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RESEARCH ARTICLE

Effects of biochar application on nitrogen leaching, ammonia volatilization and nitrogen use efficiency in two distinct soils

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Abstract

This study was conducted to determine the effect of biochar application on nitrogen (N) leaching, ammonia (NH_3) volatilization, and fertilizer N use efficiency (NUE) in two soils with different properties (loamy and sandy). Ryegrass (*Lolium perenne* L.) incubation experiments (with ^{15}N-enriched urea applied) and an N loss simulation study were conducted at biochar application rates of 2% and 4%. The results showed that ^{15}N utilization increased by 8.83–9.06% following the addition of biochar to sandy soil during the first season compared with the control. However, this significant effect was not observed in the loamy soil, in which significantly more urea-N was retained in the soil following biochar application. Furthermore, based on the results of the N leaching and NH_3 volatilization experiments, 29.19% and 28.65% NO_3^-N leaching reductions were induced by 2% and 4% biochar amendments in loamy soil, decreasing the total inorganic N that was leached (NH_4^+-N plus NO_3^-N) by 26.46% and 26.82%, respectively. However, although the amount of leached NH_4^+-N decreased in biochar-amended sandy soil, the cumulative NH_3 volatilizations were 14.18–20.05% higher than in the control, and 22.55% more NO_3^--N was leached from biochar-amended sandy soil, resulting in a negative effect on N retention. According to this study, biochar can be effectively used to improve the NUE in sandy soil and reduce N loss from loamy soil.

Keywords: Biochar, nitrogen retention, nitrogen loss, loamy soil, sandy soil

1. Introduction

Nitrogen (N) is an essential element that is required for plant growth, and the application of N fertilizer to agricultural soil is an effective measure for enhancing crop yields. Farmers, especially in developing countries, often apply N fertilizer in excessive amounts in an attempt to maximize yields. In 2008, the amount of N fertilizer applied in China was 2.3×10^7 t, accounting for 1/3 of the total N consumption worldwide (Zhu. 2008). This excessive N application results in a decrease in nitrogen use efficiency (NUE) and pollutes the adjacent water and atmospheric systems (Yoo *et al*., 2014). Those N losses represent the inherent inefficiencies in current nutrient management systems and result in not only environmental pollution but also additional economic costs to farmers.

The application of biochar to agricultural soil is a potential way of increasing nutrient bioavailability and decreasing nutrient leaching from soil (Shen *et al*., 2016; Lehmann *et al*., 2003). Many studies have reported that biochar incorporation could reduce inorganic N leaching and increase N retention in the soil (Major *et al*., 2012; Sun *et al*., 2017; Yao *et al*., 2012). The mechanisms underpinning the effects of biochar on N retention in soil are not well understood, but some potential processes have been proposed: a). Biochar has a high cation exchange capacity (CEC) (Ding *et al*., 2010; Nelissen *et al*., 2012) and changes the soil pH (Novak *et al*., 2009), leading to the direct absorption of NH_4^+ and NO_3^-. b). Biochar can enhance the water-holding capacity (WHC) of the soil and thus reduce the total volume of leachate (Ouyang *et al*., 2013; Zheng *et al*., 2013). c). Due to microbial immobilization (Ippolito *et al*., 2012), biochar, especially when pyrolyzed at low temperatures, usually contains considerable amounts of labile carbon (Nelissen *et al*., 2012). This carbon can serve as a microbial substrate, resulting in microbial demand for inorganic N, which thereby immobilizes the N through biotic processes (Lehmann *et al*., 2003 Nelissen *et al*. 2012 and 2014; Zheng *et al*. 2013). Ammonia volatilization is another mechanism that accounts for the loss of fertilizer-derived N. This process tends to increase following the addition of biochar (Reverchon *et al*., 2014; Yang *et al.*, 2015) because most biochars have a high pH and serve as liming agents (Novak *et al*., 2009). However, previous studies have shown that biochar could adsorb ammonia through its functional acid groups (Asada *et al*., 2002) or through its high CEC (Taghizadehtoosi *et al*., 2012).

