

N Volatilization from Arizona Irrigation Waters

E.R. Norton and J.C. Silvertooth

Abstract

A laboratory study was initiated to investigate the potential loss of fertilizer nitrogen (N) through volatilization at four different temperatures (25, 30, 35, and 40°C) out of irrigation waters collected from a number of Arizona locations. Complete water analysis was conducted on each of the water samples. A 300 ml volume of each water was placed in 450 ml beakers open to the atmosphere in a constant temperature water bath with 10 mg of analytical grade (NH₄)₂SO₄ added to each sample. Small aliquots were drawn at specific time intervals over a 24 hour period and then analyzed for NH₄⁺-N concentrations. Results showed potential losses from volatilization to be highly temperature dependent. Total losses (after 24 hours) ranged from 30-48% at 25°C to over 90% at 40°C. In this study where (NH₄)₂SO₄ was used as the N source, the initial concentration of SO₄⁻-S in the solution had a repressive effect on volatilization due to the decreased availability of free NH₄⁺ in waters with high initial SO₄⁻-S concentrations due to the formation of complex ion pairs (NH₄SO₄⁻). It was also observed that at lower temperatures complexation and ion pair formation affected volatilization of NH₃ by reducing the NH₄⁺ activity in solution and thereby reducing NH₃ volatilization. Potential volatilization loss of fertilizer N from these irrigation waters was found to be significant and should be considered when making decisions regarding fertilizer N applications for crop production in Arizona.

Introduction

Efficient management of N in a soil plant system is often difficult due to the various transformations to which N is subjected. Transformations that lead to a loss of available N include the conversion of inorganic (available) N to organic (unavailable) N through immobilization and the conversion of NO₃⁻-N to N₂O and N₂ through denitrification, losses through NO₃⁻-N leaching, and losses due ammonia volatilization all contribute to a decline in efficiency of fertilizer N (Jansson and Persson, 1982). In order to increase the efficiency with which fertilizer N is applied and utilized by plants it is critical that an attempt be made to quantify and characterize the potential fates of fertilizer N.

Loss of fertilizer N has been estimated to range from 20% to 80% of applied N (Catchpoole and Henzel, 1975; Henzel, 1972; Lemon, 1978; Hargrove et al., 1977; Hargrove and Kissel, 1979; and Power, 1980). One potential loss that has become increasingly critical with the increase in the use of urea over the past 20 years is ammonia volatilization. It has been shown that several factors influence the loss of fertilizer N through ammonia volatilization. Ferguson et. al. (1984) found that an increase in the hydrogen ion (H⁺) buffering capacity of the soil reduced soil pH and thereby reduced loss of fertilizer N through volatilization. This research indicated that soil H⁺ buffering capacity is a better indicator of potential NH₃ volatilization than soil pH. Clay et al. (1990) investigated the effects of soil temperature, soil water content, and nitrification and hydrolysis inhibitors on NH₃ volatilization. Ammonia volatilization was highest in the field under conditions of daily maximum soil temperature and decreasing water content. A 100-fold decrease in NH₃ volatilization was observed in treatments of urea plus N-(n-butyl) thiophosphoric triamide (NBPT), a urease enzyme inhibitor (Clay et al., 1990).

Application of N fertilizers through irrigation water has become increasingly popular. This method allows the producer to apply fertilizer with minimal costs associated with the application. However, in open irrigation systems such as furrow and sprinkler irrigation there is a potential for NH₃ volatilization from the water prior to entering the soil (Miyamoto et al., 1975; Henderson, 1955). This is especially true for NH₄⁺ based fertilizers and any other form

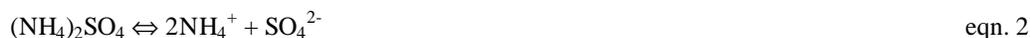
containing free NH_3 such as anhydrous NH_3 . This problem can be exacerbated by high pH waters (Miyamoto et al., 1975). Henderson (1955) found that loss of fertilizer N applied through sprinkler jets was most directly correlated to the pH of the fertilizer solution and that by controlling the pH of the fertilizer solution mixed with the irrigation water subsequent losses due to volatilization were minimized. Volatilization losses were as high as 70% of applied N as the pH of the fertilizer solution approached 10 and reduced to less than 10% when pH was maintained at 8 or less (Henderson, 1955).

DuPlessis and Kroontje (1964) showed that an increase in OH^- concentration of a soil solution would favor a shift to NH_3 in the reaction



An increase in solution pH will lead to an increase in the concentration of NH_3 and thus an increase in the potential for NH_3 volatilization. For example, at pH 6.0, 7.0, and 8.0 the mole fraction of NH_3 in equilibrium with NH_4OH and NH_4^+ is 0.026, 0.26, and 2.6 respectively (Ferguson, 1984).

Miyamoto et al. (1975) reported N losses of up to 73% from irrigation waters. The addition of NH_3 or NH_4^+ based fertilizers to irrigation water results in the formation of various forms of N including: $\text{NH}_3(\text{aq})$, NH_4OH , NH_4^+ and other ion pairs depending upon the ionic composition of the water. A partial pressure gradient of NH_3 will develop between the irrigation water and the atmosphere. The dissolved ammonia once exposed to the atmosphere is then readily subject to volatilization (Miyamoto, 1975). DuPlessis and Kroontje (1964) proposed the following set of reactions (eqn. 2 and 3) to describe the addition of ammonium sulfate to an aqueous solution.



These equilibrium reactions will be dependent upon several factors including temperature and ionic composition of the water (common ion effect, salt effect, complexation). Depending on the ionic composition of the solution many other reactions will take place affecting the activity of NH_3 and thus affecting potential volatilization.

There has been extensive research quantifying NH_3 volatilization losses from soils and cropping systems. However, little research has been conducted on N loss from irrigation waters through volatilization. The objective of this study was to investigate the loss of fertilizer N through volatilization from irrigation waters from 10 different sources in Arizona. The effect of temperature on the rate of N loss was also addressed.

