Agriculture, Ecosystems and Environment 276 (2019) 21–30

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Combined biochar and nitrogen fertilization at appropriate rates could balance the leaching and availability of soil inorganic nitrogen

Shuailin Li[a,b,1], Shuo Wang[c,1], Zhouping Shangguan[a,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Shaanxi 712100, China

[b] University of Chinese Academy of Sciences, Beijing 100049, China

[c] Institute of Vegetables, Tibet Academy of Agriculture and Animal Husbandry Sciences, Lhasa, 850032, China

ARTICLE INFO

Keywords:
Nitrate capture
Ammonium
N retention
Ion exchange membranes
Dryland farming
Wheat

ABSTRACT

Biochar has been proposed to ameliorate soil properties and plant growth. However, it remains unclear how the interaction between biochar and nitrogen (N) fertilizer impacts soil inorganic nitrogen (SIN) leaching and availability in dryland systems. Therefore, a two-year field experiment was carried out on the Loess Plateau in northern China to study the effects of biochar combined with N fertilizer on the leaching and availability of SIN. Biochar applied at 0, 20 and 40 t ha^{-1} (B0, B1 and B2, respectively) interacted with three N fertilization levels (0, 120 and 240 kg N ha^{-1}; N0, N1 and N2, respectively). Winter wheat (*Triticum aestivum* L.) was cultivated in a winter wheat-summer fallow cropping system. We measured wheat aboveground biomass and residual SIN in the soil profile (0–60 cm at 10 cm intervals) using standard extraction methods (2 M KCL, shaking at 25 °C for 1 h). Additionally, to ascertain whether field-aged biochar captured SIN and to determine residual SIN availability, we also used a modified extraction method (2 M KCL, shaking at 60 °C for 2 h) and ion exchange membranes (IEMs) to extract SIN from plow layer soil (0–20 cm). Our results indicated that biochar application alone in the absence of N fertilization had no significant effect on wheat biomass or residual SIN in the soil profile. However, compared with the application of N fertilizer alone, the application of biochar at 20 t ha^{-1} combined with N fertilizer not only increased wheat biomass by 12.2–13.8% but also significantly decreased residual NO_3^--N in the subsoil by 13.2–74.7%. Nevertheless, long-term N fertilization at 240 kg N ha^{-1} led to large amounts of residual NO_3^--N without a significant increase in crop biomass, which inevitably increased the risk of leaching during the fallow period. Although the application of biochar at 40 t ha^{-1} combined with N fertilizer more effectively decreased residual SIN in the subsoil, this approach was impractical because it decreased wheat biomass. Furthermore, the difference between NO_3^--N extracted via the modified method and via the standard method increased with biochar application under each N level. Thus, field-aged biochar absorbed a certain amount of NO_3^--N, thereby sequestering N in the soil after two years of N fertilization. Hence, biochar could reduce the residual NO_3^--N available for leaching during the fallow period. However, notably, overuse of biochar could reduce the amount of NO_3^--N available not only for leaching but also for crops. Ultimately, the application of biochar at 20 t ha^{-1} combined with N fertilization at 120 kg N ha^{-1} is a promising dual-win strategy for improving N availability while concurrently mitigating SIN leaching.

1. Introduction

Biochar is a carbonaceous product obtained by heat-treating biomass under conditions of limited or no oxygen (O) (i.e., pyrolysis) (Mukherjee and Zimmerman, 2013). Because of its interactions with plant-soil-microbial components, biochar has been used to improve soil properties and plant growth (Major et al., 2010; Zheng et al., 2013; Sika and Hardie, 2014). Additionally, biochar adsorbs nutrients, increases the soil water-holding capacity and enhances soil microbial community structure, all of which contribute to increased nitrogen (N) retention (Zheng et al., 2013; Xu et al., 2016; Haider et al., 2017). However, reports concerning the leaching and availability of soil inorganic nitrogen (SIN) after biochar application are contradictory (Thi Thu Nhan et al., 2017).

* Corresponding author at: Xinong Rd. 26, Institute of Soil and Water Conservation, Yangling, Shaanxi 712100, China.
E-mail address: shangguan@ms.iswc.ac.cn (Z. Shangguan).

[1] These authors contributed equally to this work and should be considered co-first authors.

https://doi.org/10.1016/j.agee.2019.02.013
Received 5 October 2018; Received in revised form 16 February 2019; Accepted 19 February 2019
0167-8809/

Increases in N availability in response to biochar addition are generally attributed to increased soil pH, reduced soil tensile strength and increased soil water-holding capacity (Gul et al., 2015). In addition, biochar usually increases plant biomass and N uptake in acidic soils but has little effect in neutral or alkaline soils (Liu et al., 2018). In contrast, biochar reduces N availability by increasing the available surface area, which leads to N adsorption, and by increasing the carbon (C):N ratio, which leads to N immobilization (Gul and Whalen, 2016). The main implications of this pattern may lead to decreases in both SIN availability and leaching (Thi Thu Nhan et al., 2017). However, the application of biochar combined with N fertilizer can offset N deficiencies caused by N immobilization (Prommer et al., 2014; Thi Thu Nhan et al., 2017). Studies have shown that the nutrient supply capacity of biochar in combination with N fertilizer is greater than that of biochar or N fertilizer alone (Schulz et al., 2013; Agegnehu et al., 2016). For example, Agegnehu et al. (2016) reported that, compared with the application of N fertilizer alone in an acidic Eutric Nitisol, the application of acacia biochar at 10 t ha^{-1} combined with N fertilizer resulted in a slight increase in biomass, indicating increased N availability. In addition, the results of our previous simulation studies showed that apple branch biochar applications at less than 2% (w/w, approximately 40 t ha^{-1}) not only increased wheat yields (Li and Shangguan, 2018) but also significantly mitigated SIN leaching losses in a neutral silty clay soil (Li et al., 2018).

However, the available scientific evidence on this topic has been obtained mostly from short-term (< 6 months) incubation or soil column experiments, while results from long-term field studies focusing on the availability and leaching of SIN are lacking (Sorrenti and Toselli, 2016). Considering that the benefits of biochar vary with soil type, application rates of biochar and mineral fertilizer, and experimental conditions (Thi Thu Nhan et al., 2017; Liu et al., 2018), a better understanding of the long-term effects of combinations of biochar and N fertilization on the availability and leaching of SIN in natural dryland field conditions is necessary.

Fallow tillage methods play a major role in improving soil water storage in dryland agricultural systems (Sun et al., 2018). On the Loess Plateau of China, winter wheat is usually planted in early October and harvested in early June, while more than 60% of the annual rainfall occurs in the fallow season (Xiao et al., 2017). Therefore, most of the residual SIN in the soil is leached by this concentrated precipitation (Li et al., 2014; Dai et al., 2016). In addition, Dai et al. (2016) reported that N fertilization levels significantly affected NO_3^--N leaching, mainly from the topsoil. However, limited information is available about the effects of biochar on residual SIN and its availability for leaching under different N levels, which is important for N management in the field. SIN in the soil is typically quantified by extraction with 2 M KCl and shaking at 25 °C for 1 h (Keeney and Nelson, 1982). However, standard extraction methods may underestimate the NO_3^--N stocks of biochar-soil mixtures (Haider et al., 2016), and more than 50% of total NO_3^--N can potentially be released in subsequent extractions (Hagemann et al., 2017). Hence, a large amount of SIN may be captured by biochar and sequestered in the soil. The IEM method may provide a reliable measure of nutrient exchangeability over a range of soils and can accurately predict SIN availability (Johnson et al., 2005; Qian and Schoenau, 2007; Cambouris et al., 2014). Thus, a modified extraction method could be used to ascertain whether field-aged biochar captures SIN, and IEMs could be used to examine the availability of residual SIN.

On the basis of the above information, we conducted a two-year biochar field experiment on the Loess Plateau of northern China. We hypothesized that combining biochar and N fertilizer might increase N availability and mitigate leaching. In addition, biochar could capture SIN, especially in high-biochar-application-rate treatments, thus reducing residual SIN exchangeability. The specific objectives of this research were to (1) study the long-term effects of combining biochar with N fertilizer on SIN leaching and availability in the field; (2) determine whether field-aged biochar retains SIN; and (3) assess the effects of biochar on the availability of residual SIN under different N levels.

