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## **High Water Regime Can Reduce Ammonia Volatilization from Soils under Potato Production**

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**Abstract:** This research was conducted with Biscayne marl soil and Krome gravelly loam from Florida and Quincy fine sand and Warden silt loam from Washington to determine ammonia ( $\text{NH}_3$ ) volatilization at various temperature and soil water regimes. Potassium nitrate ( $\text{KNO}_3$ ), ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ), ammonium sulfate [ $(\text{NH}_4)_2\text{SO}_4$ ], or urea were applied to the soil at a rate of  $75 \text{ kg N ha}^{-1}$ . Soil water regime was maintained at either 20% or 80% of field capacity (FC) and incubated at 11, 20, or  $29^\circ\text{C}$ , which represented the minimum, average, and maximum temperatures, respectively, during the potato growing season in Washington. Results indicated that the ammonia volatilization rate at 20% FC soil water regime was two- to three-fold greater than that at 80% FC. The cumulative volatilization loss over 28 days was up to 25.7%. Results of this study demonstrated that ammonia volatilization was accelerated at low soil water regimes.

**Keywords:** Ammonia volatilization, field capacity, potato, temperature

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## INTRODUCTION

Ammonia ( $\text{NH}_3$ ) volatilization is a process whereby the ammonium form of nitrogen (N) is applied to the soil and emits into the atmosphere in the gaseous form. This mechanism of N loss can occur from either inorganic N fertilizers or organic N sources converted to ammonium ( $\text{NH}_4^+$ ) form. The global emission of N as ammonia ( $\text{NH}_3$ ) has been estimated to be approximately 54 million Mg N  $\text{yr}^{-1}$  (Bouwman et al. 1997; Saffigna and Freney 2002). A considerable portion of the global emitted  $\text{NH}_3$  is of agricultural origin. In fact,  $\text{NH}_3$  volatilization is one of the most significant pathways for N loss from crop production systems that use high inputs of N fertilizers (Fenn and Hossner 1985; Gezgin and Bayraklı 1995). According to FAO (2001), annual N loss via volatilization over the world has been as much as 19.05 million Mg from 110.9 million Mg N applied as either mineral fertilizers or manures (i.e., 17.2% N loss). For example, 14% of 61.7 million Mg of mineral fertilizer N applied annually to upland crops worldwide is lost via  $\text{NH}_3$  volatilization. In wetland rice cultivation, volatilization N loss can be as high as 20%, as evident from the 2.3 million Mg N  $\text{year}^{-1}$  N lost by  $\text{NH}_3$  emission from the annual use of 11.8 million Mg total N. Excess ammonia emission causes environmental concerns because of its potential for depletion of ozone layer, as well as economic loss by increasing cost of production inputs (FAO 2001; Damodar and Sharma 2000; Fenn and Hossner 1985).

Ammonia emission is dependent on the soil pH, with the greatest losses at  $\text{pH} > 7.5$ . He et al. (1999) reported that ammonia volatilization from surface-applied ammonium sulfate increased with increasing pH from 4.5 to 8.5, and the N losses were much greater during the first 7 days. In addition to soil pH (He et al. 1999), soil moisture (Fenn and Hossner 1985) also influences  $\text{NH}_3$  volatilization. Fenn and Hossner (1985) reported a possible correlation of  $\text{NH}_3$  loss with ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) application rates and temperature. The correlation coefficient between temperature and N loss was 0.42 (Fenn and Hossner 1985).

The high pH found in agricultural soils in southern Florida, which can range from 7.2 to 8.2, is either derived directly from limestone parenting materials (Li 2001) or underlain by calcium carbonate ( $\text{CaCO}_3$ ). Soils also can have a high pH through long-term irrigation with high-pH water (Obreza, Alva, and Calvert 2003). South Florida is underlain by a shallow limestone aquifer. The groundwater contains a high concentration of calcium bicarbonate, commonly more than  $100 \text{ mg L}^{-1}$ , with a water pH as high as 8.0 (Herr and Shaw 1989; Zhang, Li, and Ma 2003). High pH irrigation water may directly contribute to N fertilizer loss through ammonia volatilization, especially when a fertigation system is used (Norton and Silvertooth 2001).

Most of the research on  $\text{NH}_3$  volatilization was conducted under either rice (Bacon et al. 1988; Bowmer and Muirhead 1987; Dhyani and Mishra 1992) or wheat (Gezgin and Bayraklı 1995) production systems. Information is seriously lacking on  $\text{NH}_3$  volatilization losses in potato production systems.

Potato is one of Florida's high-value winter and early spring crops and is responsible for the state being ranked the fourth nationally in value of potatoes produced in the USA. The 2005 values of potatoes for FL and WA were about \$130 million and \$535 million, respectively, while that for the US was about \$3.0 billion (NPC, 2006). The 2005 area and production of potatoes for FL (winter and spring combined) were  $11.7 \times 10^3$  ha and  $0.36 \times 10^6$  Mg, respectively, and those for WA were  $62.4 \times 10^3$  ha and  $4.33 \times 10^6$  Mg, respectively (NPC, 2006). The current fertilizer recommendation for potatoes in Washington (Mattos et al. 2003; Alva 2004) is one-third at planting and the remaining two-thirds as in-season fertilizations. The preplant N is generally applied as urea or ammonia nitrate, with the in-season N applied as urea ammonium nitrate form. These N sources are vulnerable for ammonia volatilization losses. The objectives of this research are to 1) estimate ammonia volatilization rates from different N sources in potato production region soils from Florida and Washington, 2) quantify the effects of soil moisture and temperature on ammonia volatilization, and 3) identify relationships among soil types, soil moisture levels, and incubation temperatures on  $\text{NH}_3$  volatilization from different fertilizer sources.