Northeast China is a key location for commercial food production. The sandy soil in this area is dominated by low-activity clays and soil organic matter, with low fertility and WHC. N leaching from sandy soils is considerably higher than that from other agriculture soils (Wang *et al*., 2015), resulting in a low NUE. Although the loamy soils in this region usually contain high levels of organic matter and high N fertility, harvesting the biomass removes substantial amounts of nutrients from soils, and the soil fertility and organic matter have declined rapidly in recent years (Gao *et al*., 2009). To maximize crop production, large amounts of N fertilizer are input annually, leading to a total N loading that is much greater than the crop N demand. Given that the benefits of biochar application vary with soil type and land use and to avoid the negative impact of biochar in field applications, it is important to understand how biochar influences the fate of fertilizer N (urea) from the two major agricultural soils in Northeast China.

In this study, the authors conducted an isotope (^{15}N) tracing study and leaching experiments to determine whether biochar application is an effective measure for controlling N losses from loamy and sandy soils. The specific objective of this study was to quantify the changes in the NUE when biochar was added as a soil amendment and to investigate the potential ability of biochar to reduce inorganic N leaching and NH_3 volatilization.

2. Material and Methods

2.1. Soils and biochars

Loamy soil was collected from Shenyang Agriculture University (41° 83′N, 123° 58′E), and the previous crop was maize. Sandy soil was collected from local farmland near Zhangwu County (42° 25′E, 122° 66′N), Liaoning Province, and the previous crop was peanut. According to the FAO classification system, the loamy and sandy soils used in the present study were classified as a Hapli-Udic Cambisol and an Arenosol, respectively. Soil samples from the top 20 cm were collected at the end of each growing season, air dried for 2 weeks and passed through a 2-mm sieve for future study. The basic properties of the soils used here are shown in Table 1.

The commercially available maize stover biochar used in this study was produced under "oxygen-limited" conditions at 400–500 °C for approximately 2 hours by Jinhefu Agricultural Development Company, Liaoning, China. Thirty-five percent of the maize stover biomass was converted to biochar. The biochar was comminuted by being passed through a 2-mm sieve and then thoroughly mixed to obtain a fine homogeneity that would allow it to be mixed more uniformly with the soil. The basic properties of the biochar are shown in Table 1.

Table 1. Basic properties of the tested soils and biochar

Properties		Loamy soil	Sandy soil	Biochar
TC (%)		1.12	0.52	64.5
TN (%)		0.15	0.08	1.14
TP ($g \cdot kg^{-1}$)		0.22	0.12	0.38
TK ($g \cdot kg^{-1}$)		2.05	0.98	3.23
	Sand	55.85	82.07	NA
Texture (%)	Silt	29.60	14.81	NA
	Clay	14.55	3.12	NA
pH		7.30	7.01	9.11
WHC (%)		49.99	38.84	NA
Surface area ($m^2 \cdot g^{-1}$)		NA	NA	1.33

For pH determination, soil:water=1:2.5; biochar:water=1:25

TC: Total Carbon; TN: Total Nitrogen; TP: Total Phosphorus; TK: Total Potassium; WHC: Water-Holding Capacity; NA: Not Available.

2.2. Ryegrass incubation experiment

A two-season ryegrass (*Lolium perenne* L.) cultivation experiment was conducted. For each soil, three treatments were performed in triplicate: (1) soil alone (control), (2) soil amended with 2% (w/w) biochar (2% BC), and (3) soil amended with 4% (w/w) biochar (4% BC). ^{15}N-enriched urea, with an enrichment of 50.16 atom%, was applied as the N fertilizer at a rate of 280 mg•kg^{-1} soil.

After the soil samples and biochar were dried and sieved through a 2-mm sieve, 4 or 8 g of biochar was mixed thoroughly with 200-g soil samples. Of this 200 g, 180 g was used to fill a 450-mL Mason jar, and then 0.5 g of ryegrass seeds was sown; the remaining 20 g of soil was used to fill the jar to the top. A urea solution and deionized water were then added to increase the soil moisture to 60% WHC.

All jars were placed in a growth cabinet for the first 40 days under an alternating day/night temperature and light regime of 27/15 °C and 14/10 h, respectively, with a relative humidity of 60%. Each jar was weighed daily, and the water loss was supplemented. After the 40-day incubation, the ryegrass was sampled, dried at 65 °C to a constant weight, and 5 g soil was collected for future study. During season 2, the soil and incubation conditions were the same as those used in season 1 but without the application of urea. After the dry weight of the ryegrass was determined, the plant samples were finely ground, and the total C and N contents were measured using an elemental analyzer (Elementar Macro Cube, Langenselbold, Germany). The ^{15}N abundance was determined using isotope ratio mass spectrometry (Thermo Fisher, Waltham, MA, USA).