Table 1
Initial characteristics of the soil.

pH	CEC (cmol kg^{-1})	Clay	Silt	Sand	SOC	Total N
7.99	21.01	250.3	679.3	70.3	13.15	0.73
Total P	Total K	NO_3^--N	NH_4^+-N	Available P	Available K	
0.82	16.55	3.02	2.57	13.92	206.2	

Note: CEC is the cation exchange capacity. Clay < 0.002 mm, silt 0.002-0.05 mm, sand.0.05–2 mm. SOC is the soil organic carbon. The units of clay, silt, sand, SOC, total N, total P and total K are grams per kilogram. The units of NO_3^--N, NH_4^+-N, available P and available K are milligrams per kilogram.

2. Materials and methods

2.1. Experimental site, soil and biochar

This field experiment was conducted from October 2015 to July 2017 in Yangling, Shaanxi, China (34°18′15″ N, 108°02′30″ E; 530 m elevation). The experimental site is located in the southern region of the Loess Plateau. The climate of the area is characterized as semihumid, with a mean annual precipitation of 599 mm (2016–2017), of which more than 70% occurs between June and October (Fig. S1).

The soil (0–20 cm layer) physical and chemical properties determined before the experiment are shown in Table 1. The soil type is a Lou soil (Eum-Orthic Anthrosol) and is considered silty clay according to the USDA system. The soil pH was measured with a pH meter at a soil to water ratio of 1:2.5 (w/v). The cation exchange capacity (CEC) was measured via the ammonium acetate compulsory displacement method (Gaskin et al., 2008). The soil organic C content was assayed via dichromate oxidation (Nelson et al., 1982), and the total N content of the soil was assayed using the Kjeldahl method (Bremner and Mulvaney, 1982). NO_3^--N and NH_4^+-N were extracted by shaking for 1 h with a 2 M KCl solution and analyzed via flow injection analysis (TRAACS 2000, Bran and Luebbe, Norderstedt, Germany). The total phosphorus (P) content of the soil was determined using the molybdenum blue method after digestion with H_2SO_4-$HClO_4$ at 300 °C for 2 h (Qian et al., 2013). Available P was extracted with 0.5 M sodium (Na) bicarbonate and quantified using the molybdenum blue method (Jin et al., 2016). Soil total potassium (K) was quantified by digesting the soil samples in a mixture of HF and $HClO_4$, and soil available K was measured via the neutral ammonium acetate extraction method (Bolland et al., 2002). The concentration of K in the digest or leachate was then measured by atomic absorption spectrophotometry (ICE 3000, Thermo, USA).

Apple (*Malus pumila* Mill.) branches constituted the feedstock for biochar production. The furnace temperature was increased from ambient room temperature to 450 °C at a rate of 30 °C min^{-1}, after which the temperature was maintained at 450 °C for approximately 8 h. The biochar was ground and subsequently passed through a 5 mm sieve for use. The physicochemical properties of the biochar are shown in Table 2, and the applied measurement methods have been described previously (Li et al., 2017). Briefly, the pH was measured with a pH meter at a biochar to water ratio of 1:2.5 (w/v). The specific surface area of the biochar was assessed using the Brunauer-Emmett-Teller (BET) method (Micro ASAP2460, Micromeritics, USA), and the electrical conductivity (EC) was determined in a 1:5 (w/v; g cm^{-3}) biochar:water mixture. The concentrations of elemental C, N, hydrogen (H) and O in the biochar were determined using an elemental analyzer (Flash 2000, Thermo Fisher, USA). After the biochar was digested by aqua regia (produced by mixing nitric acid and hydrochloric acid together at a volumetric ratio of 1:3), the total K, P, Na, calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn) and lead (Pb) contents were measured using an inductively coupled

Table 2
Physical and chemical characteristics of the biochar used in this study.

Surface area (m^2 g^{-1})	pH	CEC (cmol kg^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})	C:N	H (g kg^{-1})	O (g kg^{-1})	Total P	Total K
14.22	9.67	34.65	670.15	5.70	117.57	21.71	71.79	1802.1	6003.4
NO_3^--N	NH_4^+-N	Available P	Na	Ca	Mg	Fe	Cu	Mn	Zn
0.52	1.86	23.68	639.2	24185.1	3196.5	5745.8	9.9	91.5	37.3

Note: CEC is the cation exchange capacity. The units of total P, total K, NO_3^--N, NH_4^+-N, available P, Na, Ca, Mg, Fe, Cu, Mn and Zn are milligrams per kilogram.

plasma (ICP) optical spectrometer (Vista Axial, Varian Medical Systems, USA). Available P was extracted with 0.5 M Na bicarbonate and quantified using the molybdenum **blue** method (Jin et al., 2016). Additionally, scanning electron microscopy (SEM) images (JSM-6360 LV, JEOL, Japan) were used to examine cross-sections of the biochar samples, which exhibited an definitive tubular pore structure (Fig. S2). The variability in functional groups of the biochar was investigated via Fourier transform infrared (FTIR) spectroscopy (Vertex 70 FTIR, Bruker Corporation, Germany) (Fig. S3).

2.2. Experimental design

This study used a randomized block design that included two experimental factors. Biochar was applied at 0, 20 and 40 t ha^{-1} (B0, B1 and B2, respectively, hereafter); N (in the form of urea) was applied at 0, 120 and 240 kg N ha^{-1} (N0, N1 and N2, respectively, hereafter). Only winter wheat (*Triticum aestivum* L. cv. Xiaoyan No. 22) was cultivated, and each treatment was replicated three times. Each plot had an area of 16 m^2 (i.e., 4 × 4 m), and the plots were separated by pathways that were 0.5 m wide to avoid cross-contamination and treatment effects. Biochar was manually added to the plow layer soil (0–20 cm) once using a shovel until mixing occurred before sowing in October 2015. Basal applications of urea to the plow layer soil were performed once a year before sowing (i.e., in mid-October 2015 and 2016). No tillage occurred during the growth stage, although weeds were regularly removed by hand. Wheat was harvested manually at maturity on 28 May 2016 and 2 June 2017 by cutting the aboveground biomass at the soil level, and the four central rows of plants were then oven dried to a constant weight at 65 °C to determine the total aboveground biomass. During the experiment, natural rainfall was the sole water supply, and the fallow period lasted from June to mid-October. To represent the availability of NO_3^--N and NH_4^+-N accurately at the end of the cropping cycle, three pairs of cation and anion IEMs were randomly inserted into the 0–20 cm layer of soil in each plot in October 2016 and then removed in June 2017. An increasing extraction time generally leads to increasing ion accumulation on these membranes (Johnson et al., 2005), and a long period of extraction (greater than three months) may predict equilibrium with the N concentration in the soil (Drohan et al., 2005). The cation and anion IEMs (20 × 2 cm, HeCEM Grion 7321 and HeAEM Grion 7171, Hangzhou Grion Environmental Technology Co., Ltd, China) were imbedded with plastic stakes prior to the experiments; the counterions on the resin membranes were Na^+ and HCO_3^- (Johnson et al., 2005).

2.3. Soil sampling and analyses

After harvest in 2017, the soil was sampled at five locations that were randomly selected within each plot at depths of 0 to 60 cm at 10 cm intervals using a soil drilling sampler whose inner diameter was 4 cm. All samples were sieved through a 2 mm screen, after which the roots and other debris were removed. Every five samples from each plot were subsequently mixed together to form a single sample; these samples were immediately stored in cooled boxes that were then transported to the laboratory for the measurements of NO_3^--N and NH_4^+-N concentrations.

NO_3^--N and NH_4^+-N concentrations in the soil profile (0–60 cm grouped by 10 cm intervals) were determined using the standard extraction method. Briefly, field-fresh soil (10 g) was placed in 40 mL of 2 M KCl, after which it was shaken at 200 rpm at 25 °C for 1 h and then filtered (round filter ø 90 mm) (Keeney and Nelson, 1982; Haider et al., 2016). An automated flow injection analyzer (Autoanalyser 3, Bran + Luebbe, Germany) was used to measure the NO_3^--N and NH_4^+-N concentrations in the extracts. The SIN concentration was determined as the sum of the NO_3^--N and NH_4^+-N concentrations. Additionally, we used the concentration data to calculate the stocks of NO_3^--N, NH_4^+-N and SIN in the soil profile using the following equation:

$$S_N = C_N \times D \times H \times 10^{-1}$$

where S_N is the stock of the different N forms (kg ha^{-1}); C_N is the concentration of NO_3^--N, NH_4^+-N or SIN (mg kg^{-1}); D is the bulk density (g cm^{-3}, Table S1); and H is the thickness of the soil layer (cm).