## MATERIALS AND METHODS

### Soils

Quincy fine sand (mixed, mesic Xeric Torripsamments) and Warden silt loam (coarse-silty, mixed, mesic, Xerollic Camborthids, dark grayish-brown soil) soils from Washington were sampled from the Columbia Basin potato production region in south central region of the state. This area of the state is well known for production of high potato yields in the nation and the world, as evident from high yield of 70 to 80 Mg ha<sup>-1</sup> and a mean yield of 60 Mg ha<sup>-1</sup>. The soils are sandy (sand content  $\geq 95\%$ ) and well drained, and the growing period is characterized by lack of cloud cover, high daytime temperature, and cool nights. The mean annual rainfall is about 150 mm; therefore, potatoes are highly dependent on irrigation for crop production.

The main soils used for potato production in south Florida are Biscayne marl (loamy, carbonatic, hyperthermic, shallow Typic Fluvaquents) soil and Krome gravelly loam (loamy-skeletal carbonic, hyperthermic Lithic Udorthents). These two soils were collected from the commercial potato farms. The annual rainfall in south Florida ranges from 980 to 1651 mm. Some of the properties of these soils used in this study are presented in Table 1.

### Incubation Temperature

The incubation temperatures adapted in this study were based on the mean temperature in the selected production region over the growing season. In the Columbia Basin production region of Washington, the maximum and

**Table 1.** Characteristics of the four soils tested from Florida and Washington

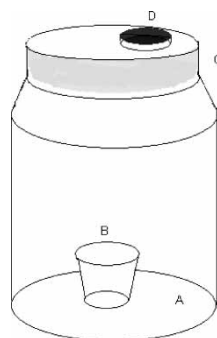
Soil	Source location	pH	EC ( $\mu\text{S}/\text{cm}$ )
Biscayne marl soil	Florida	7.27	457
Krome gravelly loam	Florida	7.69	131
Quincy fine sand	Washington	6.65	49
Warden silt loam	Washington	6.46	93

minimum temperatures for the potato growing season are 29°C and 11°C, respectively, based on the previous four years (2000 to 2003) of daily climatic data. This accounts for an average temperature of 20°C. In Florida, the growth season for potato is from October to the following May. The corresponding maximum, average, and minimum temperatures are 26.5, 22.5, and 18.4°C. These temperatures are within the range of those in Washington; hence, 29, 20, and 11°C were used as the incubation temperature for this investigation.

### Recovery of Applied Ammonia by Trapping Sponges (Experiment 1)

Ammonia volatilization recovery was measured following a modified method of Cabrera et al. (1994) and He et al. (1999). A 500-mL plastic bottle with a screw-cap closure for the 4.5-cm-i.d. mouth (Rubbermaid, Inc. Wooster, Ohio) was used to incubate the soil. A sponge (Yellow Flower Sponges, Arrow Plastic Manufacturing Company, Elk Grove Village, Ill.) spiked with 0.8 mL of trapping solution was inserted into the mouth of the bottle to trap volatilized ammonia. The trapping solution consisted of 35 mL of concentrated phosphoric acid, 250 mL of glycerol, and 715 mL of deionized water (He et al. 1999).

A 25-mL conical plastic beaker containing 15 mL of 0.2 mol L<sup>-1</sup> sodium hydroxide (NaOH) was placed at the bottom of the bottle (Figure 1). One mL of variable concentrations of ammonium N (as ammonium sulfate) was added to the bottom of the bottle with a micropipette to achieve total N per bottle of 0.00, 0.25, 0.50, 1.00, or 2.00 mg. A sponge spiked with 0.8 mL of trapping solution was inserted into the bottle mouth, and the bottle was closed with a screw cap with a short pour spout of 1.7 cm i.d. The spout was kept open to ensure air exchange inside and outside the bottle. An 8-mm-diameter sponge spiked with 150  $\mu\text{l}$  of trapping solution was inserted to protect the 5-cm-diameter sponge from air contamination during incubation. Each bottle was placed inside a sealed plastic Ziploc<sup>®</sup> storage bag (23 cm  $\times$  30 cm) to avoid any external contamination and prevent loss of moisture. The bottles were then shaken to turn over the conical beakers and mix the NaOH and ammonium sulfate [(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>] solution. Then the bottles were incubated at 29°C for 24 h. Before sampling, the bottle suction was applied for 60 s to trap the volatilized ammonia by the sponge. The sponge sampled to measure trapped NH<sub>3</sub> was placed in a 17-cm  $\times$  10-cm



**Figure 1.** Schematic diagram of the basic elements of the apparatus used to recover ammonia emission from ammonium sulfate. A) 1 mL 45 mg N/mL  $(\text{NH}_4)_2\text{SO}_4$  was added at the bottom by a micropipette. B) 15 mL 0.2 mol/L NaOH was held in the conical beaker. C) A sponge spiked with 800  $\mu\text{L}$  of trapping solution was inserted in the mouth of the 500-mL plastic bottle to trap the volatilized ammonia. D) A small sponge spiked with 150  $\mu\text{L}$  trapping solution was inserted into a short pour spout of the screw cap on the bottle to protect the bottle from any contamination from air. Then the bottle was put into a Ziploc<sup>®</sup> storage bag to keep the moisture inside. After that, the bottle was shaken to turn over the beaker and start the reaction between  $(\text{NH}_4)_2\text{SO}_4$  and NaOH and drive up all of the ammonia from the sulfate.