Materials and Methods

Ten irrigation waters were collected from various locations in the state of Arizona. Complete water analyses were performed for each of the ten water samples prior to beginning the laboratory study. Analytical grade ammonium sulfate (10 mg) was added to 300 mL of each of the ten water samples in open 450 mL beakers. Beakers were then placed in a shaking water bath to maintain constant temperature. Small aliquots (10 ml) were drawn starting at time 0 (time of beaker placement into the water bath) and at 0.25, 0.5, 1, 2, 4, 6, 8, 12, and 24 hours. Each water sample was replicated four times at each of four temperatures (25°C , 30°C , 35°C , and 40°C) for a total of 1,600 experimental observations. Aliquots were then analyzed for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ using an Alpkem continuous flow analyzer (Alpkem Corporation, Perstorp Analytical, 151 Graham Road, P.O. Box 9010, College Station, TX 77842).

Data was subjected to analysis of variance with temperature as the main effect and water source as the subunit effect. Data was also subjected to multi-variate linear regression analysis to determine which water quality characteristic most highly correlated with loss of N from the irrigation water sample. Linear regression was also performed to examine the rate of N loss as a function of time. All statistical analyses were performed according to guidelines outlined by Gomez and Gomez (1984) and the SAS institute (1994).

Results and Discussion

The ten Arizona locations associated with each water source are shown in Table 1. Locations were selected that sampled a variety of agricultural waters used for irrigation in locations that ranged from 32 meters to just under 1000 meters in elevation. A complete characterization of each of the ten water sources was performed. Results from these analyses are shown in Table 2.

Analysis of Variance

Percent N loss was calculated for each of the ten water sources at each temperature by subtracting the final concentration (time = 24 hours) from the initial concentration (time = 0 hours) and dividing by the initial concentration of $\text{NH}_4^+\text{-N}$. Results of the overall analysis of variance demonstrated a significant difference due to the water source and a significant difference due to temperature with observed significance levels (OSL) <0.0001 for both effects. A significant interaction between water source and temperature was also observed (OSL = 0.0394). To investigate the significant interaction term percent loss was plotted as a function of temperature for each of the ten irrigation sources (Figure 1). Regression of these values was also performed and the slopes of the regression equations are presented in Table 3. In general, percent loss of N from the water sources with lower concentrations of soluble salts, specifically $\text{SO}_4^{2-}\text{-S}$, increased as temperature increased, as evidenced by the larger slope value of the regression (Table 3).

Means separation tests were performed using a Student Newman Keuls (SNK) comparison of temperature by each source (Table 4). For all water sources, a significant increase in the percent N loss was observed as temperature increased. These differences were significant ($\alpha = 0.05$) for each source (Table 4). Means separations (SNK) were also performed comparing water source by each temperature (Table 5). Significant differences were observed among water sources at each temperature with higher losses of N occurring in water sources with lower total dissolved salts, specifically $\text{SO}_4^{2-}\text{-S}$.

Regression Analysis

Linear regression analysis was performed examining the fraction of $\text{NH}_4^+\text{-N}$ loss as a function of time (Table 6). A first order model was successfully used to fit most data. However, in a few cases a second order polynomial provided the best fit. In all cases regression parameter estimates were significant at $\alpha = 0.01$. In general the fit of the model increased dramatically with an increase in temperature as evidenced by r^2 values (Table 6). Figures 2-11 show the regression curves associated with each source and temperature.

The rate of $\text{NH}_4^+\text{-N}$ loss increases dramatically with temperature as does the general fit of the regression model. At lower temperatures a higher fraction of $\text{NH}_4^+\text{-N}$ loss is observed early in the 24 hour period (0-5 hours). The method of analysis for $\text{NH}_4^+\text{-N}$ measures the activity of NH_4^+ in solution and does not measure total soluble NH_4^+ concentration including the fraction that has been involved in ion pair formation and complexation reactions in the solution. In general, complexation in a natural water proceeds rather quickly to some state of equilibrium (Stumm and Morgan, 1996). The reactions associated with complexation and ion pair formation will also be temperature dependent. As temperature increases the energy in the solution increases which disrupts the complexation and ion pair associations. Thus, an increase in complexation or ion pair formation at the lower temperature regimes would account for the observed increase in the fraction of apparent $\text{NH}_4^+\text{-N}$ loss at the early sample times compared to the higher temperatures.

In order to validate this theory a series of speciation simulations were conducted utilizing a chemical speciation computer model developed by the United States Geological Survey (USGS). The model used is a Microsoft Windows© interface for the newly released *PHREEQC* version 2.2 (Parkhurst and Appelo, 1999) entitled *PHREEQCI* (Charlton et al., 1997). The software allows for the input of the chemical characteristics of a given solution and then performs a speciation. The software also allows for the addition of a chemical reactant to the original solution to which a new speciation is performed. In this case, 10 mg of $(\text{NH}_4)_2\text{SO}_4$ was added to the original solution and the speciation was then performed. Results from the speciation model reveals a decrease in the amount of complexation and ion pair formation as temperature increases (Figure 12). Figure 12 illustrates that as temperature increases the activity of NH_4SO_4^- decreases. This would indicate that at lower temperatures and early sample times the increase in the fraction of $\text{NH}_4^+\text{-N}$ loss was due to complexation effects and not volatilization.

Another item of interest that has practical implications for production agriculture is the fact that many of the water sources at 30 and 35°C, which is not uncommon in the summer months in Arizona, can lose up to 30% of applied N

in the first 10 hours after application. At higher temperatures that loss can increase to 50%. These results indicate potential losses of N through volatilization when using NH_4^+ -N sources.

