

Biochar Effectively Reduces Ammonia Volatilization From Nitrogen-Applied Soils in Tea and Bamboo Plantations

Lei Chu, H. M. K. Darshika Hennayake and Haijun Sun*

Co-Innovation Center for Sustainable Forestry in Southern China, College of Forestry, Nanjing Forestry University, Nanjing, 210037, China.

*Corresponding Author: Haijun Sun. Email: hjsun@njfu.edu.cn.

Abstract: Intensive practices in forest soils result in dramatic nitrogen (N) losses, particularly ammonia (NH₃) volatilization, to adjacent environmental areas. A soil column experiment was conducted to evaluate the effect of bamboo biochar on NH₃ volatilization from tea garden and bamboo forest soils. The results showed that biochar amendment effectively reduced NH₃ volatilization from tea garden and bamboo forest soil by 79.2% and 75.5%, respectively. The soil pH values increased by 0.53-0.61 units after biochar application. The NH₄⁺-N and total N of both soils were 13.8-29.7% and 34.0-41.9% higher under the biochar treatments than under the control treatment, respectively. In addition, the soil water contents of the two biochar-amended soils were significantly higher ($P < 0.05$), by 10.7-12.5%, than that of the soils without biochar amendment. Therefore, biochar mitigates NH₃ volatilization from the tested forest soils, which was due to the increases in soil NH₄⁺-N, total N and water contents after biochar amendment. Our main findings suggest that biochar addition is an effective management option for sustainable forest management.

Keywords: Atmospheric environment; biochar; forest soil; NH₃ volatilization; nitrogen; soil pH

1 Introduction

The intensive use and/or unreasonable management of synthetic chemical fertilizers over the last century has both increased agricultural and forest productivity and modified biogeochemical cycles in terrestrial ecosystems, causing severe negative environmental impacts [1-5]. In particular, tea and bamboo plantation systems usually receive high levels of nitrogen (N) fertilizer (range from 450 to 1200 kg N per hectare) to increase tea production [6-7]. The amount of N lost via leaching, runoff and nitrification-denitrification and methods to effectively mitigate these losses have been well documented [8-11]. Recent studies have indicated that ammonia (NH₃) emissions have been increasing over the last few decades on a global scale [12]. Moreover, losses of N by volatilization of NH₃ from urea reach high levels in forest soils [13-14]. However, methods to suppress the potential NH₃ volatilization from forest soils have not been clarified until now. Therefore, sustainable management of plantation tea and bamboo forests is of significance for enhancing the N use efficiency of forest plants and reducing NH₃ volatilization.

Biochar, in addition to acting as a carbon sink to mitigate global climate change and as an adsorbent to eliminate agricultural pollutants [11,15,16], can also reduce NH₃ volatilization from saline soil and rice paddy soil if used at appropriate rates [17-18]. Nevertheless, the mechanisms by which biochar amendment influences NH₃ volatilization from intensively managed forest soils receiving a high load of N fertilizer, such as tea garden and bamboo forest systems, is not well-known.

Compared with soils planted with other plants/cropping systems, most intensively managed plantation forest soils have relatively lower soil pH [7,19]. According to previously reported data, biochar can have lower pH depending on feedstock, temperature, etc., however, they are typically greater than 8.0 [15,20]. Here, we hypothesize that alkaline biochar addition can decelerate the acidifying processes of N-

applied intensively managed forest soils. Surface area and net surface charge have shown significant effects on ammonium (NH_4^+) sorption and desorption in biochars [21]. Attributing to the nutrient sorption function, biochar could increase soil N retention and decrease the N losses, including NH_3 volatilization.

Furthermore under intensive farming practices, changes in the soil texture which lead to a decreased water retention capacity [22]. Biochar application to forest soils generally increases soil moisture retention [15]. The pH, NH_4^+ -N, and the water content of topsoil are the main factors influencing the NH_3 volatilization rate in agricultural and forest soils [17]. Therefore, the specific aim of the current work was to determine the impacts of biochar application on NH_3 volatilization losses from N-applied intensively managed forest (i.e., tea garden and bamboo forest) soils. Moreover, the mechanism by which biochar changed the pH, NH_4^+ -N and the water content related to the NH_3 volatilization rate were determined.

