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Effects of various fertilization depths on ammonia volatilization in Moso bamboo (*Phyllostachys edulis*) forests

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ABSTRACT

The objective of this study was to investigate the effects of various fertilization depths on NH_3 volatilization loss in Moso bamboo forests in the Huanshan county, Anhui province, China. A complete randomized block design with five treatments was used, including 0 (T_0); 10 (T_{10}); 20 (T_{20}) and 30 (T_{30}) cm application depths and no fertilizer treatment (control). Results showed that NH_3 volatilization was detected in a single peak curve after fertilization, peaking at the third day for T_0 and T_{10} treatments, and the sixth day for T_{20} and T_{30} treatments, respectively. Twelve days later, the fluxes declined to a low level similar to the control. The mean NH_3 volatilization flux decreased with the increase of fertilization depth, ranged from 0.71 kg/ha/day for T_{30} treatment to 1.68 kg/ha/day for T_0 treatment. More than 80% of total NH_3 volatilization occurred within the first eight days. After the experiment, the cumulative NH_3 volatilization of T_0 treatment was 26.8 kg/ha, accounting for 20.8% of the total nitrogen (N) application. Compared with the surface application, deep application of N fertilizer was effective in reducing N loss through NH_3 volatilization. T_{20} treatment is recommended in terms of increasing N absorption, diminishing N leaching loss and labor cost.

Keywords: nitrogen; NH_4^+-N concentration; urease activity; cation exchange capacity; macronutrient

Nitrogen (N) is one of the most important elements for plant growth (Burton et al. 2007) and the most commonly growth-limiting nutrient in ecosystems (Goodman et al. 2013). Therefore, N fertilizer application has become an important measure to promote plant growth and improve the yield (Smethurst 2010). However, the N use efficiency (NUE) is relatively low in China, commonly ranging from 30–35% (Wu et al. 2010). As a result, much of N applied to fields is lost either by nitrification-denitrification, ammonia (NH_3) volatilization, leaching or runoff (Das et al. 2009). N loss not only led to the waste of fertilizer, and more seriously, it exacerbated the environmental pollutions (Guo et al. 2010).

NH_3 volatilization, which is the main way of N loss (Xu et al. 2012), accounted for 40–50% of the total N under advantageous conditions, equivalent to 71% of the total N loss (Zhu 1992). It is also recognized as a major source of atmospheric NH_3 (Carozzi et al. 2013). When deposited, the NH_3 may contribute to water eutrophication and soil acidification (Sommer and Hutchings 1995). Moreover, NH_3 is also an important precursor of PM 2.5 (particulate matter with aerodynamic diameter of 2.5 μm or less), which affects human health (Arogo et al. 2003).

Moso bamboo (*Phyllostachys edulis*) is an economically and ecologically important species characterized by rapid biomass accumulation in Southern China. In order to improve the stand production, fertilizers have been applied in Moso bamboo forests. Moreover, N demand and N uptake are, among all nutrient elements, largest in each growth period (Su 2012). Therefore, urea is commonly used in Moso bamboo forests. However,

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very little information is available regarding the NH_3 volatilization after the application of urea in different depths in this region.

Therefore, the objective of this study was to investigate the effects of urea application depths on NH_3 volatilization in Moso bamboo forests. More specifically, we studied the NH_3 fluxes and cumulative NH_3 volatilization in different fertilization depths, and examined the main factors affecting NH_3 volatilization. Finally, the optimized fertilization depth was proposed in terms of reducing the NH_3 volatilization loss and increasing the absorption.

MATERIAL AND METHODS

Site description. This study was conducted in the Huangshan county, Anhui province, China. The Moso bamboo forests were naturally regenerated, with a stand density of 1537 trees/ha, a mean height of 14.6 m, and an average diameter at breast height (1.3 m, DBH) of 11.4 cm. The region is characterized by a humid mid-subtropical monsoon climate. The soil is classified as ultisols according to the USDA soil classification. The initial properties of soil (0–60 cm) were as follows: bulk density, 1.13 ± 0.15 (mean ± standard deviation (SD)) g/cm^3; pH, 4.86 ± 0.07; organic C, 28.65 ± 2.13 g/kg; total N, 1.65 ± 0.13 g/kg; and cation exchange capacity (CEC), 73.16 ± 4.67 mmol$_+$/kg, respectively.

