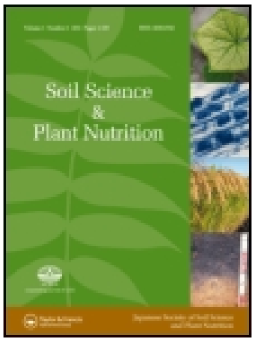

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Effects of soil properties on ammonia volatilization

Duan Zhenghu & Xiao Honglang

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Effects of Soil Properties on Ammonia Volatilization

Duan Zhenghu and Xiao Honglang

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, 260 Donggang West Road, Lanzhou, 730000, P.R. of China

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By using a small culture dish located above a large-sized closed dish with soil samples to trap emissions as well as applying multivariate analysis methods, the influence of soil properties on ammonia volatilization and their correlation was studied. The results showed that the ammonia volatilization rates were positively correlated with the soil pH, $CaCO_3$, and total salt contents but negatively correlated with the organic matter content, CEC, and clay content. Of the three negative correlation factors, the CEC was most highly correlated with ammonia volatilization, while among the three positive correlation factors, the pH predominated. These results enabled to assess the magnitude of ammonia volatilization from soils. According to the correlation equation of ammonia volatilization versus pH and CEC, the potential of ammonia volatilization of some soils in China was determined and the soils were divided into four groups. It was concluded that by increasing the application rate of organic matter ammonia volatilization might decrease.

Key Words: **ammonia volatilization, NH_3, nitrogen, soil properties.**

A large number of studies on ammonia volatilization losses from soils have been carried out (Terman 1979; Fenn and Hossner 1985; Duan and Zhou 1990). Actual losses of NH_3 from soils are controlled by the soil cation exchange capacity (CEC) and buffering capacity, and can be related to the soil organic matter (OM) status and texture (Fenn et al. 1982; Ferguson et al. 1984; O'Toole et al. 1985). Increased soil pH has been shown to positively affect NH_3 volatilization from both urea (Ernst and Massey 1960; Watkins et al. 1972) and other NH_3 sources (Mills et al. 1974; Vlek and Stumpe 1978; Donovan and Logan 1983). The influence of native soil pH values, however, has not been fully elucidated (Martin and Chapman 1951). Reynolds and Wolf (1987) also reported that NH_3 volatilization from soil is a very complex process. Among all the soil properties affecting ammonia volatilization, no single property appeared to dominate, and no special soil property consistently controlled ammonia volatilization from soil. Different conditions and mechanisms may exert different influences on the processes of ammonia volatilization. Hence, it is essential to conduct systematic and multiple factorial analyses to understand the processes and the mechanism of ammonia volatilization and to determine the general effects of different factors and different soil types on ammonia volatilization.

MATERIALS AND METHODS

1. **Soil samples.** Twenty-two samples of soils distributed in different regions of

China were selected. The soil samples were air-dried and sieved through a 1 mm screen.

2. Determination of ammonia volatilization. An amount of 0.5 kg air-dried soil for each sample with water content of 16% and application of 2 and 1 g of chemical analysis-grade reagent, NH_4HCO_3, respectively, was used. Each treatment was replicated twice and then the samples were placed in an incubator at 25°C to determine the amount of ammonia volatilization from soil continuously. The ammonia volatilization from soil was determined using a large-sized closed dish under entirely sealed conditions: the soil sample was put into a culture dish 5 cm high and 20 cm in diameter, in which a small culture dish, 9 cm in diameter, containing 30 mL of 2% boric acid was placed for trapping ammonia volatilized from soil. The amount of ammonia volatilization from soil was determined using standard acid and mixed indicators.

3. Analysis. All the soil physical and chemical properties were determined using routine methods (Nanjing Institute of Pedology, Chinese Academy of Sciences 1978). Mineral N was first extracted with 20% NaCl and the content of N was determined by the Kjeldahl method (reduction with Zn-$FeSO_4$).

Table 1. Chemical and physical properties and cumulative NH_3 volatilization amount of the soils studied.