Ziploc<sup>®</sup> storage bag, and  $\text{NH}_4^+$  from the sponge was extracted once with 25 mL of 1.0 mol  $\text{L}^{-1}$  potassium chloride (KCl) solution.

### Ammonia Volatilization from Different N Fertilizers Applied to Four Soils (Experiment 2)

For a given soil (as described previously), 300 g (dry weight) of the soil was placed in the incubation bottle. The surface area of the bottle was  $\sim 60 \text{ cm}^2$ . The soil water content was adjusted to either 20% or 80% of field capacity. The percentages of water in the four soils (v/m based on oven-dry soils) were 12.0, 8.4, 4.8, and 6.7 for 20% FC and 48.3, 33.4, 19.8, and 26.0 for 80% FC, respectively. One mL of nitrogen solution (as potassium nitrate, ammonium nitrate, ammonium sulfate, or urea) was uniformly applied on the soil surface with a micropipette. The amount of N applied was 45 mg N per bottle, equivalent to  $75 \text{ kg ha}^{-1}$  based on surface area. A treatment with only deionized water was incubated as a control to measure the ammonia volatilization from the soils. Thus, this experiment comprised four soils  $\times$  five N sources (including the control)  $\times$  three replications, which resulted in 360 total incubation bottles. Each of the incubation bottles with these treatments was placed in a sealed plastic Ziploc<sup>®</sup> storage bag (23 cm  $\times$  30 cm) and maintained at 29, 20, or 11  $^\circ\text{C}$  in incubators (Precision Incubator, 6DM, THELCO<sup>®</sup> High Performance Incubators, Precision, Ottawa, Canada). The sponge with

trapping solution was sampled at each incubation period after 1, 3, 7, 14, and 28 days of incubation and a new sponge (with trapping solution) was placed to trap  $\text{NH}_3$  for the subsequent incubation period.

### Ammonia Analyses

The concentration of  $\text{NH}_4\text{-N}$  was determined in an AutoAnalyzer III (Bran + Luebbf GmbH, Werkstrasse, Norderstedt, Germany) according to EPA method 350.1 (EPA 1993; Alpkem Corporation 1989).

## RESULTS AND ANALYSIS

### Recovery of Applied Ammonium Sulfate (Experiment 1)

The recovery of ammonia emission from  $(\text{NH}_4)_2\text{SO}_4$  ranged from 96.5% to 102.3% with an average standard deviation of 3.1% (Table 2). This confirms that the technique is efficient in complete recovery of ammonia produced. Likewise, this test also showed that  $0.2 \text{ mol L}^{-1}$  NaOH raised the pH high enough for complete transformation of  $\text{NH}_4\text{-N}$  into  $\text{NH}_3$  form. The  $\text{pK}_a$  for ammonia is 9.3.

$$\log_{10} \frac{\text{NH}_3}{\text{NH}_4^+} = \text{pH} - \text{pK}_a \quad (1)$$

Thus, at pH 13.3, which is the pH of  $0.2 \text{ mol L}^{-1}$  NaOH, 99.99% of  $\text{NH}_4\text{-N}$  is transformed into  $\text{NH}_3$  form. The transformation is 50% at pH 9.3.

### Differences in Rate of Ammonia Volatilization (Experiment 2)

Summary of ANOVA statistics presented in Table 3 show that  $\text{NH}_3$  volatilization was significantly ( $P < 0.0001$ ) influenced by the effects of soil type,

**Table 2.** Recovery of ammonia emission from ammonium sulfate (experiment 1)

$\text{NH}_4^+\text{-N}$ added (mg)	$\text{NH}_4^+\text{-N}$ recovered (mg)	Recovery	
		(%)	SD
10.1	10.4	102.3	2.3
19.8	20.0	101.3	0.2
37.1	35.8	96.5	4.2
77.6	76.8	98.9	5.5
Average	35.8	99.7	3.1

**Table 3.** Summary of ANOVA test for factors influencing NH<sub>3</sub> volatilization

Source	DF	Pr > F
Time	4	<0.0001
Soil	3	<0.0001
Fertilizer	4	<0.0001
Temperature	2	<0.0001
Moisture	1	<0.0001
Replication	2	0.9908
Fertilizer × moisture	4	<0.0001
Soil × moisture	3	<0.0001
Soil × fertilizer	12	<0.0001
Time × fertilizer	16	<0.0001
Time × soil	12	<0.0001
Time × moisture	4	<0.0001
Time × temperature	8	<0.0001
Fertilizer × temperature	8	0.0205
Soil × temperature	6	0.0136
Temperature × moisture	2	0.2056

source of N, soil water content, and incubation duration as well as temperature (Table 3). The effects of interaction between the factors were also significant, except that between temperature and moisture ( $P = 0.2056$ ).