Multi-variate Regression Analysis

Multi-variate linear regression analysis was performed in an effort to identify water quality characteristics that may influence the loss of N through volatilization. Percent loss was regressed on the water quality data contained in Table 2. The technique used to accomplish this analysis was a backward elimination technique as outlined by the SAS Institute (1994). The final model retains only those variables that contribute significantly to the overall model. Variables found to contribute significantly to the overall model are found in Table 7 along with the parameter estimate and the OSL for that parameter. The most significant factor was temperature which was positively correlated with percent N loss along with electrical conductivity of the water (EC_w) and carbonate concentration. Two variables that were negatively correlated and produced negative regression coefficients included pH and SO_4^- -S concentrations. However, the ranges associated with the pH values encountered with these ten water sources was very small (8.1 – 8.6). Research investigating NH_3 volatilization in the past has clearly demonstrated a positive relationship between pH and NH_3 volatilization (Du Plessis and Kroontje, 1964).

The other variable for which a negative parameter estimate was calculated was SO_4^- -S. This variable appeared to have a real effect on the rate of N loss through volatilization. As demonstrated in Figure 13, when the slope of the regression of percent loss as a function of temperature are plotted as a function of SO_4^- -S concentration a negative relationship is observed. The relationship between decreasing rates of N loss through volatilization with increasing concentration of SO_4^- -S is most likely due to an application of Le Chatelier's principle, or the "common ion effect", which predicts that a salt will be less soluble if one of its constituent ions is present in solution (Harris, 1991). As the concentration of SO_4^- -S increases, the solubility of the $(\text{NH}_4)_2\text{SO}_4$ decreases (eqn. 3), producing a reduction in the amount of NH_4^+ activity, which in turn reduces the potential for NH_3 volatilization.

Conclusions

The potential loss of fertilizer N placed in irrigation waters should be accounted for when making decisions about fertilizer N management. This is particularly true when considering the form of fertilizer being used. Potential losses may be greater under conditions where fertilizers are used containing high concentrations of free NH_3 or NH_4^+ . It was also observed that potential losses are much greater at temperatures above 35°C and may exceed 50% loss in the first 10-12 hours of application. Water quality appears to have an impact on NH_3 volatilization. In this study the higher concentrations of SO_4^- -S had an impact on reducing the amount of volatilization due to the decreased solubility of $(\text{NH}_4)_2\text{SO}_4$. In general, higher concentrations of total soluble salts (i.e. EC_w) tended to increase the potential loss of N through volatilization.

Literature Cited

- Catchpoole, V.R., and E.F. Henzel. 1975. Loss of nitrogen from pastures. p. 82-83. *In* C.S.I.R.O. Tropic. Agron. Div. Rep. 1974-1975.
- Charlton, S.R., C.L. Macklin, and D.L. Parkhurst. 1997. PHREEQCI--a graphical user interface for the geochemical computer program PHREEQC: U.S. Geological Survey Water-Resources Investigations Report 97-4222.
- Clay, D.E., G.L. Maizer, and J.L. Anderson. 1990. Ammonia volatilization from urea as influenced by soil temperature, soil water content, and nitrification and hydrolysis inhibitors. *Soil Sci. Soc. Am. J.* 54:263-266.
- Du Plessis, M.C.F., and W. Kroontje. 1964. The relationship between pH and ammonia equilibria in soil. *Soil Sci. Soc. Amer. Proc.* p. 751-754.
- Ferguson, R.B., D.E. Kissel, J.K. Koelliker, and W. Basel. 1984. Ammonia volatilization from surface-applied urea: Effect of hydrogen ion buffering capacity. *Soil Sci. Soc. Am. J.* 48:578-582.
- Gomez, K.A. and A.A. Gomez. 1984. *Statistical Procedures for Agricultural Research*, Inc. Ed. John Wiley and Sons, Inc.
- Hargrove, W.L., D.E. Kissel, and L.B. Fenn. 1977. Field measurements of ammonia volatilization from surface applications of ammonium salts to a calcareous soil. *Agron. J.* 69:473-476.
- Hargrove, W.L., and D.E. Kissel. 1979. Ammonia volatilization from surface applications of urea in the field and laboratory. *Soil Sci. Soc. Am. J.* 43:359-363.
- Harris, D. 1991. *Quantitative chemical analysis*. 3rd ed. W.H. Freeman and Company, NY.
- Henderson, D.W., W.C. Bianchi, and L.D. Doneen. 1955. Ammonia loss from sprinkler jets. *Agric. Eng. June*:398-399.
- Henzell, E.F. 1972. Loss of nitrogen from nitrogen-fertilized pasture. *J. Aust. Inst. Agric. Sci.* 38:309-310.
- Jansson, S.L., and J. Persson. 1982. Mineralization and immobilization of soil nitrogen. *In* *Nitrogen in Agricultural Soils* (ed. F.J. Stevenson) pp. 229-252. American Society of Agronomy Monograph No. 22. Madison, WI.
- Lemon, E.R. 1978. Nitrous oxide exchange at the land surface. *In* D.R. Neilsen, and J.G. MacDonald (ed.) *Nitrogen in Field Soil*. Academic Press, New York. p. 493-521.
- Miyamoto, S., J. Ryan, J.L. Stroehlein. 1975. Sulfuric acid for the treatment of ammoniated irrigation water: I. Reducing ammonia volatilization. *Soil Sci. Soc. Amer. Proc.* 39:544-548.
- Parkhurst, D.L., and C.A.J. Appelo. 1999. User's guide to PHREEQC (Version 2)--a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99-4259.
- Power, J.F. 1980. Response of semiarid grassland sites to nitrogen fertilization: II. Fertilizer recovery. *Soil Sci. Soc. Am. J.* 44:550-555.
- SAS Institute. 1994. *The SAS system for Windows*. Release 6.10. Sas Institute Inc., Cary NC.
- Stumm, W., and J.J. Morgan. 1996. *Aquatic chemistry: chemical equilibria and rates in natural waters*. 3rd Ed. John Wiley and Sons, Inc. NY.

Table 1. Geographical location of sample for each of the 10 water sources.