Soil type	Soil mineral N^z (mg kg^{-1})	Total N soil (g kg^{-1})	Organic matter (g kg^{-1})	pH	Total salt content (g kg^{-1})	CEC (cmol(+) kg^{-1})	Clay (<0.001 mm) (%)	$CaCO_3$ (g kg^{-1})	NH_3 (cmol kg^{-1})
Tier soil	45.5	1.01	13.03	8.20	2.45	10.401	14.04	103.2	0.670
Baishan soil	42.6	0.55	9.20	8.20	1.82	6.906	12.18	115.6	1.474
Mountain meadow soil	20.1	0.96	14.47	7.25	1.82	19.543	37.36	1.2	0.131
Tier soil	47.8	1.06	17.46	7.88	2.58	10.767	14.30	19.5	0.322
Yellow Niba soil	63.8	0.92	14.04	6.65	2.15	22.801	10.78	0.0	0.194
Baishan soil	76.8	0.96	14.30	7.84	2.69	12.920	16.13	99.7	0.350
Light-coloured meadow soil	23.2	0.60	10.41	8.23	2.35	6.361	9.06	71.7	2.190
Red waxy soil	86.6	1.24	16.41	7.98	2.53	13.234	17.18	113.8	0.278
Black waxy soil	67.2	1.12	16.68	8.00	2.49	14.368	16.36	38.9	0.237
Loessal soil	32.1	0.78	12.26	8.29	1.91	6.178	6.37	79.1	1.224
Sierozem	8.7	1.24	12.20	8.85	5.56	8.022	10.48	79.4	1.358
Tier soil	10.7	0.76	12.04	8.15	1.88	9.198	12.53	85.5	1.169
Yellow Niba soil	17.9	0.72	9.61	7.08	1.65	24.272	46.45	0.5	0.073
Heilu soil	9.8	1.12	13.13	7.95	1.85	10.842	10.49	38.9	0.671
Meadow soil	105.3	1.43	23.80	7.35	1.98	25.393	23.30	36.7	0.354
Meadow chernozem	32.1	1.26	20.34	7.25	1.88	17.442	20.90	2.5	0.335
Dark brown soil	29.5	0.98	27.18	6.15	1.58	19.259	13.29	0.0	0.060
Irrigation-warp soil	33.0	0.86	10.20	8.15	2.03	9.431	32.93	104.4	1.740
Chestnut soil	45.5	1.87	11.43	7.75	2.12	14.576	8.47	90.3	1.503
Red soil	23.7	1.17	17.19	4.47	0.88	8.278	37.89	0.0	0.056
Yellow-brown soil	72.3	1.18	17.37	6.45	2.08	14.413	13.10	0.6	0.360
Laterite	42.3	1.70	31.76	4.32	0.95	9.895	54.98	0.0	0.136

[z] Soil mineral N was first extracted with 20% NaCl and the contents of N were determined by the Kjeldahl method (reduction with Zn-$FeSO_4$).

RESULTS AND DISCUSSION

1. Correlation analysis between soil properties and ammonia volatilization

In this study, a total of 22 samples representing soil types with significant differences in soil properties affecting ammonia volatilization were selected, including red soil, laterite, yellow-brown soil, dark brown soil, meadow soil, meadow chernozem, light-coloured meadow soil, mountain meadow soil, Heilu soil, yellow Niba soil, loess soil, Tier soil, Baishan soil, irrigation-warping soil, sierozem, chestnut soil, and brown desert soil. These soils displayed a remarkable variability in their physical and chemical properties (Table 1), with a mineral N content ranging from 8.7 to 105.3 mg kg^{-1} soil, total N content from 0.38 to 1.87 g kg^{-1}, organic matter content from 6.36 to 51.43 g kg^{-1}, $CaCO_3$ content from 8 to 115.9 g kg^{-1}, total salt content from 0.88 to 25.42 g kg^{-1}, pH from 4.32 to 9.12, CEC from 4.919 to 25.393 cmol(+) kg^{-1} soil, and <0.001 mm clay content (3.97 to 54.98%). To each soil sample the same amount of NH_4HCO_3 was added to determine the ammonia volatilization rate for 10 d. The results obtained are given in Table 1 (the results of the treatments with 1 g NH_4HCO_3 applied are omitted here).