Soil samples from the plow layer (0–20 cm) were also extracted via modified extraction methods. Briefly, field-fresh soil (10 g) was placed in 40 mL of 2 M KCl, after which it was shaken at 200 rpm at 60 °C for 2 h and then filtered (round filter ø 90 mm). Generally, an extraction temperature greater than 50 °C facilitates SIN captured by biochar release, likely shortening equilibration times (Haider et al., 2016; Hagemann et al., 2017), because the 2-dimensional surface water flow in biochar particles changes to a 3-dimensional inner-pore water flow and becomes much faster when the temperature surpasses 50 °C (Conte et al., 2014). The IEMs were washed with distilled water to remove adherent soil and then extracted by shaking in 50 mL of 2 M KCl at 200 rpm at 25 °C for 1 h (Cambouris et al., 2014). The SIN concentrations of the extracts were measured with an automated flow injection analyzer.

2.4. Statistical analysis

The reported results are the means of the three replicates. Two-way ANOVA (at a $p < 0.05$ significance level) was performed to assess significant differences, and multiple comparisons were adjusted for Duncan's multiple range test at a probability level of 0.05. Correlation analysis was performed using Pearson’s correlation (for normally distributed data) or Spearman’s correlation (for abnormally distributed data). All statistical analyses were performed using SPSS 20.0 software (SPSS Inc., Chicago, USA).

3. Results

3.1. Effects of biochar on wheat aboveground biomass under different N levels

The aboveground biomass of wheat was significantly influenced by the biochar, N fertilizer and their interactions (Fig. 1). Biochar application alone did not significantly increase the aboveground biomass but had a slightly positive effect. However, compared with the B0 treatment, the B1 treatment under N1 and N2 significantly increased the aboveground biomass by 13.8% and 12.2%, respectively. In contrast, the B2 treatment under N1 and N2 negatively affected the aboveground biomass (Fig. 1). Compared with B0N1, B2N1 significantly reduced the

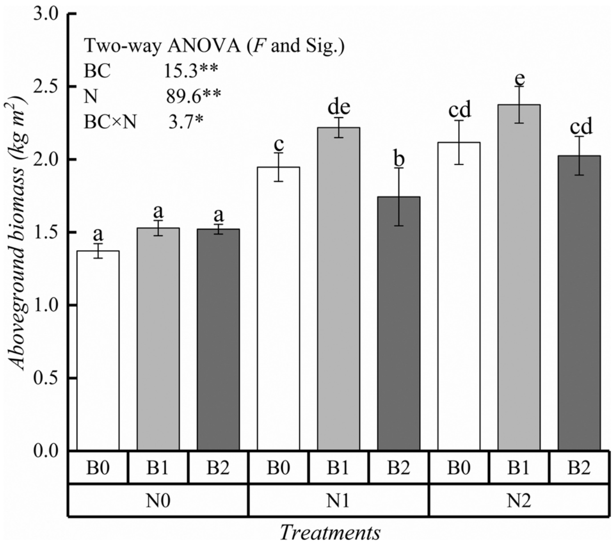

Fig. 1. Total wheat aboveground biomass under different treatments. B, N and B × N represent biochar and nitrogen fertilizer application rates and their interaction, respectively. ** $p < 0.001$; * $p < 0.05$. N0, N1 and N2 refer to non-urea conditions and conditions in which urea was added at 120 kg N ha^{-1} and 240 kg N ha^{-1}, respectively. B0, B1 and B2 refer to the application of no biochar and biochar applications in the plow layer soil at 20 t ha^{-1} and 40 t ha^{-1}, respectively. The different letters on the bars indicate significant differences ($p < 0.05$).

aboveground biomass by 10.6%.

3.2. Residual NO_3^--N, NH_4^+-N and SIN in the soil profile

Overall, the biochar, N fertilizer and their interactions significantly influenced the concentrations and stocks of NO_3^--N, NH_4^+-N and SIN in the soil profile, all of which were negatively correlated with biochar application rate (Table 3). Additionally, the SIN was more strongly correlated with NO_3^--N than with NH_4^+-N.

3.2.1. Residual NO_3^--N

Regardless of the biochar application rate, residual NO_3^--N increased with increasing N fertilization level (Fig. 2 and Table 3). Furthermore, the application of biochar under N0 increased the NO_3^--N stock in the plow layer soil but did not significant affect the NO_3^--N stock in the subsoil (20–60 cm) (Fig. 2d). However, the NO_3^--N concentrations and stocks decreased with biochar application under N1 and N2 (Fig. 2). Compared with the application of N fertilizer alone under N1 and N2, the B1 treatment reduced the NO_3^--N stocks in the subsoil by 13.2% and 74.7%, respectively. Nevertheless, the NO_3^--N stock in the subsoil of B1N2 was approximately tenfold greater than that of B1N1 (Fig. 2e and f).

3.2.2. Residual NH_4^+-N

The concentrations of NH_4^+-N under all treatments fluctuated along the soil profile (Fig. 3a, b and c). In particular, B1N1 increased the NH_4^+-N concentrations and stocks throughout the soil profile (Fig. 3b and e). The B2 treatment generally had a decreasing effect on the concentration of NH_4^+-N. The stock of NH_4^+-N in the subsoil of B2N0 was significantly lower (10.9% lower) than that of B0N0 (Fig. 3d). In addition, compared with B0N2, B2N2 significantly reduced the NH_4^+-N stock in the plow layer soil by 24.4% (Fig. 3f).

3.2.3. Residual SIN

Residual SIN increased with N fertilization level, which was attributed mainly to residual NO_3^--N (Fig. 4 and Table 3). Biochar did not significantly affect the concentrations and stocks of SIN in the soil profile under N0 (Fig. 4a and d). However, SIN in the subsoil decreased with biochar application under N1 and N2 (Fig. 4).

3.3. NO_3^--N, NH_4^+-N and SIN in plow layer soil extracted by the modified method and IEMs

3.3.1. NO_3^--N extracted via the modified method and IEMs

The concentration of NO_3^--N extracted via the modified extraction method (NO_3^--N_m) was consistently 2.0–109.7% greater than that extracted via the standard extraction method (NO_3^--N_s) (Fig. 5). Biochar application increased the difference between NO_3^--N_m and NO_3^--N_s (NO_3^--$N_{m\text{-}s}$), which was influenced by the interaction of biochar and N fertilizer (Fig. 5 and Table 4). In particular, B1N2 presented greater NO_3^--N_s, NO_3^--N_m and NO_3^--$N_{m\text{-}s}$ concentrations than did the other treatments. The concentration of NO_3^--N extracted from IEMs (NO_3^--N_{IEM}) ranged from 14.22 to 173.46 mg m^{-2} and increased in response to N fertilization; however, the same concentration generally decreased with biochar application, with the exception of that in B1N1 (Fig. 5 and Table 4).

3.3.2. NH_4^+-N extracted via the modified method and IEMs

The concentration of NH_4^+-N extracted via the modified extraction method (NH_4^+-N_m) was -2.0–24.4% greater than that extracted via the standard extraction method (NH_4^+-N_s) (Fig. 6). The difference between NH_4^+-N_m and NH_4^+-N_s (NH_4^+-$N_{m\text{-}s}$) was affected only by N fertilization (Table 4). In addition, the concentration of NH_4^+-N extracted from IEMs (NH_4^+-N_{IEM}) generally tended to increase with increasing biochar application under each N level (Fig. 6).

3.3.3. SIN extracted via the modified method and IEMs

Overall, the concentration of SIN extracted via the modified method (SIN_m) was 5.0–45.3% greater than that of SIN extracted via the standard method (SIN_s) (Fig. 7). SIN_s, SIN_m and the difference between them ($SIN_{m\text{-}s}$) were significantly affected by biochar, N fertilizer and

Table 3
Results of two-way ANOVA and correlation analyses of variables in the soil profile.

