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Effects of biochar on soil water and temperature, nutrients, and yield of maize/soybean and maize/peanut intercropping systems**

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A b s t r a c t. A two-year field experiment was conducted to evaluate the ability of biochar to improve the soil environment of intercropping systems. There were two planting systems (maize/soybean, maize/peanut intercropping) coupled with three biochar application rates (0, 15, and 30 t ha^{-1}). Changes in the soil water content, soil bulk density, temperature, soil nutrients and yield were recorded. Under the influence of rainfall, biochar significantly increased soil water storage at the 0-30 cm soil layer. The maximum increment of soil water storage was 15.5% with the maize/peanut intercropping at 15 t ha^{-1} treatment at the tassel stage. Both biochar treatments significantly increased the soil effective accumulated temperature at the seedling stage and jointing stage. The greatest increment in soil effective accumulated temperature was achieved using the maize/peanut intercropping at 15 t ha^{-1} treatment. The effects of biochar on soil effective accumulated temperature were weakened at the tasselling, grain filling and mature stages. After biochar application, the soil mineral nitrogen content was significantly reduced at the seeding stage, but significantly increased by 25.2-48.9% at the tasselling and grain filling stages. The soil ammonium and nitrate nitrogen content of the soybean and peanut ridges was significantly higher than those of the corn ridges. The total yield of maize/soybean increased by 12.8-13.7% and the total yield of maize/peanut intercropping increased by 15.9-18.0% relative to the treatment without biochar. Therefore, both 15 t ha^{-1} and 30 t ha^{-1} effectively regulated the soil water, nutrient and temperature at the jointing, tasselling and grain filling stages, which enhanced the positive effects of intercropping on crop yield. From an analysis of the yield results, it was found that biochar may be more significant in the maize/peanut intercropping system.

K e y w o r d s: biochar, intercropping, water storage, effective accumulated temperature, mineral nitrogen

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INTRODUCTION

Intercropping is an important agricultural planting technique that improves resource utilization efficiency through interactions between different crop species (Chen *et al*., 2010). The implementation of a reasonable intercropping strategy could improve the efficiency with which plants utilize light, temperature, fertilizer, water and other natural resources, it could also reduce the risk of pests, diseases, and weed competition and increase the yield per unit area (Oswald *et al*., 2002; Hussain *et al*., 2020). The annual area in China sown under intercropping conditions is more than 2.8×10^7 ha, among which the area of legume intercropping exceeds 1×10^7 ha (Miao *et al*., 2011). Therefore, continuous improvement in the production of the intercropping planting model is important to ensure food security.

Because legumes can obtain nitrogen from the atmosphere through biological nitrogen fixation, the intercropping of Gramineae and Leguminosae species can enhance yields, this has been confirmed by previous studies (Green *et al*., 2019). When intercropped with grasses, legumes can act as nutrient donors for grass crops, thereby increasing the nitrogen utilization rate (Pirhofer *et al*., 2012). In addition, the intercropping of *Gramineae* species and legumes allows for the optimization of the temporal and spatial growth patterns of the above ground and underground parts, which has the potential not only to promote the efficient use of resources such as light and heat but it could also increase the efficiency with which plants utilize nutrients and water through interactions within the rhizosphere (Sekiya *et al.,* 2011). However, all crops in the late growth stage of both gramineous and leguminous growth also require large amounts of nutrients. Given that the nutrient requirements exceed supply, gramineous crops suppress the growth of leguminous crops, thereby reducing yields. Liao (2019) showed that biochar amendment could alter the soil bacterial community by assimilating plant-derived carbon, which plays an important role in nutrient cycling and in improving plant performance in intercropping systems in the late growth stage in a legume-based intercropping system. Liu (2020) found that the dry matter accumulation of peanuts during the maturity stage was 43.97% lower than that produced by monocropping, in a corn/peanut intercropping experiment. Zhang *et al*. (2017) showed that the yield resulting from soybean and peanut intercropping with corn was reduced by 8.4 and 48.7%, respectively, compared to the single cropping of soybean and peanut. Therefore, it is of great significance to continuously enhance the soil nutrient supply during the critical growth period of plants in order to balance resource competition in intercropping systems.

