, 2, 1, 0.5, and 0.25 mm), shocked for 30 s to obtain six aggregate size classes (i.e., > 5, 2–5, 1–2, 0.5–1, 0.25–0.5, and < 0.25 mm), and it was ensured that the soil particles on the topmost sieve were always below the water surface during each oscillation. The aggregates that remained in each sieve were transferred to a container, oven dried at 60 °C, and weighed. The soil aggregate stability (SAS) was expressed by the mean weight diameter (MWD, mm), the geometric mean diameter (GMD, mm), and the percentage of water stable aggregates that were greater than 0.25 mm ($R_{>0.25}$, %) (Zhang et al. 2020).

2.5 Statistical analysis

Statistical analysis was performed using SPSS Statistics (IBM Corp., Armonk, USA), and the data plotting was performed using Origin 2018 (OriginLab, Northampton, USA). Factorial analyses of SWC and ST were conducted using two-way analysis of variance (ANOVA). Factorial analyses of BD, TP, PSD, Ks, aggregate fractions, and SAS were conducted using one-way ANOVA. Least significant difference (LSD at $P < 0.05$) was used to assess the differences among the means.

3 Results

3.1 Changes in the water content and temperature of amended soils

All three amendments increased the temperature (ST) of the amended soil (Fig. 2a). However, the ST showed significant differences among differently amended soils, with the highest values in grass peat–amended soil (GP) followed by weathered coal–amended soil (WC), and biochar-amended soil (BC). Specifically, compared with unamended soil (SC), the ST increased by 0.71 °C, 0.41 °C, and 0.18 °C in GP, WC, and BC, respectively ($P < 0.05$) (Fig. 2b). There were interaction effects between treatment and time on the cumulative monthly average soil temperature (mST) (Table 2). Specifically, compared with SC, the cumulative

