

## Urea Transformation and Nitrogen Loss in Waterlogged Soil Column

Su-II Seol, Sang-Mo Lee, Gwang-Hyun Han Woo-Jung Choi and Sun-Ho Yoo\*

School of Agricultural Biotechnology, College of Agriculture and Life Sciences,  
Seoul National University, Suwon 441-744, Korea

Received March 13, 2000

An experiment was conducted to obtain the quantitative data on the transformation and loss of applied urea-N in waterlogged soil columns. The soil columns were pre-incubated for 35 days to develop oxidized and reduced soil conditions prior to urea application. After urea application at the rate of 150 kg N ha<sup>-1</sup> (29.5 mg N), the amounts of nitrogen which were volatilized, leached, and remained in soil column were measured during 38 days of incubation period. On 2 and 4 days of incubation, 54.1% (15.9 mg N) and 98.4% (29.0 mg N) of the applied urea was hydrolyzed, respectively. Most of the applied urea was completely hydrolyzed within 6 days. After urea application, the rates of ammonia volatilization were increased with the floodwater pH when the floodwater pH were higher than 7.0. The maximum rate of ammonia volatilization was 0.3 mg d<sup>-1</sup> when pH of the floodwater showed maximum value of 7.6. The total amount of volatilized nitrogen was 6.1% (1.8 mg N) of the applied urea-N. A 63.2% (18.6 mg N) of the applied urea was remained in soil as NH<sub>4</sub><sup>+</sup>-N, and 28.0% (8.2 mg N) of the applied urea was leached as NH<sub>4</sub><sup>+</sup>-N at the end of the incubation. Amount of NO<sub>3</sub><sup>-</sup>-N in soil was smaller than 2.0 mg throughout the incubation period. The total amount of NO<sub>3</sub><sup>-</sup>-N leached was very small, which value was 1.8 mg. It suggested that nitrification process was not significant in waterlogged soil column of this study due to high infiltration rate of urea solution applied to the soil column. Therefore only small amount of NO<sub>3</sub><sup>-</sup>-N was lost by denitrification and leaching process.

**Key words:** urea transformation, ammonia volatilization, leaching, waterlogged soil.

Nitrogen accounts for about 67% of the fertilizer (N+P+K) applied to rice crops and over 90% of total fertilizer-N consumption by rice is in the urea form.<sup>1)</sup> Despite this impressive growth in urea production and use, researches over the past 20 to 30 years have shown that N fertilizers are generally inefficient, with less than 40% of the applied N normally used by lowland rice.<sup>2,3)</sup> In addition, N is difficult to manage in flooded soil systems due to the complicated transformations it undergoes. To improve the efficiency of urea, agronomists must know and understand the fate of applied urea N under flooded soil conditions. Submergence of paddy soil results in development of a thin oxidized soil surface layer and an underlying reduced soil layer. Establishment of two distinct soil layers favors simultaneous nitrification and denitrification. The chemical, biological, and physical properties of the two distinct soil layers strongly influence biochemical process in transforming one form of N to another from flooded rice soils.<sup>4,5)</sup>

Urea transformations have been studied extensively under oxidized soil conditions, but reported effects of soil submergence are vary and are not completely understood.<sup>6,7,8)</sup> Under oxidizing conditions, NH<sub>4</sub><sup>+</sup> is oxidized to NO<sub>3</sub><sup>-</sup>, which is highly mobile and easily leached from soil. Nitrogen produced after urea hydrolysis under reducing conditions will proceed up to ammonia formation only. The NH<sub>4</sub><sup>+</sup> will

equilibrate between soil solution and exchangeable fractions, be in nonexchangeable forms, and be lost through leaching or volatilization.<sup>9)</sup> After urea hydrolysis, the thin, oxidized surface layer promotes oxidation of NH<sub>4</sub><sup>+</sup> to NO<sub>3</sub><sup>-</sup>, and the reduced subsurface layer supports reduction of NO<sub>3</sub><sup>-</sup> to N<sub>2</sub>O and N<sub>2</sub>.<sup>10)</sup>

Redox potentials of oxidized zone of flooded soils may remain as high as +500 mV. If reduction process is sufficiently intense, soil may have a redox potential as low as -300 mV. In reduced soil layer, anaerobic organisms utilize progressively weaker electron acceptors in place of O<sub>2</sub> for respiration. Nitrate, the next strongest electron acceptor, is reduced to N<sub>2</sub> or N<sub>2</sub>O gas (denitrification) at around +220 mV of redox potential after complete consumption of O<sub>2</sub>.<sup>5)</sup>

Ammonia volatilization and denitrification (to N<sub>2</sub>O and N<sub>2</sub>) are the two major loss mechanisms of N, causing poor fertilizer efficiency in paddy soils even when leaching and runoff are eliminated.<sup>11,12)</sup> Ammonia volatilization is a major loss mechanism that affects the efficiency of urea and other N fertilizers in irrigated lowland rice. The magnitude of ammonia loss depends on wind speed, temperature, rainfall, ammoniacal-N (NH<sub>4</sub><sup>+</sup>+NH<sub>3</sub>) concentration, pH, and cation exchange capacity.<sup>13)</sup> In Asian rice fields, the high floodwater ammoniacal-N concentrations following N application, high temperatures common in the tropics, and elevated floodwater pH resulting from photosynthetic activity create a favorable environment for ammonia loss.<sup>14,15)</sup>