Concentration variable		Two-way ANOVA			Spearman correlation		Pearson correlation		
		B	N	B × N	B	N	NO_3^--N	NH_4^+-N	SIN
	NO_3^--N	**	**	**	−0.165**	0.840**	1	0.147	0.992**
	NH_4^+-N	*	*	*	−0.199**	−0.041		1	0.273**
	SIN	**	**	**	−0.253*	0.793**			1
Stock variable		Two-way ANOVA			Spearman correlation		Pearson correlation		
		B	N	B × N	B	N	NO_3^--N	NH_4^+-N	SIN
	NO_3^--N	**	**	**	−0.173*	0.839**	1	0.266**	0.988**
	NH_4^+-N	*	*	*	−0.194*	−0.058		1	0.413*
	SIN	**	**	**	−0.332*	0.729**			1

Note: All analytical data are the values of variables in the soil profile (0–60 cm, at 10 cm intervals), and the results show the overall situation. B, N and B × N represent biochar and nitrogen fertilizer and their interactions, respectively. SIN is the sum of NO_3^--N and NH_4^+-N. ** $p < 0.001$; * $p < 0.05$.

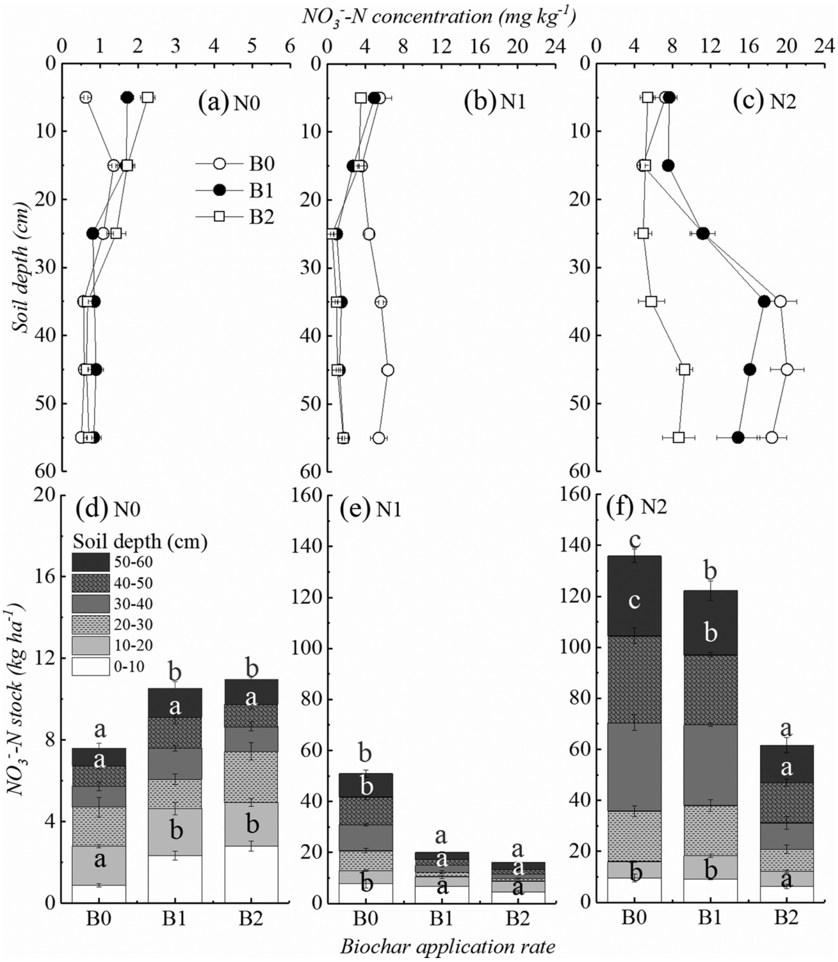

Fig. 2. NO_3^--N concentrations and stocks in the soil profile. N0, N1 and N2 refer to non-urea conditions and conditions in which urea was added at 120 kg N ha^{-1} and 240 kg N ha^{-1}, respectively. B0, B1 and B2 refer to the application of no biochar and biochar applications in the plow layer soil at 20 t ha^{-1} and 40 t ha^{-1}, respectively. The different lowercase letters in subgraphs d, e and f indicate significant differences ($p < 0.05$) between treatment means: the black letters in the 10–20 cm section refer to the plow layer soil (0–20 cm), the white letters in the 50–60 cm section refer to the subsoil (20–60 cm), and the dark gray letters above the bar refer to the total soil profile (0–60 cm).

their interactions (Table 4). As shown in Fig. 7, biochar application increased the SIN_s, SIN_m and SIN_{m-s} under N0. However, under N1 and N2, SIN_s decreased with biochar application, whereas SIN_m was not influenced, with the exception of that in B1N2. Additionally, the concentration of SIN extracted from IEMs (SIN_{IEM}) under N1 and N2 generally decreased with biochar application, which was consistent with the results for NO_3^--N_{IEM} (Figs. 5 and 7).

4. Discussion

4.1. Effects of combined biochar and N fertilizer applications on the availability and leaching of SIN

Our results indicated that the application of biochar alone had no significant effect on N availability or SIN leaching, but the effects of biochar were most evident when combined with N fertilization (Figs. 1 and 3), which is in agreement with the findings of several other authors (Van Zwieten et al., 2010; Antonio Alburquerque et al., 2013; Li and Shangguan, 2018). Additionally, biochar application alone had a slightly positive effect on crop biomass and significantly increased the residual NO_3^--N in the plow layer soil (Figs. 1 and 2d). These positive effects were likely not due to the nutrients present in the biochar and were instead attributed mostly to biochar-stimulating microorganisms that mineralize soil native organic N, thereby eliminating N starvation (Ameloot et al., 2015; Gul and Whalen, 2016), because the biochar contained lower concentrations of NO_3^--N (0.52 mg kg^{-1}) than did the initial soil (3.02 mg kg^{-1}) (Tables 1 and 2).

Compared with N fertilization alone, the B1 treatment significantly increased aboveground biomass, but the opposite pattern was observed in response to the B2 treatment. This finding suggested that N availability was sensitive to the interactions of biochar and N fertilizer and thus affected plant assimilation (Thi Thu Nhan et al., 2017), and this sensitivity strongly depended on the biochar application rate. Baiga and Rao (2017) reported that coapplication of N with biochar at 10 t ha^{-1} could improve dry matter production and N uptake because of improved soil N mineralization parameters such as mineralization potential and the coefficient of the mineralization rate. In our work, B1 combined with N fertilization not only increased N availability but also mitigated NO_3^--N leaching. Hence, the increase in crop biomass observed under B1N1 and B1N2 may partly account for the significant decrease in residual SIN in the subsoil (Figs. 1 and 4). Similarly, Xiao et al. (2017) reported that the application of biochar at 20-30 t ha^{-1} combined with N fertilizer at 225 kg ha^{-1} significantly increased maize N uptake and reduced both total residual soil NO_3^--N and the extent of NO_3^--N leaching. A surprising finding of our work was that there was no significant difference between the wheat biomass in B1N1 and B1N2 (Fig. 1); however, the residual SIN content mainly in NO_3^--N was much greater in the subsoil of B1N2 than in that of B1N1 (Fig. 4). Thus, long-term N fertilizer applications at 240 kg N ha^{-1} exceeded the needs of the crops, which inevitably led to large amounts of residual NO_3^--N and increased the risk of leaching during the fallow period, which was accompanied by concentrated rainfall (Dai et al., 2016; Xiao et al., 2017). Compared with the other fertilization treatments, the B2 treatment more effectively protected SIN against leaching; however, this level of application is impractical because of reduced crop production (Figs. 1 and 4). Therefore, the B1N1 combination was the best strategy for achieving the dual goals of improving N availability and mitigating SIN leaching.