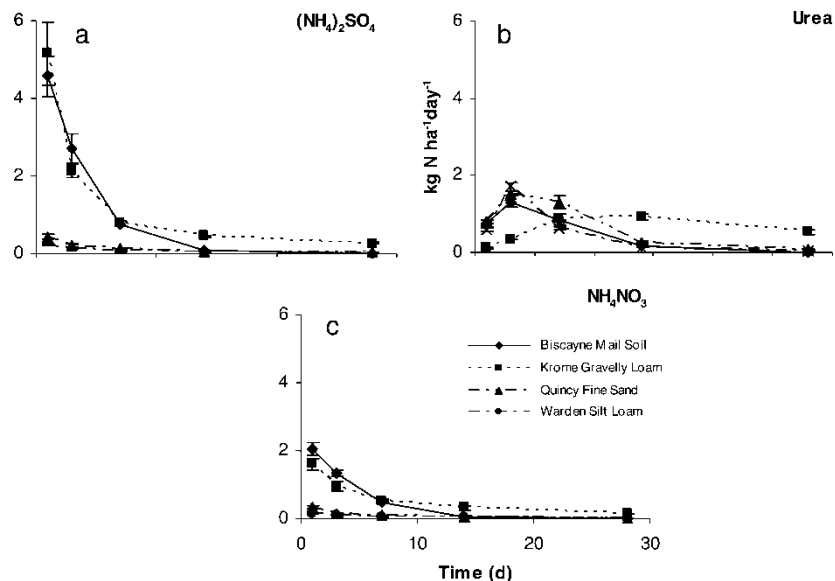
### Soil Water Content

Soil water content significantly influenced ammonia volatilization across all soils, N sources, incubation time, and temperatures. The mean NH<sub>3</sub> emissions ( $n = 900$ ) were 398.2 and 139.6 g N ha<sup>-1</sup> day<sup>-1</sup> at 20% and 80% field capacity (FC), respectively. The NH<sub>3</sub> emission rates were almost four-fold greater at 20% FC as compared to that at 80% FC and 29°C incubation temperature. The results suggest that low soil water content increases the volatilization loss (Figures 2–4).

### Nitrogen Sources

The mean NH<sub>3</sub> volatilization rates ( $n = 360$ ) were 611.2, 441.0, 284.7, 4.4, and 3.3 g N ha<sup>-1</sup> day<sup>-1</sup> for (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, urea, ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>), potassium nitrate (KNO<sub>3</sub>), and the control, respectively. Under both 20% and 80% FC at 29°C, the NH<sub>3</sub> emission rates from ammonium sulfate were 1.2- to 4.4-fold greater than those of urea. This is because all of N in the ammonium sulfate is in NH<sub>4</sub><sup>+</sup> form and thus readily subject to gaseous loss,





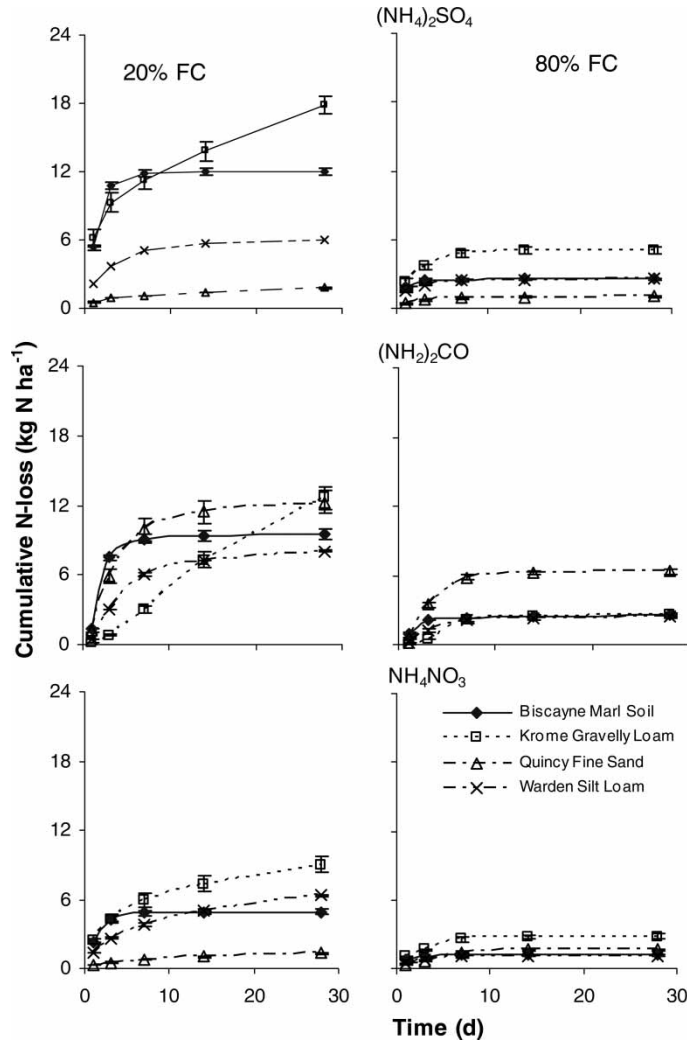
**Figure 2.** Ammonia volatilization dynamic rates from different N sources applied to four soils incubated at 20°C and at 20% field capacity (FC) soil water regimes. Vertical lines at each data point represent the standard error of the mean.

whereas the urea form of N has to be transformed into  $\text{NH}_4^+$ , which can then be subject to  $\text{NH}_3$  emission. In contrast to the other three soils, in the Quincy fine sand,  $\text{NH}_3$  volatilization from urea was almost 5-fold greater than that from ammonium sulfate. This may suggest that Quincy fine sand has very high activity of urease, which could have contributed to rapid transformation of urea into  $\text{NH}_4^+$  form. In the Krome gravelly loam soil at 11°C, the  $\text{NH}_3$  volatilization rates from ammonium sulfate were 4.4- and 4.0-fold greater than those from urea at 20% and 80% FC soil water content, respectively.

A low level of ammonia volatilization was also observed in the control treatment. This amount was very similar to that from applied  $\text{KNO}_3$ . The  $\text{NH}_3$  volatilization from  $\text{KNO}_3$ -applied soil was 1.2- to 1.7- and 1.3- to 3.4-fold greater than those from no-N-applied soils at 80% and 20% FC soil water contents, respectively.