2.3. NH_3 volatilization experiment

An enclosure method was used to capture and measure the NH_3 volatilization, as described by Wang *et al.* (2002). The rates of biochar and urea amendments were consistent with the previous two experiments. In detail, 80 g of soil with or without biochar amendment was placed in a 450-mL Mason jar. A urea solution (8 mL) and deionized water were added to bring the moisture content up to 60% WHC. The experiments were initiated immediately after wetting. The generated NH_3 was trapped in 10 mL of 2% boric acid, mixed with methyl red and bromocresol green indicators, and then dispensed into a small vessel inside the incubation jars. The boric acid vessels were removed and replaced daily until the color of the mixed indicator did not change, and the trapped NH_3 was titrated with 0.01 M HCl.

2.4. Leaching experiment

A leaching experiment was conducted by following a modified method as described by Laird et al. (2010). The leaching columns were designed using a 50-mL (27 mm diameter, 140 mm long) Plastipak medical syringe (with the piston removed). Each column was fixed with filter papers (New Star, Hanzhou, China), and each contained 15 g of quartz sand. Then, 20 g of each soil sample with or without biochar amendment was added, and the bulk density was set so it would be close to that of the field conditions. Finally, 20 g of quartz sand was used to fill the soil columns to the top to avoid soil disturbance during leaching. A urea solution (6 g•L^{-1}) was applied at a rate of 280 mg•kg^{-1} soil. The six treatments were the same as those described for the ryegrass incubation experiment, and each treatment was replicated three times.

Deionized water was added to the soil columns following the application of the urea solution to obtain 60% WHC, and then, the samples were incubated at 27 °C. After 2 days, the first leaching event began; 20 mL of deionized water was added to the top of the column, the leachate was collected at the bottom of each column until it had totally leached out (approximately 7 hours), and then the leachate volume was recorded. The NH_4^+-N and NO_3^--N concentrations in the leachate were measured using a continuous flow analyzer (SEAL AA3, Jean, Germany).

2.5. Statistical analyses

The data were analyzed by one-way ANOVA using SPSS version 19 (IBM Corporation, New York, USA). Significant differences among the means were assessed with the least significant difference (LSD) test at a 0.05 probability level. The figures shown in this article were generated using GraphPad Prism 5 (GraphPad Software, Inc., La Jolla, USA) and Microsoft Excel 2003.

3. Results

3.1. Effect of biochar on nitrogen adsorption and ryegrass growth

The ryegrass total N contents and ^{15}N enrichment were analyzed, and the results are shown in Figure 1. Generally, the biochar application slightly influenced the total N contents of the ryegrass, and the only significant differences were found in ryegrass grown in loamy soil during the first season, with decreases of 4.0 and 2.29 mg•g^{-1} ryegrass N following the applications of 2% and 4% biochar, respectively, when compared to ryegrass harvested from the control soil.

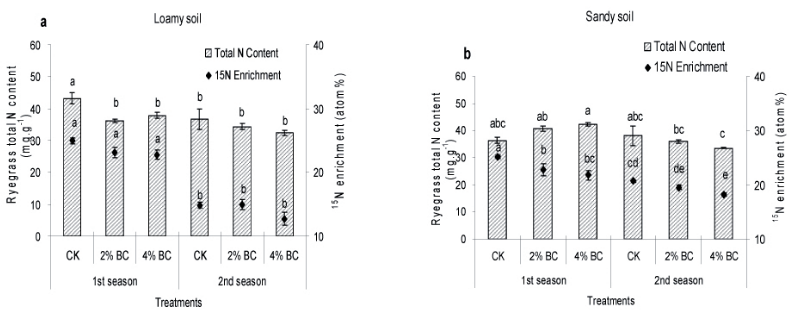

Figure 1. Effect of biochar addition on the total N content and ^{15}N enrichment in ryegrass. a. Loamy soil. b. Sandy soil. 2% BC: soil amended with 2% (w/w) biochar; 4% BC: soil amended with 4% biochar. Different letters indicate a significant difference (p<0.05).

Seasonal differences in ryegrass ^{15}N enrichment were found in both soils, but biochar-induced differences were only observed in the sandy soil. Specifically, in loamy soil, the ryegrass ^{15}N enrichment reached 22.8–24.9 atom% ^{15}N during the first season, which decreased to 12.7–15.0 atom% ^{15}N during the second season, and the values showed significant reductions in the sandy soil. However, significant effects induced by biochar application only occurred in sandy soil, in which the values were significantly lower than the control when 2% and 4% biochar was applied during the first season and when 4% biochar was applied during the second season.