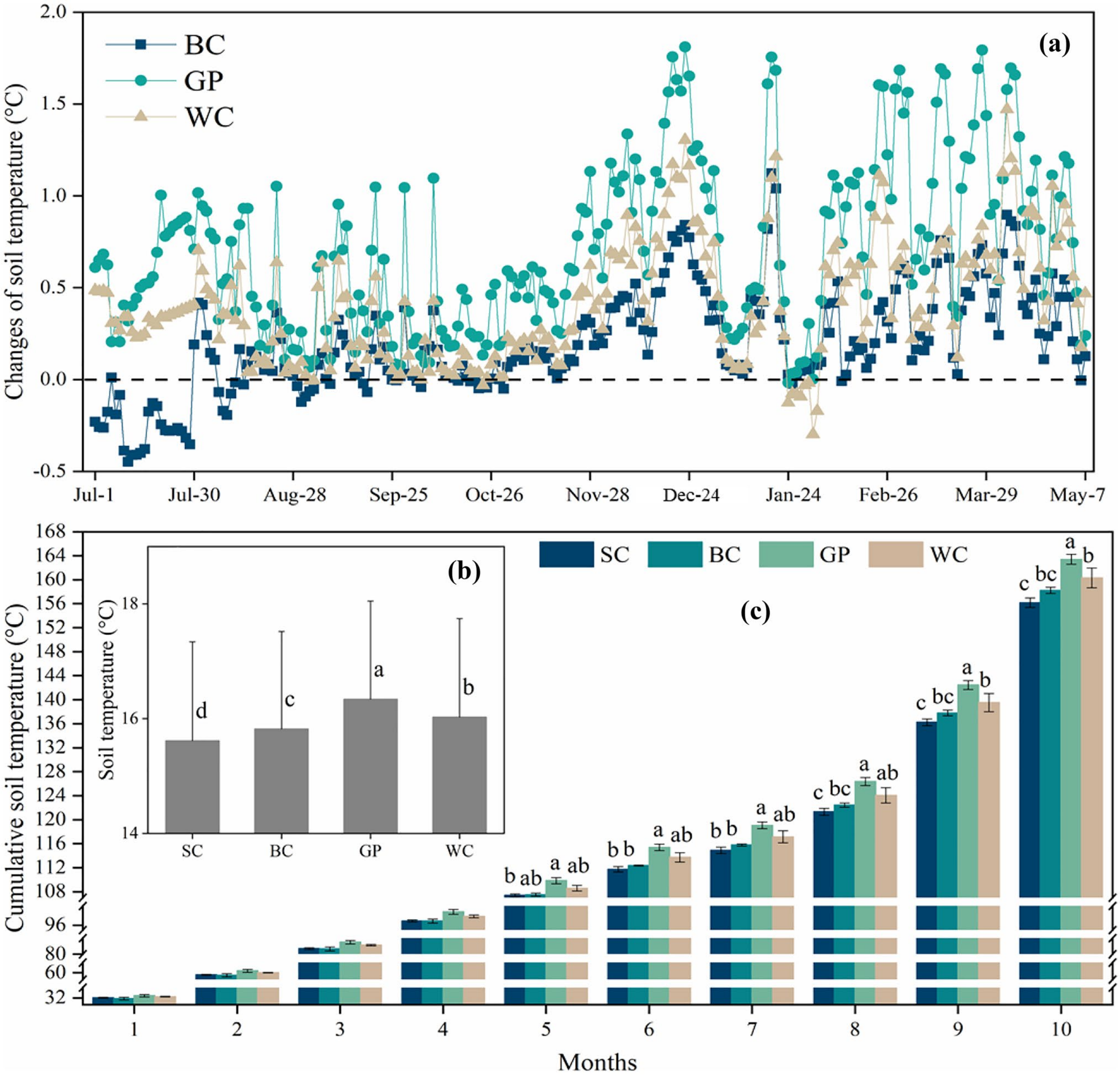


Fig. 2 The changes of soil temperature (**a**), the soil temperature (**b**), and the cumulative soil temperature (**c**) in differently amended soils. "Soil temperature changes (**a**)" refer to "the increment of daily average soil temperature ($n = 248$)." "Soil temperature (**b**)" refers to "the mean of the soil temperature for 10 months"; the data are expressed as the mean ± standard error ($n = 3$). "Cumulative soil temperature (**c**)" refers to "the cumulant of monthly average soil temperature," i.e., "2" in the x axis refers to the sum of the monthly average soil temperature for the first 2 months (July and August); the data are expressed as the mean ± standard error ($n = 3$). Different lowercase letters above the columns indicate significant differences among treatments ($P < 0.05$). SC (control, soil without amendment); BC (soil amended with biochar); GP (soil amended with grass peat); WC (soil amended with weathered coal)

mST of GP in the first 5 to 10 months increased by 2.45 °C, 3.36 °C, 4.17 °C, 5.04 °C, 6.20 °C, and 7.24 °C, respectively ($P < 0.05$), while that of WC in the first 8 to 10 months increased by 2.73 °C, 3.29 °C, and 4.11 °C, respectively ($P < 0.05$) (Fig. 2c). No significant differences in cumulative mST was found between the BC and SC groups (Fig. 2c).

Compared with SC, the daily average water content (SWC) of amended soil increased in BC and decreased in GP (Fig. 3a). There were no interaction effects between treatment and time on the monthly average soil water content (mSWC) and cumulative mSWC (Table 2). The main effects analysis showed that the SWC increased by 23.8% in BC and decreased by 10.5% in GP ($P < 0.05$) (Fig. 3b). The cumulative mSWC from July to April increased by 27.1% in BC and decreased by 9.83% in GP ($P < 0.05$) (Fig. 3c). No significant differences in SWC and cumulative mSWC was found between the WC and SC groups (Fig. 3c).

3.2 Changes in the aggregate fractions and stability of amended soils

The amendments had significant effects on the soil aggregate fraction (Fig. 4). In WC, the fraction of 1–2 mm aggregates increased by 47.6% and the fraction of 2–5 mm aggregates increased by 65.8%, compared with SC ($P < 0.05$). In contrast, the fraction of 0.5–1 mm aggregates decreased by 13.6% in BC and 10.8% in GP ($P < 0.05$). Furthermore, the aggregate stability (SAS) of WC clearly improved (Fig. 5). Specifically, the mean weight diameter (MWD) increased by 18.9%, the geometric mean diameter (GMD) increased by 12.9%, and the percentage of water-stable aggregates ($R_{>0.25}$) increased by 8.86%, compared with SC ($P < 0.05$) (Fig. 5). No significant differences was observed between SC and BC/GP in MWD, GMD, and $R_{>0.25}$.