As urea is a nonionic compound, it is susceptible to

\*Corresponding author  
Phone: 82-331-290-2413; Fax: 82-331-293-8608  
E-mail: shyoo@plaza.snu.ac.kr

leaching in soil, but at a slower rate than nitrate. Urea can be weekly adsorbed by soil and is simultaneously hydrolyzed to ammonium bicarbonate by soil urease.<sup>16)</sup> Urea is retained within soil due to salt formation between urea and the carboxyl groups of soil organic matter<sup>17)</sup> Leaching losses of urea may occur by two processes: (1) urea leached itself from the soil, and (2) urea migrating below the rooting zone is hydrolyzed, nitrified, and then leached as nitrate. Leaching losses of N from the crop root zone can be considerable and contribute to the accumulation of nitrate in ground and surface water that would be nonpoint pollutant source.<sup>18)</sup>

In order to obtain the quantitative data on the transformation and loss of applied urea in waterlogged soil, the column study was carried out.

### Materials and Methods

Cultivated paddy soils of experimental farm belonging to College of Agriculture and Life Sciences, Seoul National University was used for this study. The collected soil was air-dried, passed through a 2-mm sieve, and analyzed for pH with 1:5 (soil:distilled water) method using pH meter (DMS, DMP2000), organic matter using Walkley-Black method, inorganic nitrogen using Kjeldahl method, cation exchange capacity using 1N-ammonium acetate (pH 7.0) method, and soil texture using pipette method.<sup>19,20)</sup> Table 1 shows the properties of soil used in this study.

**Leaching study.** Soil columns were prepared by packing soil into 5 cm (i.d.) × 20 cm (length) acryl column packed to establish uniform bulk density of 1.2 g cm<sup>-3</sup>. The bottom of the column was covered with an acryl sheet that had a small opening in the middle for water flow. The bottom of the column was filled with sea sand and covered with a piece of filter paper. The soil columns were saturated sufficiently with tap water from the bottom. Floodwater depth was maintained to 2 cm using mariotte bottle, and flow rate was adjusted to 2 cm d<sup>-1</sup>. The soil temperature was kept at 25°C by constant temperature water circulation system (Fig. 1). The soil columns were pre-incubated for 35 days to develop oxidized and reduced soil conditions. After that, urea was applied by replacing floodwater with urea solutions of 150 kg N ha<sup>-1</sup> equivalent to 29.45 mg N in each column except for the control. The soil columns were incubated for 2 to 38 days at 25°C.

**Sampling and analysis of soil and floodwater.** At 2, 4, 6, 9, 12, 18, 24, 31, and 38 days of incubation periods, the columns were disassembled into 2-cm sections. *Ehs* (redox potential) of floodwater and each column section were measured using an *Eh* meter with platinum redox and silver/

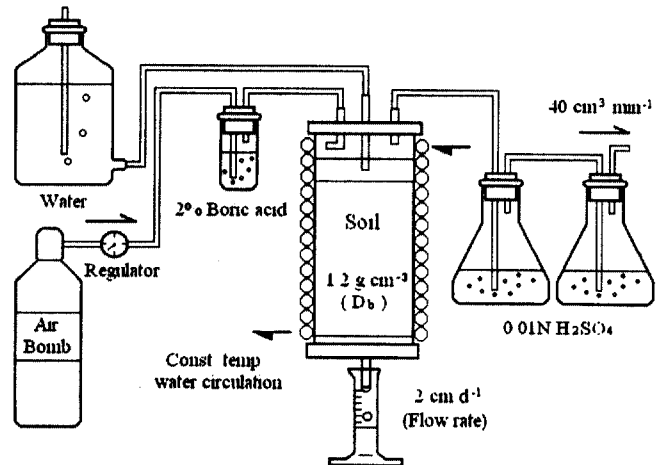


Fig. 1. Schematic diagram of soil leaching column and associated ammonia trap system.