Experimental design. A completely randomized block design was applied in July 2015. Totally five treatments were applied to 15 experimental plots (20 m × 30 m) with three replications. The treatments were applied as follows: a control treatment with no fertilizer (control); fertilization at soil depth of 0 cm (T_0); 10 cm (T_{10}); 20 cm (T_{20}) and 30 cm (T_{30}). Urea (46.4% N), calcium superphosphate (5.2% P) and potash chloride (49.8% K) were applied once by furrow application at 242, 178 and 147 kg/ha, respectively (Su 2012). Furrows (20 cm width) were dug along the contour every two meters. The original soil was backfilled after fertilization.

Measurement of NH_3 volatilization. NH_3 volatilization from soil was measured *in situ* using a kind of venting method (Figure 1). After fertilization, a cylindrical PVC tube (10 cm diameter, 15 cm length) was inserted 2 cm into soil. Two pieces of sponge (11 cm diameter, 2 cm thickness) dipped into the ammonia absorbent (20 g/kg H_3BO_3) were placed in the PVC tube. The upper sponge was equal to the top of the tube, and the lower was 4 cm above soil surface.

Samples of three replications were taken randomly from each plot. The NH_3 was collected every day after fertilization until there were no differences in the volatilization rates among the five treatments. When sampled, the lower sponge was removed, saved in a reclosable bag and replaced by another piece of sponge soaked in H_3BO_3 solution. NH_3 concentration in the acid was titrated with standardized 0.02 mol/L H_2SO_4 solution. NH_3 flux was calculated using the following formula:

$$NH_3 \text{ (kg/ha/day)} = M/(A \times D) \times 10^{-2}$$

Where: M – amount of NH_3 volatilization measured in each PVC tube (NH_3-N kg/ha); A – cross-sectional area of PVC tube (m^2); D – time interval of two adjacent sampling (day).

Soil sampling and analysis. Soil samples were collected (0–40 cm) using a soil sampler with a diameter of 5 cm at three random fertilization furrows in each plot. Soil samples from the same plot were mixed, transported to the laboratory within 0.5 h and then immediately stored at 4°C in a refrigerator before analysis. The ammonium (NH_4^+-N) concentration was measured at 625 nm by the indophenol blue colorimetric method using the soil samples that were stored in the refrigerator (Denmead et al. 1976). All soil samples were air dried at room temperature and sieved with 2 mm × 2 mm mesh to remove gravel and large debris. Urease activity (UA) was assayed in air dried soil by the method of Kumar et al. (2015). The cation

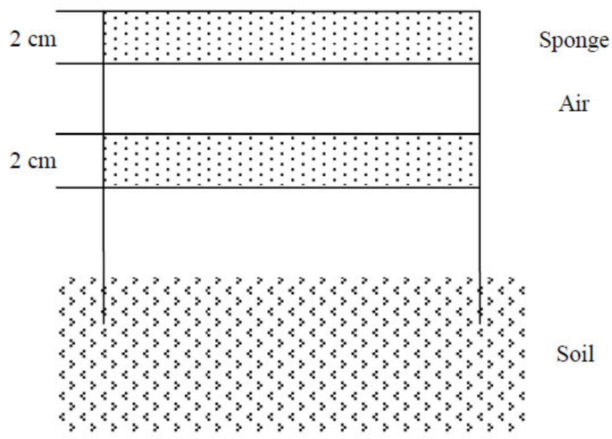

Figure 1. Description of the venting method for NH_3 volatilization

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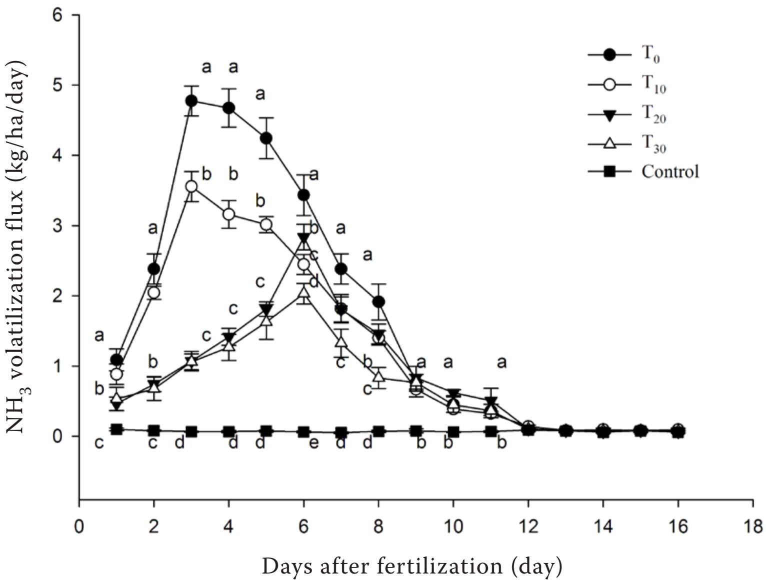