To determine the relations between soil properties and ammonia volatilization, a scatter diagram of ammonia volatilization rates versus soil properties was drawn, which exhibited exponential function relation and good suitability (Fig. 1). It is more important to obtain a linear relation in the case of simple correlation. The linear correlation was the basis for simple correlation analysis. Then the amount of ammonia volatilization was converted into

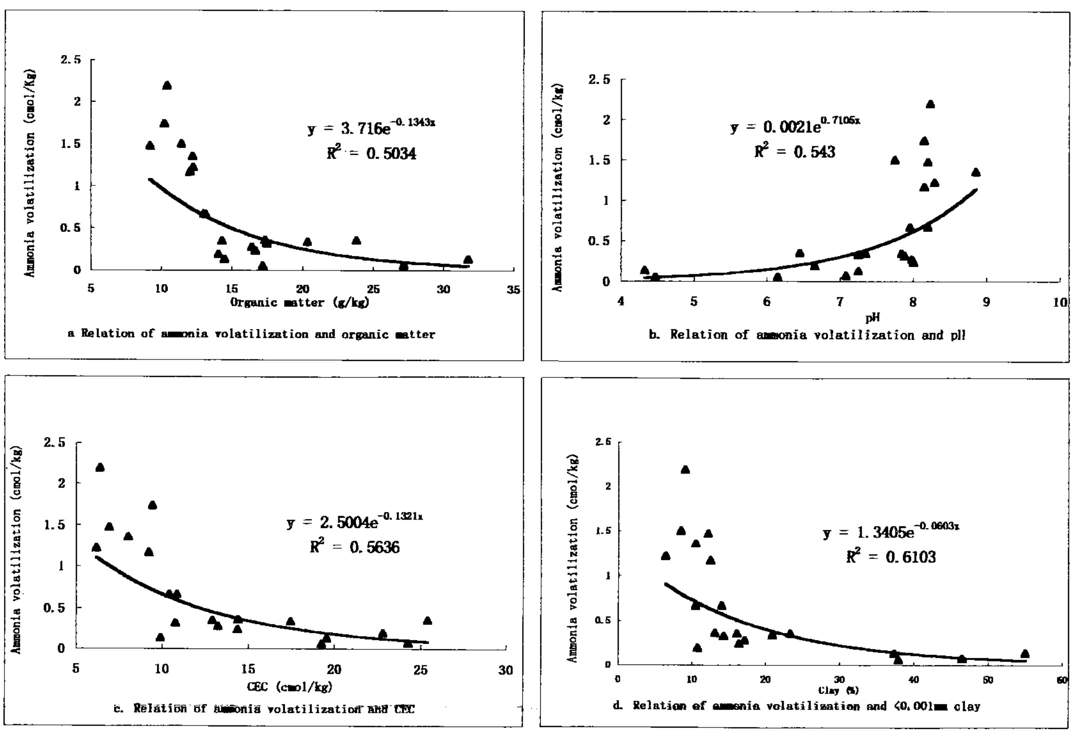

Fig. 1. Scatter diagram of ammonia volatilization and soil properties.

Table 2. Correlation analysis between soil properties and ammonia volatilization losses.