silver chloride reference electrode (ORION, Model 250A). A portion of each section was extracted with 2 M KCl solution containing a urease inhibitor, phenylmercuric acetate (PMA), and Urea-N, NH<sub>4</sub><sup>+</sup>-N, and NO<sub>3</sub><sup>-</sup>-N were determined. Soil extracts (50 ml) were transferred to distillation flasks, and 0.4 g heavy MgO (ignited at 600°C) was added to make strong alkaline condition. The flasks were connected to steam distillation apparatus and commenced with distillation. The distillates were collected in flasks containing 10 ml of 0.01 N H<sub>2</sub>SO<sub>4</sub>. The contents of exchangeable NH<sub>4</sub><sup>+</sup>-N in the distillates were determined through titration with 0.01 N NaOH to the end point of bromocresol green-methyl red mixed indicator. After removal of NH<sub>4</sub><sup>+</sup>-N, 0.5 g finely ground Devarda alloy was added to reduce NO<sub>3</sub><sup>-</sup> to NH<sub>4</sub><sup>+</sup>, and the NH<sub>4</sub><sup>+</sup>-N liberated through steam distillation with the same method as described above was determined. A blank test was carried out throughout the procedure. An aliquot (1–10 ml) of the extracts containing up to 70 µg urea-N were added into 50-ml volumetric flasks to make 10 ml volume with 2 M KCl-PMA solution, and 30 ml color reagent made of diacetyl monoxime (DAM), thiosemicarbazide (TSC), H<sub>3</sub>PO<sub>4</sub>, and H<sub>2</sub>SO<sub>4</sub> was added. The flasks were swirled and placed in a boiling water bath. After 27 min, the flasks were removed from the bath and cooled immediately in running water (13–20°C) for 15 min. The contents were made to 50 ml by adding distilled water and mixed thoroughly. Absorbance of the color-developed solutions was measured at 527 nm using UV-Vis spectrometer (SHIMADZU, UV-1601). A calibration curve was prepared using 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 mg l<sup>-1</sup> of standard urea-N solution.

Table 1. Properties of soil used.

pH (1:5)	CEC (cmol kg <sup>-1</sup> )	O.M. (g kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> -N		sand	silt (%)	clay	Texture
			(mg kg <sup>-1</sup> )					
5.0	10.4	28.0	11.5	12.9	52.2	28.3	19.5	Sandy Loam

**Sampling and analysis of volatilized ammonia and leachate.** Volatilized ammonia was trapped using two flasks containing 0.01 N H<sub>2</sub>SO<sub>4</sub> with an air flow system (Fig. 1). The flow rate of air was about 1 replacement volume of space above the floodwater per minute (40 cm<sup>3</sup> min<sup>-1</sup>). The daily content of trapped volatilized NH<sub>3</sub>-N was determined through titration with 0.01 N NaOH to the end point of bromocresol green-methyl red mixed indicator. Leachate was collected everyday and analyzed for NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, and urea-N using the same methods for soil samples. To conserve NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>, and urea in leachate, the pH of the leachate was adjusted between 1.5 and 2 with the addition of conc. H<sub>2</sub>SO<sub>4</sub>. The acidified leachate was neutralized with NaOH immediately before determination.

### Results and Discussion

**Oxidation-reduction state of waterlogged soil.** The redox potentials (*Eh*) of soil column with depth during incubation period are presented in Table 2. Since the silver/silver chloride electrode was used as a reference, 199 mV (at 25°C) was added to the measured potential values to calibrate for normal hydrogen electrode. Reddy and Patrick recommended an *Eh* value of 300 mV as the breakpoint between oxidized and reduced zones.<sup>21)</sup> Letey *et al.* observed that denitrification occurred at 200 and 250 mV of redox potential,<sup>22)</sup> and Bailey and Beauchamp found that the redox potential maintained at 200 mV as long as there was nitrate in the soil, and dropped to lower values only after the nitrate was disappeared.<sup>23)</sup> Applied to our experimental conditions, oxidizing condition was maintained around 500 mV at the depth between 0 and 2 cm, and reducing condition under 300 mV was developed below 2 cm throughout the incubation period. It suggested that both oxidized and reduced soil layers were developed in saturated soil columns of this study. Thus, nitrification and denitrification of the applied nitrogen were thought to take place in the oxidized and reduced soil layers, respectively.

**Distributions of Urea-N in floodwater and soil.** The distributions of urea-N in floodwater and soil at 2 and 4 days after urea application are presented in Fig. 2. In soil incubated for 2 days, the total amount of remained urea-N

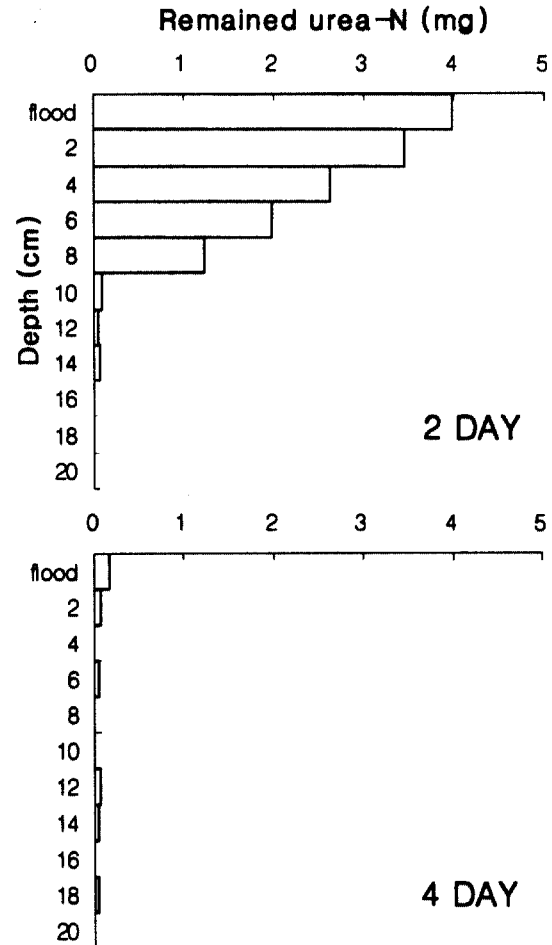


Fig. 2. Distributions of urea-N in floodwater and soil after urea application.