Sample #	Sample Location (Elevation)	Source of Water
1	Yuma, AZ (32m)	Colorado River Water
2	Gila Bend, AZ (219m)	Gila River / Paloma Ranch Well Field
3	Buckeye, AZ (304m)	Roosevelt Irrigation District (RID)
4	Maricopa, AZ (361m)	Well water (Maricopa Agricultural Center – University of Arizona)
5	Maricopa, AZ (361m)	Colorado River Water (Maricopa-Stanfield Irrigation District - MSID)
6	Coolidge, AZ (422m)	San Carlos Irrigation District (SCID)
7	Marana, AZ (601m)	Well water (Marana Agricultural Center – University of Arizona)
8	Marana, AZ (601m)	Central Arizona Project – CAP (Colorado River Water)
9	Safford, AZ (901m)	Gila River Water
10	Safford, AZ (901m)	Well water (Safford Agricultural Center – University of Arizona)

Table 2. Water composition data for each of the 10 sources.

Sample #	pH	Ca	Mg	Na	K	CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻ -S	NO ₃ ⁻ -N	PO ₄ ²⁻ -P	EC	SAR	SSP	TSS
-----mg L ⁻¹ -----												ds m ⁻¹	Adj.	ppm	
1	8.2	74	33	130	4.8	0	148.8	120	100	0.5	0.03	0.7	6.2	46.4	611
2	8.6	180	56	590	11.6	4.8	151.3	820	160	5.6	0.31	1.9	21.5	64.9	1981
3	8.3	42	29	250	8.7	1.2	185.4	340	48	3.8	0.14	1.0	13.7	69.8	909
4	8.4	220	40	330	4.9	1.2	102.5	420	230	16.4	0.06	1.5	11.1	49.9	1366
5	8.5	69	22	170	4.2	2.4	70.8	160	110	3.2	0.03	0.7	7.2	57.9	612
6	8.6	46	13	61	5.1	8.4	87.8	75	39	0.9	0.25	0.4	3.3	43.1	337
7	8.6	25	6	66	2.2	4.8	109.8	41	22	4.0	0.02	0.5	4.3	61.4	281
8	8.1	60	33	100	4.9	0	90.3	93	93	0.2	0.02	0.5	4.4	42.7	475
9	8.4	40	12	110	7.1	2.4	131.8	150	17	0.8	0.09	0.5	6.4	60.2	471
10	8.3	41	13	380	3.3	1.2	302.6	300	78	5.5	0.04	1.3	25.3	83.8	1125

Table 3. Regression parameter estimates (slope) for data presented in Figure 3.

Source	Slope (Significant at $\alpha = 0.05$)
Yuma (Colorado River)	3.204
Gila Bend (Gila River/Paloma Ranch)	3.592
Buckeye (RID)	3.786
Maricopa (well)	2.085
Maricopa (CAP)	3.515
Coolidge (SCID)	2.736
Marana (well)	3.992
Marana (CAP)	2.582
Safford (Gila River)	3.395
Safford (well)	3.252

Table 4. Analysis of variance and means separation by temperature for each water source.

Source	1	2	3	4	5	6	7	8	9	10
	-----Percent Loss-----									
40°C	89.6 a	88.5 a	94.7 a	73.5 a	83.0 a	86.4 a	91.0 a	88.6 a	86.4 a	90.4 a
35°C	68.5 b	64.2 b	77.9 b	56.1 b	52.9 b	60.2 b	65.4 b	59.3 b	70.1 b	74.8 b
30°C	53.2 c	53.5 c	61.9 c	46.2 c	34.7 c	54.3 c	45.1 c	54.1 c	39.7 c	53.6 c
25°C	41.3 d	32.2 d	36.9 d	42.1 d	30.7 c	42.8 d	31.2 d	47.4 d	41.3 c	43.4 d
SNK	2.8	1.6	1.7	3.5	4.5	3.6	6.4	3.2	3.7	4.3
OSL	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
C.V.	10.2	6.2	5.8	14.6	20.0	13.1	24.4	11.5	13.6	14.7

Table 5. Analysis of variance and means separation by water source at each temperature.

Source	Percent Loss			
	25°C	30°C	35°C	40°C
Yuma (Colorado River)	41.3 ab*	53.2 b	68.5 c	89.6 cd
Gila Bend (Gila River/Paloma Ranch)	32.2 c	53.5 b	64.2 d	88.5 d
Buckeye (RID)	36.9 b	61.9 a	77.9 a	94.7 a
Maricopa (well)	42.1 ab	46.2 c	56.1 f	73.5 g
Maricopa (CAP)	30.7 c	34.7 e	52.9 g	83.0 f
Coolidge (SCID)	42.8 ab	54.4 b	60.2 e	86.4 e
Marana (well)	31.2 c	45.1 c	65.4 d	91.0 b
Marana (CAP)	47.4 a	54.1 b	59.3 e	88.6 d
Safford (Gila River)	41.3 ab	39.7 d	70.2 c	86.4 e
Safford (well)	43.4 ab	53.6 b	74.8 b	90.4 bc
SNK Critical Range	4.6	3.4	1.7	1.0
Coefficient of Variation	26.4	15.6	5.9	2.7
Observed Significance Level	0.0001	0.0001	0.0001	0.0001

* Means followed by the same letter are not significantly different according to an SNK means separation test.

Table 6. Regression analysis parameter estimates for fraction of NH_4^+ -N loss as a function of time.