Biochar is widely used in agriculture as a soil amendment to improve soil quality and increase crop productivity. Biochar has a rich pore structure, large specific surface area, and a high surface charge density, which has the potential to reduce nutrient leaching, promote crop nutrient absorption, and subsequently improve crop productivity (Lehmann *et al*., 2003; Sohi *et al*., 2010). Biochar can improve the utilization efficiency of soil nutrients (*e.g.*, Al, Ca, Mg, B and Mo) by moderately increasing soil pH and the availability of trace elements, it can also inhibit the release of NO, N_2O, and N_2 resulting from denitrification by stabilizing the soil structure and improving the release of soluble carbon, nitrogen loss is also reduced by increasing the soil nutrient adsorption capacity (Abel *et al*., 2013; Major *et al*., 2010). In low organic matter loam soils, adding 20 t ha^{-1} of biochar without applying nitrogen increased the maize yield by 15.8%, while adding 40 t ha^{-1} of biochar increased the yield by 7.3%. When applying nitrogen fertilizer, adding 20 t ha^{-1} of biochar increased the maize yield by 8.8%, while adding 40 t ha^{-1} of biochar increased the maize yield by 12.1% (Liu *et al*., 2013). Dai *et al*. (2019) showed that the corn yield increased significantly with the increase in the soil content of biochar. Previous studies designed to determine the impact of biochar on crop productivity have mainly focused on single planting systems. By contrast, few studies have examined the ability of biochar to alleviate water-nutrient competition resulting from intercropping planting techniques.

The aim of this experiment was to characterize the effects of biochar on crop yield, soil water, soil temperature, and nutrients under an intercropping system to reveal the positive effects of biochar on that system. Another research goal was to establish whether biochar can enhance the nutrient supply in the grain filling and maturing stage of crop growth and alleviate the fierce nutrient competition between crops in the intercropping system.

MATERIALS AND METHODS

The experiment was carried out from May 2019 to October 2020 at the interdisciplinary research centre of the College of Water Resources at Shenyang Agricultural University. The area is located in the east of Shenyang City (41°84' N, 123°57' E, 44.7 m above sea level). It has a temperate continental monsoon climate with cold and dry winters, and high-temperature and rainy summers. The soil texture in this area is a brown loam soil. The average annual precipitation is 721.9 mm. Precipitation in the summer accounted for almost 70% of the total precipitation recorded. The physical and chemical properties of the soil are as follows: organic carbon; 31.5 g kg^{-1}, total nitrogen; 1.0 g kg^{-1}, total phosphorus; 8.1 g kg^{-1}, total potassium; 15.7 g kg^{-1}. The two-year precipitation record observed during the experiments is shown in Fig. 1.

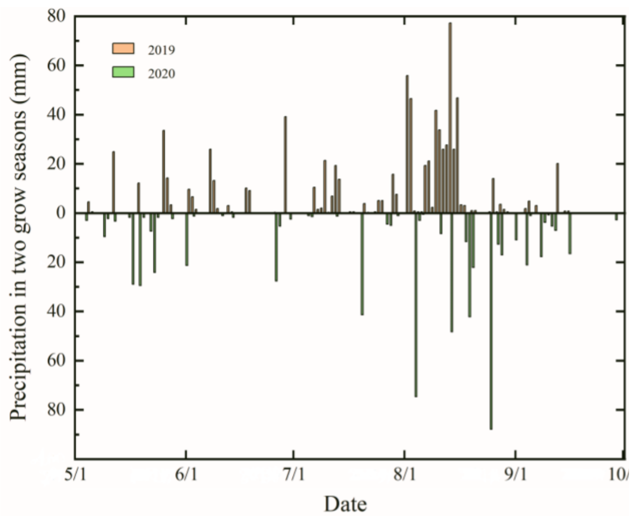

Fig. 1. Precipitation in the two growth seasons.

The field experiments were conducted in the form of a two-factor randomized block design, with two levels of intercropping planting techniques and three levels of biochar applied for six treatments over three replicates. The intercropping planting techniques used for the first factor, included maize/soybean intercropping (MS), and maize/peanut intercropping (MP). The second factor biochar application rates were as follows: 0 t ha^{-1} (T_0), 15 t ha^{-1} (T_1), and 30 t ha^{-1} (T_2).