was 9.5 mg. The amount of the urea-N in the upper layer was 3.5 mg and decreased with depth (Fig. 2). The floodwater had a high urea-N content of 4.0 mg. Some of the urea reached to 8-cm depth. After 4 days, the total amount of remained urea-N in soil decreased to 0.3 mg, and floodwater also showed a low amount of 0.2 mg. The urea was not detected in floodwater and soil after 6 days of incubation, suggesting that hydrolysis of urea was completed within 6 days after urea application.

**Distributions of NH<sub>4</sub><sup>+</sup>-N in floodwater and soil.** The

Table 2. Progressive changes in redox potential (mV) of waterlogged soil column.

Depth(cm)	Days after urea treatment								
	Control	2	4	6	9	12	18	24	31
Floodwater	485.3	490.0	536.8	547.8	505.9	547.6	536.6	565.2	524.6
02	467.8	511.3	508.8	524.3	489.8	513.3	517.9	552.9	501.3
24	206.2	337.8	270.5	164.2	179.5	154.9	193.5	193.4	139.5
46	138.2	221.0	227.5	180.0	163.5	143.1	134	143.7	77.4
68	126.2	229.5	236.0	184.1	173.5	154.0	145.7	141	60.4
812	111.5	194.4	215.6	181.3	170.5	138.3	139.7	140.1	50.9
1216	85.8	163.3	166.8	176.0	161.9	116.0	134.6	126.6	50.7
1620	101.4	144.7	155.9	158.2	160.9	115.9	129.4	126.0	83.8

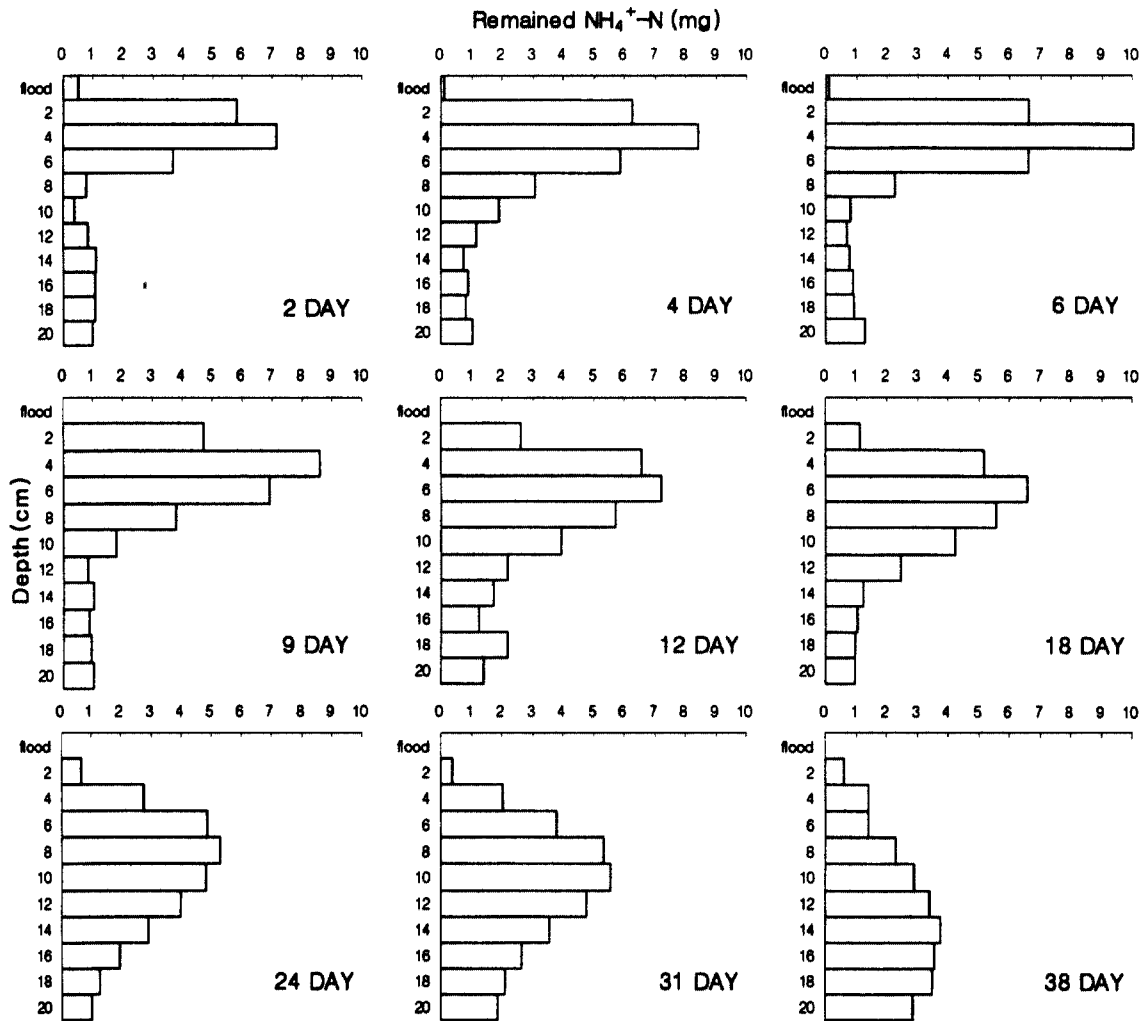


Fig. 3. Distributions of  $\text{NH}_4^+\text{-N}$  in floodwater and soil after urea application.