Variable	Mineral N	Total N	Organic matter	pH	$CaCO_3$	Total salt content	CEC	Clay	NH_3 volatilization
Mineral N									
Total N	0.2197								
Organic matter	0.3080	0.2948		***	**				**
pH	0.0128	−0.2364	−0.6753		***	*		**	***
$CaCO_3$	0.0942	−0.0370	−0.5443	0.6955			*	*	***
Total salt content	−0.0196	0.0033	−0.3210	0.4876	0.3839			*	*
CEC	0.3677	0.1438	0.2814	−0.1853	−0.5341	−0.1732			**
Clay	−0.0939	0.0486	0.3769	−0.6442	−0.4293	−0.4590	0.2220		**
NH_3 volatilization	−0.1226	0.0086	−0.5706	0.7183	0.7541	0.4252	−0.5681	−0.5648	

Significance at *: 5%, **: 1%, and ***: 0.1% levels.

a linear relation through logarithmic transformation and the correlation coefficients shown in Table 2 were determined.

As shown in Table 2, soil mineral N and total N contents exerted an almost negligible effect on ammonia volatilization and their correlation coefficients were −0.1226 and 0.0086, respectively, while the correlation coefficients of the pH, $CaCO_3$, and total salt contents with ammonia volatilization were 0.7183, 0.7541, and 0.4252, respectively, suggesting a significant correlation. These results indicated that the higher the pH, $CaCO_3$ content, and total salt content, the higher the ammonia volatilization. However, other three soil factors, organic matter content, CEC and clay content, were negatively correlated with ammonia volatilization, i.e. they inhibited ammonia volatilization.

The above correlation analysis indicated that in most of the cases the results obtained were in agreement with previously reported findings and with general theories as in the case of the pH and ammonia volatilization (Ernst and Massey 1960). In addition, the CEC and clay content also affected the absorption of NH_4^+ and NH_3 and thus reduced the NH_4^+ concentration in the solution as well as ammonia volatilization (Gasser 1964; Zhao 1981). However, there were also exceptions, for instance, ammonia volatilization was not related to the mineral N and total N contents, but was positively correlated with the $CaCO_3$ and total salt contents, indicating that ammonia volatilization is a complex process that cannot be expressed by a simple correlation coefficient alone.

2. Estimation of ammonia volatilization

We carried out a stepwise regression analysis for all the eight characteristic data of the 22 soil samples representing 17 soil types. The last two factors, soil pH and CEC, were significantly correlated with ammonia volatilization and we obtained the following binary linear regression equation:

$$\log Y = -1.9074 + 0.27533X_1 - 0.00379X_2 \qquad (r^2 = 0.7116) \qquad (1)$$

Where Y is the amount of ammonia volatilization (cmol kg^{-1}); X_1 is the pH value; X_2 is the CEC (cmol(+) kg^{-1})......

These results suggest that the pH and CEC are the most important factors controlling ammonia volatilization, in other words, the interaction of these two factors resulted in 71.16% of volatilization losses of ammonia. However, the correlation analysis showed that the factors relates to ammonia volatilization which were significantly correlated with the $CaCO_3$ content, total salt content, clay content, and organic matter content were not

Table 3. Path analysis of the effect of soil properties on ammonia volatilization.

Character	Effect							
	Mineral N	Total N	Organic matter	pH	$CaCO_3$	Total salt content	CEC	Clay
Mineral N	−0.0370	−0.0081	−0.0141	−0.0005	−0.0035	0.0007	−0.0136	0.0035
Total N	0.0484	0.2201	0.0649	−0.0520	−0.0082	0.0007	0.0316	0.0107
Organic matter	−0.0219	−0.0210	−0.0712	0.0481	0.0387	0.0229	−0.0200	−0.0268
pH	0.0063	−0.1184	−0.3381	0.5007	0.3482	0.2442	−0.0928	−0.3226
$CaCO_3$	0.0132	−0.0052	−0.0761	0.0972	0.1398	0.0537	−0.0746	−0.0600
Total salt content	0.0000	0.0000	0.0008	−0.0012	−0.0009	0.0024	−0.0004	0.0011
CEC	−0.1397	−0.0546	−0.1069	0.0704	0.2029	0.0658	−0.3799	−0.0843
Clay	0.0081	−0.0042	−0.0325	0.0556	0.0371	0.0396	−0.0192	−0.0863
Correlation coefficient of ammonia volatilization	−0.1226	0.0086	−0.5706	0.7183	0.7541	0.4252	−0.5689	−0.5648

The elements on the same soil properties crossed indicate the direct effect coefficient.

included in Eq. 1. As for the contribution of each soil property to ammonia volatilization, path analysis is a widely used evaluation method.