The plot sizes of each plot were 3×6 m^2 under plastic film mulching on every ridge as shown in Fig. 2. Corn was sown at a density of 6.67×10^4 seeds ha^{-1}, and soybeans and peanuts were both sown at a density of 12×10^4 seeds ha^{-1}. Biochar was prepared through the anaerobic pyrolysis of corn stover at a high temperature of 450°C with a residence time of 18 min. The basic physical and chemical properties of biochar are organic carbon 515 g kg^{-1}, total nitrogen 10.2 g kg^{-1}, total phosphorus 8.1 g kg^{-1} and total potassium 15.7 g kg^{-1}. Before starting the experiment, biochar was distributed evenly and stirred repeatedly with a shovel to mix it with the topsoil (0-30 cm). In both years of the study, the cultivars of corn, soybean and peanut respectively were Liangyu 777, Dongdou No. 1, and Baisha 308. The crops were planted in a single row per ridge. The width of the ridges was 20 cm, while the distance between the two ridges was 15 cm. The height of the ridges was 10 cm, and the length of the ridge was 6 m.

Fig. 2. Experimental site.

The numbers of corn and legume (soybean and peanut) plants in each ridge were 20 and 36, respectively. During the test period, no irrigation water was supplied; thus rainfall was the only supplementary water source. Before sowing, nitrogen fertilizer 280 kg ha^{-1}, phosphorus 135 kg ha^{-1}, and potassium 155 kg ha^{-1} were applied to all plots. The treatments are shown in Table 1.

Table 1. Experimental design

Intercropping system	Biochar treatment		
	T_0	T_1	T_2
Maize+soybean	MST_0	MST_1	MST_2
Maize+peanut	MPT_0	MPT_1	MPT_2

T_0 – (0 t ha^{-1}), T_1 – (15 t ha^{-1}), T_2 – (30 t ha^{-1})

TDR (Diviner 2000 by SenTek Corporation, Australia) was used to measure soil volumetric moisture content at soil depths of 10, 20, 30, 40, 50, 60 cm, and 3 Trime tubes were buried in each plot. To calculate the soil water storage (*SWS*) value and analyse the differences between the treatments in each growth period, we first calculated the average bulk density of soil at the 0-30 cm and 30-60 cm depth in each growth period. The soil bulk density was measured once every growth period using the ring knife method (Wu *et al*., 2019). Soil bulk density was only determined in 2019 and it was also used to calculate SWS in 2020. Soil water storage was calculated using Eq. (1) by Milly *et al*. (1994):

$$SWS = \frac{\theta_m \rho_b h}{\rho_w}\ , \qquad (1)$$

where: *SWS* is the average soil water storage capacity in each period (mm), θ_m is the soil volumetric moisture content (%), ρ_b is the soil bulk density (g cm^{-3}), h is the depth of the soil layer (mm) and ρ_w is the water density (g cm^{-3}). The *SWS* for each treatment between 0 and 60 cm is the sum of *SWS* for each soil layer.

The soil temperatures at different depths of 5, 10, 15, 20 and 25 cm, were observed at 6:00 and 14:00 with a curved tube ground thermometer. The soil effective accumulated temperature (SEAT) was calculated using Eq. (2) by Xu *et al*. (2020):

$$K = N(T - 10)\ , \qquad (2)$$

where: K is the SEAT (°C), N is the duration of different growth periods (d), T is the average soil temperature, and 10°C is the effective threshold temperature for crop growth.

In each growth period, soil samples from the corn and soybean (or peanut) ridge were taken at a 10-20 cm depth. Soil samples, derived from five randomly selected points per plot were passed through a 2 mm sieve after blending, and air-dried in a laboratory. Following this, 5 g of each soil sample was extracted using 50 ml of 2 M KCl solution. Concentrations of NH_4^+-N and NO_3^--N were determined using the AA3 Continuous Flow Analytical System manufactured by Bran + Luebbe from Germany.

At the end of each growth stage, seeds of corns, soybeans and peanuts were air-dried outdoors for 10-13 days and the yields were calculated based on a 14% moisture content.

The growth stages in this experiment were respectively, the seedling stage, jointing stage, tasselling stage, grain filling stage and maturity stage based on the main corn crop.

All data were subjected to analysis using a two-way variance (ANOVA) which utilized SAS9.3 software. The separation of the means was performed using the least significant difference (LSD). The figures were plotted using Origin 2021.