distributions of  $\text{NH}_4^+\text{-N}$  in floodwater and soil at 2, 4, 6, 9, 12, 18, 24, 31, and 38 days after urea application are shown in Fig. 3. The total amount of  $\text{NH}_4^+\text{-N}$  in soil before urea application was 7.1 mg, but it was increased to 23.0, 30.3, and 31.0 mg at 2, 4, and 6 days after urea application, respectively, due to hydrolysis of the applied urea. However, it tended to decrease from 30.7 mg at 9 days to 25.7 mg at 38 days. At 2~4 cm depth, the amounts of  $\text{NH}_4^+\text{-N}$  showed the maximum values of 7.1, 8.4, 10.1, and 8.6 mg on 2, 4, 6, and 9 days, respectively. Since the  $\text{NH}_4^+\text{-N}$  moved down slowly with time due to mass flow and diffusion by concentration gradient<sup>5)</sup>, the maximum values of amount of  $\text{NH}_4^+\text{-N}$  were appeared at 4~6 cm on 18 days, at 6~8 cm on 24 days, and at 14~16 cm on 38 days.

**Distributions of  $\text{NO}_3^-\text{-N}$  in floodwater and soil.** Figure 4 shows the distributions of  $\text{NO}_3^-\text{-N}$  in floodwater and soil at 2, 4, 6, 9, 12, 18, 24, 31, and 38 days after urea application. During 38 days of incubation period, the distributions of  $\text{NO}_3^-\text{-N}$  did not have any typical pattern such as those of urea-N and  $\text{NH}_4^+\text{-N}$ . The total amount of  $\text{NO}_3^-\text{-N}$  in soil was small, below 2.4 mg of the value at 2 days, during the

incubation period, which was thought to have resulted from denitrification loss, leaching loss or both. The amount of  $\text{NO}_3^-\text{-N}$  in the oxidized soil layer also maintained to low value.

**Loss by ammonia volatilization.** The changes in content of volatilized ammonia and pH of floodwater during incubation period after urea application are shown in Fig. 5. The ammonia volatilization rate sharply increased and recorded a maximum value of a 0.28 mg N d<sup>-1</sup> at 2 days with the highest pH value of 7.6 after urea application. The rate decreased to below the control value measured before urea application after 7 days of incubation. The pH of the floodwater varied from 6.9 to 7.6 being consistent with the changes in the ammonia volatilization rate during incubation period. The ammonia volatilization rate is related to the concentration of  $\text{NH}_4^+$  in the floodwater.<sup>5)</sup> In this experiment, the initial increase in pH of the floodwater after urea application was suggested to be mainly caused by the elevation of initial  $\text{NH}_4^+\text{-N}$  concentration resulted from the hydrolysis of urea remained in the floodwater and soil near the water-soil boundary layer. After 7 days of incubation, pH