Path analysis can be used to evaluate the direct effect and indirect effect (via other factors) of factors on ammonia volatilization, and the algebraic sum of both effects represents the total contribution of a given factor and other factors to ammonia volatilization. This is because the algebraic sum of path coefficients involves the use of simple correlation coefficients, and path coefficients are equivalent to the standardized deviation regression coefficients in regression analysis. For example, the path analysis of the effects of pH and CEC on ammonia volatilization can be conducted as follows:

In each column of Table 3, the elements on the same soil properties crossed represent the path coefficient for the direct effect of a given factor on ammonia volatilization. The other elements represent the path coefficient for the indirect effect of a given factor (via other factors) on ammonia volatilization. Table 3 (column 4) indicates that the pH exerted a larger direct effect on ammonia volatilization, with a path coefficient value up to 0.5007. At the same time, the indirect effects of pH via organic matter, $CaCO_3$, CEC, clay, mineral N, total N, and total salt contents gave path coefficient values of 0.0481, 0.0972, 0.0704, 0.0556, −0.0005, −0.0520, and −0.0012, respectively. Among them, the former four exerted a weak positive effect and promoted ammonia volatilization, while the latter three exerted a very weak negative effect and inhibited ammonia volatilization. Therefore, the interaction of all the soil properties enhanced the effect of the pH on ammonia volatilization, with a total value of 0.7183 for the coefficient. These results indicate that the pH was a key factor because it affected directly the concentrations of ammonia and ammonium in the soil solution.

Based on the effect of the CEC on ammonia volatilization (Table 3, column 7), the direct effect was not very significant, with a path coefficient value up to −0.3799, but it resulted in a larger total effect (−0.5689) on ammonia volatilization as it interacted with other soil properties. This is because, except for the indirect effect of CEC via total N which was weakly positive (0.0316), that the indirect effect of CEC via the other factors was negative. These findings indicate that the CEC exerted a direct effect on the adsorption and fixation of NH_4^+ concentration, and inhibited the effect on ammonia volatilization via the other factors.

The same method was applied to analyze the effects of mineral N, total N, organic matter, $CaCO_3$, total salt, and clay contents on ammonia volatilization and the values of the coefficients for the total effect were −0.1226, 0.0086, −0.5706, 0.7541, 0.4252, and −0.5648, respectively (Table 3). Among the six factors with a significant effect on ammonia volatilization, three factors, i.e. organic matter content, CEC, and clay content exerted a negative effect and inhibited ammonia volatilization, while those factors, i.e. pH, $CaCO_3$, and total salt contents exerted a positive effect and promoted ammonia volatilization. When assessing and comparing the magnitude of ammonia volatilization of one or two soils, the effects of the above-mentioned six factors on ammonia volatilization must be considered. Although four factors, i.e. organic matter content, clay content, $CaCO_3$, and total salt contents showed a significant correlation with ammonia volatilization, they exerted weaker direct effects on ammonia volatilization and the values of the coefficients for the direct effects were −0.0712, −0.0863, 0.1398, and 0.0024, respectively. Two factors, i.e. soil pH and CEC showed a significant correlation with ammonia volatilization, and also exerted a larger direct effect on ammonia volatilization, with values of the path coefficients up to 0.5007 and −0.3799, respectively. Therefore the regression analysis enabled to obtain the binary linear regression equation for the pH and CEC. These date indicate that among the six soil properties related to ammonia volatilization listed above, the pH and CEC were essential factors while the four others were accessory factors.

Based on the regression Eq. 1, the potential of ammonia volatilization of some important soils in China was determined and is presented in Table 4.

Based on the soil the calculated values, the soils in China can be roughly divided into four groups in relation to the potential of ammonia volatilization:

Table 4. Estimated rates of ammonia volatilization from soils in China.