The ryegrass dry weights and the proportion of N derived from fertilizer and soil are presented in Table 2.

Table 2. The total amount and proportion of ryegrass N uptake from fertilizer and soil

	Treatments	Total ryegrass N ($mg \cdot pot^{-1}$)	Ryegrass N derived from fertilizer		Ryegrass N derived from soil		Ryegrass dry weight (g)
			Total amount ($mg \cdot pot^{-1}$)	Ratio (%)	Total amount ($mg \cdot pot^{-1}$)	Ratio (%)	
1st season	Loamy soil						
	CK	37.75 ± 0.43 a	18.62 ± 0.36 a	49.32 a	19.12 ± 0.44 ab	50.68	0.88 ± 0.03 ab
	2% BC	32.15 ± 1.17 b	14.7 ± 1.05 b	45.72 ab	17.4 ± 0.20 b	54.28	0.89 ± 0.04 ab
	4% BC	37.09 ± 2.29 a	16.75 ± 1.55 ab	45.16 ab	20.34 ± 0.80 a	54.84	0.98 ± 0.08 a
	Sandy soil						
	CK	20.59 ± 1.09 c	10.23 ± 0.54 c	49.68 a	10.35 ± 0.85 c	50.32	0.58 ± 0.02 c
	2% BC	34.10 ± 0.96 ab	15.31 ± 0.35 b	44.90 ab	18.79 ± 0.38 ab	55.10	0.79 ± 0.05 b
	4% BC	35.32 ± 0.66 ab	15.18 ± 0.34 b	43.00 b	20.14 ± 0.94 a	57.00	0.83 ± 0.01 b
2nd season	Loamy soil						
	CK	19.44 ± 2.37 a	5.63 ± 0.54 bc	28.48 c	13.81 ± 1.84 a	71.52	0.53 ± 0.02 ab
	2% BC	17.79 ± 1.03 a	5.19 ± 0.2 bc	29.17 c	12.60 ± 0.93 ab	70.83	0.52 ± 0.02 ab
	4% BC	17.67 ± 0.30 a	4.40 ± 0.41 c	24.90 d	13.27 ± 0.17 ab	75.10	0.55 ± 0.01 a
	Sandy soil						
	CK	19.01 ± 1.53 a	7.76 ± 0.69 a	40.82 a	11.25 ± 0.85 ab	59.18	0.45 ± 0.02 b
	2% BC	16.29 ± 0.52 a	6.72 ± 0.21 ab	41.25 ab	10.03 ± 0.38 b	58.75	0.45 ± 0.02 b
	4% BC	18.67 ± 1.6 a	6.70 ± 0.69 ab	35.89 b	11.97 ± 0.91 ab	64.11	0.83 ± 0.01 a

2% BC: soil amended with 2% (w/w) biochar; 4% BC: soil amended with 4% biochar.

Values represent the means ± standard errors, where n=3.

Different letters represent a significant difference during the same season at the $p<0.05$ level.

Biochar significantly ($p<0.05$) promoted the adsorption of total N, fertilizer N, and soil N by ryegrass during the first season in the sandy soil. Consequently, compared to the control, the ryegrass dry weight was increased by 36.2% and 43.1% following 2% and 4% biochar applications, respectively. However, no significant differences were observed during the second season or in loamy soil.

3.2. Effect of biochar on soil nitrogen contents

Following two seasons of cultivation, the total N contents of the loamy soil averaged 0.1% and 0.14%, and the addition of 4% biochar significantly increased the soil total N content by 27.4% (Figure 2). However, the total N contents in the sandy soil only averaged 0.029% and 0.034% among the three treatments, and the biochar addition had no significant effect on the total N content when compared to the control soil. The greatest difference in soil ^{15}N enrichment was observed in loamy and sandy soils (Figure 2).

In the loamy soil, the ^{15}N enrichment increased by 0.30 atom% ^{15}N and 0.34 atom% ^{15}N following the application of 2% and 4% biochar, respectively.

No significant differences were observed between the two biochar applications rates used, indicating that the addition of biochar could increase the capacity for fertilizer N retention in loamy soil. However, in the sandy soil, there were decreases of 0.43 atom% and 0.54 atom% ^{15}N upon the addition of 2% and 4% biochar, respectively.