In line with the results of the B2 treatment under fertilization, other studies have also indicated that biochar amendment does not increase

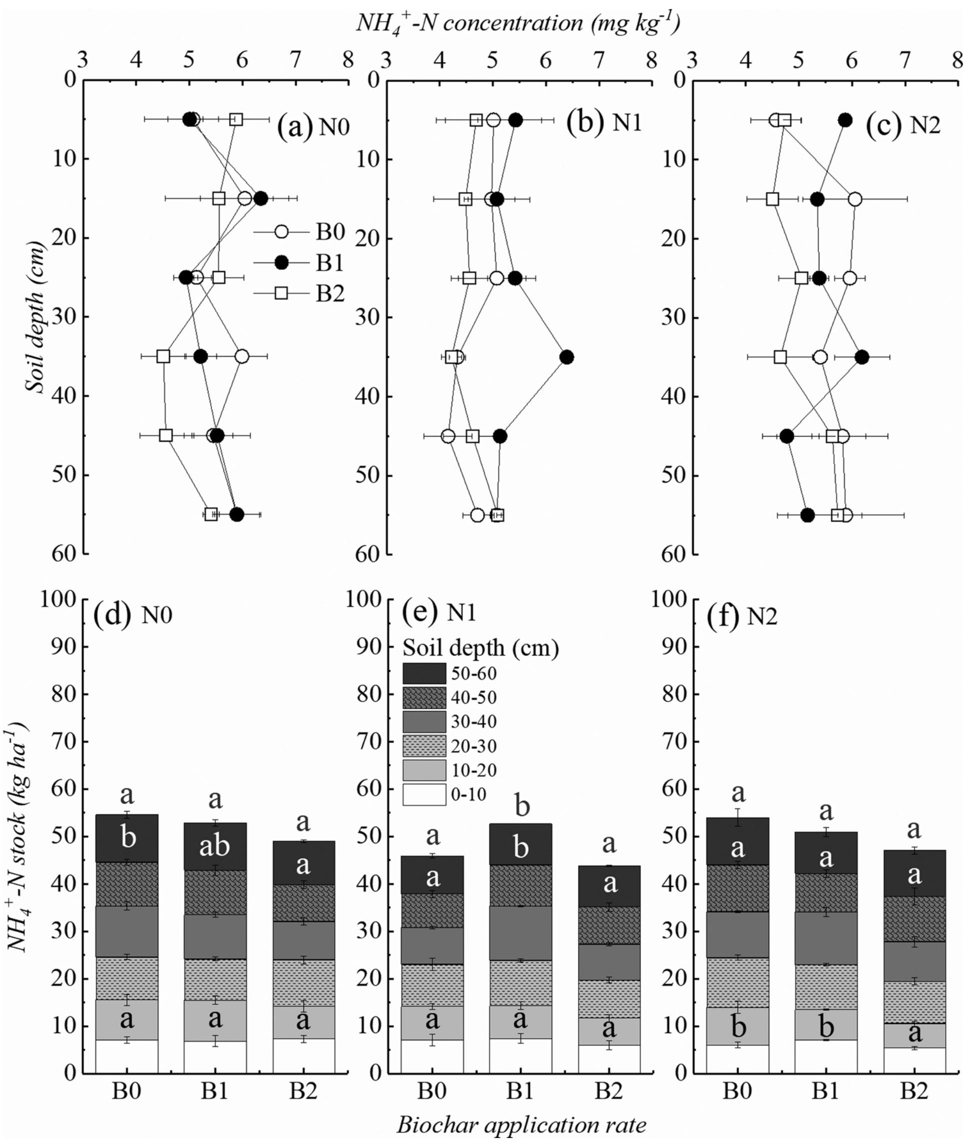

Fig. 3. NH_4^+-N concentrations and stocks in the soil profile. N0, N1 and N2 refer to non-urea conditions and conditions in which urea was added at 120 kg N ha^{-1} and 240 kg N ha^{-1}, respectively. B0, B1 and B2 refer to the application of no biochar and biochar applications in the plow layer soil at 20 t ha^{-1} and 40 t ha^{-1}, respectively. The different lowercase letters in subgraphs d, e and f indicate significant differences ($p < 0.05$) between treatment means: the black letters in the 10–20 cm section refer to the plow layer soil (0–20 cm), the white letters in the 50–60 cm section refer to the subsoil (20–60 cm), and the dark gray letters above the bar refer to the total soil profile (0–60 cm).

crop growth but does significantly reduce SIN stocks in the subsoil (Güereña and Riha, 2013; Hagemann et al., 2017). A meta-analysis revealed that excess applications of biochar ($\geq$ 80 t ha^{-1}) significantly inhibit plant biomass and N uptake (Liu et al., 2018). In addition, a previous pot-based experiment conducted by our group indicated that high rates of biochar applications (approximately 80 t ha^{-1}) led to significant reductions in wheat yields, mainly due to NO_3^--N capture by biochar (Li and Shangguan, 2018). However, the threshold of the beneficial biochar application rate in the field was lower than that in incubation and pot-based experiments, likely due to the limited water resources in the natural dryland field. Although biochar may increase the total soil water-holding capacity, much of this is below the permanent wilting point, so plant available water may actually decrease under dry conditions (Haider et al., 2017), exerting concomitant effects on the availability of SIN, particularly in the form of soluble NO_3^--N (Xu et al., 2016; Li et al., 2018). Additionally, large amounts of biochar may adsorb large amounts of NO_3^--N for an extended period, thus leaving less NO_3^--N available for both plant uptake and leaching (Haider et al., 2016; Sun et al., 2017; Thi Thu Nhan et al., 2017), which will be discussed more in the next chapter. Such findings help to elucidate why biochar treatments under fertilization significantly reduce residual SIN, although the B2 treatment did not increase crop biomass.

Many studies have indicated that less NH_4^+-N is leached from biochar-treated soil columns than from untreated soil columns (Zheng et al., 2013; Sika and Hardie, 2014; Pratiwi et al., 2016). However, in our work, the amount of residual NH_4^+-N in the subsoil slightly decreased in response to only B2 (Fig. 3). This finding was obtained because NH_4^+-N may be readily adsorbed onto negatively charged clay minerals in silty clay soil (Li et al., 2018). In addition, woody biochar usually presents a lower CEC, fewer acidic functional groups, and lower labile C compound contents than does crop-derived and herbaceous biochar (Harvey et al., 2012; Wang et al., 2016; Thi Thu Nhan et al., 2017). Additionally, biochar applied at a rate greater than 40 t ha^{-1} generally induces a significant increase in soil NH_3 volatilization, although woody biochar tends to decrease soil NH_3 volatilization because of an adsorption effect (Liu et al., 2018). However, verification of whether the B2 treatment led to an increase in NH_3 volatilization and thus reduced NH_4^+-N content requires further investigation. Moreover, B1N1 increased the stock of NH_4^+-N in the soil profile to a particularly high level (Fig. 5b), which was likely not due to pronounced NH_4^+-N adsorption (Haider et al., 2016). Hence, the relatively higher NH_4^+-N and lower NO_3^--N concentrations observed in B1N1 may be due to relatively lower nitrification rates, as suggested by Sun et al. (2017), and reduced NH_3 volatilization, as reported by Clough et al. (2013).

