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Gaseous Nitrogen Loss from Urea Fertilizers in Asian Cropping Systems

J. R. Freney, J. R. Simpson, Zhu Zhao-liang and Aziz Bidin

Australian Centre for International Agricultural Research
Canberra 1989

Contents

Foreword

With increasing demands for food to meet the growing population throughout Asia, increasing quantities of nitrogen fertilizer are being used, particularly urea. However, urea broadcast on rice paddies by the method commonly used by farmers can lead to the loss of from 30 to 90% of the applied nitrogen. This loss represents an enormous cost to farmers, and ways need to be found to increase the uptake of nitrogen by rice.

The project reviewed in this report addressed this problem by linking Australian scientists at CSIRO Division of Plant Industry with scientists at the Institute of Soil Science in Nanjing, and other centres in the People's Republic of China, and at the Malaysian Agricultural Research and Development Institute at Serdang, Malaysia.

This partnership yielded important results, most of which have been published in a variety of refereed scientific journals (listed at the back of this report). We feel it is vital to future work in this area that the approaches taken in this successful ACIAR-supported project, including a general statement of results, be made more widely known particularly throughout the greater Asian region. I am sure that agronomists and soil scientists will find the information in this publication interesting and hope that they will delve further into the research results in the journal papers listed.

In adition to those listed as authors of this report, the following scientists made significant contributions towards the success of this project: K. H. Bowmer, Cai Gui-xin, P. M. Chalk, S. L. Chapman, Chen De Li, Chen Jian, S. K. De Datta, O. T. Denmead, I. E. Galbally, Huang Wei-xiang, E. Humphreys, A. V. Jackson, R. Leuning, Liu Chung Chu, Z. Malik, F. M. Melhuish, A. R. Mosier, W. A. Muirhead, W. N. Obcemea, J. G. Real, Ren Zu-jian, M. Samson, Shi Xiu-zhu, A. C. F. Trevitt, Wang Bing-hui, R. Wetselaar, R. J. G. White, Xi Zhen-bang, Yao Zhen, Zhang Shao-lin, and Zhu Zong-wu.

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Background

It is imperative that the yields of food crops be increased throughout Asia to feed the huge and increasing population. Nitrogen supply is a major yield constraint, especially for rice, and thus N fertilizer plants are being constructed throughout Asia to meet the increasing demand. For economic and efficient production, there is a widespread move to urea as the major form of N produced and used. This decision has created new emphasis on the hazards of N wastage through inefficient use and gaseous N losses. Nitrogen fertilizer is costly for the Asian farmer, accounting for up to half his capital outlay in each crop, and is likely to become more expensive. It is therefore essential that fertilizer N be used efficiently. Currently this is not so, and recoveries of applied N by rice can be as low as 10% and rarely exceed 50%. Attempts to improve the efficiency of urea are hampered by a lack of understanding of the reasons for the poor recoveries.

It was thought until recently that the reason for the poor recoveries was that large amounts of nitrogen were being lost by denitrification. However, losses of up to 48% of the applied urea have now been found to occur through ammonia volatilisation. Thus the possibility exists that ammonia volatilisation is a major cause of N fertilizer inefficiency in rice throughout Asia, but proper measurements have been made at only a few field sites. Further measurements at a large number of sites are needed to determine the scope of these losses, both from flooded rice and from upland crops.

Because environmental conditions have a large effect on ammonia loss the results of such a survey will be useful only if the losses are assessed with techniques that do not change the microenvironment and thus the extent of the loss (e.g. micrometeorological methods). Adaptations of these techniques that are less laborious and expensive to use are required for survey purposes.

Because it is known that nitrogen can also be lost by denitrification, leaching and runoff, any survey of ammonia loss should be accompanied by measurements of nitrogen lost by these other processes. Only when the relative importance of the various loss processes is established can appropriate strategies be designed to reduce the losses.