Source	Temperature	Regression Parameters			
	$^{\circ}\text{C}$	r^2	b_0	b_1	b_2
Yuma	25	0.2549	0.1890	0.0095	--
	30	0.5236	0.1411	0.0161	--
	35	0.8363	0.0523	0.0265	--
	40	0.9552	0.0351	0.0377	--
Gila Bend	25	0.2470	0.1228	0.0093	--
	30	0.6262	0.1203	0.0173	--
	35	0.9127	0.0225	0.0168	0.00038
	40	0.9688	0.0208	0.0370	--
Buckeye	25	0.1330	0.1836	0.0080	--
	30	0.6361	0.1343	0.0187	--
	35	0.8465	0.0594	0.0157	0.00059
	40	0.9826	0.0047	0.0629	-0.00097
Maricopa (well)	25	0.1314	0.2369	0.0090	--
	30	0.2125	0.1547	0.0127	--
	35	0.5785	0.0734	0.0188	--
	40	0.9585	-0.0150	0.0302	--
Maricopa (CAP)	25	0.3254	0.1455	0.0104	--
	30	0.5251	0.0592	0.0122	--
	35	0.9083	0.0363	0.0075	0.00055
	40	0.9718	0.0134	0.0288	0.00023
Coolidge	25	0.3963	0.1788	0.0110	--
	30	0.2449	0.1804	0.0155	--
	35	0.9590	0.0109	0.0187	0.00026
	40	0.9708	0.0237	0.0353	--
Marana (well)	25	0.3534	0.2076	0.0354	-0.00104
	30	0.3077	0.1677	0.0126	--
	35	0.7181	0.0914	0.0220	--
	40	0.9733	-0.0168	0.0460	-0.00029
Marana (CAP)	25	0.3962	0.1868	0.0137	--
	30	0.1611	0.2925	0.0110	--
	35	0.8883	0.0344	0.0123	0.00046
	40	0.9758	0.0289	0.0363	--
Safford (Gila River)	25	0.1592	0.2070	0.0082	--
	30	0.8100	0.0611	-0.0072	0.00088
	35	0.8828	0.0734	0.0256	--
	40	0.9512	0.0358	0.0361	--
Safford (well)	25	0.2125	0.2119	0.0111	--
	30	0.6579	0.1125	0.0180	--
	35	0.9551	-0.0270	0.0319	--
	40	0.9604	0.0156	0.0551	-0.00075

*All parameters listed are significant at the $\alpha = 0.05$

Table 7. Multi-variate linear regression analysis results using the backward elimination model selection criteria.

Variable	Parameter Estimate	OSL
β_0 Intercept	2.88630	0.00093
β_1 Temperature	0.03203	<0.0001
β_2 pH	-0.40383	0.0033
β_3 Carbonate	0.01728	0.0550
β_4 Electrical Conductivity	0.09883	0.0025
β_5 Sulfate	-0.000755	0.0026

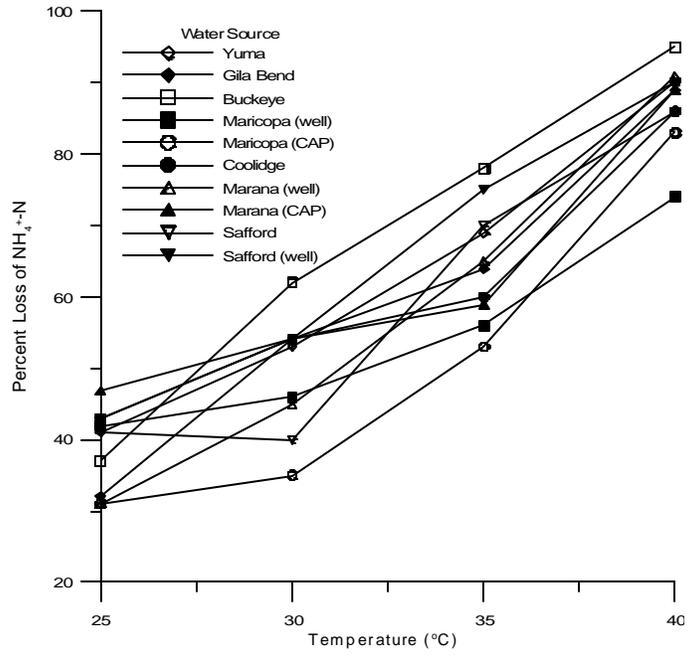


Figure 1. Percent loss of $\text{NH}_4^+\text{-N}$ as a function of temperature for all water sources.

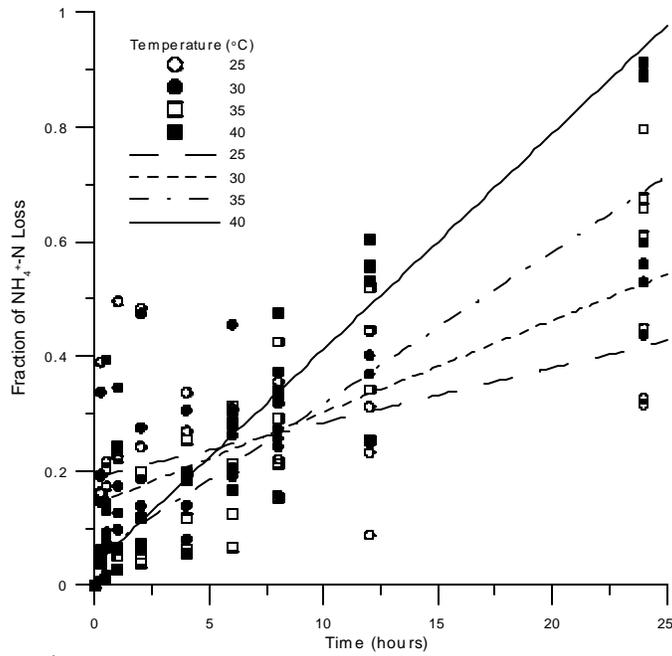


Figure 2. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Yuma (Colorado River water).

