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Positive effects of apple branch biochar on wheat yield only appear at a low application rate, regardless of nitrogen and water conditions

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Abstract

Purpose The agriculture industry is under intense pressure to produce more food with a lower environmental impact, while also mitigating climate change. Biochar has the potential to improve food security while improving soil fertility and sequestering carbon. The aim of our research was to evaluate the effects of apple branch biochar on wheat yield and soil nutrients under different nitrogen (N) and water conditions.

Materials and methods Durum wheat was grown for nearly 6 months in pots with silt clay soil supplemented with apple branch biochar. The biochar was applied at five rates (0, 1, 2, 4, and 6% *w*/*w*; B0, B1, B2, B3, and B4), and N fertilizer was applied at three rates (0, 0.2, and 0.4 g kg^{-1}; N0, N1, and N2). From the jointing to maturation stages, the soil water content was controlled at two rates to simulate sufficient water and drought conditions (75 and 45% of field capacity; W1 and W2). After harvest, we investigated grain yield and soil nutrient status.

Results and discussion The application of biochar alone had a positive effect on wheat production and soil nutrients, especially under sufficient water conditions. Compared with the addition of N fertilizer alone, the addition of biochar at B1 and B2 combined with N fertilizer under sufficient water conditions increased the crop yield by 7.40 to 12.00%, whereas this was not the case under drought stress. Furthermore, regardless of water conditions, compared with N fertilizer application alone, a high rate of biochar application (B3 and B4) led to a significant decrease in the grain yield of approximately 6.25–21.83%. Biochar had strong effects on soil nutrients, with NO_3^- and available phosphorus contents and the C:N ratio exerting the greatest effects on wheat yield.

Conclusions The effects of biochar on wheat production and soil nutrients varied with the biochar application rate, N fertilizer application rate, and water conditions. Drought stress weakened or offset the positive effect of biochar on crop production, especially under the high-N level (N2) conditions. The optimum application combination was 1% (or possibly even less) apple branch biochar (B1) and moderate N fertilizer (N1).

Keywords Apple branch biochar · Application rate · Drought · Nitrogen · Wheat yield

1 Introduction

Wheat is the third most produced cereal after maize and rice and one of the most widely cultivated crops in the world (Alburquerque et al. 2013). However, most agricultural soils are limited in their ability to supply nutrients to crops because available ionic forms of nutrients are susceptible to loss via conversion to gaseous forms (e.g., NH_3 and N_2O), leaching (i.e., NO_3^- and ortho-P ions) and fixation or precipitation reactions (i.e., precipitation of ortho-P ions and NH_4^+ fixation) (Gul and Whalen 2016). In addition, as dry land covers 45% of the earth's surface (Schimel 2010), the availability of water resources is a major limiting factor for wheat production

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(Rockström et al. 2007). Unbalanced or excessive application of nitrogen (N) fertilizers is performed to obtain higher yields, which has caused serious environmental problems (Olmo et al. 2016). Therefore, the agriculture industry is under pressure to produce more food with a lower environmental impact (Farrell et al. 2014).

The carbon-rich by-product produced by pyrolysis in an oxygen-limited environment is termed “biochar” (Lehmann et al. 2011). Biochar has the potential to improve food security while also sequestering carbon (C) and mitigating climate change (Kuppusamy et al. 2016). The ability of biochar to improve soil physicochemical and biological qualities for crop production has been widely reported. The effects of biochar on soil include enhanced porosity; reduced bulk density and reduced evapotranspiration, which increase aeration and the water-holding capacity (Githinji 2013; Ibrahim et al. 2013; Schulz et al. 2014; Bayabil et al. 2015); improved nutrient retention through cation adsorption; alterations in soil pH (Gul et al. 2015); and changes in the soil microbial community, which can affect the activity of beneficial soil microbes and nutrient cycles that indirectly affect crop yields (Kuppusamy et al. 2016). Enhanced crop yields due to biochar application have frequently been observed in sub-boreal forests, paddies, and vegetable fields. However, in several studies, biochar has not increased crop yield (Yao et al. 2017). Furthermore, the beneficial effects of biochar on crop production are most evident when biochar is combined with mineral fertilizer (Asai et al. 2009; Schulz and Glaser 2012). For example, Alburquerque et al. (2013) found that biochar combined with mineral fertilizer led to approximately 20–30% increases in grain yield compared with the use of mineral fertilizer alone, and these results suggested that biochar can act as a source of available phosphorus. These findings and those of other studies demonstrate that the benefits of biochar amendment are variable and depend on the type of biochar, application rate, soil type, fertility status, and environmental conditions (Cranedroesch et al. 2013; Mukherjee and Lal 2014; Olmo et al. 2016). This variability and uncertainty regarding the benefits of biochar has severely limited the large-scale implementation of biochar application.