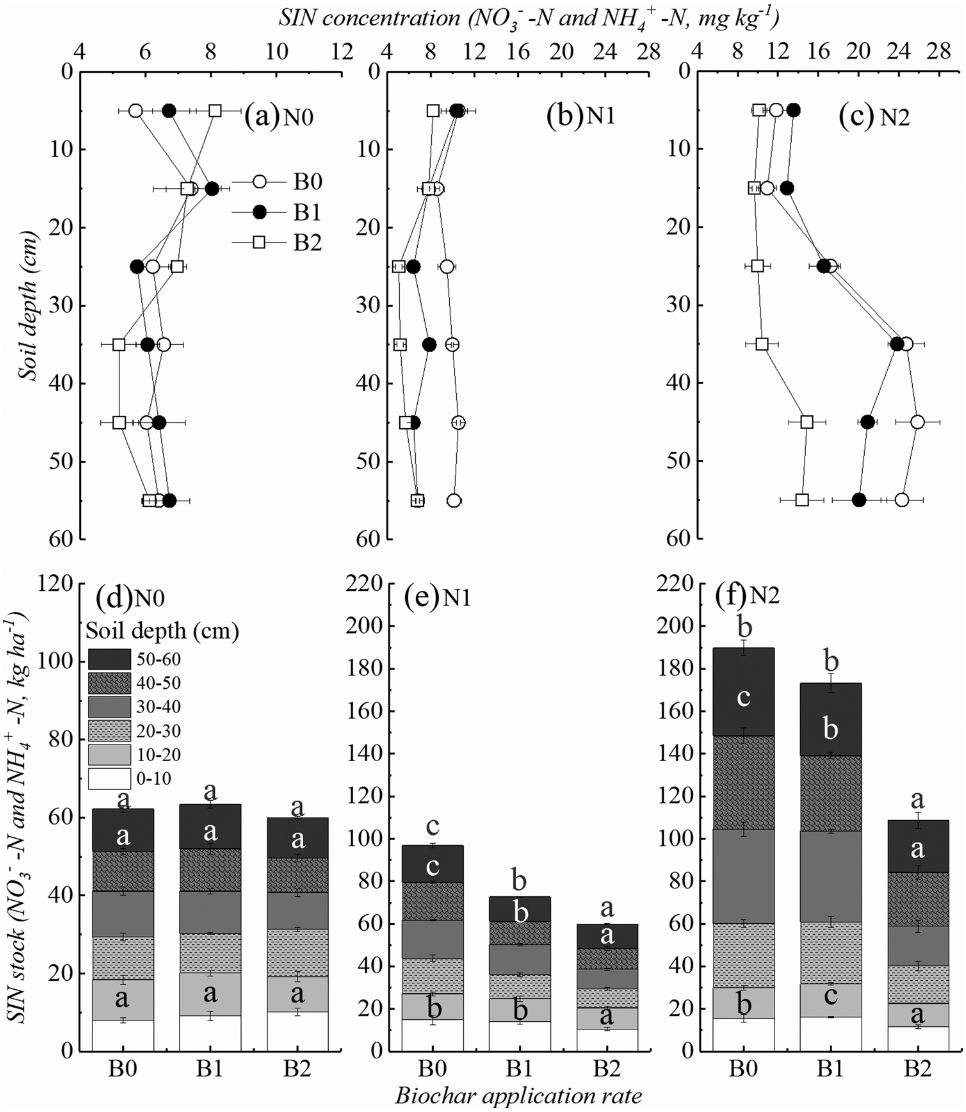

Fig. 4. SIN (NO_3^--N and NH_4^+-N) concentrations and stocks in the soil profile. N0, N1 and N2 refer to the non-urea conditions and conditions in which urea was added at 120 kg N ha^{-1} and 240 kg N ha^{-1}, respectively. B0, B1 and B2 refer to the application of no biochar and biochar applications in the plow layer soil at 20 t ha^{-1} and 40 t ha^{-1}, respectively. The different lowercase letters in subgraphs d, e and f indicate significant differences ($p < 0.05$) between treatment means: the black letters in the 10–20 cm section refer to the plow layer soil (0–20 cm), the white letters in the 50–60 cm section refer to the subsoil (20–60 cm), and the dark gray letters above the bar refer to the total soil profile (0–60 cm).

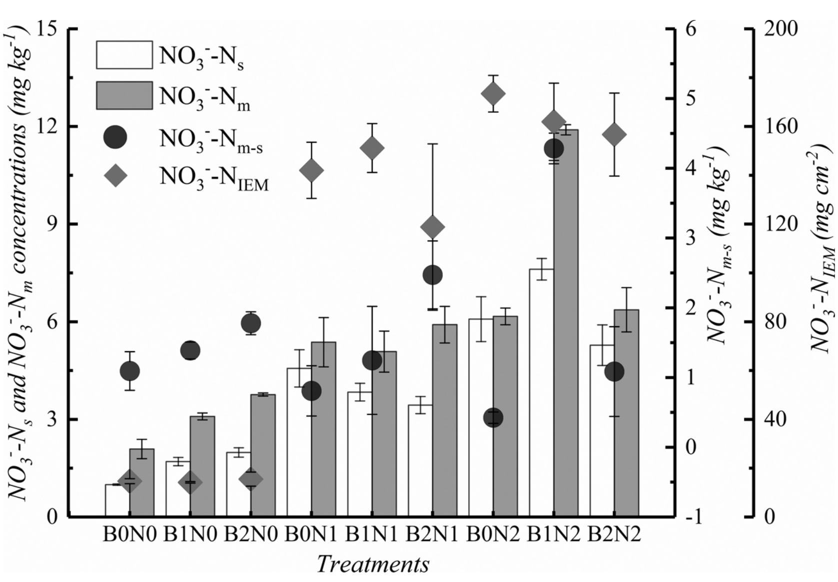

Fig. 5. NO_3^--N concentrations extracted via different methods from plow layer soil. B0, B1 and B2 refer to the application of no biochar and biochar applications in the plow layer soil at 20 t ha^{-1} and 40 t ha^{-1}, respectively. N0, N1 and N2 refer to non-urea conditions and conditions in which urea was added at 120 kg N ha^{-1} and 240 kg N ha^{-1}, respectively. NO_3^--N_s is the NO_3^--N extracted via the standard method (2 M KCl, shaking for 1 h at 25 °C). NO_3^--N_m is the NO_3^--N extracted via the modified method (2 M KCl, shaking for 2 h at 60 °C). NO_3^--$N_{m\text{-}s}$ is the difference in NO_3^--N extracted via the modified method and via the standard method. NO_3^--N_{IEM} is the NO_3^--N extracted from IEMs.

Table 4
Relationships among N forms extracted via different methods and the results of two-way ANOVA.

Parameter	Method	Correlations			Results of two-way ANOVA			
		Standard	Modified	IEMs	B	N	B × N	R^2
NO_3^--N	Standard	1	0.903**	0.857**	**	**	**	0.963
	Modified		1	0.694**	**	**	**	0.971
	IEMs			1	NS	**	NS	0.952
NH_4^+-N	Standard	1	−0.246	−0.395*	NS	*	NS	0.265
	Modified		1	0.158	NS	NS	NS	0.238
	IEMs			1	**	*	NS	0.551
NO_3^- + NH_4^+ (SIN)	Standard	1	0.883**	0.782**	*	**	**	0.920
	Modified		1	0.695**	**	**	**	0.947
	IEMs			1	NS	**	NS	0.952
NO_3^--$N_{m\text{-}s}$	–	–	–	–	**	NS	**	0.863
NH_4^+-$N_{m\text{-}s}$	–	–	–	–	NS	*	NS	0.388
$SIN_{m\text{-}s}$	–	–	–	–	*	*	**	0.650

Note: The correlations are between different extraction methods, and the ANOVA refers to the comparisons among treatments. B, N and B × N represent biochar and nitrogen fertilizer application rates and their interaction, respectively. ** $p < 0.001$; * $p < 0.05$; NS: not significant; R^2: proportion of the explained variance. NO_3^--$N_{m\text{-}s}$, NH_4^+-$N_{m\text{-}s}$ and $SIN_{m\text{-}s}$ are the differences in NO_3^--N, NH_4^+-N and SIN extracted via the modified method and the standard method.

4.2. Biochar capture of SIN and availability of residual SIN

To determine whether the reduced SIN content observed under the biochar treatments was partly due to sequestration by biochar and the availability of residual SIN, we used a modified extraction method and IEMs to extract SIN from plow layer soil. The results indicated that shaking the soil samples at a high temperature for a long time could facilitate the release of SIN in biochar-amended soil, especially for NO_3^--N. In addition, the NO_3^--$N_{m\text{-}s}$ and $SIN_{m\text{-}s}$ generally increased with biochar application under each N level (Figs. 5 and 7). This finding explains the diminishing of NO_3^--N, which was captured by field-aged biochar and is usually underestimated by the standard extraction method (Haider et al., 2016). Moreover, the modified extraction method may still be insufficiently powerful to extract all biochar-captured NO_3^--N, which is sometimes retrieved via KCl extraction and depends on the biochar pore size distribution and the capture mechanism involved (Haider et al., 2016; Hagemann et al., 2017). These characteristics suggest that biochar exhibits a certain potential to retain N in the soil and that underestimating NO_3^--N retention in biochar-amended soils is possible, despite the use of NO_3^--N_m.

NO_3^--N_{IEM} decreased with biochar application after two years of N fertilization (Fig. 5), which suggests that biochar reduces the residual NO_3^--N available for both leaching and crop uptake. Similarly, Antonio Alburquerque et al. (2013) reported that biochar applications at 2.5% (w/w) resulted in decreased SIN_{IEM} and aboveground N concentrations in wheat, regardless of the mineral fertilization level. Sika and Hardie (2014) reported that leached pine wood biochar-amended soils contained only low concentrations of exchangeable NO_3^--N (5.8–8.0 mg kg^{-1}) and NH_4^+-N (0–7.3 mg kg^{-1}), despite the observed strong decrease in SIN leaching. Additionally, some studies have detected improved mineral N accumulation using a standard extraction method in biochar-amended soils but without a concurrent increase in yield (Borchard et al., 2012; Güereña and Riha, 2013), because some of the NO_3^--N_s present in biochar-amended soils may already be unavailable (Borchard et al., 2012; Haider et al., 2016). However, the NO_3^--N retained in the biochar-amended soil was clearly resistant to leaching, which could explain why B1N2 increased NO_3^--N_s in the plow layer soil but reduced both NO_3^--N_{IEM} and NO_3^--N_s in the subsoil (Figs. 2 and 5). Therefore, although there were significant positive correlations between NO_3^--N_{IEM} and NO_3^--N_s or NO_3^--N_m (Table 3), NO_3^--N_m provides only an index of the relative "true" stock in biochar-amended soils in most cases and may be inadequate as a basis for precise soil management recommendations. Additionally, the quantification of how much biochar-captured NO_3^--N can be regarded as belonging to the available N pool for crop uptake while avoiding leaching requires further research.