Soil type	Location	pH	CEC (cmol(+) kg^{-1})	NH_3 volatilization potential (cmol kg^{-1})	Classification
Yellow soil	Renhuai, Guizhou	4.9	19.6	0.05	Group I
Yellow-brown soil	Wuxi, Jiangsu	5.9	22.2	0.074	
Red soil	Tianmu Mountain	5.8	20.4	0.082	
Laterite	Taihu	5.5	12.2	0.140	Group II
Red soil	Xingning, Guangdong	5.6	11.4	0.160	
Red soil	Yanyuan, Sichuan	5.6	10.6	0.170	
Carbonate cinnamon soil	Luliang Mt, Shanxi	7.5	20.3	0.244	Group III
Yellow chao soil	Fengqiu, Henan	8.5	19.0	0.514	
Yellow chao soil	Beijing	7.9	12.1	0.642	
Tier soil	Wugong, Shaanxi	7.9	12.9	0.600	
Heilu soil	Shaanxi	8.5	11.6	0.986	
Oasis soil	Turpan	8.1	15.9	0.402	
Yellow chao soil	Fengqiu, Henan	8.8	8.1	1.614	Group IV
Sierozem	Gongshang, Xinjiang	8.8	10.2	1.340	
Sierozem	Lanzhou, Gansu	8.6	8.6	1.360	
Sierozem	Zhongwei, Ningxia	8.5	7.9	1.364	
Gray desert soil	Paotai, Xinjiang	8.9	8.5	1.660	
Gray-brown desert soil	Junggar Basin	8.6	4.7	1.992	
Brown desert soil	Kuruktag	8.3	3.95	1.688	
Brown desert soil	Hotan, Xinjiang	8.6	3.45	2.134	
Loess soil	Cafang, Yanan	8.2	6.8	1.238	

Group I: Soils located south of Changjiang River, pH$<$7, CEC$>$20, potential of ammonia volatilization is less than 0.10 cmol kg^{-1};

Group II: Soils located south of Changjiang River, pH$<$7, CEC$<$20, potential of ammonia volatilization ranges from 0.10–0.20 cmol kg^{-1};

Group III: Calcareous soils distributed north of Changjiang River and Qinling Mountain, pH$>$7, CEC$>$10, potential of ammonia volatilization ranges from 0.20–1.00 cmol kg^{-1};

Group IV: Calcareous soils with low fertility and dry land soils distributed north of Changjiang River and Qinling Mountain, pH$>$8, CEC$<$10, potential is higher than 1.00 cmol kg^{-1}.

3. Methods of prevention of ammonia volatilization

Among the six soil properties listed above, five cannot be improved and only the organic matter content can be artificially changed. Hence, by increasing the application rate of organic matter ammonia volatilization may decrease due to the highly negative effect of organic matter on ammonia volatilization (−0.5706), implying that the higher the soil organic matter content, the lower the losses of ammonia from soil. Owing to the large amount of nitrogen present in organic matter, application of organic manure in combination with inorganic fertilizers may contribute to the increase of the soil nitrogen content and avoid the losses of nitrogen via ammonia volatilization, thus promoting the growth of crops. It is worth noting that organic matter is a better nitrogen source, but since a stronger deammonification may occur during the decomposition processes, the loss of ammonia from soil is inevitable. But why does it prevent ammonia volatilization? This can be explained by the weaker direct effect of organic matter (−0.0721) and stranger indirect effect of the interaction of the pH (−0.3381) and CEC (−0.1069). Thus, despite the negligible effect of organic matter on ammonia volatilization, the soil pH value markedly decreased and soil adsorption was considerably enhanced due to the formation of various organic acids and humus during the decomposition process of organic matter, resulting in a significant inhibition of ammonia volatilization losses. Hence, we suggest that the application of an adequate amount of organic manure may enable to prevent ammonia volatilization losses and to enhance the efficiency of utilization of nitrogen fertilizers.

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