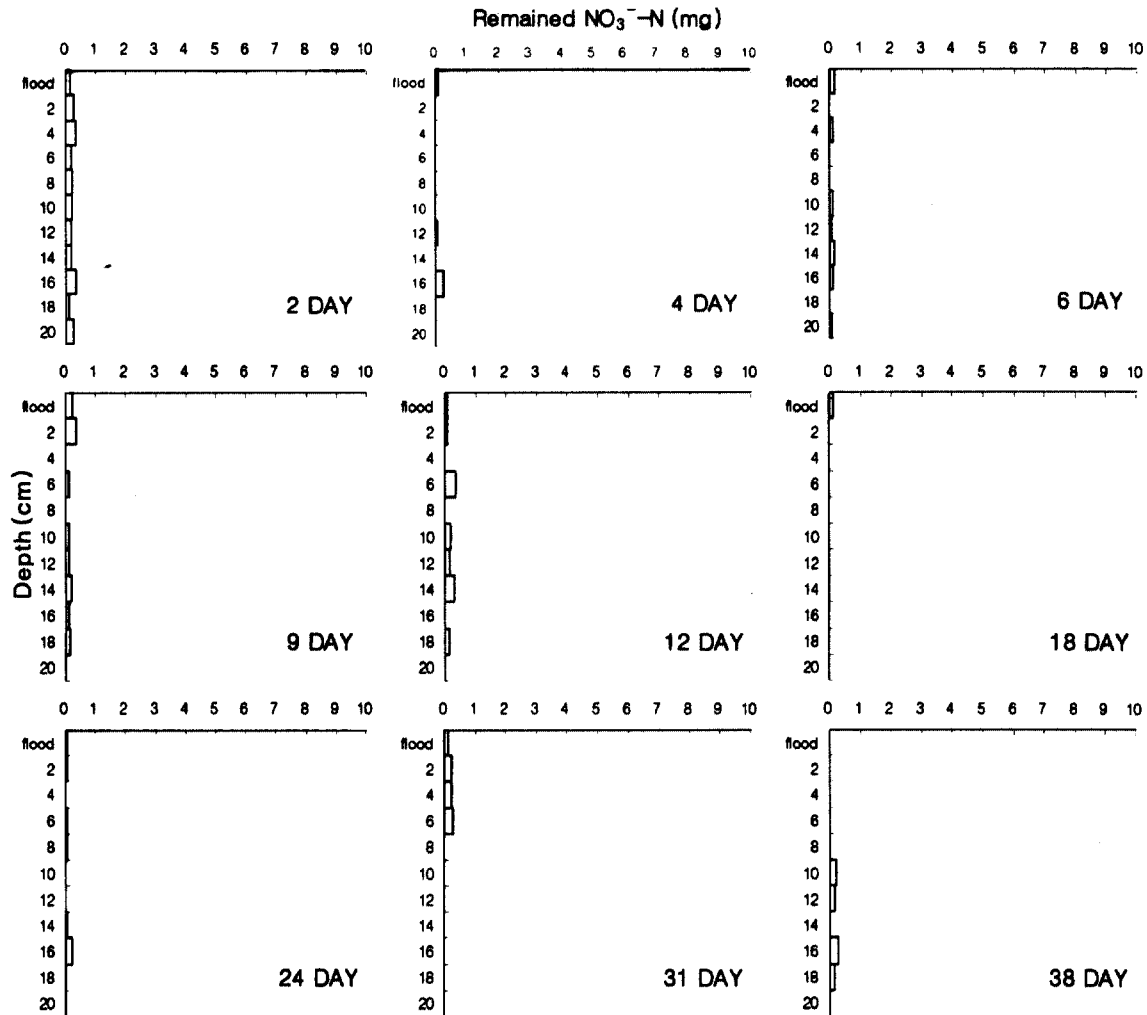


Fig. 4. Distributions of  $\text{NO}_3\text{-N}$  in floodwater and soil after urea application.

of the floodwater was nearly constant at the level of 7.0, and the ammonia volatilization rate decreased to the control value. In this situation, the amounts of remained urea-N and  $\text{NH}_4^+\text{-N}$  were nearly zero. Mikkelsen *et al.* concluded that if the floodwater pH stays below pH 7.0,  $\text{NH}_3\text{-N}$  losses from broadcast applications of N are likely to be of little

agronomic significance in lowland rice production.<sup>24)</sup> The total amount of  $\text{NH}_4^+\text{-N}$  lost through volatilization during incubation period was 1.80 mg. If all of the volatilized ammonia trapped by 0.01 N  $\text{H}_2\text{SO}_4$  came from the applied urea (29.5 mg N), the total amount of volatilized nitrogen during incubation period would be 6.1% of the total N

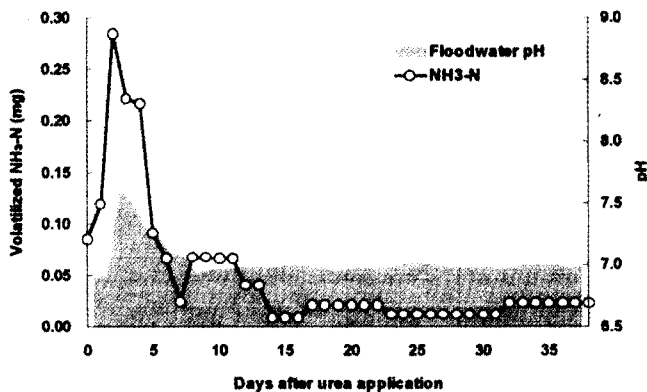


Fig. 5. Daily amount of volatilized ammonia as affected by floodwater pH.

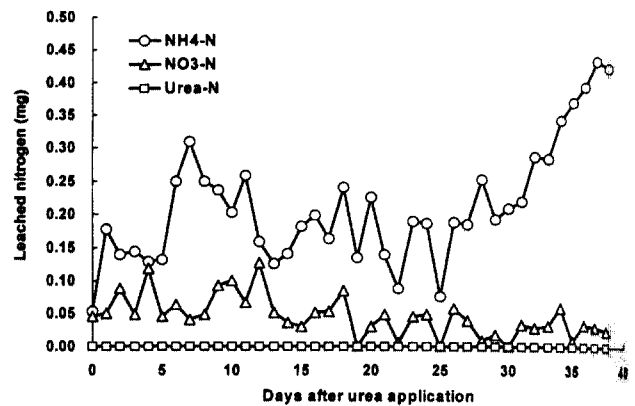


Fig. 6. Daily amount of urea-N,  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3\text{-N}$  by leaching.