Apple branches are a widely distributed agricultural wood waste resource in China (Li et al. 2017). The potential effects of apple branch biochar used in combination with N fertilizer on wheat yield and soil nutrients under different water conditions are unclear. We hypothesized that biochar application combined with N fertilizer could enhance crop production, especially under drought conditions. Therefore, wheat was grown under different treatments (involving different biochar application rates, N fertilizer levels, and water conditions). The experimental objectives were to evaluate the effects of apple branch biochar on wheat yield and soil nutrients under different water conditions when applied either (1) alone or (2) along with N fertilizer.

2 Materials and methods

2.1 Biochar and soil characteristics

Apple branches (*Malus pumila* Mill.) were pyrolized using the dry distillation method at the Shanxi Ruixin Bioenergy Technology Development Company in Shanxi, China. The furnace temperature was ramped up from ambient room temperature to 450 °C and then maintained at this temperature for approximately 8 h. The biochar was ground and passed through a 2-mm sieve. The detailed biochar properties are shown in Table 1, and the analytical methods were previously described (Li et al. 2017).

The soil was classified as silt-clay soil according to the US Department of Agriculture system, containing 16.81, 73.02, and 10.17% clay, silt, and sand, respectively. Bulk soil was collected from the 0- to 20-cm soil layer in *Yangling*, China (34° 17′ 57″ N, 108° 04′ 06″ E) and then air-dried and ground to pass through a 2-mm sieve. The soil characteristic analyses were the same as those used in a previous report (Li et al. 2017), and the obtained values were as follows: 7.88 soil pH; 368.33 $\mu S\ cm^{-1}$ electrical conductivity; 3.32 $g\ kg^{-1}$ total organic carbon; 0.47 $g\ kg^{-1}$ total N; 18.2 $mg\ kg^{-1}$ NO_3^-; 15.90 $mg\ kg^{-1}$ NH_4^+; and 1.27 $mg\ kg^{-1}$ Olsen-P.

2.2 Wheat growth experiment

An outdoor pot growth experiment was performed with winter wheat (*Triticum aestivum* L. cv., Xiaoyan no. 22) at an experimental station of the Institute of Soil and Water Conservation (34° 17′ 55″ N, 108° 04′ 04″ E). This experimental site is

Table 1 Physical and chemical characteristics of the biochar used in this study

Surface area ($m^2\ g^{-1}$)	pH	Total C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	C:N	H ($g\ kg^{-1}$)	O ($g\ kg^{-1}$)	NO_3^-	NH_4^+	Available P
14.2217	9.67	670.15	5.70	117.57	21.71	71.79	0.52	1.86	23.68
P	K	Na	Ca	Mg	Fe	Cu	Mn	Zn	Pb
1802.1	6003.4	639.2	24,185.1	3196.5	5745.8	9.9	91.5	37.3	6.2

The units of NO_3^-, NH_4^+, available P, P, K, Na, Ca, Mg, Fe, Cu, Mn, Zn, and Pb are milligrams per kilogram located on the southern boundary of the Loess Plateau, which has a temperate semi-humid climate and a mean annual temperature of 13 °C. The complete randomized study design consisted of a factorial experiment in which the biochar application rate, N fertilizer (urea) level, and water conditions were used as the primary factors, with four replicate pots per treatment. Ten plants were cultivated in each pot. Calcium superphosphate was used as phosphate fertilizer and was applied at a rate of 0.2 g P_2O_5 kg^{-1} soil. The cylindrical plastic pots (30 cm high and 20 cm in diameter) were filled with 12 kg of either dry soil or the soil-biochar mixture. We included five biochar application rates: 0, 1, 2, 4, and 6% *w*/*w* on a dry weight basis (hereafter referred to as B0, B1, B2, B3, and B4, respectively). We also included three N fertilization levels: N0 (no urea), N1 (0.2 g kg^{-1}), and N2 (0.4 g kg^{-1}), and two water conditions: W1 (75% of field capacity during the whole growing season, simulating normal water conditions) and W2 (75% of field capacity before the jointing stage and 45% of field capacity from the jointing stage to the mature stage, simulating drought conditions during these periods).