3.3 Changes in bulk density, total porosity, pore size distribution, and saturated hydraulic conductivity of amended soils

All three amendments significantly decreased the bulk density (BD) and increased the total porosity (TP) of amended soils compared with SC (Fig. 6). The BD decreased by 8.33% in BC, 6.57% in WC, and 5.26% in GP ($P < 0.05$); and the TP increased by 11.4% in BC, 9.11% in WC, and 8.95% in GP ($P < 0.05$). Additionally, the amendments changed the pore size distribution (PSD) of the amended soils (Fig. 7). In WC, the mesopores (30–300 μm) increased by 28.0% ($P < 0.05$); in BC, the macropores (> 300 μm) and micropores (5–30 μm) increased by 164% and 12.7%, respectively ($P < 0.05$); while in the GP, the macropores (> 300 μm) and mesopores (30–300 μm) increased by 154% and 24.1%, respectively ($P < 0.05$) and the ultra-micropores (< 5 μm) decreased by 5.61% ($P < 0.05$) compared with SC (Fig. 7). No significant differences in saturated hydraulic conductivity (Ks) was detected between the amended soils and SC, while the highest Ks value was observed in WC, which increased by 31.2% compared with SC ($P = 0.085$) (Fig. 8).

4 Discussion

4.1 Changes in the physical properties of the three amended soils

The effect of organic amendments on soil physical properties depends on the type of amendment (Diacono and Montemurro 2010; Liu et al. 2018a; Mohawesh and Durner 2019). The application of weathered coal, biochar, and grass peat had different effects on the physical properties of the loamy clay soil after 1 year under field conditions.

Soil aggregates play a key role in maintaining the soil structure (Mustafa et al. 2020). Improving aggregate stability is important for the reduction of the susceptibility of soil to runoff, erosion, and crusting (Rabot et al. 2018). In our study, weathered coal significantly increased the fraction of large soil aggregates (1–5 mm). This can be attributed to the improvement in the organic carbon content due to the application of weathered coal. Studies have shown that increasing the organic carbon content is beneficial for soil aggregate formation by stimulating biological activity to increase bonding agents (Liu et al. 2016; Rahman et al. 2017; Zhang et al. 2020). Additionally, weathered coal contains generous amounts of humic acid, and the colloidal properties of which can improve the cohesion of soil particles (Zhang et al. 2017; Liu et al. 2019). Moreover, humic acid is difficult

Table 2 Results of two-way ANOVA evaluating the effects of treatment and time on monthly average soil temperature (mST), cumulative mST, monthly average soil water content (mSWC), and cumulative mSWC

Source	mST		Cumulative mST		mSWC		Cumulative mSWC	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Treatment	33.092	**< 0.001**	59.459	**< 0.001**	18.652	**< 0.001**	24.047	**< 0.001**
Time	13,063.783	**< 0.001**	14,665.815	**< 0.001**	40.424	**< 0.001**	105.634	**< 0.001**
Treatment*time	0.858	0.665	2.302	**< 0.05**	0.491	0.980	0.398	0.996