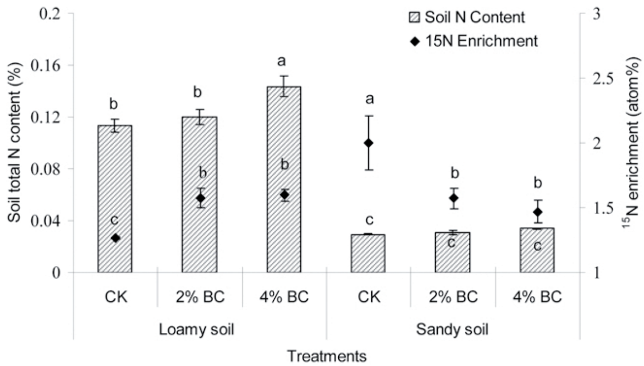

Figure 2. Effect of biochar application on total N contents and ^{15}N enrichment in the soil at the end of incubation. 2% BC: soil amended with 2% (w/w) biochar; 4% BC: soil amended with 4% biochar. Different letters indicate significant differences (p<0.05).

3.3. Effects of biochar on NH_3 volatilization

The total NH_3 volatilization from the soil increased markedly within 5–6 days of the urea application (Figure 3). The cumulative NH_3 volatilization from loamy soil ranged from 2.87 to 3.67 mg•kg^{-1}, and it was markedly lower than that of the sandy soil (39.37–47.23 mg•kg^{-1}). The stimulation of NH_3 volatilization following biochar addition was observed in both types of soil. Compared with the control treatment, significantly more (27.87%) NH_3 was volatilized following the addition of 4% biochar to loamy soil, and 14.18% and 19.99% increases were observed after the addition of 2% and 4% biochar, respectively, to the sandy soil.

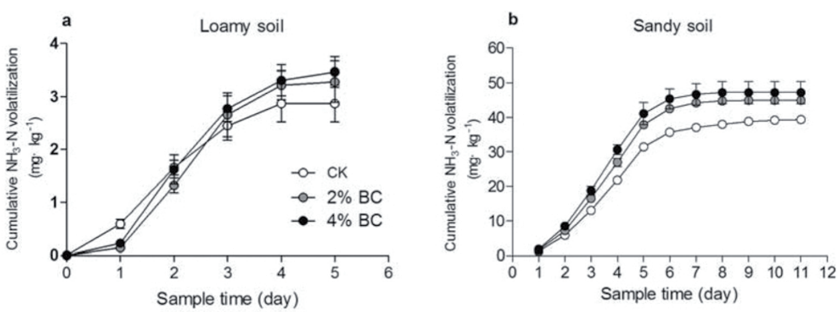

Figure 3. Cumulative ammonia volatilization from soil with and without 2% and 4% biochar amendments following urea applications in a. loamy soil and b. sandy soil

3.4. Effect of biochar on N leaching from soil

As shown in Figure 4, there were marked differences in inorganic N leaching between the loamy and sandy soils. In the loamy soil, most of the NH_4^+-N was leached during the last three leaching events, which occurred during days 20–40 of the incubation, and less than 3 mg•kg^{-1} NH_4^+-N was leached prior to the 20-day incubation period. By contrast, 90% of the leached NH_4^+-N from the sandy soil was leached during the first one or two events, with minimal NH_4^+-N leaching observed during later events. This finding indicates that loamy soil was better at retaining NH_4^+-N than sandy soil. The positive effect of biochar on the total NH_4^+-N leaching was only found in sandy soil, wherein the addition of 2% and 4% biochars reduced the leached NH_4^+-N to 2.59 and 3.56 mg•kg^{-1}, respectively, which corresponded to 48.5% and 66.7% of the total NH_4^+-N leached from the control soil. However, the negative effects of biochar addition on NH_4^+-N leaching were observed in the loamy soil (Figure 4a). The cumulative amount of NO_3^--N leached from the loamy soil was considerably higher than that leached from sandy soil (Figure 4b, d), and the leaching behavior was different between the two soils. Specifically, compared with the control, significantly (p<0.05) more (43.6%) NO_3^--N leached from the sandy soil under the 4% BC treatment, but no effect was observed under the 2% BC treatment. In the loamy soil, the NO_3^--N leaching was approximately 30% lower in the 2% and 4% biochar-amended soils, corresponding to a reduction of 57.41 mg•kg^{-1} N compared with the control.