The pots were randomly arranged outside under an open hyaline awning to facilitate the water control experiment. Wheat seeds were sown on October 15, 2015, and ten plants were left at the seedling stage. The soil moisture was adjusted to the specified treatment levels by weight and was maintained during the growing season with daily watering. The position of the pots was changed weekly to avoid the influence of microclimate variability. The wheat was harvested on May 26, 2016. During plant growth, the mean air temperature was 11.88 °C, and the monthly mean temperature is shown in Fig. S1 (Electronic Supplementary Material). After harvest, the grain weight of each pot was determined.

2.3 Analytical methods

The soil chemical properties of each treatment were determined after harvest. The soil organic carbon (SOC) content was assayed via dichromate oxidation (Nelson and Sommers 1982), and the total N (TN) content of the soil was assayed using the Kjeldahl method (Bremner and Mulvaney 1982). The available P (A-P) content was extracted with 0.5 M sodium bicarbonate and quantified using the molybdenum blue method (Jin et al. 2016). Because NO_3^- may be retained in biochar pores and likely cannot be completely extracted using standard extraction methods (Jassal et al. 2015; Kammann et al. 2015a), the NO_3^- and NH_4^+ contents were extracted by a modified method by vigorously shaking a fresh sample (10 g) with 40 ml of 2 mol L^{-1} KCl at 60 °C for 60 min. After the extract was filtered, the NH_4^+ and NO_3^- concentrations were measured using a continuous flow analytical system (Autoanalyzer 3, Bran+Luebbe, Germany) (Haider et al. 2016).

2.4 Statistical analysis

A multi-way ANOVA was performed at the $P < 0.05$ significance level to assess the significant differences among the different rates of biochar addition, N fertilizer levels, and water conditions as well as their interactions. Correlations were analyzed using the Pearson test (two-tailed, $P < 0.05$). All statistical analyses were performed with SPSS 20.0 software (SPSS Inc., Chicago, IL, USA).

3 Results and discussion

When biochar was applied alone (under N0 conditions), the wheat yield was affected by both the biochar application rate and water conditions ($P < 0.05$). Compared with production in control soil under the same water conditions, the addition of biochar to the soil in the absence of N fertilization increased wheat grain production by 14.77 to 43.02%, with the exception of the N0W1B4 and N0W2B3 treatments (Fig. 1(a)). Furthermore, under N0W1 conditions, the yields of B2, B3, and B1 were significantly higher than that of B0 by 43.02, 29.76, and 21.29% ($P < 0.05$), respectively. Under N0W2 conditions, the yields of B2 and B4 were significantly higher than that of B0 by 24.26 and 23.31% ($P < 0.05$), respectively (Fig. 1(a)).

However, the yield increases in the biochar-treated soils relative to the control soil were clearly lower than the

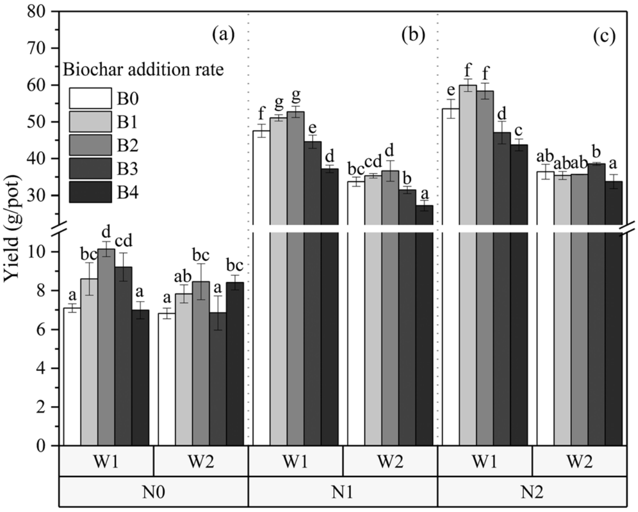

Fig. 1 Effects of biochar on the wheat grain yield. B0, B1, B2, B3, and B4 refer to no biochar input and the incorporation of biochar into the soil at 1, 2, 4, and 6% by mass, respectively. W1 and W2 refer to soil water contents of 75 and 45% of field capacity, respectively (from the wheat jointing stage to the mature stage). N0, N1, and N2 refer to no-urea conditions and urea addition at 0.2 and 0.4 g kg^{-1}, respectively. The vertical bars in the figures represent the standard errors of the means ($n = 4$). Bars with the same letter show no significant difference at $P < 0.05$

increases observed with the use of N fertilizer alone, which were 570.66% (N1) and 655.01% (N2) under W1 conditions and 394.86% (N1) and 434.65% (N2) under W2 conditions (Fig. 1). The increase in the N nutrient status of the soil due to N fertilizer addition resulted in an increase in the wheat yield. This finding indicates that the N0 soils presented nutrient limitation; thus, although biochar contains many nutrients (Table 1), it might not act as a sufficient source of immediately available nutrients to wheat, regardless of the biochar application rate or water conditions. These results are consistent with those of previous studies in which crop yields exhibited a limited response to biochar application alone (Zwieten et al. 2010; Alburquerque et al. 2013).