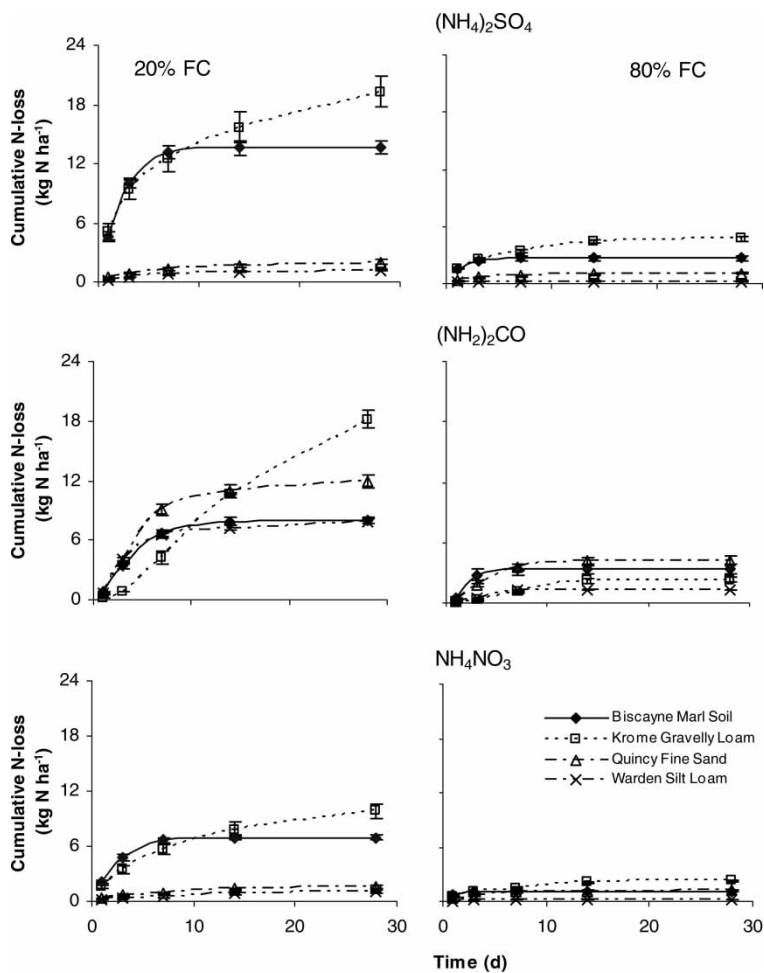
## Time

Ammonia volatilization in all soils is significantly time dependent (Table 2). The average rates for all N sources, except for urea, decreased with time. The average rates with an n of 360 for each of the five measured times were 619.7, 402.6, 209.6, 78.3, and 34.4 g N ha<sup>-1</sup> day<sup>-1</sup> for the time increments of 0–1,



**Figure 3.** Cumulative ammonia volatilization from different N sources applied to four soils incubated at 29°C at either 20% or 80% of field capacity (FC) soil water regimes. Vertical lines at each data point represent the standard error of the mean.

1–3, 3–7, 7–14, and 14–28 days, respectively. The critical range of Duncan’s multiple range test is 52.9 g N ha<sup>-1</sup>day<sup>-1</sup> when  $\alpha$  is 0.05 and the number of means is 2. Volatilization rates leveled off toward the last two time increments. In the urea-amended soils, the NH<sub>3</sub> volatilization rate peaked during intervals of 3–7 or 7–14 days. This lag is indicative of delay in transformation of urea into NH<sub>4</sub><sup>+</sup> form.



**Figure 4.** Cumulative ammonia volatilization from different N sources applied to four soils incubated at 20°C at either 20% or 80% of field capacity (FC) soil water regimes. Vertical lines at each date point represent the standard error of the mean.

### Soil

At the three incubation temperatures, the average N volatilization rate from  $(\text{NH}_4)_2\text{SO}_4$  showed the greatest difference among the soils, whereas the difference was least for urea, except  $\text{KNO}_3$  and the control. However, at 29°C with 20% FC soil water content, the average N volatilization rates from  $(\text{NH}_4)_2\text{SO}_4$  showed a 10.1-fold difference between four soils based on the biggest and least rates, that is, from 63.2 g N ha<sup>-1</sup>day<sup>-1</sup> for the Quincy fine sand to 636.4 g N ha<sup>-1</sup>day<sup>-1</sup> for Krome gravelly loam, respectively (Table 4).

**Table 4.** Average rates of ammonia emission ( $\text{g N ha}^{-1} \text{ day}^{-1}$ ) from soils that received different forms of N and the ratio of  $\text{NH}_3$  volatilization at 20% FC vs. that at 80% FC at 29, 20, or 11°C for 28 days