Figure 2. Changes in NH_3 volatilization fluxes of five treatments after fertilization. Different letters in a column indicate significant differences at $P < 0.05$. The mean of bars indicate the standard deviation. Control – no fertilizer; T_0 – 0, T_{10} – 10, T_{20} – 20, T_{30} – 30 cm

exchange capacity (CEC) was determined by the method of Eisazadeh et al. (2012). Briefly, 10 g of the air dried soil were placed into a 100 mL centrifuge tube. Next, 50 mL of 0.3 mol/L $BaCl_2$ solution was added, and the tube was shaken for 15 min. Then, the sample was centrifuged at 3000 rpm for 20 min, and the supernatant was discarded very carefully to avoid loss of solids. After the addition of 50 mL of 0.3 mol/L $CaCl_2$ solution, the sample was shaken for 30 min, centrifuged, and the supernatant was collected into a 100 mL volumetric flask. Finally, the extracted solution was analysed using an ICP spectrometer (USA).

Statistical analysis. One-way analysis of variance (ANOVA) and the least significant difference (*LSD*) were used to test the significant differences between treatments. Statistical significance was set at $P < 0.05$.

RESULTS

NH_3 volatilization flux. NH_3 volatilization fluxes of all fertilization treatments were higher than that of the control (Figure 2). For fertilized treatments, NH_3 volatilization fluxes showed a similar changing trend with time, namely increasing first and then decreasing. However, the NH_3 volatilization flux in unfertilized treatment was relative low, and remained unchanged. NH_3 volatilization fluxes of T_0 and T_{10} treatments increased immedi-

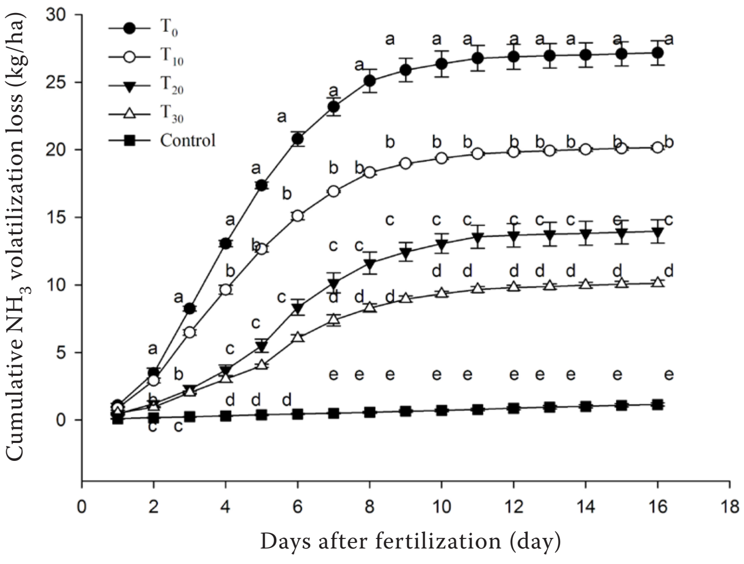

Figure 3. Changes in cumulative NH_3 volatilization of five fertilization treatments. Different letters in a column indicate a significant difference at $P < 0.05$. The mean of bars indicate the standard deviation. Control – no fertilizer; T_0 – 0, T_{10} – 10, T_{20} – 20, T_{30} – 30 cm

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Table 1. Cumulative NH_3 volatilization loss and its ratio to applied fertilizer nitrogen (N)