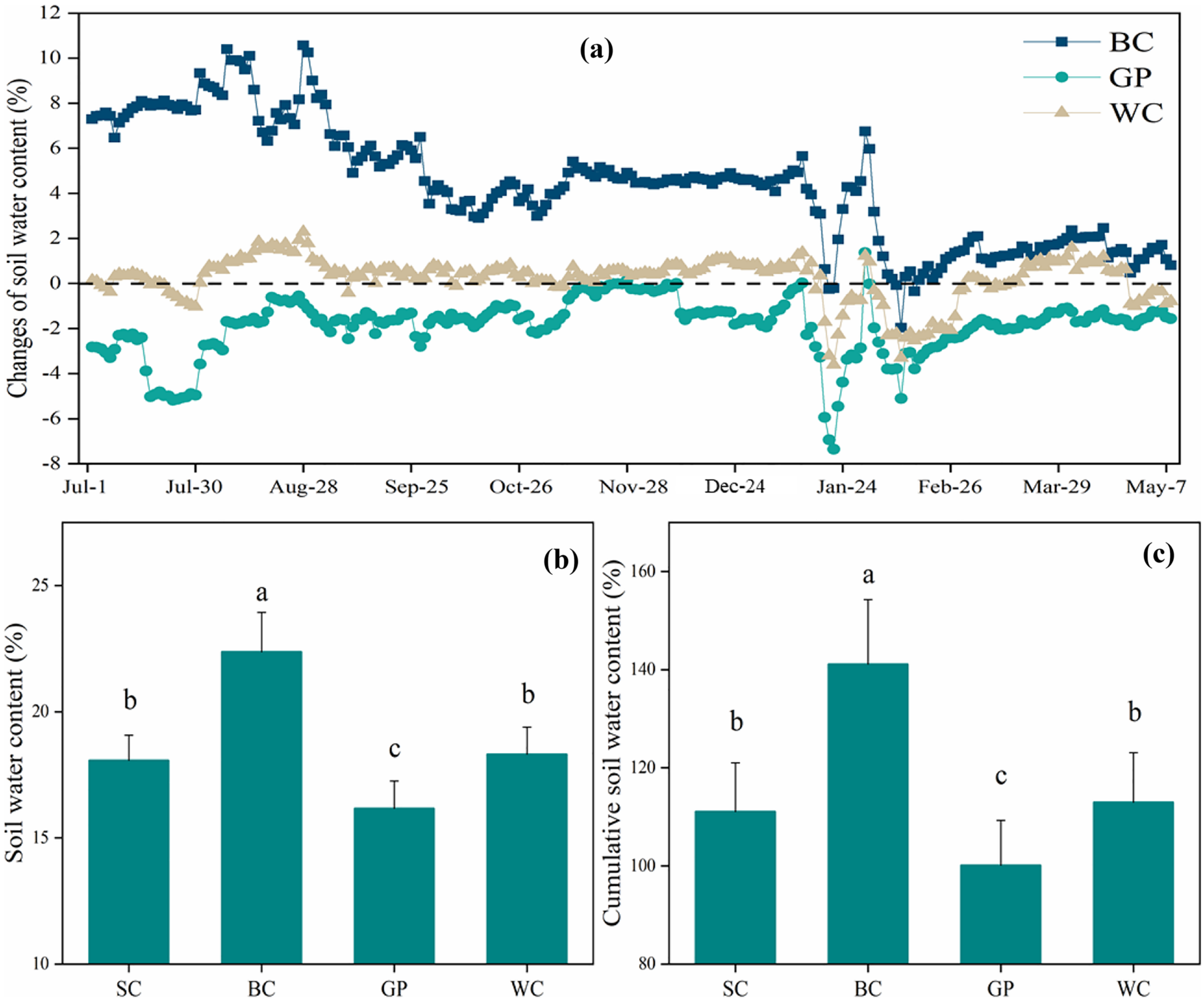


Fig. 3 The changes of soil water content (**a**), the soil water content (**b**), and the cumulative soil water content (**c**) in differently amended soils. "Soil water content changes (**a**)" refer to "the increment of daily average soil water content ($n=248$)." "Soil water content (**b**)" refers to "the mean of the soil water content for 10 months"; the data are expressed as the mean ± standard error ($n=3$). "Cumulative soil water content (**c**)" refers to "the cumulant of monthly average soil water content from July to April"; the data are expressed as the mean ± standard error ($n=3$). Different lowercase letters above the columns indicate significant differences among treatments ($P<0.05$)

to decompose and can remain in the soil for a long time; thus, the aggregates formed based on humic acid have good water stability. This can explain the significant improvement in aggregate stability in weathered coal–amended soils in this study. Similar to weathered coal, biochar and grass peat are also carbon-rich organic materials. However, the application of biochar and grass peat did not promote the formation of large soil aggregates and aggregate stability within 1 year in this study. Generally, biochar has high resistance to soil microbial decomposition (Peng et al. 2019); thus, it is difficult to promote the formation of aggregates and improve aggregate stability in a short-term experiment. Biochar may be useful for improving the formation and stability of soil aggregates in the long term. Grass peat was formed from the partial decomposition of organic material under waterlogged conditions, and the effects of grass peat depended on the degree of decomposition and storage time after extraction from waterlogged conditions (Klavins and Purmalis 2013; Rezanezhad et al. 2016). The grass peat used in our study had a lower carbon content (125 g kg^{-1}) than weathered coal (310 g kg^{-1}) and biochar (399 g kg^{-1}). In addition, it may contain substances that are difficult to decompose (Klavins and Purmalis 2013). Consequently, the application of grass peat may be insufficient to promote the formation of large soil aggregates within 1 year. Overall, only the application of weathered coal promoted large aggregate formation in