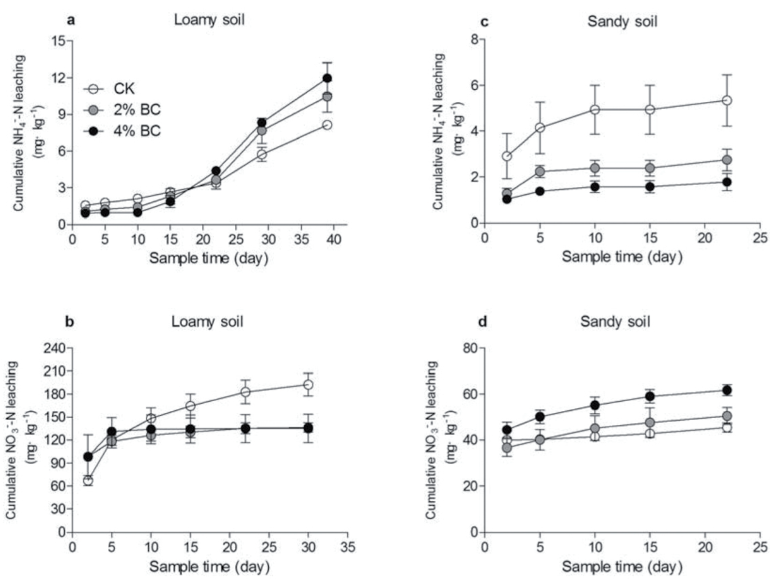

Figure 4. Cumulative nitrogen leaching from loamy soil (a–b) and sandy soil (c–d). 2% BC: soil amended with 2% (w/w) biochar; 4% BC: soil amended with 4% biochar. The data represent the means ± standard deviations. Different letters indicate significant differences (p<0.05).

4. Discussion

4.1. Effects of biochar on ryegrass growth and the fate of fertilizer N

In the present study, biochar application was observed to have a positive effect on ryegrass growth in sandy soil; however, no significant effect was found in loamy soil. This trend was consistent with a previous meta-analysis, which documented that the soil texture is a factor related to the plant growth response to biochar addition. Specifically, biochar could promote crop growth in soil with coarse textures rather than in fine-textured soil (Jeffery *et al*., 2011). The increased ryegrass growth could also be attributed to the promoted ryegrass N adsorption by biochar. Based on our data (Table 2 and Table 3), the total N uptake and NUE were significantly increased by 14.73 g•pot^{-1} and 7.9% (in the first season), respectively, following the addition of biochar to the sandy soil. This result was consistent with the finding of Huang *et al*. (2014), who showed that biochar application resulted in a 23–27% increase in fertilizer N uptake by rice. Additionally, our data showed that adding 2% and 4% biochar increased fertilizer N utilization by 9.06% and 8.83% and soil N by 81.55% and 94.59%, respectively, compared with the corresponding control. The results demonstrated that biochar not only promoted fertilizer N utilization but also enhanced soil N availability to the plant. This result occurred because biochar can act as a soil conditioner, altering the soil chemical and microbial properties and resulting in an increased uptake of soil nutrients that were not available in otherwise poor soils (Shen *et al*., 2016; van Zwieten *et al*., 2010a). For specific nutrients, soil N might be mineralized into inorganic N when N supplementation is not sufficient for plant use or when the demand for biochar induces microbial activity (Nelissen *et al.,* 2012; Muhammad *et al*., 2016).

Table 3. Effect of biochar on the rate of recovery and loss of labeled urea

	Treatments	NUE (%)			^{15}N residual ratio (%)	Total recovery (%)	Loss rate (%)
		1st season	2nd season	Total			
Loamy soil	CK	32.67 a	10.05 bc	42.72 a	7.31 c	50.03 a	49.97
	2% BC	26.35 b	9.27 bc	35.62 b	10.35 b	45.97 ab	54.03
	4% BC	29.91 ab	7.85 c	37.76 ab	12.64 a	50.40 a	49.60
Sandy soil	CK	18.27 c	13.85 a	32.12 c	3.44 d	35.56 d	64.44
	2% BC	27.33 b	11.19 ab	38.52 ab	2.68 e	41.2 bc	58.80
	4% BC	27.10 b	11.97 ab	39.07 ab	2.69 e	41.76 bc	58.24

Unlike the trend in sandy soil, the fertilizer N residual ratio increased by 3.04% and 5.33% in 2% and 4% biochar-amended loamy soil, respectively, while the total ryegrass N uptake and fertilizer N adsorption were not significantly affected. These results demonstrated that biochar application has contrasting effects on the fate of fertilizer N in soils with different properties. Previous studies have shown that using biochar as a soil N conditioner can potentially increase fertilizer N retention in soil, and explains this benefit was primarily derived from biochar's direct adsorption effect (van Zwieten *et al.*, 2010b) or the indirect microbial immobilization effect, because biochar contain energy substance that can serve as microbial substrates (Ippolito *et al.*, 2012); However, in some cases, N availability may decrease (Lehmann *et al.*, 2003).