N form	Soil	29°C					20°C					11°C				
		20% FC		80% FC		Ratio (a/b)	20% FC		80% FC		Ratio (a/b)	20% FC		80% FC		Ratio (a/b)
		(a)	SS <sup>a</sup>	(b)	SS		(a)	SS	(b)	SS		(a)	SS	(b)	SS	
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	Biscayne Marl Soil	429.2	bB	91.3	bB	4.7	486.8	bB	96.4	bB	5.0	594.0	aA	228.7	aA	2.6
	Krome Gravelly Loam	636.4	aA	179.5	aA	3.5	688.7	aA	168.4	aA	4.1	539.3	bA	114.2	bB	4.7
	Quincy Fine Sand	63.2	dD	37.4	cC	1.7	73.2	cC	37.2	cC	2.0	60.0	cB	37.7	cC	1.6
	Warden Silt Loam	215.6	cC	90.2	bB	2.4	43.3	cC	9.0	dD	4.8	28.7	cB	11.5	dC	2.5
Urea	Biscayne Marl Soil	338.2	bB	90.2	bB	3.7	285.1	cC	121.9	bAB	2.3	612.8	aA	387.6	bB	1.6
	Krome Gravelly Loam	450.8	aA	93.0	bB	4.8	648.9	aA	83.4	cBC	7.8	330.5	cB	59.7	cC	5.5
	Quincy Fine Sand	437.7	aA	225.8	aA	1.9	424.5	bB	152.3	aA	2.8	408.8	bB	168.3	aA	2.4
	Warden Silt Loam	286.6	bB	87.0	bB	3.3	281.9	cC	46.7	dC	6.0	325.1	cB	48.0	cC	6.8
NH <sub>4</sub> NO <sub>3</sub>	Biscayne Marl Soil	176.0	cC	44.3	cC	4.0	248.0	bB	41.3	bB	6.0	257.6	aA	167.6	aA	1.5
	Krome Gravelly Loam	322.5	aA	99.8	aA	3.2	350.6	aA	80.3	aA	4.4	212.5	bB	52.0	bB	4.1
	Quincy Fine Sand	47.9	dD	58.6	bB	0.8	57.4	cC	41.6	bB	1.4	31.3	cC	32.4	cC	1.0
	Warden Silt Loam	226.7	bB	39.0	cC	5.8	37.4	cC	5.6	cC	6.6	21.0	dC	6.7	dD	3.1
KNO <sub>3</sub>	Biscayne Marl Soil	4.6	aA	1.6	bB	2.8	3.5	aA	1.1	cC	3.2	4.5	aA	10.9	aA	0.4
	Krome Gravelly Loam	2.9	bB	2.0	aA	1.4	2.2	bB	2.2	aA	1.0	1.4	cC	2.6	bB	0.5
	Quincy Fine Sand	2.5	bB	1.9	aA	1.3	3.5	aA	1.8	bB	2.0	2.2	bB	2.6	bB	0.8
	Warden Silt Loam	1.2	cC	1.6	bB	0.7	1.3	dD	1.0	cC	1.3	2.0	bB	2.0	cB	1.0
Control	Biscayne Marl Soil	0.9	aA	1.3	abAB	0.7	1.1	abAB	1.1	aA	0.9	1.7	aA	6.7	aA	0.3
	Krome Gravelly Loam	1.0	aA	1.1	bB	0.8	0.7	cC	0.7	bB	1.1	1.6	bAB	2.3	cC	0.7
	Quincy Fine Sand	0.9	aA	1.4	aAB	0.7	1.0	bB	1.2	aA	0.9	1.9	aA	2.1	cC	0.9
	Warden Silt Loam	0.9	aA	1.5	aA	0.6	1.2	aA	1.2	aA	1.0	1.2	cB	3.0	bB	0.4

<sup>a</sup>SS means statistical significance. All four soils with the same fertilizer that share the same lowercase in the same column do not differ significantly ( $P < 5\%$ ), and those followed by the same uppercase letter do not differ very significantly ( $P < 1\%$ ) by Duncan's multiple range test.

Similar comparison at 11°C showed a 20.7-fold increase, that is, from 28.7 g N ha<sup>-1</sup>day<sup>-1</sup> for the Warden silt loam to 594.0 g N ha<sup>-1</sup>day<sup>-1</sup> for Biscayne marl soil (Table 4), respectively.

### Temperature

The N volatilization rates were significantly influenced by the temperature. The average N emission rate of 322.4 g N ha<sup>-1</sup>day<sup>-1</sup> at 29°C was significantly greater than those at 20°C (259.5 g N ha<sup>-1</sup>day<sup>-1</sup>) and 11°C (224.9 g N ha<sup>-1</sup>day<sup>-1</sup>). The NH<sub>3</sub> emission showed a narrow range as the incubation temperature decreased from 20°C to 11°C. This indicated that temperature colder than 20°C did not affect NH<sub>3</sub> emission much (Figures 3–5).