Interestingly, biochar application at low rates (B1 and B2) combined with N fertilizer (N1 and N2) enhanced crop productivity, especially under sufficient water conditions (W1) (Fig. 1(b, c)). The biochar application rate, N fertilization level, water conditions, and their interactions had significant effects on the wheat yield ($P < 0.05$; Table 2). Furthermore, under N1W1 conditions, B1 and B2 significantly enhanced the wheat yield by 7.40 and 10.87%, respectively, compared with B0N1W1. Under N1W2 conditions, compared with B0N1W2, B1 and B2 increased the grain yield by 4.72 and 8.64% ($P < 0.05$), respectively (Fig. 1(b)). Under N2W1 conditions, the highest wheat grain production was obtained in the B1N2W1 treatment ($P < 0.05$), which resulted in an increase of 11.99% ($P < 0.05$) relative to B0N2W1 (Fig. 1(c)). However, under N2W2 conditions, biochar had no significant effect on the grain yield, regardless of application rate (Fig. 1(c)). Our results suggest that in drought-affected areas, the positive effects of biochar on wheat grain production may be limited because they are highly dependent on both water conditions and N fertilization levels, although the internal porosity of biochar may help to increase the water-holding capacity and soil available water capacity for plants (Hansen et al. 2016). Furthermore, a synergistic effect of biochar and N fertilizer was only observed at low biochar application rates (B1 and B2), whereas high biochar application rates (B3 and B4) offset or even blocked the positive effect of N fertilizer on crop production, thereby considerably reducing the wheat yield (Fig. 1(b, c)). Under sufficient water conditions, compared with the use of the N fertilizer alone, B3 and B4 resulted in decreases in the grain yield of approximately 6.12–25.23%, whereas under drought conditions, B3 and B4 led to 6.71 and 19.14% ($P < 0.05$) decreases in the grain yield, respectively.

The detected increases in nutrient efficiency after biochar amendment were primarily related to greater nutrient retention (Kammann et al. 2015b), an increased water-holding capacity (Laird et al. 2010), nutrient immobilization caused by liming effects (Brassard et al. 2016), and enhanced soil biological properties, such as a more favorable root environment and microbial activities that favor nutrient availability (Olmo et al. 2016). However, excessively high amounts of biochar can inhibit plant growth, which might be related to N immobilization caused by high contents of volatiles as well as toxic and harmful substances and reduced levels of microbial activity and nutrient uptake (Ding et al. 2016; Spokas et al. 2011). Additionally, wheat production generally did not increase/decrease with the biochar application rate, which was consistent with the findings of previous studies. For example, Uzoma et al. (2011) found that the maize grain yield significantly increased by 150 and 98% after biochar application at 15 and 20 t ha^{-1}, respectively, compared with the control. Asai et al. (2009) observed that the application of biochar at 4, 8, and 16 t ha^{-1} decreased the grain yield by 23.3, 10, and 26.7%, respectively. These findings indicate that the biochar-soil interaction is complicated and that the mechanism through which biochar influences wheat production can vary depending on the biochar application rate and soil nutrient status.

Furthermore, the cost benefits of biochar application methods in agricultural systems is heatedly debated. For example, although industrialization of biochar production and biochar product use for agriculture have been promoted in China (Pan et al. 2015), China's current bioelectricity subsidy

Table 2 Primary effects of the biochar application rate (B), N fertilization level (N), and water conditions (W) on the yield and soil nutrient variables

Parameter	B	N	W	B × N	B × W	N × W	B × N × W	R^2
Yield	2.2**	81.0**	8.1**	1.0**	0.7**	3.7**	0.5**	97.2
SOC	95.9**	0.1NS	0.1NS	0.6*	0.0NS	0.0NS	0.3NS	97.1
TN	72.3**	20.6**	0.0NS	0.75*	0.0NS	0.2*	0.3NS	93.3
C:N ratio	85.5**	8.6**	0.5**	2.6**	0.1NS	0.0NS	1.3**	98.6
NO_3^-	2.5**	90.7**	0.2**	5.0**	0.4**	0.2**	0.7**	99.8
NH_4^+	21.2**	29.2**	10.0**	14.0**	7.4**	5.4**	8.9**	96.1
PO_4^{3-}	48.7**	88.6**	43.8**	16.3**	41.1**	64.8**	34.5**	90.1