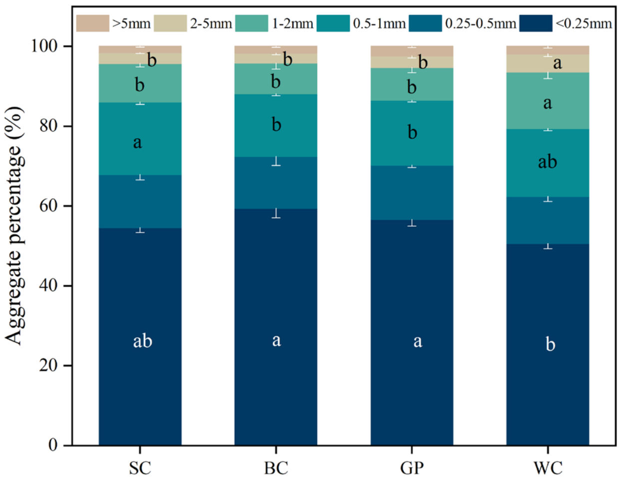


Fig. 4 The aggregate fraction in the differently amended soils. The data are expressed as the mean ± standard error of the mean. Different letters in the columns with the same color indicate significant differences among treatments ($P < 0.05$)

soil and clearly improved aggregate stability in loamy clay soil in the short term.

Soil porosity and bulk density mainly reflect the soil's air and water permeability, which is very important for the preservation of soil health and productivity (Alghamdi 2018; Blanco-Canqui and Ruis 2018). In our study, weathered coal, biochar, and grass peat were applied to the soil, and the mixing of two media (soil and amendment particles) resulted in particle rearrangement and further changed the porosity and bulk density of the amended soils. All three amendments increased the total porosity and decreased the bulk density of the amended soils. The organic amendments used in our study had lower bulk density and higher porosity compared to the experimental soil; adding them to the soil resulted in the rearrangement of soil particles and amendment particles, resulting in a weight dilution effect on the soil bulk density (Blanco-Canqui 2017; Verheijen et al. 2019). Additionally, the increase in soil aggregates also benefits the increase in porosity (Xu et al. 2020), because the additional pores will arise between amendments and the surrounding soil aggregates, as well as between the new aggregates (Rahman et al. 2018). Therefore, for the weathered coal–amended soil, the contribution of large aggregates to the total porosity cannot be disregarded after 1 year.

Compared to the total porosity, the soil pore size distribution determines many physicochemical processes in the soil (Blanco-Canqui 2017; Meyer et al. 2018). In our study, the pore size distribution of the amended soil was measured via a water retention curve to estimate the effects of the three organic materials on the pore size distribution. All organic amendments increased soil pores (> 300 μm and 30–300 μm) in amended soils after 1 year. This might be the result of particle rearrangement, which can create additional pore spaces between amendments and the surrounding soil aggregates/particles. In addition, the application of organic amendments can promote soil animal activities by providing a carbon source to soil animals; in turn, the activities of soil animals are conducive to the development of larger pores; thus, there is a high probability of biological perturbation (such as earthworms) contributing to the generation of large soil pores under field conditions (Blanco-Canqui

Fig. 5 Stability characteristics of soil aggregates in the differently amended soils. The data are expressed as the mean ± standard error of the mean. Different letters indicate significant differences among treatments ($P < 0.05$). $R_{>0.25}$ (the proportion of aggregates that were greater than 0.25 mm); MWD (the mean weight diameter of aggregates); GMD (the geometric mean diameter of aggregates)