RESULTS

Table 2 shows that in the maize/soybean intercropping system, compared with the T_0 treatment, the T_1 and T_2 treatments increased the maize yield by 14.2 and 13.3%, respectively. The soybean yield increased by 4.84 and 14.52%, respectively, and the total yield increased by 12.8 and 13.8% with increasing biochar rates, respectively (2019). However, T_2 decreased the maize yield in 2020. In the maize/peanut intercropping system, the maize yield was also significantly increased through biochar application, the average peanut yield increased by 19.1 and 32.0%, and the total yield increased by 13.8 and 11.8% with increasing biochar application, respectively, as compared with the T_0 treatment during the two growing seasons. It may be observed that biochar addition significantly increased the overall yield of the intercropping system, and the yield-increasing effect of biochar with regard to peanuts reached a very significant level ($p<0.01$). In the case of the maize yield, the rate of increase tapered off with the increase in the amount of biochar added.

Table 2. Maize and legume (soybean or peanut) yields in the intercropping systems during the two grow seasons

Intercropping mode	Biochar	2019				2020			
		Maize ($t\,ha^{-1}$)	Soybean ($t\,ha^{-1}$)	Peanut ($t\,ha^{-1}$)	Total ($t\,ha^{-1}$)	Maize ($t\,ha^{-1}$)	Soybean ($t\,ha^{-1}$)	Peanut ($t\,ha^{-1}$)	Total ($t\,ha^{-1}$)
Maize+soybean	T_0	6.42b	1.24b	–	7.66b	6.21ab	1.30b	–	7.51b
	T_1	7.33a	1.30ab	–	8.64a	7.60a	1.32b	–	8.92a
	T_2	7.28a	1.42a	–	8.71a	5.56b	1.46a	–	8.02ab
Maize+peanut	T_0	6.19b	–	1.05c	7.25b	6.45b	–	1.11c	7.55b
	T_1	7.12a	–	1.28b	8.40a	7.14a	–	1.29b	8.43a
	T_2	7.16a	–	1.40a	8.56a	6.52b	–	1.45a	7.97ab
Intercropping system		ns	–	–	ns	ns	–	–	ns
Biochar		**	*	**	**	**	*	**	*
Intercropping×biochar		ns	–	–	ns	ns	–	–	ns

Different letters mean significant difference at p<0.05, * significant at p<0.05, ** significant at p<0.01.

Table 3. Soil bulk density at different soil layers in the intercropping systems

Soil depth (cm)	Treatment	Soil bulk density ($g\,cm^{-3}$)				
		Seedling	Jointing	Tasselling	Grain filling	Mature
		Stage				
0-30	MST_0	1.28	1.36	1.42	1.47	1.48
	MST_1	1.26	1.35	1.41	1.46	1.48
	MST_2	1.25	1.35	1.39	1.46	1.46
	MPT_0	1.29	1.36	1.42	1.47	1.47
	MPT_1	1.28	1.34	1.41	1.46	1.45
	MPT_2	1.24	1.33	1.40	1.45	1.45
30-60	MST_0	1.57	1.57	1.57	1.56	1.57
	MST_1	1.57	1.57	1.57	1.57	1.58
	MST_2	1.56	1.55	1.55	1.55	1.56
	MPT_0	1.57	1.58	1.58	1.57	1.57
	MPT_1	1.56	1.58	1.56	1.58	1.57
	MPT_2	1.56	1.57	1.56	1.57	1.56

Table 4. Soil water storage as affected by biochar in the intercropping systems

Soil depth (cm)	Treatment	Soil water storage in 2019 (mm)					Soil water storage in 2020 (mm)				
		Seedling	Jointing	Tasselling	Grain filling	Mature	Seedling	Jointing	Tasselling	Grain filling	Mature
		Stage									
0-30	MST_0	98.4	89.6d	90.7b	90.3c	138.6c	96.4	97.0	114.6	105.8b	134.3b
	MST_1	94.6	96.1c	99.9a	104.3a	145.5ab	94.1	100.3	119.2	124.7a	150.0a
	MST_2	99.7	102.6a	103.3a	104.2a	149.2a	98.2	102.9	116.4	123.1a	146.3a
	MPT_0	93.2	97.0bc	88.8b	94.5bc	141.1bc	100.4	100.5	117.8	114.6ab	127.5c
	MPT_1	94.1	99.9abc	96.4ab	97.6b	141.5bc	98.3	101.9	111.3	118.2ab	131.0b
	MPT_2	93.5	101.4ab	102.6a	102.1ab	145.9ab	100.6	102.7	116.6	126.2a	140.6ab
30-60	MST_0	131.4	140.7abc	138.3c	130.7b	164.9c	171.8	158.5	137.5b	162.9	179.3
	MST_1	136.3	137.3c	139.7bc	136.0a	172.5ab	174.4	160.3	145.6ab	172.5	182.2
	MST_2	135.3	139.3bc	142.8a	137.4a	174.0a	169.5	156.7	139.2b	160.0	177.4
	MPT_0	132.5	145.1a	136.2d	130.8b	167.3bc	179.8	171.0	140.6b	163.9	180.1
	MPT_1	134.2	144.7ab	140.8ab	138.4a	174.0a	175.4	171.8	151.5a	168.6	177.9
	MPT_2	134.7	143.9ab	141.3ab	136.4a	174.1a	173.9	163.1	148.1a	165.4	177.1
0-30	Intercropping mode	ns	**	ns	ns	ns	ns	ns	ns	ns	ns
	Biochar	ns	*	**	*	*	ns	ns	ns	*	**
	Intercropping×Biochar	ns	**	*	*	*	ns	ns	ns	*	*
30-60	Intercropping mode	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
	Biochar	ns	ns	**	**	**	ns	ns	*	ns	ns
	Intercropping×Biochar	ns	*	**	*	*	ns	ns	*	ns	ns