The proportion of the explained variance (SS_x/SS_{total}) and the level of significance for each factor and their interactions are indicated. R^2 is the percentage of total variance explained by the model. SOC and TN are the soil organic carbon content and soil total nitrogen content, respectively

NS not significant

$^*P < 0.05$; $^{**}P < 0.001$

scheme makes gasification more financially attractive for investors than pyrolysis (Clare et al. 2015). Therefore, Yao et al. (2015) suggested that a high application rate of 10 t ha^{-1} may not return a profit to the farmer, due to the high cost of biochar, although utilization of biochar at high application rates can increase soil C and crop yields, decrease greenhouse gas emissions and reduce nutrient run-off from soils. However, Mohammadi et al. (2017) reported that converting residues to biochar and application at the maximum beneficial rate (18 t ha^{-1}, similar to B1 in our study) enhanced the net present value of rice production by 12% after 8 years of application relative to the traditional practice of open burning of rice residues. Furthermore, many recent studies have indicated that the use of biochar compound fertilizer (in which biochar is applied at a lower dose as an ingredient) would help achieve greater agronomic and economic benefits (Joseph et al. 2013; Qian et al. 2014; Zheng et al. 2017). In this study, the finding that the wheat yield was enhanced only by the B1 and B2 combined with N fertilizer application indicated that apple branch biochar is much more cost-effective at a low application rate. Moreover, considering economic feasibility for farmers, more attention should perhaps be paid to the effects of low-dosage biochar application (e.g., less than 1 t ha^{-1}) on crop productivity. In addition, using apple branch biochar to produce compound fertilizer may be an option for achieving high economic benefits for farmers. Ultimately, increasing the agronomic value of biochar is essential for the pyrolysis scenario to compete as an economically viable, cost-effective mitigation technology (Clare et al. 2015).

3.1 Changes in soil nutrients

The beneficial effects of biochar addition on crop production may be determined by changes in soil properties and nutrient availability (Sohi et al. 2010). Many studies have indicated that incorporating biochar into soil can improve the soil structure and enhance water retention (Baiamonte et al. 2015; Ding et al. 2016). In addition, biochar contains various organic and inorganic forms of N and P, including NO_3^-, NH_4^+, and ortho-P (Gul and Whalen 2016), which may also contribute to the beneficial effects. In the present study, the addition of biochar alone increased the levels of some soil available nutrients. Under N0W1 conditions, compared with B0, the biochar treatments (except for B4) increased the NO_3^- content by 48.66–256.49% (Fig. 2(a1)) and the A-P content by 32.34–51.41% (except for B2; Fig. 2(c1)). The NH_4^+ content of B1 was higher than that of B0 by 46.42% ($P < 0.05$; Fig. 2(b1)). However, under N0W2 conditions, compared with B0, the other biochar treatments resulted in A-P content decreases of 13.70–35.13% ($P < 0.05$; Fig. 2(c1)); B2 and B4 yielded NO_3^- decreases of 72.52 and 85.53% ($P < 0.05$; Fig. 2(a1)), respectively, and B2 resulted in a significant decrease in NH_4^+ of 18.38% ($P < 0.05$; Fig. 2(b1)). These results indicated that