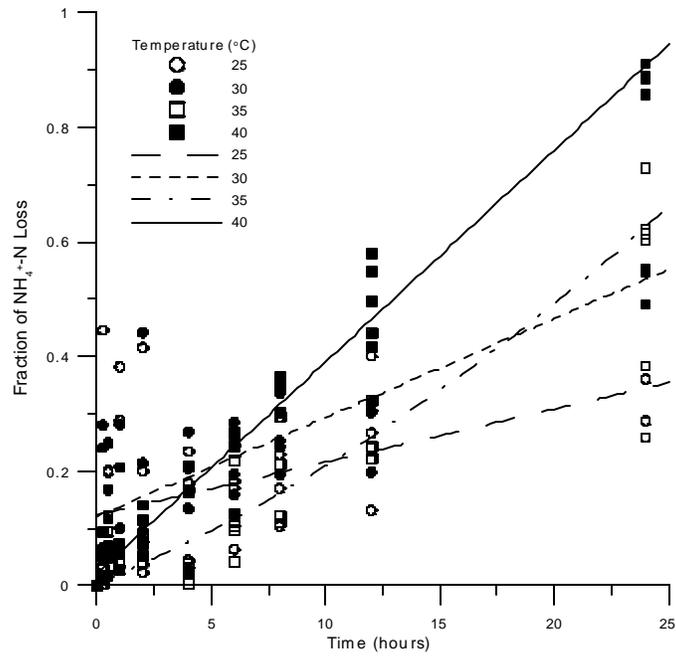


Figure 3. Fraction of NH_4^+ -N loss through volatilization, Gila Bend.

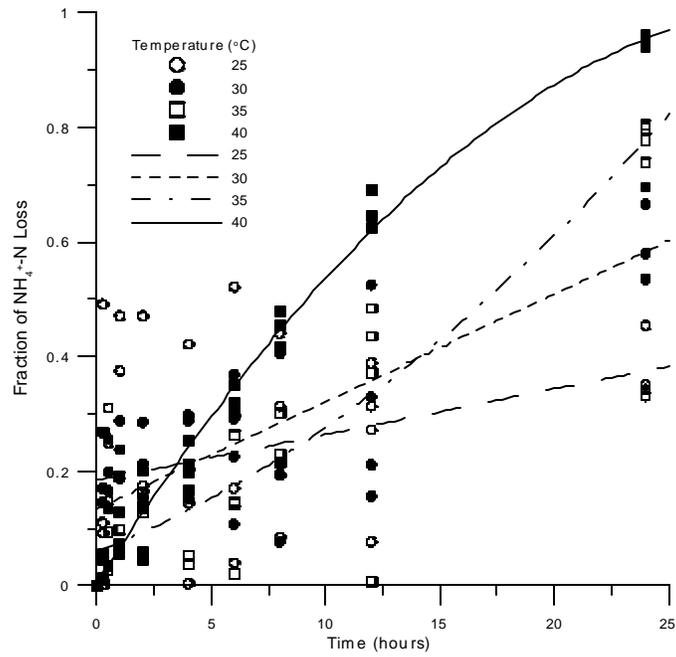


Figure 4. Fraction of NH_4^+ -N loss through volatilization, Buckeye (RID water).

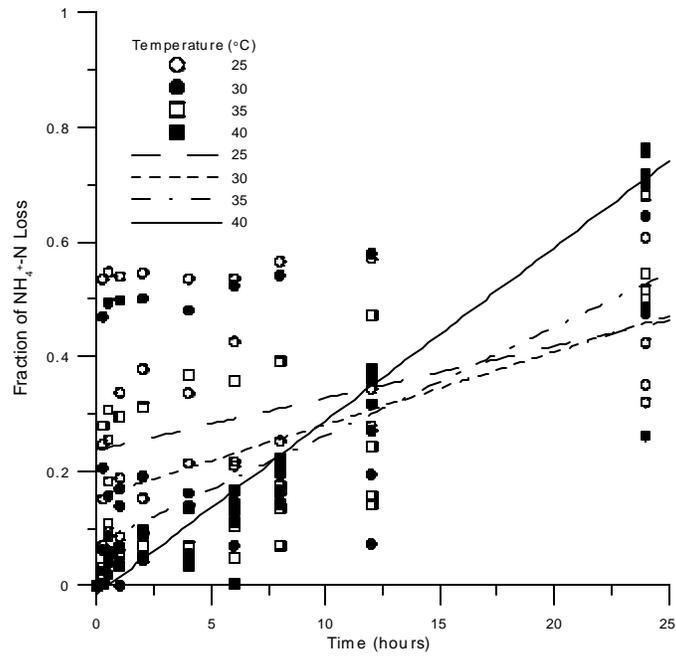


Figure 5. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Maricopa (well water).

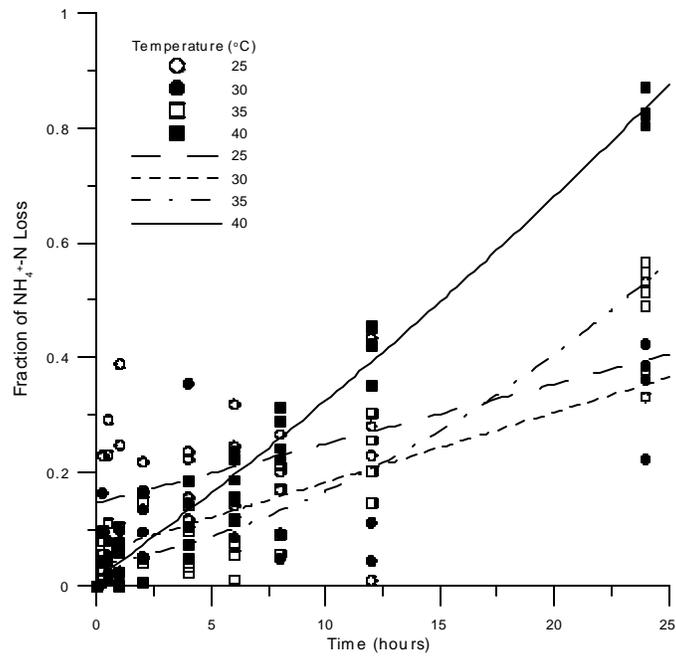


Figure 6. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Maricopa (CAP water).