**Table 3. Urea-N balance during the incubation period.**

	2 Day		4 Day		6 Day	
	mg	%	mg	%	mg	%
Urea-N in floodwater	3.99	13.55	0.15	0.51	0.00	0.00
Urea-N in soil	9.53	32.36	0.31	1.05	0.00	0.00
Urea-N in leachate	0.00	0.00	0.00	0.00	0.00	0.00
Unhydrolyzed urea-N	13.52	45.91	0.46	1.56	0.00	0.00
Hydrolyzed urea-N	15.93	54.09	28.99	98.44	29.45	100.00

Applied urea-N = 29.45 mg

Unhydrolyzed urea-N = Urea-N in leachate + Urea-N in soil + Urea-N in floodwater

Hydrolyzed urea-N = Applied urea-N - Unhydrolyzed urea-N

**Table 4-1.  $\text{NH}_4^+$ -N balance during the incubation period.**

	2 Day		4 Day		6 Day		9 Day	
	mg	%	mg	%	mg	%	mg	%
$\text{NH}_4^+$ -N in floodwater before incubation	0.00		0.00		0.00		0.00	
$\text{NH}_4^+$ -N in floodwater after incubation	0.52		0.13		0.12		0.00	
Increase of $\text{NH}_4^+$ -N in floodwater	0.52	3.26	0.13	0.45	0.12	0.41	0.00	0.00
$\text{NH}_4^+$ -N in soil before incubation	7.08		7.08		7.08		7.08	
$\text{NH}_4^+$ -N in soil after incubation	22.97		30.33		31.02		30.65	
Increase of $\text{NH}_4^+$ -N in soil	15.89	99.75	23.3	80.20	23.94	81.29	23.57	80.03
$\text{NH}_4^+$ -N in leachate	0.32	2.10	0.59	2.04	0.97	3.29	1.76	5.98
Volatilized $\text{NH}_4^+$ -N	0.40	2.51	0.84	2.90	1.00	3.40	1.16	3.94
Increase of total $\text{NH}_4^+$ -N	17.13	107.53	24.81	85.58	26.03	88.39	26.49	89.95
$\text{NH}_4^+$ -N from urea hydrolysis	15.93		28.99		29.45		29.45	

**Table 4-2.  $\text{NH}_4^+$ -N balance during the incubation period.**

	12 Day		18 Day		24 Day		31 Day		38 Day	
	mg	%	mg	%	mg	%	mg	%	mg	%
$\text{NH}_4^+$ -N in floodwater before incubation	0.00		0.00		0.00		0.00		0.00	
$\text{NH}_4^+$ -N in floodwater after incubation	0.00		0.00		0.00		0.00		0.00	
Increase of $\text{NH}_4^+$ -N in floodwater	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{NH}_4^+$ -N in soil before incubation	7.08		7.08		7.08		7.08		7.08	
$\text{NH}_4^+$ -N in soil after incubation	35.00		29.44		29.78		32.13		25.68	
Increase of $\text{NH}_4^+$ -N in soil	27.92	94.80	22.36	75.93	22.70	77.08	25.05	85.06	18.60	63.16
$\text{NH}_4^+$ -N in leachate	2.38	8.08	3.43	11.65	4.39	14.91	5.71	19.39	8.24	27.98
Volatilized $\text{NH}_4^+$ -N	1.33	4.52	1.44	4.89	1.55	5.26	1.63	5.54	1.8	6.11
Increase of total $\text{NH}_4^+$ -N	31.63	107.40	27.23	92.46	28.64	97.25	32.39	109.98	28.64	97.25
$\text{NH}_4^+$ -N from urea hydrolysis	29.45		29.45		29.45		29.45		29.45	

applied.

**Loss by leaching.** Loss of urea-N,  $\text{NH}_4^+$ -N, and  $\text{NO}_3^-$ -N through leaching during 38 days of incubation period after urea application are presented in Fig. 6. During the incubation period, urea-N in leachate was not detected, which suggested that all of the applied urea was hydrolyzed in floodwater and soil while moving through soil before being leached. The total amount of leached  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N during incubation period was 8.2 and 1.8 mg, respectively. Loss of  $\text{NH}_4^+$ -N through leaching was about

fivefold higher than that of  $\text{NO}_3^-$ -N. The amount of leached  $\text{NH}_4^+$ -N tended to increase at the end of incubation period by the movement of  $\text{NH}_4^+$ -N in soil (Fig. 3). Patrick and Mahapatra suggested that  $\text{NH}_4^+$ -N is much less subjected to leaching than  $\text{NO}_3^-$ -N in submerged soil due to its adsorption on the cation exchange complex. However, loss of  $\text{NH}_4^+$ -N through leaching is greater in waterlogged soil than in well-drained soil because  $\text{NH}_4^+$ -N accumulates in reduced soil layer and reduced Fe and Mn displace  $\text{NH}_4^+$ -N from the exchange complex and under a constant head of water  $\text{NH}_4^+$ -