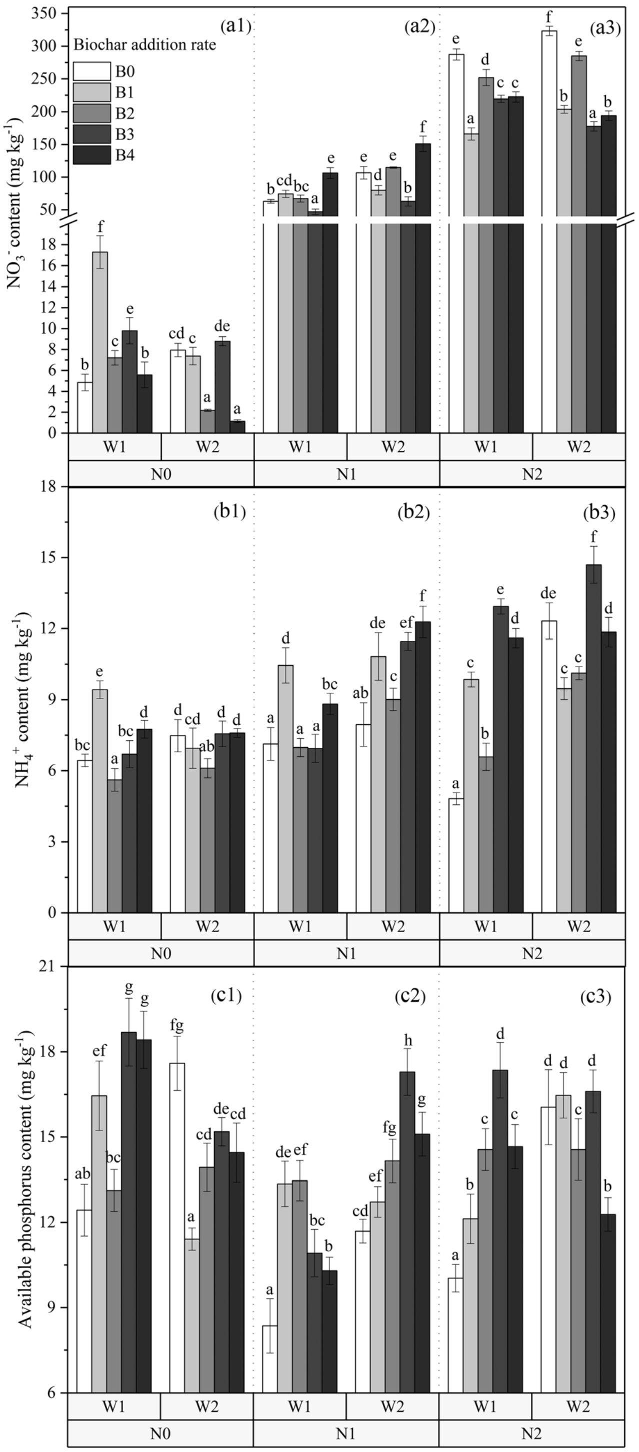

Fig. 2 Soil nitrate content, soil ammonium content, and soil available P content observed in the different treatments. B0, B1, B2, B3, and B4 refer to no biochar input and the incorporation of biochar into the soil at 1, 2, 4, and 6% by mass, respectively. W1 and W2 refer to soil water contents of 75 and 45% of field capacity, respectively (from the wheat jointing stage to the mature stage). N0, N1, and N2 refer to no-urea conditions and urea addition at 0.2 and 0.4 g kg^{-1}, respectively. The vertical bars in the figures represent the standard errors of the means ($n = 4$). Bars with the same letter show no significant difference at $P < 0.05$

under drought conditions, biochar addition decreased the availability of nutrients, possibly due to nutrient adsorption by the polyporous biochar.

Overall, the NO_3^-, NH_4^+, and A-P contents of the soil were affected by the biochar addition rate, N fertilizer level, water conditions, and their interactions (Table 2). A positive correlation was observed between the NO_3^- content and wheat yield (Table 3). Noticeably, under N2 conditions, biochar application led to decreases in the NO_3^- content of the soil under both the sufficient water and drought conditions of 11.88 to 45.20% relative to the B0N2 soil (Fig. 2(a3)). Previous studies have suggested that the availability of nutrients to plants may be limited because of the characteristics of biochar (i.e., low N content, negligible inorganic matter content, and high C:N ratio) (Rajkovich et al. 2012; Alburquerque et al. 2013), which may result in biochar application offsetting N fertilizer effects (Asai et al. 2009). A negative correlation was also observed between the C:N ratio and yield in our study ($P < 0.05$; Table 3). The C:N ratio under the biochar application treatments increased with the biochar application rate and was higher than that of the B0 treatment by 46.72–174.28% ($P < 0.05$; Fig. 3(c)). The increased C:N ratio caused microbial N immobilization and decreased the extractable NO_3^- contents, which has been noted in previous studies (Sdc et al. 2012; Brassard et al. 2016). In addition, the lack of pretreatment (e.g., composting or loading nutrients) of the biochar would render it reactive towards nutrients in a soil-fertilizer system, making it a competitor for, rather than provider of, nutrients for plant growth (Joseph et al. 2018). For example, Kammann et al. (2015b) observed that scrap wood biochar applied at a rate of 2% (*w*/*w*) with mineral fertilization significantly reduced the above-ground biomass yield of *Chenopodium quinoa* to 60% of that of an equally fertilized control; conversely, amendment with 2% (*w*/*w*) co-composted biochar increased the biomass yield up to 305% compared with that of the control. Hence, these authors demonstrated that co-composting considerably promoted the positive effects of biochar, largely via nitrate capture and delivery.