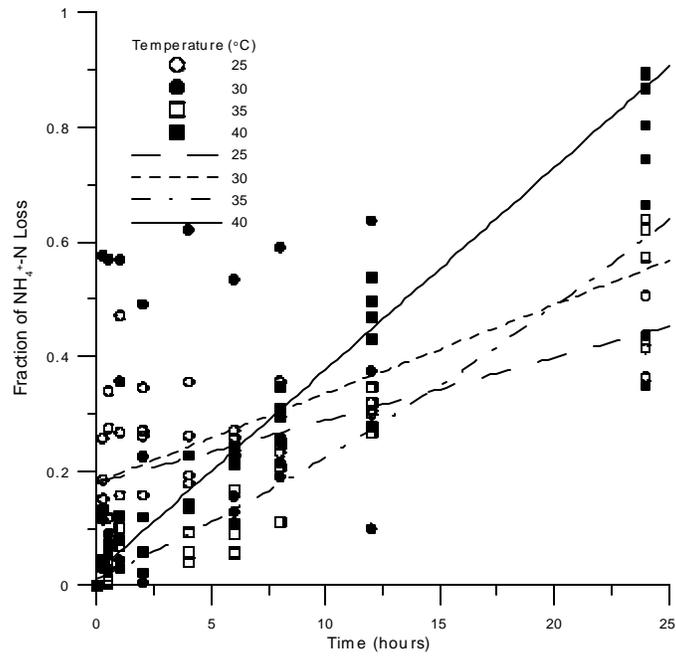


Figure 7. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Coolidge (San Carlos River water).

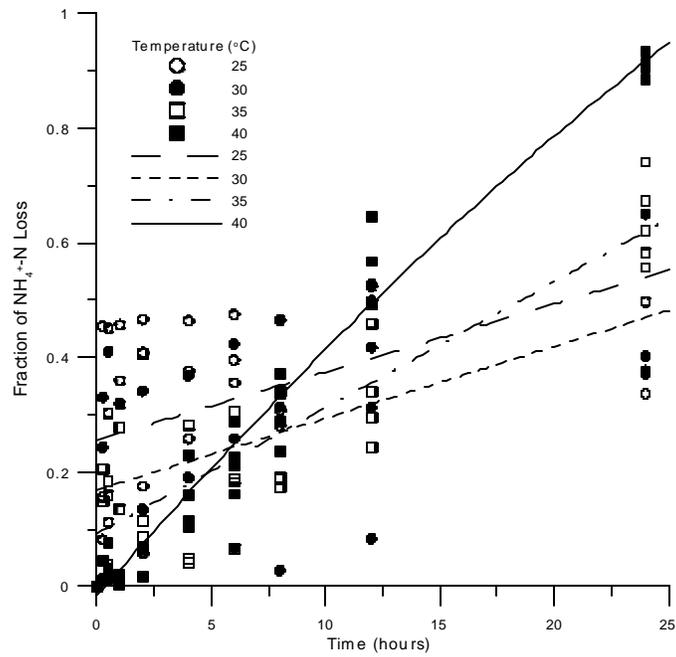


Figure 8. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Marana (well water).

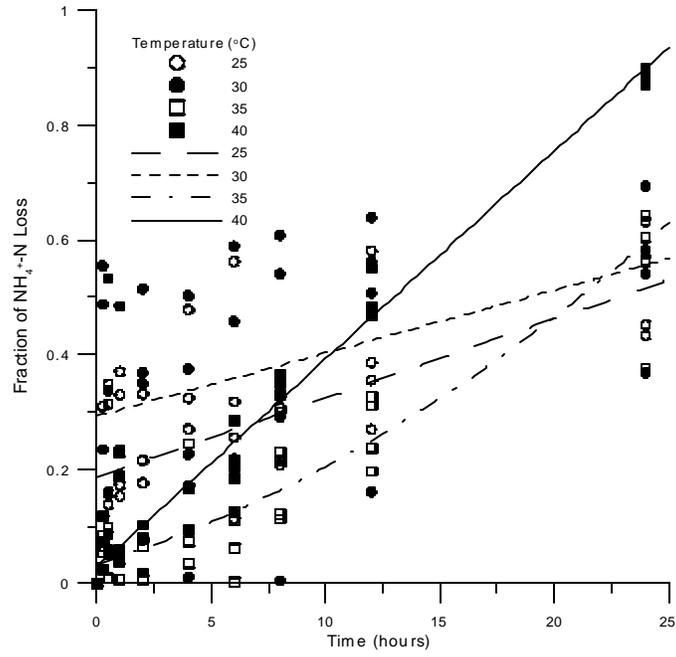


Figure 9. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Marana (CAP water).

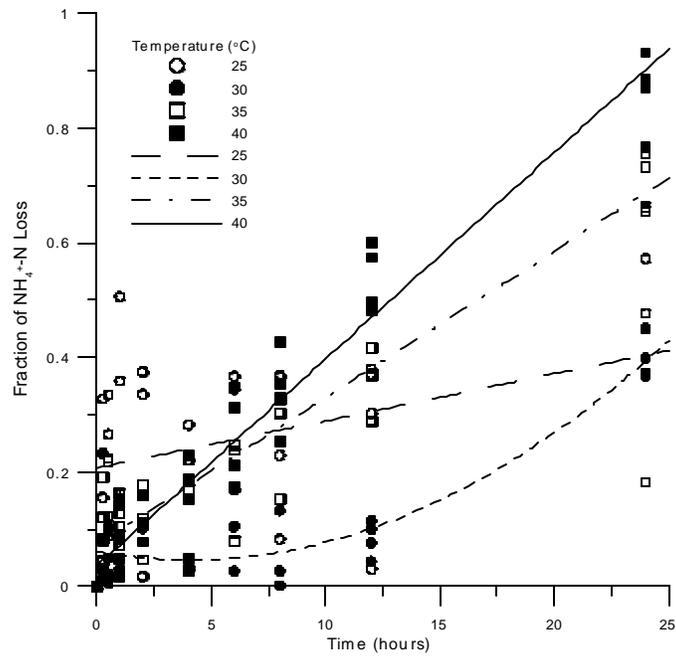


Figure 10. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Safford (Gila River water).