Explanations as in Table 2.

Table 3 shows that the soil bulk density of the cultivated layer gradually increased in the early stage and later stage of the study. Table 4 shows the *SWS* value at the 0-30 cm and 30-60 cm depth in each growth period for different treatments during the two growth seasons.

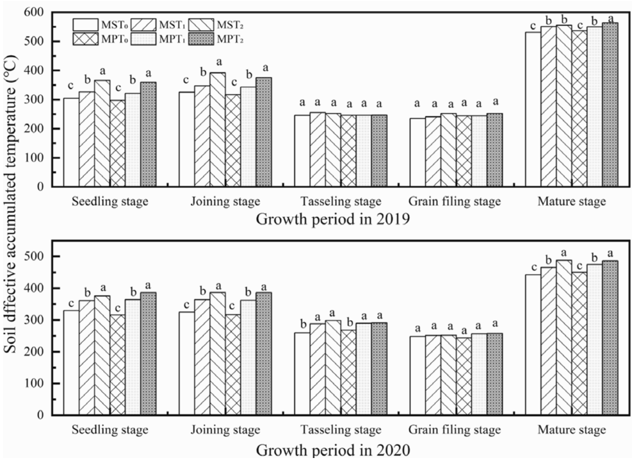

Fig. 3. Effect of biochar on the soil effective accumulated temperature at the 0-25 cm depth in different growth periods.

During the entire growth period, the *SWS* value increased with the increasing biochar content of the soil. The *SWS* at the 0-30 cm depth did not increase significantly in the seedling stage but it did increase significantly in the tasselling stage (2019) and grain filling stage (2019 and 2020). In the tasselling stage, the *SWS* value of the 0-30 cm soil depth increased by 15.5% for the treatment of the MP system in which 30 t ha^{-1} biochar was applied at a 0-30 cm depth, but there was no significant difference in 2020 according to Table 4. For different soil depths, the impact of biochar on soil water storage was mainly concentrated in the 0-30 cm layer, whereas the impact of biochar on the 30-60 cm layer was relatively weak. It may be observed that biochar mainly affected the top soil layer, and the *SWS* value was optimal at an application rate of 30 t ha^{-1}.

It may be observed from Fig. 3 that T_1 and T_2 significantly increased the soil effective accumulated temperature (SEAT) in the seedling and jointing stages. SEAT increased as the amount of biochar added increased. The maximum increase in the rate was obtained for treatment T_2 under the MP system at the seedling stage, and the increase rate was more than 20% across the two years of the study. During the tasselling and grain filling stage, biochar did not significantly impact the SEAT. In the mature period, the effect of different biochar application rates on the SEAT was significant, but the observed increase in SEAT was not as pronounced in the mature period as it was in the previous period. Indeed, the greatest increase observed in the mature stages was only 5.2%. Due to less rainfall and the leaf area index, biochar can demonstrate significant effects on SEAT in the early period of plant growth, and it was weaker in the middle and later periods when rainfall was sufficient and the *SWS* value was higher.

