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,
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$_3$BO$_3$) 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$_3$BO$_3$ solution. NH$_3$ concentration in the acid was titrated with standardized 0.02 mol/L H$_2$SO$_4$ solution. NH$_3$ flux was calculated using the following formula:

\[
\text{NH}_3\text{ (kg/ha/day)} = \frac{M}{(A \times D)} \times 10^{-2}
\]

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
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 BaCl₂ 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 CaCl₂ 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**

**NH₃ volatilization flux.** NH₃ volatilization fluxes of all fertilization treatments were higher than that of the control (Figure 2). For fertilized treatments, NH₃ volatilization fluxes showed a similar changing trend with time, namely increasing first and then decreasing. However, the NH₃ volatilization flux in unfertilized treatment was relatively low, and remained unchanged. NH₃ volatilization fluxes of T₀ and T₁₀ treatments increased immedi-

Figure 2. Changes in NH₃ 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; T₀ = 0, T₁₀ = 10, T₂₀ = 20, T₃₀ = 30 cm

Figure 3. Changes in cumulative NH₃ 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; T₀ = 0, T₁₀ = 10, T₂₀ = 20, T₃₀ = 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>
<thead>
<tr>
<th>Treatment</th>
<th>Total NH_{3} (kg/ha)</th>
<th>ratio (%) (^{a})</th>
<th>The first eight days NH_{3} (kg/ha)</th>
<th>ratio (%) (^{a})</th>
<th>ratio (%) (^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.15 ± 0.11(^{e})</td>
<td>0.58 ± 0.04(^{e})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{0}</td>
<td>26.84 ± 1.45(^{a})</td>
<td>20.80 ± 1.12(^{a})</td>
<td>24.89 ± 1.00(^{a})</td>
<td>19.28 ± 1.05(^{a})</td>
<td>92.73 ± 3.54(^{a})</td>
</tr>
<tr>
<td>T_{10}</td>
<td>20.20 ± 1.12(^{b})</td>
<td>15.65 ± 0.93(^{b})</td>
<td>18.32 ± 1.07(^{b})</td>
<td>14.19 ± 0.96(^{b})</td>
<td>90.69 ± 3.38(^{a})</td>
</tr>
<tr>
<td>T_{20}</td>
<td>13.97 ± 0.88(^{c})</td>
<td>10.82 ± 0.68(^{c})</td>
<td>11.61 ± 0.74(^{c})</td>
<td>8.99 ± 0.57(^{c})</td>
<td>83.11 ± 2.96(^{b})</td>
</tr>
<tr>
<td>T_{30}</td>
<td>11.34 ± 0.23(^{d})</td>
<td>8.79 ± 0.17(^{d})</td>
<td>9.35 ± 0.58(^{d})</td>
<td>7.24 ± 0.45(^{d})</td>
<td>82.45 ± 4.42(^{b})</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1–4</th>
<th>5–8</th>
<th>9–12</th>
<th>13–16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>26.02 ± 1.54(^{c})</td>
<td>23.91 ± 1.84(^{d})</td>
<td>25.93 ± 1.42(^{a})</td>
<td>24.14 ± 1.76(^{a})</td>
</tr>
<tr>
<td>T_{0}</td>
<td>48.11 ± 2.04(^{a})</td>
<td>44.62 ± 1.92(^{c})</td>
<td>6.25 ± 0.56(^{d})</td>
<td>1.02 ± 0.12(^{d})</td>
</tr>
<tr>
<td>T_{10}</td>
<td>47.74 ± 1.66(^{a})</td>
<td>42.95 ± 1.27(^{c})</td>
<td>7.54 ± 0.61(^{cd})</td>
<td>1.78 ± 0.21(^{cd})</td>
</tr>
<tr>
<td>T_{20}</td>
<td>26.48 ± 1.58(^{c})</td>
<td>56.63 ± 2.63(^{a})</td>
<td>14.79 ± 1.27(^{b})</td>
<td>2.10 ± 0.82(^{bcd})</td>
</tr>
<tr>
<td>T_{30}</td>
<td>31.16 ± 1.74(^{b})</td>
<td>51.29 ± 2.87(^{b})</td>
<td>14.78 ± 1.93(^{b})</td>
<td>2.76 ± 0.53(^{b})</td>
</tr>
</tbody>
</table>

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
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.

**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-
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$_4$-N 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$_4$-N 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$_4$-N 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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