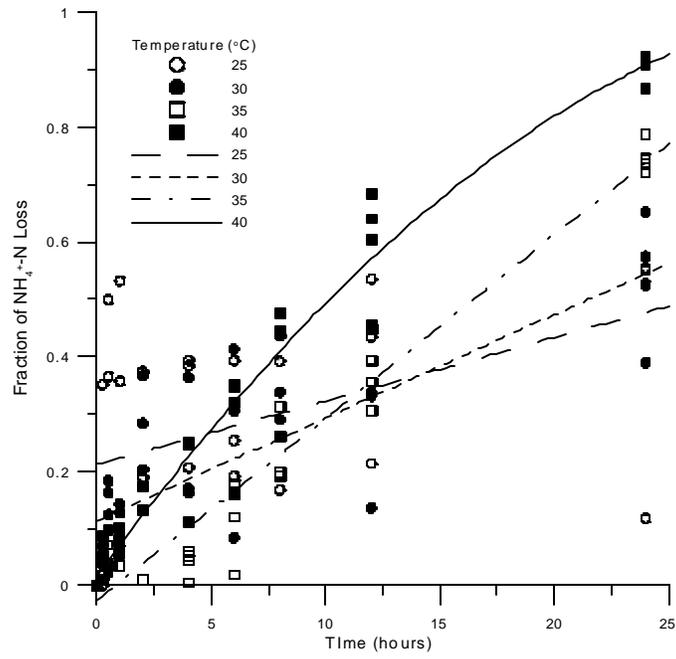


Figure 11. Fraction of $\text{NH}_4^+\text{-N}$ loss through volatilization, Safford (well water).

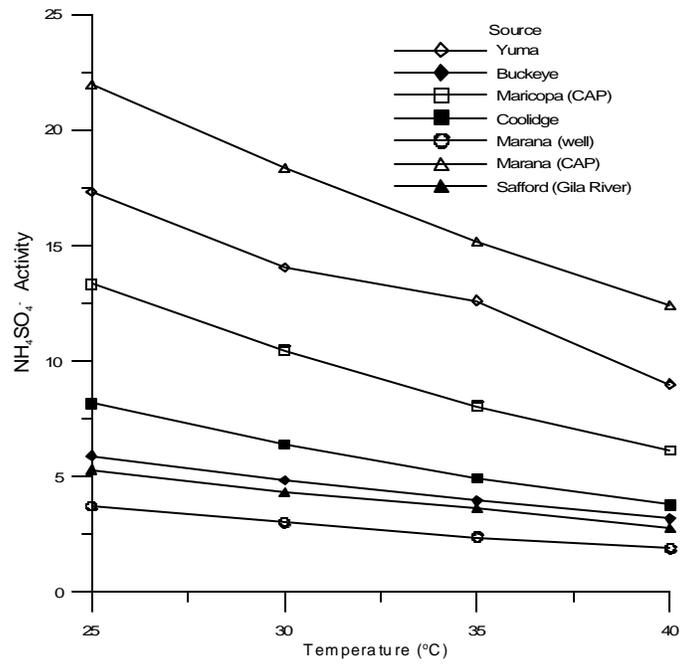


Figure 12. Activity of NH_4SO_4^- as a function of temperature.

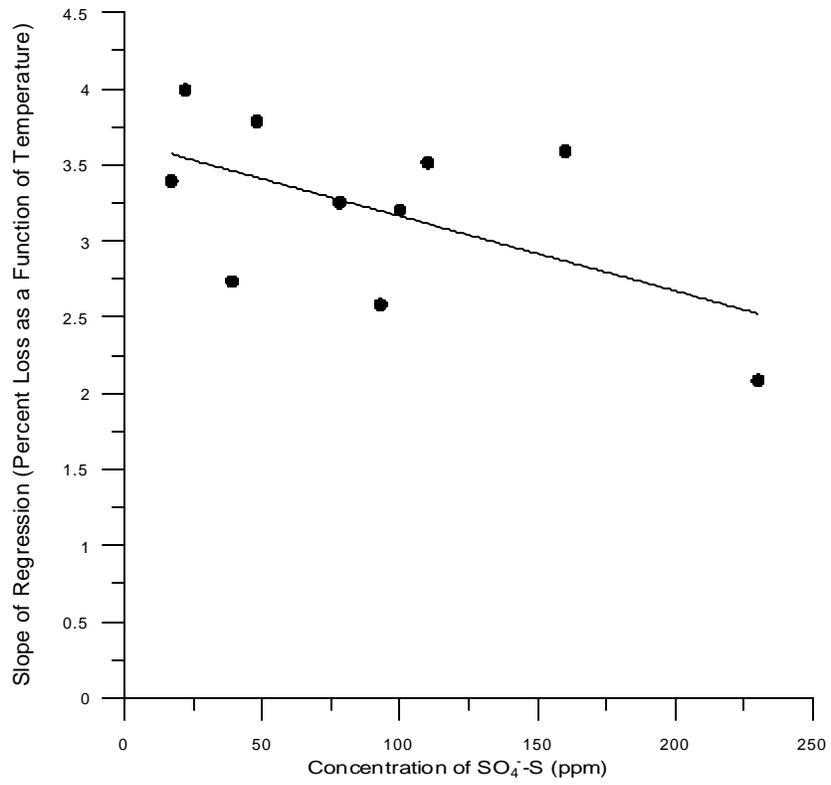


Figure 13. Regression slopes from Table 3 plotted as a function of SO₄²⁻-S concentrations.