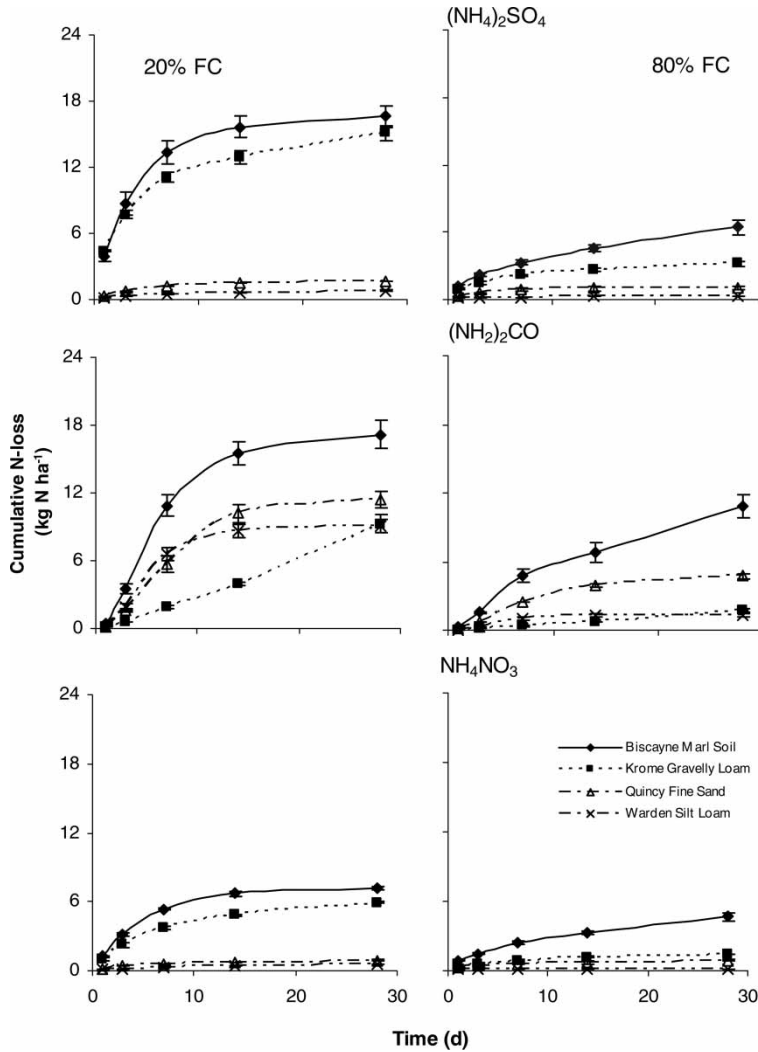
### Volatilization Loss of N as Percentage of Applied N

Soil water regime significantly influenced the N volatilization losses from all N sources, except KNO<sub>3</sub> (Table 5). The highest N loss (25.7% of applied N) occurred from (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> applied to the Krome gravelly loam soil, which was incubated at 20°C with 20% FC soil water content. Under these conditions, the percentage of N loss was very similar for urea source, whereas the N loss from NH<sub>4</sub>NO<sub>3</sub> was roughly half of that from either (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or urea. The volatilization losses from Biscayne marl soil at 20% FC and at 11°C were 22.2, 22.9, and 9.6% of N applied as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, urea, and NH<sub>4</sub>NO<sub>3</sub>, respectively. At 80% FC soil water regime, the N volatilization losses from a Biscayne marl soil were 8.5, 14.5, and 6.3% of applied N as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, urea, and NH<sub>4</sub>NO<sub>3</sub>, respectively, at 11°C.

## DISCUSSION

### pH Effects on Ammonia Volatilization and Recovery

Recovery rate of applied ammonia is the basis of whether the research method is reliable. It is also the prerequisite for subsequent research on ammonia volatilization from soils fertilized. However, there was not a recovery experiment set up to check the trapping system according to the available literatures (Fenn 1975; Al-Kanani, MacKenzie, and Barthakur 1991; Roelcke et al. 1996; Patra, Burford, and Rago 1996; Weerden and Jarvis 1997). He et al. (1999) innovatively created a method to find the recovery rate of applied ammonia. His method was to put 1 ml of ammonia solution into the bottle and then wait until the applied solution naturally dried up and, consequently, the NH<sub>3</sub> volatilized completely. Physical strategy was used for his method. This research showed that the chemical method might be a quicker way because the ratios of ammonia to ammonium



**Figure 5.** Cumulative ammonia volatilization from different N sources applied to four soils incubated at 1°C at either 20% or 80% of field capacity (FC) soil water regimes. Vertical lines at each date point represent the standard error of the mean.

increase by 25.9% when the pH increment is 0.1 unit, according to Eq. (1). Thus, 0.2 mol/L NaOH with pH 13.3 can convert 99.99% of the applied ammonium with  $pK_a$  9.3 into ammonia with  $pK_b$  4.7 and drive it up to the sponge spiked with trapping solution in a very short time. A chemical strategy may be an alternative to recover the emitted ammonia from applied ammonium.

The field capacity of each tested soil was just set the same, 20% FC or 80% FC, but the percentages of water in Florida soils, Biscayne marl soil and Krome

**Table 5.** Ammonia volatilization loss of N as percent of applied N ( $75 \text{ kg ha}^{-1}$ ) from four soils, two soil water regimes, and three incubation temperatures

N form	Temperature (°C)	20% FC								80% FC							
		Biscayne marl soil		Krome Gravelly Loam		Quincy Fine Sand		Warden Silt Loam		Biscayne marl soil		Krome Gravelly Loam		Quincy Fine Sand		Warden Silt Loam	
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	29	16.02	cB	23.76	aAB	2.36	bB	8.05	aA	3.41	bB	6.70	aA	1.40	ns	3.37	aA
	20	18.17	bB	25.71	aA	2.73	aA	1.62	bB	3.60	bB	6.29	aA	1.39	ns	0.34	bB
	11	22.18	aA	20.13	bB	2.24	bB	1.07	cC	8.54	aA	4.26	bB	1.41	ns	0.43	bB
Urea	29	12.63	bB	16.83	bB	16.34	ns	10.70	bB	3.37	bB	3.47	aA	8.43	aA	3.25	aA
	20	10.64	bB	24.23	aA	15.85	ns	10.52	bB	4.55	bB	3.11	aA	5.69	bB	1.74	bB
	11	22.88	aA	12.34	cC	15.26	ns	12.14	aA	14.47	aA	2.23	bB	6.29	bB	1.79	bB
NH <sub>4</sub> NO <sub>3</sub>	29	6.57	bB	12.04	aA	1.79	bB	8.46	aA	1.65	bB	3.72	aA	2.19	aA	1.46	aA
	20	9.26	aA	13.09	aA	2.14	aA	1.40	bB	1.54	bB	3.00	bB	1.55	bB	0.21	cC
	11	9.62	aA	7.93	bB	1.17	cC	0.78	cC	6.26	aA	1.94	cC	1.21	cB	0.25	bB
KNO <sub>3</sub>	29	0.17	aA	0.11	aA	0.09	bB	0.05	bB	0.06	bB	0.08	ns	0.07	bB	0.06	aA
	20	0.13	bB	0.08	bB	0.13	aA	0.05	bB	0.04	cC	0.08	ns	0.07	bB	0.04	bB
	11	0.17	aA	0.05	cC	0.08	cC	0.08	aA	0.41	aA	0.09	ns	0.10	aA	0.07	aA
Control	29	0.03	bB	0.04	bB	0.03	bB	0.03	bB	0.05	bB	0.04	bB	0.05	bB	0.05	bB
	20	0.04	bB	0.03	bB	0.04	bB	0.05	aA	0.04	bB	0.02	cC	0.05	bB	0.04	bB
	11	0.06	aA	0.06	aA	0.07	aA	0.04	aA	0.25	aA	0.09	aA	0.08	aA	0.11	aA