**Table 5. NO<sub>3</sub><sup>-</sup>-N balance (mg) during the incubation period.**

mg	2 Day	4 Day	6 Day	9 Day	12 Day	18 Day	24 Day	31 Day	38 Day
NO <sub>3</sub> <sup>-</sup> -N in floodwater before incubation	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
NO <sub>3</sub> <sup>-</sup> -N in floodwater after incubation	0.17	0.07	0.15	0.22	0.08	0.12	0.10	0.10	0.07
Increase of NO <sub>3</sub> <sup>-</sup> -N in floodwater	0.10	0.00	0.08	0.15	0.01	0.05	0.03	0.03	0.00
NO <sub>3</sub> <sup>-</sup> -N in soil before incubation	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
NO <sub>3</sub> <sup>-</sup> -N in soil after incubation	2.42	0.44	0.80	1.30	1.36	0.40	0.67	0.80	1.14
Increase of NO <sub>3</sub> <sup>-</sup> -N in soil	2.02	0.04	0.40	0.90	0.96	0.00	0.27	0.40	0.74
NO <sub>3</sub> <sup>-</sup> -N in leachate	0.14	0.30	0.41	0.59	0.89	1.19	1.37	1.53	1.75
Increase of total NO <sub>3</sub> <sup>-</sup> -N	2.26	0.34	0.89	1.64	1.86	1.24	1.67	1.96	2.49

N moves downward as percolation.<sup>25)</sup>

**Mass balance of applied urea-N.** The mass balance of applied urea-N during incubation period calculated from the data is shown in Table 3. The total amounts of unhydrolyzed urea-N in floodwater, soil, and leachate were 13.5 and 0.5 mg at 2 and 4 days after urea application, respectively. These amounts corresponded to 45.9 and 1.6% of the applied urea-N (29.5 mg), signifying that 54.1 and 98.4% of the applied urea-N was hydrolyzed at 2 and 4 days after urea application, respectively. The applied urea was hydrolyzed completely within 6 days. The NH<sub>4</sub><sup>+</sup>-N balance presented in Tables 4-1 and 4-2 shows the total recovery of NH<sub>4</sub><sup>+</sup>-N by comparing the total amount of increased NH<sub>4</sub><sup>+</sup>-N with the amount of NH<sub>4</sub><sup>+</sup>-N produced from hydrolysis of urea. The total amount of increased NH<sub>4</sub><sup>+</sup>-N was calculated as follows.

$$(NH_4^+-N)_{IT} = (NH_4^+-N)_{IF} + (NH_4^+-N)_{IS} + (NH_4^+-N)_{IL} + (NH_4^+-N)_{IV}$$

where,

$(NH_4^+-N)_{IT}$  = Amount of total NH<sub>4</sub><sup>+</sup>-N increased

$(NH_4^+-N)_{IF}$  = Amount of NH<sub>4</sub><sup>+</sup>-N increased in floodwater

$(NH_4^+-N)_{IS}$  = Amount of NH<sub>4</sub><sup>+</sup>-N increased in soil

$(NH_4^+-N)_{IL}$  = Amount of NH<sub>4</sub><sup>+</sup>-N increased in leachate

$(NH_4^+-N)_{IV}$  = Amount of Volatilized NH<sub>3</sub>-N increased

The total amount of increased NH<sub>4</sub><sup>+</sup>-N was 17.1 mg, and the amount of NH<sub>4</sub><sup>+</sup>-N from hydrolysis of urea was 15.9 mg at 2 days after urea application. If the total amount of increased NH<sub>4</sub><sup>+</sup>-N came from only the applied urea except for indigenous soil nitrogen, this amount corresponded to 107.5% of the NH<sub>4</sub><sup>+</sup>-N produced from hydrolysis of urea-N; that is, the recovery of NH<sub>4</sub><sup>+</sup>-N from applied urea was 107.5%. After complete hydrolysis of applied urea-N (29.5 mg) at 6 days, the total amount of increased NH<sub>4</sub><sup>+</sup>-N was 26.0 mg, and the recovery of NH<sub>4</sub><sup>+</sup>-N from applied urea was 88.4%. The recovery of NH<sub>4</sub><sup>+</sup>-N from urea during incubation period ranged between 85.6 and 110.0%, this would be attributable to mineralization, immobilization, and nitrification process.

At the end of the incubation period, total amount of nitrogen lost through ammonia volatilization was 6.1% (1.8 mg) of the applied urea-N. A 63.2% (18.6 mg) of the applied urea-N was remained in soil as NH<sub>4</sub><sup>+</sup>-N, and 28.0% (8.2 mg) of the applied urea-N was leached as NH<sub>4</sub><sup>+</sup>-N. The remainder which would be NO<sub>3</sub><sup>-</sup>-N in soil and leachate, and

denitrification loss was small with the value of 2.7% of the applied urea-N. Amount of NO<sub>3</sub><sup>-</sup>-N in soil was smaller than 2.0 mg throughout the incubation period (Table 5). The total amount of NO<sub>3</sub><sup>-</sup>-N leached was very small, which value was 1.8 mg. It suggested that nitrification was not significant in this waterlogged soil column due to high infiltration rate of applied urea solution. Therefore only small amount of NO<sub>3</sub><sup>-</sup>-N was lost by denitrification and leaching.

**Acknowledgments.** This study was supported by fund from Korea Science and Engineering Foundation (1998-04-02-08-01-2).

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