However, under N1 conditions, regardless of water conditions, the B4 treatment increased the $NO3^-$ content of the soil compared with the B0N1 treatment (Fig. 2(a2)), which suggests that net N mineralization and/or nitrification in the soil was enhanced under these biochar treatments (Yoo et al. 2014). In addition, Li et al. (2017) conducted a 108-day incubation experiment to investigate the effects of apple branch biochar on the nutrients and enzyme activities involved in N cycling, and they found that biochar exerted a positive effect on N-acetyl-β-glucosaminidase and urease activity in N-fertilized soil. These results indicated that biochar has the potential to increase the available N content for plants and enhance the effects of N fertilizer, although these changes are dependent on the N fertilizer and biochar application rates. Additionally, biochar exhibits a strong ability to absorb NO_3^- and NH_4^+ (Yoo et al. 2014; Eykelbosh et al. 2015) and can prevent nutrient losses by leaching (Pratiwi et al. 2016). However, in pot-based experiments, nutrient leaching losses do not occur, but biochar adsorption may limit N availability (Alburquerque et al. 2013), which could cause the underestimation of the beneficial effects of biochar. Furthermore, regardless of water conditions, the B1 treatment increased the wheat yield and A-P under both N1 and N2 conditions. Previous studies have suggested that the increase in alkaline phosphatase activity caused by the addition of apple branch biochar contributes to an increase in the A-P content (Li et al. 2017). Thus, biochar addition may provide a source of A-P and promote A-P generation, with beneficial effects on crop production (Alburquerque et al. 2013).

The SOC content increased with the biochar application rate (Fig. 3(a)) by 84.38–403.25% compared with that of the B0 treatment ($P < 0.05$), regardless of N and water conditions. Biochar presents a porous carbonaceous structure and an array of functional groups (Lehmann and Joseph 2009). When biochar is applied to the soil, these carbons can be sequestered in the soil for long periods of time, estimated at more than 1000 years (Brassard et al. 2016). However, recent studies have shown considerable variations in the soil respiration responses to biochar application and N conditions (Lu et al. 2014; Sui et al.

Table 3 Pearson correlation coefficients of the yields and studied soil nutrient variables

	Yield	SOC	TN	C:N	NO_3^-	NH_4^+	PO_4^{3-}
Yield	1	− 0.105	0.327	− 0.363*	0.632**	0.289	− 0.362*
SOC	− 0.105	1	0.869**	0.935**	− 0.06	0.319	0.267
TN	0.327	0.869**	1	0.665**	0.320	0.539**	0.162
C:N ratio	− 0.363*	0.935**	0.665**	1	− 0.304	0.126	0.365*
NO_3^-	0.632**	− 0.06	0.320	− 0.304	1	0.437*	0.015
NH_4^+	0.289	0.319	0.539**	0.126	0.437*	1	0.353
PO_4^{3-}	− 0.362	0.267	0.162	0.365*	0.015	0.353	1

SOC and TN are the soil organic carbon content and soil total nitrogen content, respectively