Figs 4 and 5 show that T_1 and T_2 significantly reduced the content of ammonium nitrogen and nitrate nitrogen in the soil at the seedling stage, for the two intercropping systems. Ammonium nitrogen was reduced on average by 36.6%, while nitrate nitrogen was reduced by 42.4% over the period of the two-year study. This shows that biochar exhibited an inhibitory effect on the soil mineral nitrogen content during the early stage of growth, which reduced the soil nutrient supply for crops. In the jointing stage, the inhibitory effect of biochar on soil nitrogen weakened, but the soil mineral nitrogen content was still lower than that of T_0. During the tasselling period, the biochar released ammonium nitrogen and subsequently increased the nitrate nitrogen in the soil. The mineral nitrogen content of the T_1 and T_2 treatments was greater than that of the T_0 treatment. During the grain filling stage, the content of ammonium and nitrate nitrogen in the soil under the T_1 and T_2 treatments were significantly higher on a continuous basis than those under T_0, and the soil ammonium and nitrate nitrogen content of the soybean (MS-S) and peanut (MP-P) ridges was significantly higher than that of the corn ridges. At the maturity stage, the soil mineral nitrogen content under the T_1 and T_2 treatments was still higher than that under T_0 conditions. It may be observed that from the early stage to the middle and late stages of growth, the effect of biochar on the soil mineral nitrogen content transitioned from adsorption to release, which was conducive to higher crop yield especially for peanut and soybean yield.

DISCUSSION

Because biochar has a rich pore structure, it provides more space for water adsorption in the soil, the application of biochar to cultivated soil can reduce soil bulk density but increase the *SWS* value and reduce water evaporation (Zhang *et al*., 2016, Verheijen *et al*., 2019). The results of this experiment show that the application of biochar in the soil at the early stage of crop growth had no significant effect on soil water storage, this mainly stemmed from lower rainfall in the early growth stage. However, the effect of soil water movement and rainfall at a later growth stage caused the water retention capacity of biochar to be realized, and the *SWS* values of the biochar treatments in the middle and late growth stages increased significantly. The conclusions above were consistent with the results of a previous study (Ouyang *et al*., 2013). Compared with the *SWS* value in the 30-60 cm soil layer, the increase in the *SWS* value of the biochar treatment in the 0-30 cm soil layer was more pronounced, which is consistent with the results of previous research (Bruun *et al*., 2014). Thus, biochar plays an important role in improving soil moisture status, which is important for rain-fed agriculture given that rainfall is a key factor affecting water-holding capacity.