4.2. Effect of biochar on NH_3 volatilization

As indicated in Table 4, the cumulative volatilized NH_3 from sandy soil was 39.4–47.2 mg•kg^{-1}, accounting for 42–47% of the total N loss. These losses were greater than those from loamy soil, in which the amount and proportion were only 2.9–3.5 mg•kg^{-1} and 1.4–2.3%, respectively. This finding can be explained by the fact that coarse soil usually has good aeration conditions and low WHC that favor NH_3 volatilization (Wang *et al.*, 2008).

Moreover, NH_3-N loss via volatilization from biochar-amended loamy soil and sandy soil was greater than their corresponding controls (Figure 3 and Table 4), and the amount of volatilized NH_3-N increased by 5.1% as the biochar application rate increased from 2% to 4% in sandy soil. These findings indicated that biochar addition could promote NH_3 volatilization from the applied N. This result was consistent with a previous finding by Schomberg *et al*. (2012), who reported that the NH_3 volatilization was increased by the addition of high-ash alkaline biochar with a 7-day incubation. Yang *et al*. (2015) also found that biochar potentially promoted NH_3 volatilization, and they suggested that the enhancement of the soil pH by biochar was the reason that NH_3 volatilization was favored.

Some reports have stated however, that biochar can adsorb NH_3, and one proposed mechanism for NH_3 adsorption includes the involvement of functional acid groups from biochar (Asada *et al.*, 2002; Taghizadehtoosi *et al.*, 2012). However, it is notable that in those studies, the biochar in use was acidic, with a pH of <7, whereas most biochars are alkaline, with a high pH value, including the biochar used in the present study. Therefore, we assume that biochars with pH values >7 were not suitable for reducing NH_3 volatilization.

Table 4. Total N loss and the percentage lost through each mechanism

Treatments		Total amount lost (mg·kg^{-1})	NH_3		NH_4^+-N		NO_3^--N	
			Cumulative volatilization (mg·kg^{-1})	Percentage of total N loss (%)	Cumulative leached amount (mg·kg^{-1})	Percentage of total N loss (%)	Cumulative leached amount (mg·kg^{-1})	Percentage of total N loss (%)
Loamy soil	CK	203.83 ± 8.38 a	2.87 ± 0.2 b	1.41	8.46 ± 0.48 b	4.15	192.5 ± 8.42 a	94.44
	2% BC	151.05 ± 3.86 b	3.28 ± 0.22 a	2.17	11.47 ± 0.29 ab	7.59	136.3 ± 3.57 b	90.24
	4% BC	150.52 ± 10.74 b	3.47 ± 0.17 a	2.30	11.97 ± 0.74 a	7.95	135.09 ± 10.47b	89.75
Sandy soil	CK	94.8 ± 2.62 b	39.36 ± 0.21c	41.52	5.34 ± 0.65 a	5.64	50.10 ± 2.97 b	52.84
	2% BC	96.22 ± 4.0 b	44.94 ± 0.43 b	46.71	2.75 ± 0.27 b	2.86	48.53 ± 4.10 b	50.44
	4% BC	110.45 ± 2.53 a	47.23 ± 1.85 a	42.76	1.78 ± 0.22 c	1.61	61.44 ± 1.11 a	55.63

Values represent the means ± standard errors, where n=3. Different letters represent a significant difference at p<0.05 within the same soil treatment.

4.3. Effect of biochar on N leaching

Consistent with a previous report that NO_3^--N is more mobile than NH_4^+-N and could not be easily adsorbed by soil colloids (Wang. 2008), our results showed that NO_3^--N accounted for more than 90% of the total leached inorganic N and 50.4–55.6% and 89.8–94.4% of the total N lost from sandy and loamy soil, respectively (Table 4).