*$P < 0.05$; **$P < 0.001$

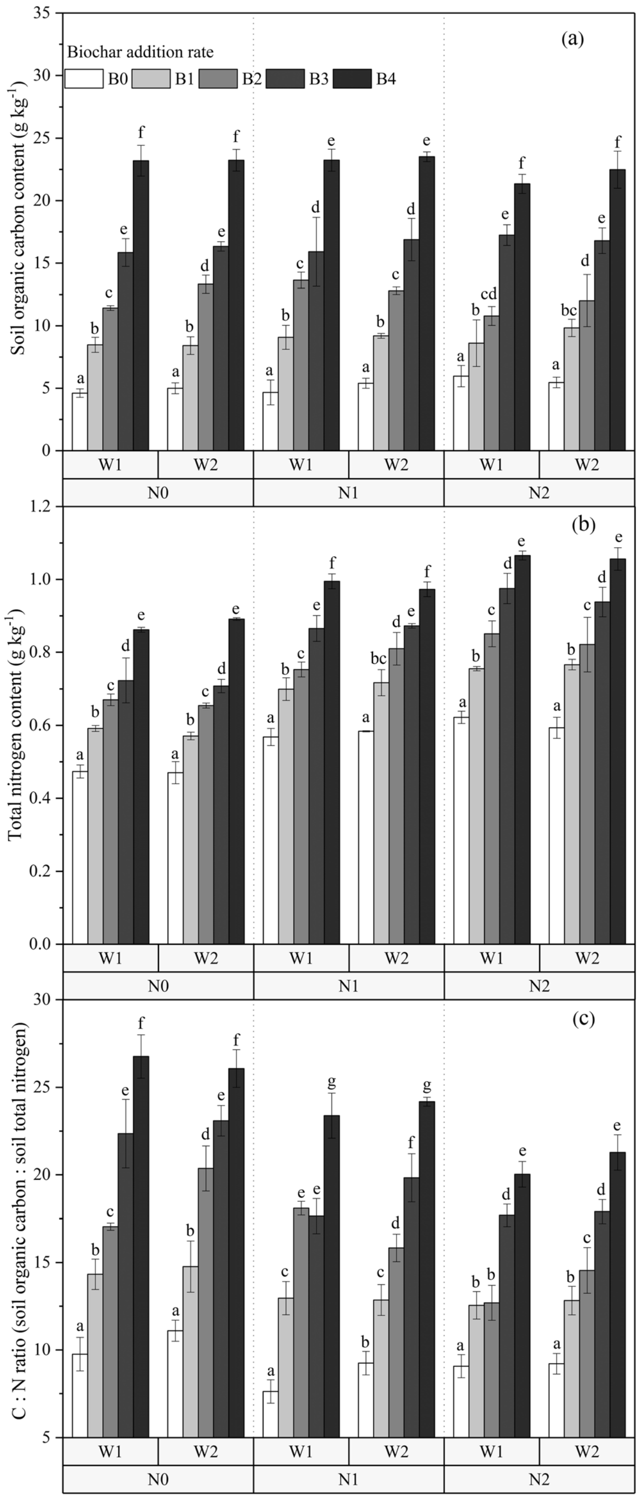

Fig. 3 Soil organic C content, soil total nitrogen content, and C:N ratio in the different treatments. B0, B1, B2, B3, and B4 refer to no biochar input and the incorporation of biochar into the soil at 1, 2, 4, and 6% by mass, respectively. W1 and W2 refer to soil water contents of 75 and 45% of field capacity, respectively (from the wheat jointing stage to the mature stage). N0, N1, and N2 refer to no-urea conditions and urea addition at 0.2 and 0.4 g kg^{-1}, respectively. The vertical bars in the figures represent the standard errors of the means ($n = 4$). Bars with the same letter show no significant difference at $P < 0.05$

2016) and have indicated that biochar can act as either a C sink or source (Zimmerman et al. 2011). Nevertheless, our previous work showed that the application of apple branch biochar at rates of 2 and 4% increased the C mineralization rate, whereas the application of 1% biochar decreased the C mineralization rate, regardless of the N level (Li et al. 2017). Therefore, the economic value of biochar application at a low rate as a soil amendment may also benefit from its carbon sequestration potential (direct and indirect) (Galinato et al. 2011). The TN content increased with the biochar application rate (Fig. 3(b)), which was similar to the results for SOC, and these variables exhibited higher values than under B0 by 21.28–89.36% ($P < 0.05$), regardless of water conditions. The biochar contained 67% C and 0.57% N, which were much higher levels than in the soil (0.03% C and 0.005% N) and resulted in linear increases in the SOC and TN. These results indicate that biochar has the potential to sequester C and release large amounts of N over a large timescale (Mukherjee and Zimmerman 2013).

4 Conclusions

The addition of biochar alone had a positive effect on wheat production, but this effect was clearly weaker compared with that of N fertilization. Compared with N fertilizer alone, the synergistic effect of biochar and N fertilizer in enhancing wheat production was only observed at low biochar application rates (B1 and B2), which resulted in an increment in the yield of 7.40–12.00%, but drought stress mitigated these positive effects. In contrast, compared with the no-biochar treatments, biochar application at high rates (B3 and B4) combined with N fertilizer resulted in a reduction in the wheat yield of 6.25–21.83%.

Biochar had a considerable influence on soil nutrients, and the most relevant effect on the wheat yield was exerted by the NO_3^- and available phosphorus contents and the C:N ratio. The increased NO_3^- and available phosphorus contents observed in B1 and B2 under specific N and water conditions contributed to the enhanced yields. However, the biochar captured NO_3^-, and the unintended transport of NO_3^- and the high C:N ratio under B3 and B4 may be the direct reasons for the reduced wheat yield. Additionally, the SOC and TN contents dramatically increased with the biochar application rate, indicating that biochar has the potential to sequester C and release large amounts of N over a large timescale.

Overall, the application of apple branch biochar at a low application rate may not only enhance wheat yields through improved nutrient availability but also mitigate global warming through carbon capture and fixation, thereby contributing to more sustainable agriculture.

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