Treatment	Total		The first eight days		
	NH_3 (kg/ha)	ratio (%)^a	NH_3 (kg/ha)	ratio (%)^a	ratio (%)^b
Control	1.15 ± 0.11^e		0.58 ± 0.04^e		
T_0	26.84 ± 1.45^a	20.80 ± 1.12^a	24.89 ± 1.00^a	19.28 ± 1.05^a	92.73 ± 3.54^a
T_{10}	20.20 ± 1.12^b	15.65 ± 0.93^b	18.32 ± 1.07^b	14.19 ± 0.96^b	90.69 ± 3.38^a
T_{20}	13.97 ± 0.88^c	10.82 ± 0.68^c	11.61 ± 0.74^c	8.99 ± 0.57^c	83.11 ± 2.96^b
T_{30}	11.34 ± 0.23^d	8.79 ± 0.17^d	9.35 ± 0.58^d	7.24 ± 0.45^d	82.45 ± 4.42^b

Different letters in a column denote a significant difference at $P < 0.05$. [a]Ratio of NH_3 volatilized to the amount of applied N; [b]Ratio of NH_3 volatilized within the first eight days to the total volatilization loss. Control – no fertilizer; T_0 – 0, T_{10} – 10, T_{20} – 20, T_{30} – 30 cm

ately, peaked at the third day (4.77 kg/ha/day and 3.56 kg/ha/day, respectively), and then declined rapidly to a low level similar to the control after day 12. While the fluxes in T_{20} and T_{30} fields reached the maximum within six days after fertilization (2.84 kg/ha/day and 2.03 kg/ha/day, respectively) and subsequently decreased. About 12 days later, NH_3 volatilization fluxes of all treatments were similar and then remained stable afterwards. Among fertilized treatments, NH_3 volatilization flux decreased with the increase of fertilization depth. T_0, T_{10}, T_{20} and T_{30} had mean NH_3 volatilization fluxes of 1.68, 1.26, 0.87 and 0.71 kg/ha/day, respectively.

Cumulative NH_3 volatilization. The cumulative NH_3 volatilization (except control) presented an S curve (Figure 3). Fertilization depth significantly decreased the cumulative emissions of NH_3 and the ratio of NH_3 volatilized to the amount of applied N (Table 1). N loss through NH_3 volatilization in T_0 treatment at the end of the experiment was the largest (26.84 kg/ha), which accounted for 20.80% of the total N application. Compared with T_0 treatment, the NH_3 volatilization losses were decreased by 24.7, 48.0 and 57.7% for the T_{10}, T_{20} and T_{30} treatments, respectively.

In terms of NH_3 volatilization process, NH_3 volatilization derived from urea could be divided into 2 stages, namely rapidly and slowly increasing stages (Table 2). The first eight days (from day 1 to 8) was recognized as the rapidly increasing stage, and then changed to the slowly increasing stage (from day 9 to 16). The cumulative NH_3 emission within the first eight days showed the same trend as total NH_3 volatilization loss (Table 1), but the ratios of NH_3 volatilized within the first eight days to the total volatilization loss were all over 80%, ranged from 82.45% for T_{30} to 92.73% for T_0 (Table 2). Therefore, the NH_3 volatilization mostly occurred in the first eight days after fertilization.

Factors affecting NH_3 volatilization. The temporal variance of NH_4^+-N concentrations, urease

Table 2. Ratios of NH_3 volatilization loss in different intervals to the total volatilization loss (%)

Treatment	Days after fertilization (day)			
	1–4	5–8	9–12	13–16
Control	26.02 ± 1.54^c	23.91 ± 1.84^d	25.93 ± 1.42^a	24.14 ± 1.76^a
T_0	48.11 ± 2.04^a	44.62 ± 1.92^c	6.25 ± 0.56^d	1.02 ± 0.12^d
T_{10}	47.74 ± 1.66^a	42.95 ± 1.27^c	7.54 ± 0.61^{cd}	1.78 ± 0.21^{cd}
T_{20}	26.48 ± 1.58^c	56.63 ± 2.63^a	14.79 ± 1.27^b	2.10 ± 0.82^{bcd}
T_{30}	31.16 ± 1.74^b	51.29 ± 2.87^b	14.78 ± 1.93^b	2.76 ± 0.53^b

Different letters in a column indicate a significant difference at $P < 0.05$. Control – fertilizer; T_0 – 0, T_{10} – 10, T_{20} – 20, T_{30} – 30 cm