2 Materials and Methods

2.1 Background Information and Soil Column Installation

The experimental soil samples were taken from the top 0-15 cm of the soil profile at six different sites from an approximately 10 000 m² tea garden in Purple Mountain, and an approximately 1 000 m² bamboo forest in Nanjing Forestry University, both located at Nanjing City, Jiangsu Province, China. The soil samples were then air-dried, ground to pass through a 2 mm nylon sieve and mixed thoroughly to obtain homogeneous subsamples before usage. A total of 1000 g of soil was then carefully repacked into each polyvinyl chloride (PVC) soil column (7.5 cm in inner diameter, 25 cm in height) with nearly the same bulk density as that under field conditions. The selected basal properties of the tested tea garden and bamboo forest soils are listed in Tab. 1.

Table 1: Detailed characteristics of soils and biochar used in the experiment

Biochar	pH	Total N (g/kg)	Available P (mg/kg)	Available K (mg/kg)	Total Organic Carbon (g/kg)	BET Surface (m ² /g)
Tea garden soil	4.62	18.30	4.40	20.90	7.6	-
Bamboo forest soil	5.01	19.15	4.61	21.06	8.6	-
Biochar	8.37	1.01	1.05	9.65	1.2	2.01

Biochar derived from bamboo sawdust, a hardwood biomass, in a continuous slow pyrolysis system at 500°C was evaluated in this experiment. A detailed procedure can be found in Feng et al. [17]. The basic characteristics of the biochar used in the present study are also shown in Tab. 1. The biochar was applied at rate of 3 % wt/wt (biochar/soil: *weight/weight*, i.e., 30 g/pot). The control treatment was applied with the same amount of N fertilizer but without biochar. Therefore, the treatments with three replications were named as Urea and Urea+biochar, for both forest soils. The quantified biochar was homogeneously mixed with tested soils when the N fertilizers were applied. Nitrogen fertilizer was applied at 200 mg/kg soil (equivalent to approximately 500 kg/ha in actual fields, due to the current popularity of N fertilization in the study region). The N fertilizer was supplied as urea (200 mg N) under the Urea treatment, and urea (170 mg N) and biochar (30 mg N) under the Urea + BC treatment, respectively. Deionized water was added to bring the soil moisture content to 65% water holding capacity and was maintained throughout the experiment.

2.2 NH_3 Volatilization Measurement

Daily NH_3 volatilization fluxes were measured with a continuous air-flow enclosure method using a transparent Plexiglas chamber (7.5 cm in inner diameter, 20 cm in height) in each column as detailed in our previous study [18]. Additionally, the NH_3 absorbent comprised 80 mL 2% boric acid mixed with an indicator of methyl red, bromocresol green, and ethanol. After returning to the laboratory, the NH_3 absorbent solution was titrated against 0.01 M H_2SO_4 . The cumulative NH_3 volatilization load was

calculated by the sum of the daily emissions over the observation period. In the current study, the observation period continued for 10 days.

2.3 pH Value, $\text{NH}_4^+\text{-N}$, Total N and Water Contents of Topsoil

On the 3rd day after the incubation experiment was finished, soil samples were taken. Immediately, soil pH was measured in deionized water at a ratio of 1:2.5 w/v using combined reference electrodes and a $\Phi 255$ pH/temp/mV meter (Coulter Bechman Co., USA). After passage through a 2 mm sieved and followed by air-drying, soil $\text{NH}_4^+\text{-N}$ was extracted by 2.0 M KCl first (extraction duration 1 h, temperature 25°C), then the concentrations in the KCl-extracted soil solution were measured by a San⁺⁺ Continuous Flow Analyzer (Skalar, Netherlands). Total N contents were determined using a PE 2400-II CHN element analyzer (Perkin Elmer Corp., USA) at 950°C. The water content was determined by oven drying (75°C) and calculating the change in weight between wet and dry samples.

2.4 Statistical Analysis

The statistical tests were performed using the statistical software package SPSS 16.0. Analysis of variance (ANOVA) was used to test the relative significance of different treatments through calculation of their mean differences. Significant differences among means were determined by Duncan's multiple range test at the $P < 0.05$ level.