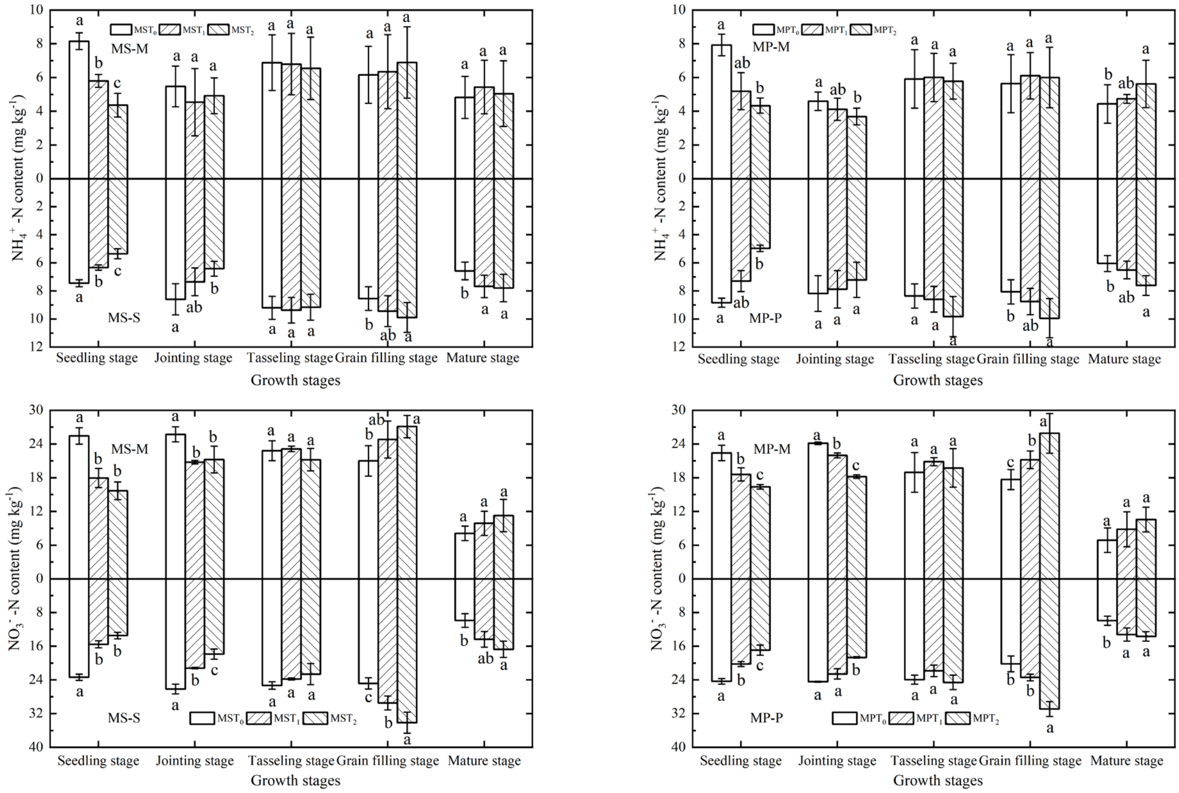

Fig. 4. Effect of biochar on the mineral nitrogen content in the intercropping systems in 2019. MS-M indicates maize ridges; MS-S indicates soybean ridges; MP-M indicates maize ridges; MP-P indicates peanut ridges.

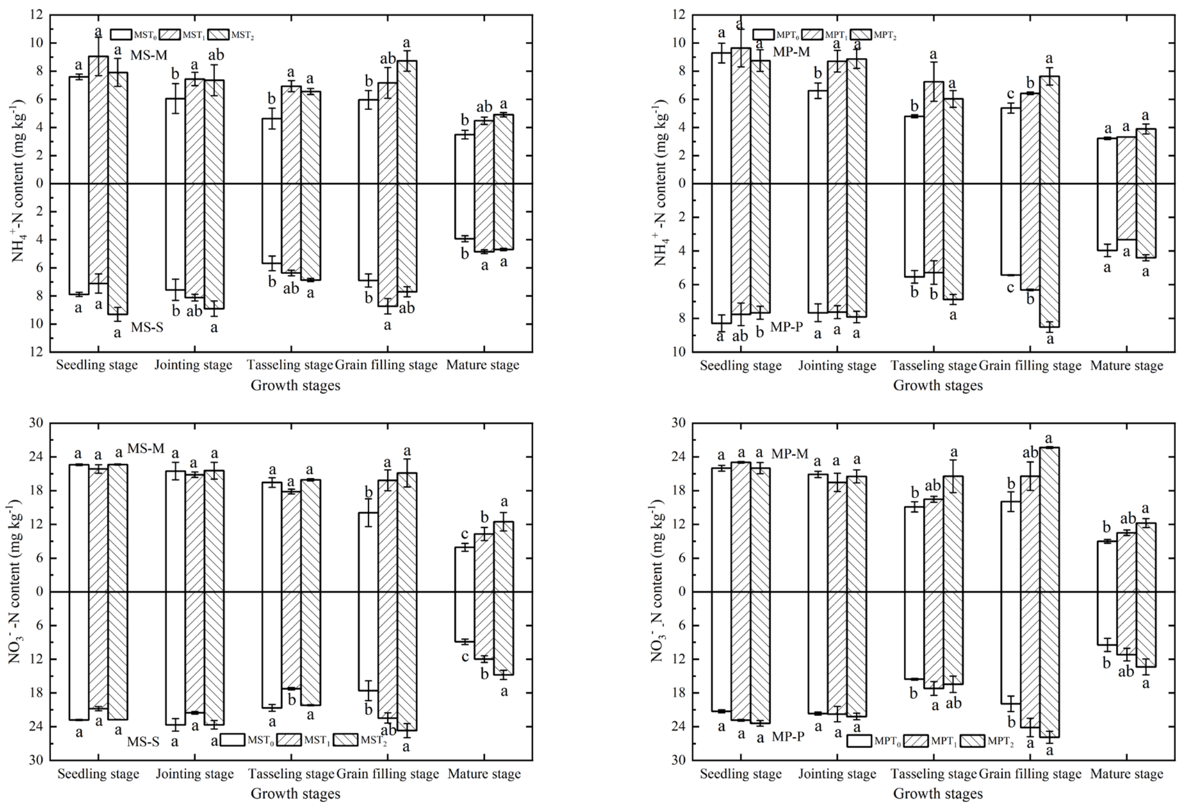

Fig. 5. Effect of biochar on the mineral nitrogen content in the intercropping systems in 2020. MS-M indicates maize ridges, MS-S indicates soybean ridges, MP-M indicates maize ridges, MP-P indicates peanut ridges.