NH_4^+-N sorption or retention is usually attributed to an increase in

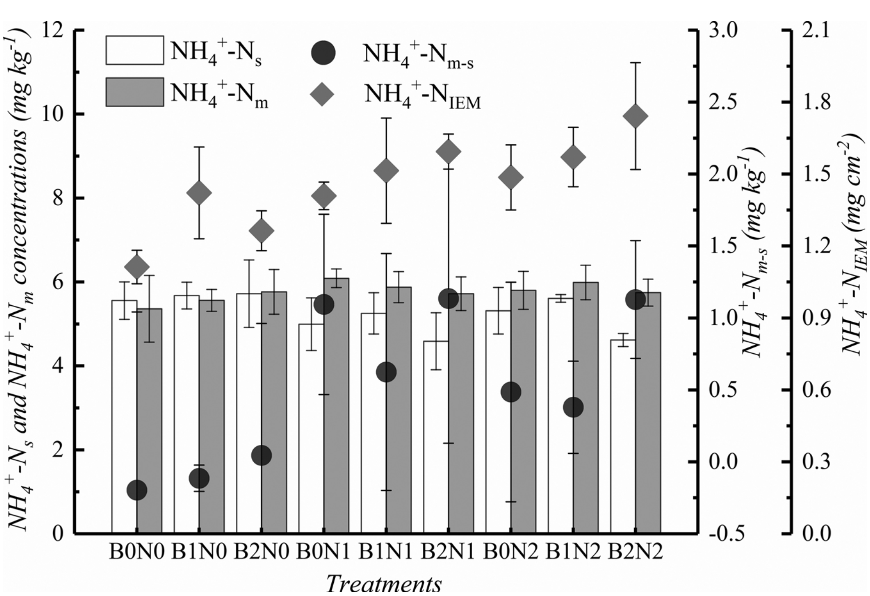

Fig. 6. NH_4^+-N concentrations extracted via different methods in the plow layer soil. B0, B1 and B2 refer to the application of no biochar and biochar applications in the plow layer soil at 20 t ha^{-1} and 40 t ha^{-1}, respectively. N0, N1 and N2 refer to non-urea conditions and conditions in which urea was added at 120 kg N ha^{-1} and 240 kg N ha^{-1}, respectively. NH_4^+-N_s is the NH_4^+-N extracted via the standard method (2 M KCl, shaking for 1 h at 25 °C). NH_4^+-N_m is the NH_4^+-N extracted via the modified method (2 M KCl, shaking for 2 h at 60 °C). NH_4^+-$N_{m\text{-}s}$ is the difference in NH_4^+-N extracted via the modified method and via the standard method. NH_4^+-N_{IEM} is the NH_4^+-N extracted from IEMs.

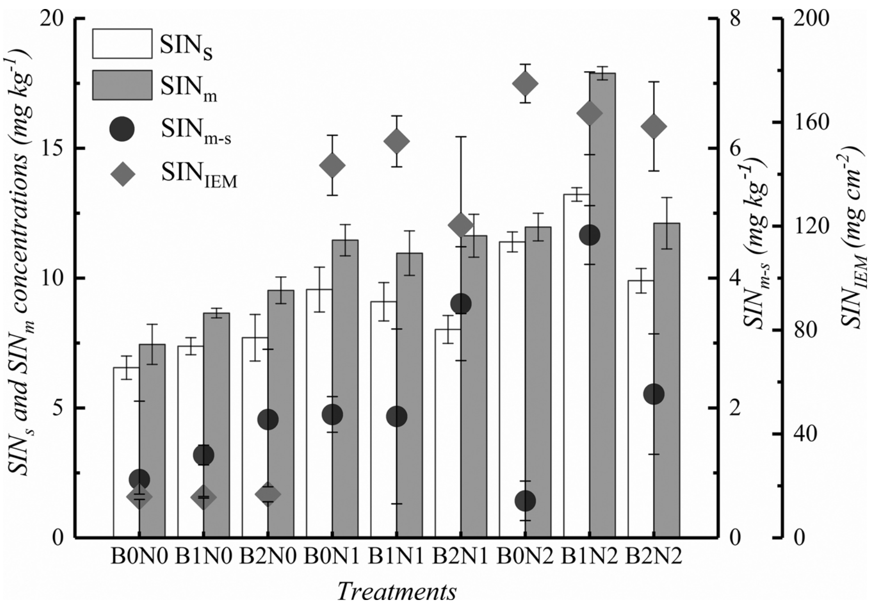

Fig. 7. SIN (NO_3^--N and NH_4^+-N) concentrations extracted via different methods from plow layer soil. B0, B1 and B2 refer to the application of no biochar and biochar applications in the plow layer soil at 20 t ha^{-1} and 40 t ha^{-1}, respectively. N0, N1 and N2 refer to non-urea conditions and conditions in which urea was added at 120 kg N ha^{-1} and 240 kg N ha^{-1}, respectively. SIN_s is the SIN extracted via the standard method (2 M KCl, shaking for 1 h at 25 °C). SIN_m is the SIN extracted via the modified method (2 M KCl, shaking for 2 h at 60 °C). SIN_{m-s} is the difference in SIN extracted via the modified method and via the standard method. SIN_{IEM} is the SIN extracted from IEMs.

CEC induced by biochar (Haider et al., 2017), because the carboxylic groups and fewer acidic groups, such as phenols and carbonyls, on the surface of biochar have a negative charge and can adsorb NH_4^+-N through electrostatic attraction (Haider et al., 2016; Liu et al., 2018). However, NH_4^+-N adsorbed onto negatively charged functional groups may be easily extracted via the standard method (Clough et al., 2013). Therefore, only the B2 treatment slightly increased NH_4^+-N_{m-s} (Fig. 6). Additionally, the N compounds adsorbed by biochar may be desorbed over time and become available (Taghizadeh-Toosi et al., 2012), which contributes to the increased NH_4^+-N exchangeability represented by NH_4^+-N_{IEM} (Fig. 6).

5. Conclusions

Biochar application alone had no significant effects on wheat biomass or SIN leaching. However, the B1N1 treatment represents a promising strategy for achieving the dual goals of increasing N availability and mitigating the leaching of SIN (mainly in NO_3^--N) in dryland systems. Compared with all the treatments, the B2 treatment more effectively mitigated SIN leaching; however, this treatment also significantly limited N availability. Hence, the overuse of biochar will make less SIN available not only for leaching but also for crop uptake. Biochar can adsorb NO_3^--N after two years of field aging; as such, biochar application generally reduces the amount of NO_3^--N available for leaching during the fallow period.

Acknowledgments

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA23070201), National Key Research and Development Program of China (2016YFC0501605 and 2015BAD22B01), Technology Innovation Project of the Chinese Central Government Guidance (YDZX2018540C004077). We especially thank the reviewers for their valuable suggestions.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2019.02.013.