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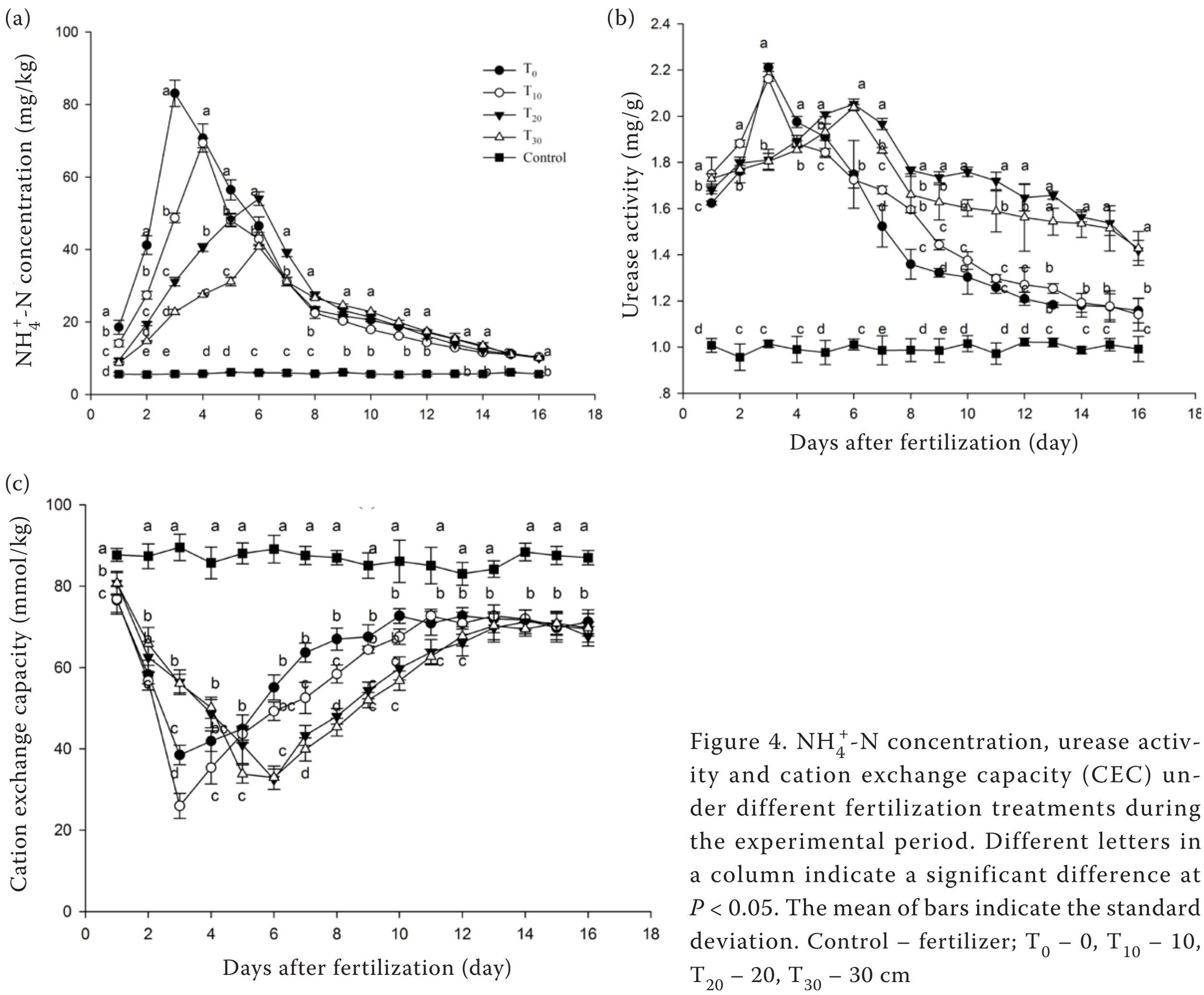

Figure 4. NH_4^+-N concentration, urease activity and cation exchange capacity (CEC) under different fertilization treatments during the experimental period. Different letters in a column indicate a significant difference at $P < 0.05$. The mean of bars indicate the standard deviation. Control – fertilizer; T_0 – 0, T_{10} – 10, T_{20} – 20, T_{30} – 30 cm

activity and CEC in soil corresponded to urea application (Figure 4, Table 3). NH_4^+-N concentrations and urease activities showed positive correlations with NH_3 volatilization fluxes for all of the fertilizer treatments. However, negative correlations were observed between NH_3 volatilization fluxes and CEC among all treatments, except control. After urea application, the NH_4^+-N concentrations increased immediately and peaked due to urea hydrolysis. Higher urease activities may accelerate the hydrolysis of urea, leading to more NH_4^+-N in the soils. Additionally, the low CEC would have provided a greater chance for the release of NH_4^+-N ions as NH_3. Then, the NH_4^+-N concentrations declined rapidly, probably because of the decrease of urease activities and the increase of CEC.