3 Results and Discussion

3.1 $\text{NH}_4^+\text{-N}$ and Total N Concentration of Topsoil (0-15 cm)

Changes in $\text{NH}_4^+\text{-N}$ influenced by biochar addition affect NH_3 volatilization in acidic soils [23]. The $\text{NH}_4^+\text{-N}$ (Fig. 1(A)) and total N (Fig. 1(B)) concentrations in the topsoil of tea plantations and bamboo forests were determined after incubation. Overall, biochar amendment tended to increase the $\text{NH}_4^+\text{-N}$ concentration of both soils. In particular, the $\text{NH}_4^+\text{-N}$ concentration was significantly ($P < 0.05$) increased by 29.7% in the bamboo forest soil. In addition, the total N content significantly ($P < 0.05$) increased with the application of biochar by 34.0% and 41.9% compared with that of the Urea treatment for tea garden and bamboo forest soils, respectively. The higher $\text{NH}_4^+\text{-N}$ and total N concentrations of the topsoil were mainly attributed to the nutrient sorption characteristics of the biochar, as reported previously [21,24]. The results of the present study indicate that biochar reduced N losses such as NH_3 volatilization from intensively managed forest soils and will be discussed below.

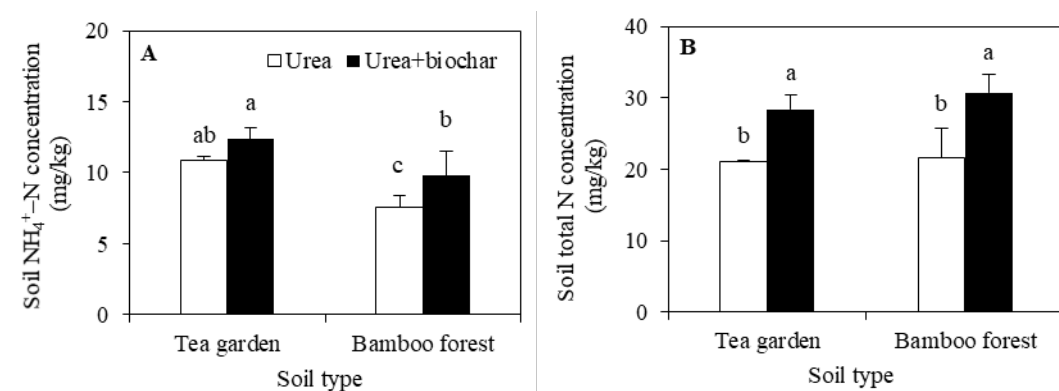


Figure 1: Effects of biochar amendment on the $\text{NH}_4^+\text{-N}$ (A) and total N (B) contents of tea garden and bamboo forest soils. Error bars indicate the SD of the means ($n = 3$). Different lowercase letters indicate significant differences among all treatments ($P < 0.05$)

3.2 Soil Water Content and Soil pH

After incubation, bamboo forest soil recorded a 6.3% higher water content than tea garden soil. Due to the typical characteristics of biochar including its high porosity and high surface area, biochar application generally increases the soil water holding capacity [15]. In this study, the soil water retention capacity for both soil types were significantly higher in biochar-amended soils than in those without biochar. The data in Fig. 2 shows that the soil water contents of the two biochar-amended soils were significantly 10.7-12.5% higher ($P < 0.05$) than those of the unamended soils. Recent studies have demonstrated that the application of biochar can significantly increase the soil water holding capacity and thus the soil moisture content in forest ecosystems. For example, Prober et al. [25] reported that the soil moisture content in mesic woodlands increased by 6-25% after the application of green-waste biochar at a rate of 20 t/ha.

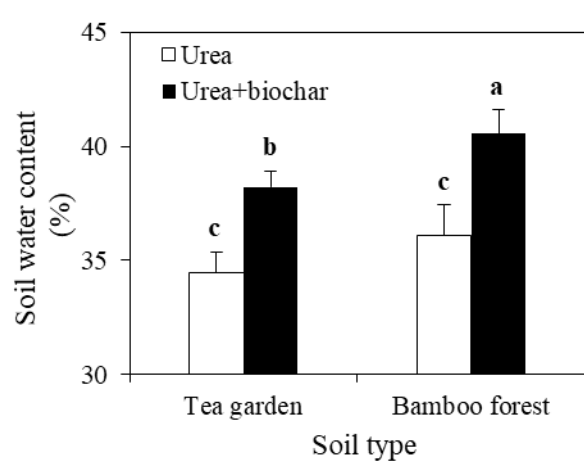


Figure 2: Effects of biochar amendment on the water content of tea garden and bamboo forest soils. *Error bars* indicate the SD of the means ($n = 3$). *Different lowercases letters* indicate significant differences among all treatments ($P < 0.05$)

Overall, bamboo forest soils had pH values 0.53-0.61 higher than those of teagarden soils. Increased soil pH levels were observed in both soils with biochar amendment (Fig. 3). Biochar is commonly alkaline, and thus can be used as a soil amendment to neutralize soil acidity and increase soil pH [26]. In the present study, the pH values of tea garden and bamboo forest soils without biochar amendments were 4.85 and 5.44, respectively. Biochar application increased the pH values of the two soils to 5.04 and 5.57, respectively (Fig. 3). Increased soil pH as a result of biochar application has been extensively investigated in agricultural soils [27] and similar results have been found in forest soils [15,28].