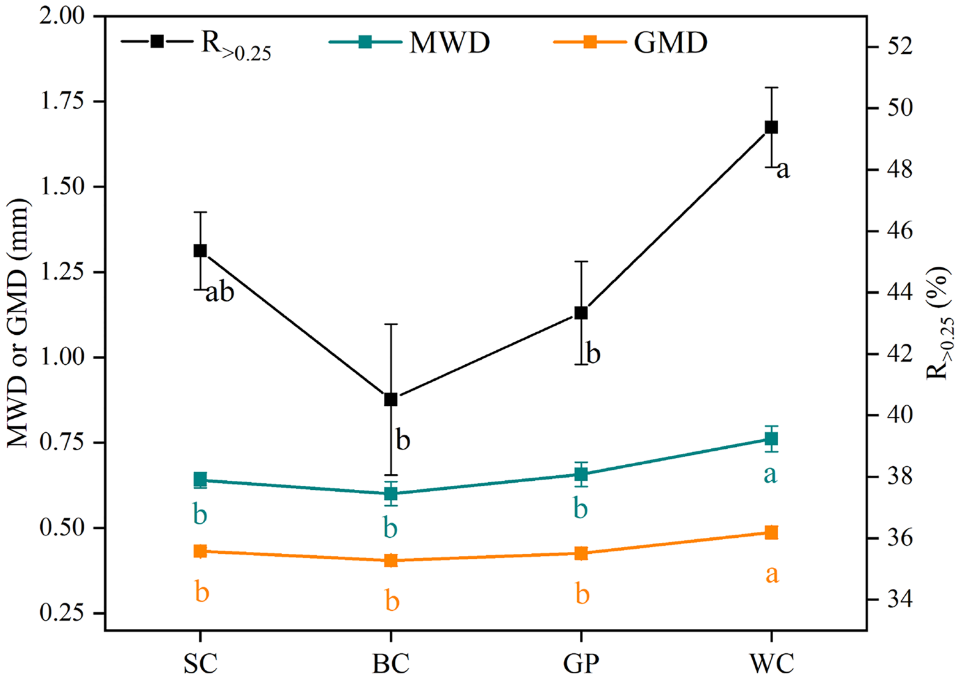
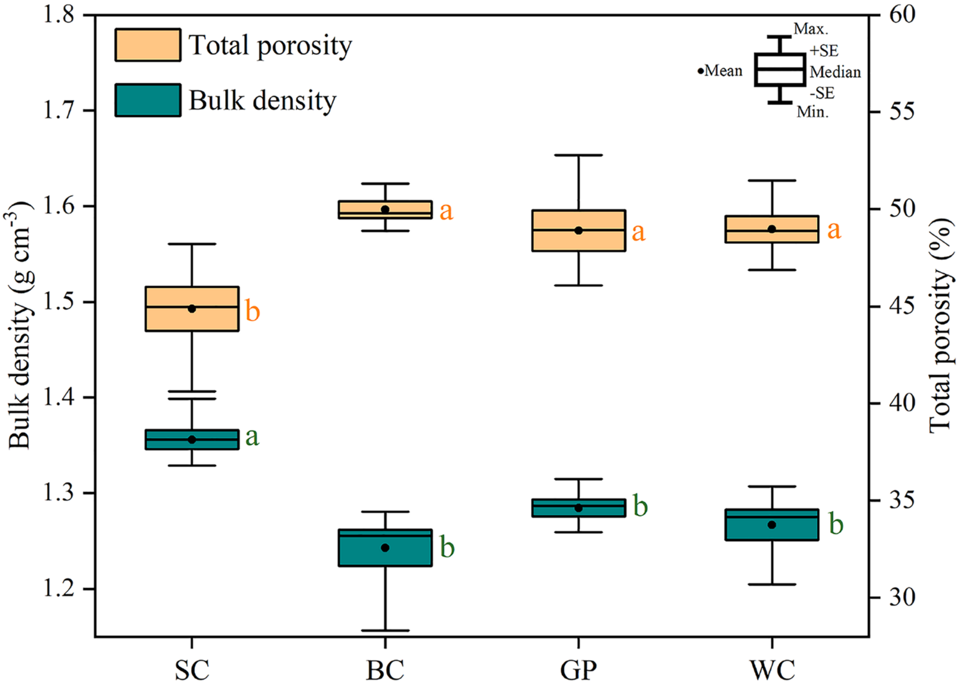


Fig. 6 Soil bulk density and total porosity in the differently amended soils. The data are expressed as the mean ± standard error of the mean. Different letters indicate significant differences among treatments ($P < 0.05$)



2017). Previous studies have shown that larger pores are related to the increase in soil organic carbon because they promote the formation of larger aggregates, and additional pores are generated between soil particles and newly created larger aggregates (Rahman et al. 2018; Xu et al. 2020). For weathered coal–amended soil, the increase in large aggregates can also be responsible for the increase in large soil pores. The increase in micropores (5–30 μm) of biochar-amended soil might be caused by the adsorption of many finer soil particles to the surface of biochar as it has a larger specific surface area.