Table 3. Correlation between NH_3 volatilization fluxes and NH_4^+-N concentration, urease activity and cation exchange capacity (CEC)

Treatment	NH_4^+-N concentration	Urease activity	CEC
Control	–0.066	0.183	–0.337
T_0	0.960**	0.953**	–0.950**
T_{10}	0.932**	0.935**	–0.949**
T_{20}	0.949**	0.911**	–0.930**
T_{30}	0.887**	0.957**	–0.878**

*$P < 0.05$; **$P < 0.01$; n = 144. Control – fertilizer; T_0 – 0, T_{10} – 10, T_{20} – 20, T_{30} – 30 cm

DISCUSSION

Reasons for low emission loss by deep application. NH_3 volatilization loss can be greatly reduced by optimum N fertilization techniques. Placement depth was an important soil resist-

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ance to NH_3 volatilization (Ma et al. 2010). In this study, N losses through NH_3 volatilization after fertilization contributed to a large extent to the applied urea in shallow treatments (T_0 and T_{10}). Other studies showed similar results, that the cumulative NH_3 loss could be up to 48% of surface-applied urea N (Pacholski et al. 2006). The low NH_3 volatilization of deep application may depend on several aspects. First, high microbiological activities in the surface soil can promote rapid hydrolysis of urea to NH_4^+-N (Zaman et al. 2004). As a result, the NH_4^+-N concentration was increased rapidly, leading to large NH_3 loss. Second, according to the negative correlations between NH_3 volatilization fluxes and CEC (Table 3), the decrease of CEC with fertilization depths indicated the increase of NH_4^+-N release. But the low NH_4^+-N concentration in deep soil layer may be a limiting factor on the release of NH_4^+-N. Additionally, deep placement of urea decreased the exposed surface area and increased the resistance to NH_3 transport (Sommer and Hutchings 1995). A long time was needed to diffuse, or it was difficult to transfer through the soil for the volatile NH_3. Finally, when fertilized at a deep placement, the more slowly released NH_4^+-N ions would have provided a better opportunity for uptake by plant roots (Zaman and Blennerhassett 2010). Moreover, these NH_4^+-N ions would be immobilized or lost by infiltration with increasing time after fertilization, thus decreasing the substrate (NH_4^+-N concentration) for NH_3 volatilization.

Determination of proper fertilizer placement depth. Deep application of N fertilizer delayed the peak of NH_3 volatilization flux and effectively decreased the loss of NH_3 volatilization and its loss ratio. Compared with the surface application, losses through NH_3 volatilization were significantly decreased by application depth. The decreased NH_3 loss can be ascribed to the significantly increased N uptake by plants and N losses through infiltration, nitrification-denitrification and soil immobilization. In order to determine the proper fertilizer placement depth, not only the reduction of N loss should be considered, but also the uptake by plant roots. However, the appropriate trade-off between N uptake and N loss is uncertain. Moso bamboo is characterized by the shallow root system, which is mainly distributed in 10–30 cm soil depth (Jiang 2007). Based on the results of N loss (NH_3 volatilization) in this study and the root distributions, both 20 cm and 30 cm are appropriate fertilization depths when the furrow practice is used in Moso bamboo forests. However, T_{30} treatment may lead to N leaching loss and require higher mechanical power input and production cost (Su et al. 2015). Therefore, T_{20} treatment is recommended in field practice.

In conclusion, this study provided an insight into NH_3 volatilization as affected by various fertilization depths in Moso bamboo forests. With the increase of fertilization depth, the NH_3 volatilization reduced, indicating that deep application of N fertilizer effectively decreased N loss through NH_3 volatilization. From the perspective of NH_3 volatilization process, the majority of NH_3 volatilization occurred within the first eight days, suggesting that managements that reduce N loss through NH_3 volatilization should be considered and conducted immediately after fertilization. The decreased NH_3 loss can be ascribed to the significantly increased N uptake by plants and N losses through infiltration, nitrification, denitrification and soil immobilization. However, the appropriate trade-off between N uptake and N loss is uncertain, and further researches should be conducted to balance N utilization and N loss in Moso bamboo forests.

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