The soil temperature is mainly driven by solar radiation. Our results show that the SEAT of biochar treatments increased significantly during the seedling and jointing stages, which mainly stemmed from the fact that the mixed application of biochar into the soil deepened the soil colour (Paz-Ferreiro *et al*., 2014). During this period, crop plants were small, and the leaves provided little shade, which permitted the soil to absorb solar radiation, leading to increases in the soil temperature. However, in the middle and late stages of crop growth under intercropping, the leaves provided extensive shading, which severely weakened the effect of soil colour on soil temperature (Sheats., 2014). Therefore, the temperature-increasing effect of biochar in the later growth period was not pronounced. Our experiments revealed that biochar had the weakest effect on SEAT during the tasselling and grain filling periods. The effect of soil temperature may also have been weakened by the increase in soil water storage associated with biochar during the tasselling and grain filling growth periods.

The soil mineral nitrogen level indicates the soil nitrogen supply capacity and can be used to evaluate soil fertility. The total nitrogen content of biochar is high, but the mineral nitrogen content is very low, it was found to be even negligible when compared with to the mineral nitrogen content in the original soil (Wu *et al*, 2020). Therefore, the performance activity of biochar to in the soil is mainly to adsorb mineralized nitrogen, rather than to supplement soil mineralized nitrogen. Also, the surface of biochar is rich in functional groups, which have the potential to adsorb soil nutrients and reduce nutrient loss. This experiment revealed that the soil mineral nitrogen content of the biochar treatment was significantly reduced in the early growth stage because of the significant absorption effect with regard to inorganic fertilizer, which was consistent with the research results by Wu *et al*. (2019). As crops grow, biochar can desorb mineral nitrogen in the soil, this results in higher soil nutrient content. Additionally, under intercropping conditions involving grasses and legumes, legumes can be used to provide nutrients for gramineous crops, and biochar can fix nutrient secretions from leguminous nodules to continuously enhance nitrogen uptake for gramineous crops (Xia *et al*., 2021). Therefore, the soil mineral nitrogen content was significantly higher for the middle and late growth stages in the biochar treatment than that in the T_0 treatment. It was also found that the soil mineral nitrogen content decreased rapidly in the middle and late growth period. There are two possible explanations for the rapid decrease in the soil mineral nitrogen content during the mature period: 1) the soil nitrogen was absorbed by crops, and 2) heavy rainfall promoted the leaching of nitrate nitrogen given that the mature period coincided with the local flooding season (Dai *et al*., 2019; Xia *et al*., 2020). Studies have shown that biochar addition increased the carbon-nitrogen ratio of the soil, as well as micronutrient elements such as B and Mo, so N uptake by leguminous crop rhizobia was also enhanced (Rondon *et al*., 2007, Guerena *et al*., 2015). By improving the absorption of N, P, and K elements in plants, biochar also inhibited cation leaching including NH_4^+, K^+, and Ca^{2+} with water (Van *et al*., 2015). This experiment also revealed that biochar treatment not only increased the mineral nitrogen content of the soil in the soybean and peanut rows but also alleviated the nutrient uptake competition between gramineous crops and legumes in the intercropping system. Li *et al*. (2006) found that biochar treatment enhanced the root interactions between the two crops in the intercropping system and increased yields. Our results show that biochar significantly increased the overall output of the intercropping system. The yields of soybeans and peanuts increased significantly, as the amount of biochar applied increased, and there was no notable difference in the corn yield between T_1 and T_2. Thus, in the MS intercropping mode, the corn yield of T_2 was less than that of T_1, which was in line with the results of a previous study (Gajda *et al*., 2016; Dai *et al*. 2019). In summary, the application of biochar can increase the output of the intercropping system under both MS and MP conditions.

CONCLUSIONS

1. The effects of biochar application on the effective accumulated temperature of soil were weakened for the middle and late growth stages. As influenced by rainfall, biochar significantly increased soil water storage in the 0-30 cm soil layer.

2. From the early stage to the middle and late stages, the effect of biochar on soil mineral nitrogen content transitioned from adsorption to release, which met the crop growth requirement.

3. The soil mineral nitrogen content of soybean and peanut ridges was significantly higher than that of the corn ridges.

4. The total yield of maize/soybean increased by 12.8-13.8% and the total yield of maize/peanut intercropping increased by 11.8-13.8% relative to the treatment without biochar.

Conflict of interest: The authors do not declare any conflict of interest

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