Soil pore size distribution greatly affects the soil hydraulic conductivity (Pires et al. 2017; Meyer et al. 2018). Generally, the increase in macropores (> 300 μm) and/or mesopores (30–300 μm) of soil is beneficial for the improvement of soil saturated hydraulic conductivity (Herath et al. 2013; Amoakwah et al. 2017). However, in our study, the saturated hydraulic conductivity in all amended soils did not significantly improve after 1 year. The soil used in the study was an expansive clay soil, which contained a large

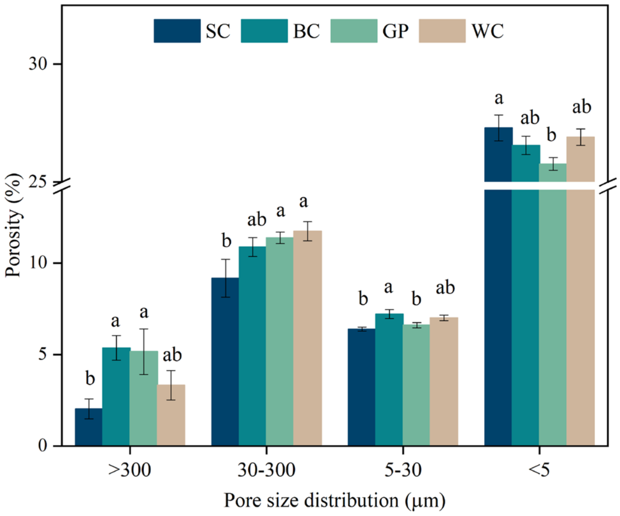


Fig. 7 Pore size distribution in the differently amended soils. The data are expressed as the mean ± standard error of the mean. Different letters indicate significant differences among soil treatments for the same pore size ($P < 0.05$)

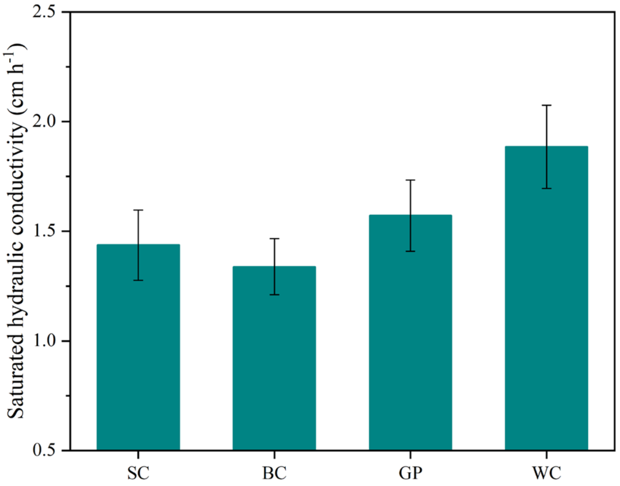


Fig. 8 Soil saturated hydraulic conductivity in the differently amended soils. The data are expressed as the mean ± standard error of the mean

number of expansive clay minerals (illite, vermiculite, and montmorillonite), and exhibited welling-shrinkage behavior as the water content changed (Wang et al. 2021). As the soil becomes wet, the clay minerals absorb water and expand, thus making the soil muddy and sticky, then making the large soil pores finer, and ultimately not being conducive to the improvement of soil saturated hydraulic conductivity (Lu et al. 2014; Lim et al. 2016; Shahsavani et al. 2020). Additionally, soil saturated hydraulic conductivity highly depends on the connectivity of the soil pore network (Rabot et al. 2018). The finer soil and amendment particles were very likely settled in larger pores by water flow in wetting–drying and freezing–thawing processes and formed obstacles, thus leading to a decrease in the connectivity of the pore network and not facilitating improvements in soil saturated hydraulic conductivity (Jačka et al. 2018). It is worth noting that the soil saturated hydraulic conductivity was higher in weathered coal–amended soil than in other amended soils. This can be ascribed to the improvement in the aggregate stability. The increase in large soil aggregates and aggregate stability can decrease the probability of the soil structure suffering from damage under high water content, thereby reducing the damage of connecting channels by the finer particles, which is beneficial for increasing soil saturated hydraulic conductivity.

The movement of water in soils is affected by soil pore structure (Pires et al. 2017). Our results showed that the application of biochar clearly increased the water content of amended soil within 1 year, which is attributed to the increase in micropores (5–30 μm), which play a major role in retaining soil water (Amoakwah et al. 2017; Alghamdi 2018). Additionally, the larger specific surface area of biochar itself can provide more adsorption sites for soil water, which can be sorbed to the biochar surface by physical and chemical sorption, thus improving the water content of biochar-amended soil (Jačka et al. 2018). In contrast, the application of grass peat clearly decreased the water content of the amended soil within 1 year. Grass peat has strong hydrophobicity because it contains large amounts of undecomposed organic materials, and its hydrophobicity increases with a decrease in soil water content (Wu et al. 2020). As the study area is prone to drought, the lower soil water content increases the repellency of grass peat–amended soil. In addition, most soil water movements are unsaturated flows under natural conditions. In general, the soil unsaturated hydraulic conductivity increases with large soil pores, meaning that the ability of the grass peat–amended soil to maintain water will be reduced as it cannot against gravity of water (Rezanezhad et al. 2010).