Note: Means followed by similar letters (lower case for  $P < 5\%$ , uppercase for  $P < 1\%$ ) within a soil water regime and a soil by each N source are not significantly different according to Duncan's multiple range test.

gravelly loam, were 12.0% and 8.4% for 20% FC and 48.3% and 33.4% for 80%; those in the Washington soils, Quincy fine sand and Warden silt loam, were 4.8% and 6.7% for 20% FC and 19.8 and 26.0% for 80% FC, respectively. Even so, the  $\text{NH}_3$  emission rates on Florida soils were much greater than those on Washington soils (Figures 2–5, Tables 4 and 5) under most conditions. The pH values of Florida soils were greater than those of Washington soils (Table 1). This may be the main reason for the differences in ammonia emission rates between the tested soils from the two states: equilibrium between  $\text{NH}_3$  and  $\text{NH}_4^+$  forms and  $\text{NH}_3$  emission are highly dependant on soil pH (He et al. 2003; Mattos et al. 2003; Havlin et al. 1999). Actually, Saffigna and Freney (2002) noticed that the loss of ammonia from an application of ammonium sulfate increased from nil at pH 7.0 to 87% at pH 10.5. Therefore, it may be one of the keys to control and adjust soil pH in practice for better management of N use in crop production.

#### Soil Water Content Effects on Ammonia Volatilization

This study demonstrated that ammonia volatilization rate at 20% FC soil water regime were three-fold greater than that at 80% FC (Tables 3–5, Figures 2–5). Thus, the results support that soil water regime is the most significant factor influencing ammonia volatilization. Soil water content plays a major role in diffusion of ammonia in soils (Gardner 1965). In extremely dry soils, as is the case at 20% FC, lack of adequate soil water content restricted downward transport of  $\text{NH}_4^+$  in the soil and thus rendered applied  $\text{NH}_4^+$  readily available for  $\text{NH}_3$  volatilization. Ammonia volatilization can occur from urea following transformation of amide form of N into the  $\text{NH}_4^+$  form in the presence of urease enzyme. According to Sardans and Penuelas (2005), low soil water content decreased urease activities by 10% to 67%. Therefore, it would appear that N volatilization loss from urea is expected to decrease at lower soil water content. However, results of this study did not support this trend as seen from Table 5. This implies that urease was not limiting at the lower soil water regime. This study demonstrated that limiting soil water availability increased the N volatilization loss and thus could cause negative effects on crop production by reducing the N availability in addition to direct effects of soil water stress on the plant growth because transport of  $\text{NH}_4^+$  by diffusion is highest at the highest soil water content (Sommer et al. 1997; Sommer and Jacobsen 1999).

#### Temperature Effects on Ammonia Volatilization

The rates of reaction that convert ammonium into ammonia double with every 10°C increase in temperature (Fenn and Kissel 1974). Results of this study generally supported this trend, except Biscayne marl soil, which showed a



reverse trend (i.e., N volatilization decreased with an increase in temperature). This may be related to the effects of soil texture and the differences in the soil microorganisms. Vazquez-Rodriguez and Rols (1997) reported that the quotient of temperature ( $Q_{10}$ ) was 2.8 for nitrification. This  $Q_{10}$  value is much greater than that of any inorganic reaction such as ammonia volatilization. Therefore, it appears that in the Biscayne marl soil at high temperature there was a rapid nitrification, which limits  $\text{NH}_4^+$  available for  $\text{NH}_3$  volatilization. This may have contributed to the lower  $\text{NH}_3$  volatilization at high temperature. Furthermore, different soils have different bacterial population and species that could influence greatly the rate of N transformation in soils. This research did not involve any microbe analysis. Therefore, further research is necessary to test this hypothesis.

Results of this study revealed that N volatilization loss was significantly influenced by the effects of soil type, soil water content, fertilizer, and temperature treatments. Across all N sources and soils used in this study, volatilization loss was greater at lower soil water regime than that at near-field-capacity soil water regime. Among the N sources,  $\text{NH}_3$  volatilization was greater from ammonium sulfate or urea as compared to that from either ammonium nitrate or potassium nitrate source. Furthermore,  $\text{NH}_3$  volatilization was greater from high pH soils sampled from Florida as compared to that from the slightly lower pH soil samples from Washington. This difference could also be influenced by other soil properties including soil texture and biological activities.

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