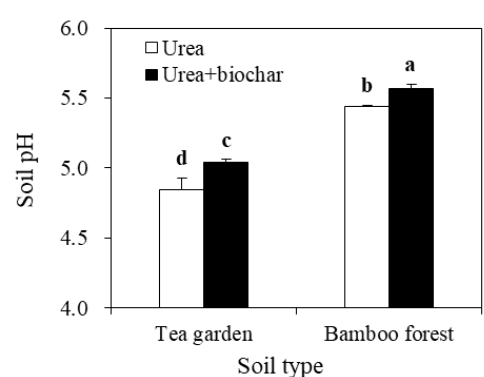


Figure 3: Effects of biochar amendment on the pH value of tea garden and bamboo forest soils. *Error bars* indicate the SD of the means ($n = 3$). *Different lowercases letters* indicate significant differences among all treatments ($P < 0.05$)

3.3 NH₃ Volatilization

NH₃ plays a significant role in the formation of atmospheric particulate matter, visible degradation and atmospheric deposition of N in sensitive ecosystems. Thus, it is important to have a clear understanding of the NH₃ sources first [12]. During the 10 days incubation period, the NH₃ volatilization losses under the Urea treatment of the tea garden soil were 6.45 mg/pot, while the losses were lower with only 3.83 mg/pot under the urea-only treatment of the bamboo forest soil (Fig. 4). The total NH₃ losses accounted for 3.22% and 1.92% of the N fertilizer applied to the tea garden and bamboo forest soils, respectively. Interestingly, biochar amendments effectively reduced the total NH₃ volatilization losses by 79.2% and 75.5% in tea plantation and bamboo forest soils, respectively (Fig. 4).

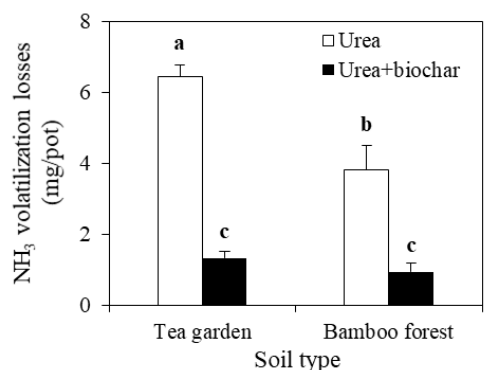


Figure 4: Effects of biochar amendment on total NH₃ volatilization losses from the tea garden and bamboo forest soils. Error bars indicate the SD of the means ($n = 3$). Different lowercase letters indicate significant differences among all treatments ($P < 0.05$)

Watkins et al. [29] indicated that NH₃ volatilization losses are directly related to the air movement, temperature, pH, NH₄⁺-N and water contents of mineral soils. According to Feng et al. [17], biochar addition may influence the pH value and the NH₄⁺-N content changes in topsoil and thereby affect the NH₃ volatilization process in forest soils. Several studies have reported a significant reduction in N losses from the soil and an increase in pH and water retention capacity when biochar was applied [15,26,29]. In our research, we also found that the application of biochar tended to increase pH levels, which may also result in slower NH₄⁺ nitrification. Additionally, biochar could absorb the NH₄⁺-N ions in the topsoil of the biochar-amended treatment, resulting in higher NH₄⁺-N contents than that of the unamended treatment. Our study demonstrated that biochar reduces NH₃ volatilization from forest soils with intensive N-application by enhancing the NH₄⁺-N and water retention capacity of the soil. It is likely that the pH value after biochar addition is not so high that the NH₃ volatilization did not increase after biochar addition. Of course, the optimum biochar addition parameters (such as the biochar type, application rate and so on) should be studied in the future, as discussed in Sun et al. [16].

4 Conclusions

The current soil column experiment found that bamboo biochar application increased the pH, NH₄⁺-N, total N, and water contents of two forest soils fertilized with N. Interestingly, biochar amendments effectively mitigated the NH₃ volatilizations from N application to tea and bamboo plantation systems, which was mainly attributed to absorption of water and NH₄⁺-N ions by biochar. Moreover, the optimum biochar management and long-term field effects need to be further investigated.

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