The variation in soil temperature at a depth of 0–10 cm is influenced by soil color, soil pore size, and soil water content (Herath et al. 2013; Zhang et al. 2013; Liu et al. 2018a). In our study, the application of all three amendments increased the amended soil temperature. This is attributed to the fact that the organic materials have a darker color than the soil. Their application darkened the soil color, which would decrease the reflectance of amended soil, which absorbed more energy compared with unamended soil, ultimately increasing its temperature (Zhang et al. 2013; Amoah-Antwi et al. 2020). Additionally, the increase in temperature of amended soils can also be attributed to the increase in soil large pores (> 30 μm) that improves the soil aeration and increases the exchange of heat energy (Herath et al. 2013). The difference in water content further led to differences in the temperature of the amended soils in our study. The highest temperature was found in the grass peat–amended soil due to the lowest soil water content, while the opposite was true in the biochar-amended soil. This can be explained by the specific heat capacity of water being higher than that of soil particles. Zhang et al. (2013) reported that soil thermal conductivity has a negative logarithmic relationship with soil water content. A higher water content attenuated the heat transfer in biochar-amended soil. No clear differences in cumulative soil temperature was detected among the four treatments from July to September, which can be ascribed to the more rainfall events and higher air temperatures which weakened the difference among these treatments.

4.2 Implications for the management of the three studied organic amendments in loamy clay soil

All the weathered coal, biochar, and grass peat can loosen the soil and make it porous by reducing the soil bulk density and increasing the total porosity. However, the effects of the three organic amendments on the other soil physical properties were significantly different; thus, the selection of organic amendments should be based on the target degraded soil and the local environmental conditions.

The application of weathered coal is beneficial for creating a favorable soil structure by increasing large soil aggregates and aggregate stability, and it may promote soil drainage with long-term application due to the highest saturated hydraulic conductivity value in weathered coal–amended soil. Thus, weathered coal is suitable for soils that are susceptible to erosion by high-frequency heavy rainfall. Biochar amendments are suitable for soil in drought-prone areas with low rainfall and strong evaporation, as the application of biochar is very beneficial for improving soil water retention capacity in the short term. However, grass peat should be applied with caution in drought-prone areas, as it can easily decrease the soil water content. Additionally, the grass peat amendment as a contrast material used in our study was expected to promote the formation and stability of aggregates. However, the results showed that grass peat did not increase aggregate stability and even reduced the aggregates in the 0.5–1 mm fraction. Peat generally contains 20–50% organic carbon (Rezanezhad et al. 2016; Uddin et al. 2019). However, it is easy to decompose after being extracted from waterlogged environments owing to the peat leaving the anaerobic environment (Berglund et al. 2019; Uddin et al. 2019). In our study, the grass peat contained only 13.5% organic carbon, which might be insufficient to increase the large soil aggregates and aggregate stability. Importantly, peatlands are valuable resources. They represent a significant carbon and energy reservoir (Rezanezhad et al. 2016). The extraction of peat at the expense of the reservoir is against the "sustainable soil management strategy." Overall, the mass use of grass peat as a soil amendment in field management is not recommended.

5 Conclusions

Our results showed that applying weathered coal, biochar, and grass peat to loamy clay soil could increase the total soil porosity and reduce the soil bulk density. The changes in aggregates, pore size distribution, water content, and temperature of the amended soils depended on the type of organic amendment used. Although the application of all three organic amendments increased the large soil pores (> 300 and 30–300 μm), these changes were insufficient to improve the saturated hydraulic conductivity of the loamy clay after 1 year. The selection of organic amendments should be based on the target degraded soil and local environmental conditions. In addition, considering that the peatland will be destroyed due to the extraction of grass peat and the decomposition of grass peat after extraction will increase greenhouse gas emissions, grass peat application as a soil management practice is not recommended. Our findings provide insights into the application of these three organic amendments as a cropland management practice in loamy clay soil.

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