References

Agegnehu, G., Nelson, P.N., Bird, M.I., 2016. Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols. Soil Tillage Res. 160, 1–13.
Ameloot, N., Sleutel, S., Das, K.C., Kanagaratnam, J., Neve, S., 2015. Biochar amendment to soils with contrasting organic matter level: effects on N mineralization and biological soil properties. Gcb Bioenergy 7, 135–144.
Antonio Alburquerque, J., Salazar, P., Barron, V., Torrent, J., del Carmen del Campillo, M., Gallardo, A., Villar, R., 2013. Enhanced wheat yield by biochar addition under different mineral fertilization levels. Agron. Sustain. Dev. 33, 475–484.
Baiga, R., Rao, B.K.R., 2017. Effects of biochar, urea and their co-application on nitrogen mineralization in soil and growth of Chinese cabbage. Soil Use Manag. 33, 54–61.
Bolland, M.D.A., Cox, W.J., Codling, B.J., 2002. Soil and tissue tests to predict pasture yield responses to applications of potassium fertiliser in high-rainfall areas of south-western Australia. Aust. J. Exp. Agric. 42, 149–164.
Borchard, N., Wolf, A., Laabs, V., Aeckersberg, R., Scherer, H.W., Moeller, A., Amelung, W., 2012. Physical activation of biochar and its meaning for soil fertility and nutrient leaching & dash; a greenhouse experiment. Soil Use Manag. 28, 177–184.
Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen - Total. Methods of soil analysis. Part 2. Chem. Microbiol. Prop. 595–624.
Cambouris, A.N., St Luce, M., Ziadi, N., Zebarth, B.J., 2014. Soil- and plant-based indices in potato production in response to polymer-coated urea. Agron. J. 106, 2125–2136.
Clough, T.J., Condron, L.M., Kammann, C., Müller, C., 2013. A review of biochar and soil nitrogen dynamics. Agronomy 3, 275–293.
Conte, P., Hanke, U.M., Marsala, V., Cimò, G., Alonzo, G., Glaser, B., 2014. Mechanisms of water interaction with pore systems of hydrochar and pyrochar from poplar forestry waste. J. Agric. Food Chem. 62, 4917–4923.
Dai, J., Wang, Z.H., Li, M.H., He, G., Li, Q., Cao, H.B., Wang, S., Gao, Y.J., Hui, X.L., 2016. Winter wheat grain yield and summer nitrate leaching: long-term effects of nitrogen and phosphorus rates on the Loess Plateau of China. Field Crops Res. 196, 180–190.
Drohan, P.J., Merkler, D.J., Buck, B.J., 2005. Suitability of the plant root simulator probe for use in the Mojave desert. Soil Sci. Soc. Am. J. 69, 1482–1491.
Gaskin, J.W., Steiner, C., Harris, K., Das, K.C., Bibens, B., 2008. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. Trans. ASABE 51, 2061–2069.
Güereña, D., Riha, S., 2013. Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system. Plant Soil 365, 239–254.
Gul, S., Whalen, J.K., 2016. Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. Soil Biol. Biochem. 103, 1–15.
Gul, S., Whalen, J.K., Thomas, B.W., Sachdeva, V., Deng, H.Y., 2015. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. Agric. Ecosyst. Environ. 206, 46–59.
Hagemann, N., Kammann, C.I., Schmidt, H.P., Kappler, A., Behrens, S., 2017. Nitrate capture and slow release in biochar amended compost and soil. PLoS One 12, e0171214.
Haider, G., Steffens, D., Muller, C., Kammann, C.I., 2016. Standard extraction methods may underestimate nitrate stocks captured by field-aged biochar. J. Environ. Qual. 45, 1196–1204.
Haider, G., Steffens, D., Moser, G., Müller, C., Kammann, C.I., 2017. Biochar reduced nitrate leaching and improved soil moisture content without yield improvements in a four-year field study. Agric. Ecosyst. Environ. 237, 80–94.
Harvey, O.R., Herbert, B.E., Kuo, L.J., Louchouarn, P., 2012. Generalized two-dimensional perturbation correlation infrared spectroscopy reveals mechanisms for the development of surface charge and recalcitrance in plant-derived biochars. Environ. Sci. Technol. 46, 10641.

Jin, Y., Liang, X.Q., He, M.M., Liu, Y., Tian, G.M., Shi, J.Y., 2016. Manure biochar influence upon soil properties, phosphorus distribution and phosphatase activities: a microcosm incubation study. Chemosphere 142, 128–135.

Johnson, D.W., Verburg, P.S.J., Arnone, J.A., 2005. Soil extraction, ion exchange resin, and ion exchange membrane measures of soil mineral nitrogen during incubation of a tallgrass prairie soil. Soil Sci. Soc. Am. J. 69, 260–265.

Keeney, D.R., Nelson, D.W., 1982. Nitrogen: inorganic forms. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. American Society of Agronomy, Madison, pp. 643–698.

Li, S.L., Shangguan, Z.P., 2018. Positive effects of apple branch biochar on wheat yield only appear at a low application rate, regardless of nitrogen and water conditions. J. Soils Sediments 18, 3235–3243.

Li, F.C., Wang, Z.H., Dai, J., Li, Q., Xue, C., Zhao, H.B., Wang, X., Olesen, J.E., 2014. Summer fallow soil management - impact on rainfed winter wheat. Acta Agric. Scand. Section B-Soil Plant Sci. 64, 398–407.

Li, S., Liang, C., Shangguan, Z., 2017. Effects of apple branch biochar on soil C mineralization and nutrient cycling under two levels of N. Sci. Total Environ. 607, 109–119.

Li, S., Zhang, Y., Yan, W., Shangguan, Z., 2018. Effect of biochar application method on nitrogen leaching and hydraulic conductivity in a silty clay soil. Soil Tillage Res. 183, 100–108.

Liu, Q., Zhang, Y., Liu, B., Amonette, J.E., Lin, Z., Liu, G., Ambus, P., Xie, Z., 2018. How does biochar influence soil N cycle? A meta-analysis. Plant Soil 426, 211–225.

Major, J., Rondon, M., Molina, D., Riha, S.J., Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil 333, 117–128.

Mukherjee, A., Zimmerman, A.R., 2013. Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar-soil mixtures. Geoderma 193, 122–130.

Nelson, D.W., Sommers, L.E., Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E., 1982. Total carbon, organic carbon, and organic matter. Methods Soil Anal. Part-Chem. Methods 961–1010.

Pratiwi, E.P.A., Hillary, A.K., Fukuda, T., Shinogi, Y., 2016. The effects of rice husk char on ammonium, nitrate and phosphate retention and leaching in loamy soil. Geoderma 277, 61–68.

Prommer, J., Wanek, W., Hofhansl, F., Trojan, D., Offre, P., Urich, T., Schleper, C., Sassmann, S., Kitzler, B., Soja, G., 2014. Biochar decelerates soil organic nitrogen cycling but stimulates soil nitrification in a temperate arable field trial. PLoS One 9, e86388.

Qian, P., Schoenau, J.J., 2007. Using an anion exchange membrane to predict soil available N and S supplies and the impact of N and S fertilization on canola and wheat growth1 1project supported by the Potash and Phosphate Institute of Canada (PPIC). Pedosphere 17, 77–83.

Qian, T.T., Zhang, X.S., Hu, J.Y., Jiang, H., 2013. Effects of environmental conditions on the release of phosphorus from biochar. Chemosphere 93, 2069–2075.

Schulz, H., Dunst, G., Glaser, B., 2013. Positive effects of composted biochar on plant growth and soil fertility. Agron. Sustain. Dev. 33, 817–827.

Sika, M.P., Hardie, A.G., 2014. Effect of pine wood biochar on ammonium nitrate leaching and availability in a South African sandy soil. Eur. J. Soil Sci. 65, 113–119.

Sorrenti, G., Toselli, M., 2016. Soil leaching as affected by the amendment with biochar and compost. Agric. Ecosyst. Environ. 226, 56–64.

Sun, H., Lu, H., Chu, L., Shao, H., Shi, W., 2017. Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH_3 volatilization in a coastal saline soil. Sci. Total Environ. 575, 820–825.

Sun, M., Ren, A.X., Gao, Z.Q., Wang, P.R., Mo, F., Xue, L.Z., Lei, M.M., 2018. Long-term evaluation of tillage methods in fallow season for soil water storage, wheat yield and water use efficiency in semiarid southeast of the Loess Plateau. Field Crops Res. 218, 24–32.

Taghizadeh-Toosi, A., Clough, T.J., Sherlock, R.R., Condron, L.M., 2012. A wood based low-temperature biochar captures NH_3-N generated from ruminant urine-N, retaining its bioavailability. Plant Soil 353, 73–84.

Thi Thu Nhan, N., Xu, C.-Y., Tahmasbian, I., Che, R., Xu, Z., Zhou, X., Wallace, H.M., Bai, S.H., 2017. Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis. Geoderma 288, 79–96.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K.Y., Downie, A., Rust, J., Joseph, S., Cowie, A., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant Soil 327, 235–246.

Wang, J.Y., Xiong, Z.Q., Kuzyakov, Y., 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. Gcb Bioenergy 8, 512–523.

Xiao, Q., Zhu, L.-x., Tang, L., Shen, Y.-f., Li, S.-q., 2017. Responses of crop nitrogen partitioning, translocation and soil nitrogen residue to biochar addition in a temperate dryland agricultural soil. Plant Soil 418, 405–421.

Xu, N., Tan, G.C., Wang, H.Y., Gai, X.P., 2016. Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. Eur. J. Soil Biol. 74, 1–8.

Zheng, H., Wang, Z.Y., Deng, X., Herbert, S., Xing, B.S., 2013. Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. Geoderma 206, 32–39.