Specifically, there were 48.5% and 66.7% reductions in the NH_4^+-N following the application of 2% and 4% biochar to the sandy soil, respectively. Ding et al. (2010) illustrated that biochar could adsorb NH_4^+-N predominantly through its high CEC, resulting in a 15.2% reduction in cumulative NH_4^+-N losses. The significant effect may also be due to the enhanced nitrification rate induced by biochar, rendering it less available for leaching. Promising mechanisms have involved biochar that could absorb the potential inhibitors of microbial metabolic pathways, such as monoterpenes and various polyphenolic compounds that are inhibitory to nitrification (Nelissen *et al*., 2012). However, in loamy soil, 40.3% more NH_4^+-N was leached from 4% biochar-amended soil. This significant ($p<0.05$) effect was attributed to the enhanced mineralization of organic N that was simulated by a high rate of biochar addition (Laird *et al*., 2010), thus increasing the soil NH_4^+-N content in the short term. This interpretation is consistent with the accelerated N dynamic following biochar addition (Nelissen *et al*., 2014).

For the biochar effect on NO_3^--N leaching, our data showed that 22.6% more NO_3^--N was leached from the soil column following the addition of 4% biochar to sandy soil when compared to the control soil (Table 4). This result occurred because most of the surface charge sites on biochar are due to carboxylate and phenolate groups, and those anionic surface charge sites will not retain NO_3^-; thus, NO_3^--N was difficult to retain by biochar (Jin *et al*., 2016). Another possible reason may lie in the finding we noted above in which biochar accelerated the nitrification rate in sandy soil, resulting in more NO_3^--N being available for leaching. However, this hypothesis cannot be fully supported without additional direct evidence. Although laboratory sorption studies have shown that biochar had a weak ability to adsorb NO_3^--N, biochar was reportedly able to mitigate NO_3^--N leaching as a soil amendment when it was incorporated into the soil (Jin *et al*., 2016; Laird *et al*., 2010). For example, Yao *et al*. (2012) reported that only 4 out of 13 biochars could adsorb NO_3^--N, and the 2 biochars added to a sandy soil were shown to reduce the NO_3^{--}N by 34–34.3%. These results contrast with our findings in sandy soil. One possible reason for the inconsistent results may be because the effects of biochar on the $NO3^-$-N adsorption ability not originated from the CEC but associated with other characteristics, such as its pore size and distribution, surface area and functional groups (Yang *et al.*, 2017), parameters known to vary with biochar types (Jin *et al*., 2016). The inconsistent result noted above indicated that the effect of biochar on the leaching of agricultural nutrients in soils was not uniform, and it varies by soil and nutrient type (Clough *et al*., 2013; Yao *et al*., 2012) as well as the interactions between soil and biochar. The authors speculate that the ability of biochar to engage in NH_4^{+-}N and NO_3^--N sorption/desorption and its mineralization/immobilization effect on soil N are two primary factors that control N leaching. These processes may be affected by abiotic and microbial processes (Bai *et al*. 2012; Lehmann *et al*., 2011), clarifying why the results obtained for biochar with respect to NH_4^+-N and NO_3^--N leaching varied with the soils. Therefore, the nutrient sorption characteristics of a given biochar and the soil reaction to a special biochar should be studied prior to its use in a particular soil amendment project.

In summary, biochar showed a significant positive effect in mitigating inorganic N losses from loamy soil

(26.46% and 26.82% of the reductions occurred after the addition of 2% and 4% biochars) and had a neutral effect in sandy soil. The primary benefit in loamy soil came from a significant reduction in the level of NO_3^--N leaching, but the potential mechanisms were not fully investigated and require future study.

5. Conclusions

The application of biochar to loamy and sandy soils had different effects on N utilization and loss. In particular, the results from the ^{15}N tracing study illustrated that biochar promoted the NUE and soil N utilization by ryegrass in sandy soil, but significant effects were not observed in loamy soil, where the fertilizer N retention ratio (%) was increased by 3.04–5.33%. This finding indicated that biochar is a soil conditioner that can either enhance fertilizer N availability or increase fertilizer N retention depending on the soil characteristics. In addition, biochar can markedly reduce NO_3^--N leaching losses from loamy soil, resulting in a 26% reduction in leached inorganic N. However, N losses via NH_3 volatilization were enhanced in the two tested soils, especially in the sandy soil. This finding was primarily a result of the fact that the added biochar was highly alkaline. In conclusion, this study reveals that biochar could improve the NUE in sandy soil and increase N retention while reducing N loss from loamy soil.

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