Objectives of the Project

1. To develop simple methods for the determination of ammonia loss after fertilizer application to flooded rice fields.
2. To test the developed, simple methods in the field against proven techniques.
3. To collect basic information on the parameters which affect ammonia volatilisation.
4. To collect information to enable us to determine the potential for ammonia loss from fertilizer applications in different regions.
5. To conduct experiments using labelled nitrogen so that the importance of loss mechanisms other than ammonia volatilisation can be assessed.

Description of Research

The ammonia sampler was constructed in the workshop of the CSIRO Division of Plant Industry, and preliminary testing was carried out in the wind tunnel and laboratory. This sampler and the other two simplified methods were compared with the standard mass balance micrometeorological method in flooded rice fields at a number of locations in Australia, China, Malaysia, and the Philippines. During these rice field experiments nitrogen fertilizers were compared as sources of nitrogen for rice, management practices were studied so that the most efficient practice could be recommended and factors affecting ammonia volatilisation were evaluated. In all of these field studies balance experiments using ^{15}N labelled fertilizers were used so that the importance of other loss processes could be determined.

Experiments were also carried out in rice fields in the Philippines, Thailand and Indonesia using one of the simplified techniques to assess the importance of ammonia loss under a wider range of conditions.

Results

Development and Testing of Methods

Three simplified methods for estimating ammonia volatilisation from flooded rice fields were developed. The most accurate and reliable method was the abbreviated mass balance technique, which involves separate measurements of wind speed and ammonia concentration in the atmosphere at one height only. The product of these two measurements gives a measure of horizontal transport. The vertical flux density of ammonia as calculated from a reference method was strongly related to the horizontal transport of ammonia at 0.8 m above the floodwater (r = 0.96 in one experiment and 0.98 in another). There was excellent agreement between observed and calculated values for ammonia loss and the consistency of the relationship between vertical flux and horizontal flux at many sites suggests that the abbreviated method can be safely used at any site without further calibration.

A less reliable estimate was obtained with an ammonia sampler which gives a measure of the horizontal transport of ammonia at one height. There was a strong linear relationship between the horizontal flux densities of ammonia measured by the sampler and the reference method (r = 0.95). The slope of the regression line was not significantly different from one and the intercept on the y axis was not significantly different from zero. The excellent agreement between the values for horizontal flux densities obtained by the two methods shows that the ammonia sampler can be used in place of the ammonia traps, flow meters and anemometers in the reference method to determine the vertical flux density of ammonia by the mass balance micrometeorological method. The vertical flux densities of ammonia determined by the sampler and the reference method were strongly related (r = 0.89). In one experiment the cumulative losses of ammonia determined by the sampler and reference method were 13.2 and 13.4% of the applied nitrogen, respectively. Both these methods require a circular area of ~ 25 m radius, and so are not suitable for the comparison of a large number of management practices with replication.

The third method developed is the bulk aerodynamic method which is useful for comparing ammonia emission from a large number of small plots with different fertilizer treatments. This technique requires measurements of wind speed (u) at a fixed height above the floodwater and measurements of floodwater pH, temperature and ammoniacal nitrogen concentration. The ammonia gas concentration (r_0) is calculated from the floodwater measurements and the flux density of ammonia (F) is determined from the relationship expressed as:

$$F = ku\,(\rho_0 - \rho_z) \qquad \text{Eqn (1)}$$

ρ_z is the background ammonia concentration in the atmosphere. The bulk aerodynamic method is not as accurate as the other two methods. For example, at one site the correlation coefficient for the relationship between flux determined by the reference method and the aerodynamic method was r = 0.856. In addition the slope of the relationship between fluxes calculated by the two methods (k) varied from site to site.

Studies were made on the reasons for the low accuracy of the ammonia fluxes calculated by the bulk aerodynamic method and the variability in k.

The relationship expressed by Eqn (1) suggests that there is a linear relationship between the transfer velocity for ammonia emission and wind speed. This may not be the case in view of the wind-tunnel studies of Bouwmeester and Vlek (1981). They suggested that at low wind speeds, the gas phase resistance dominates, while at high wind speeds the liquid phase resistance becomes more significant because of depletion of ammonia in the surface film of the liquid phase.

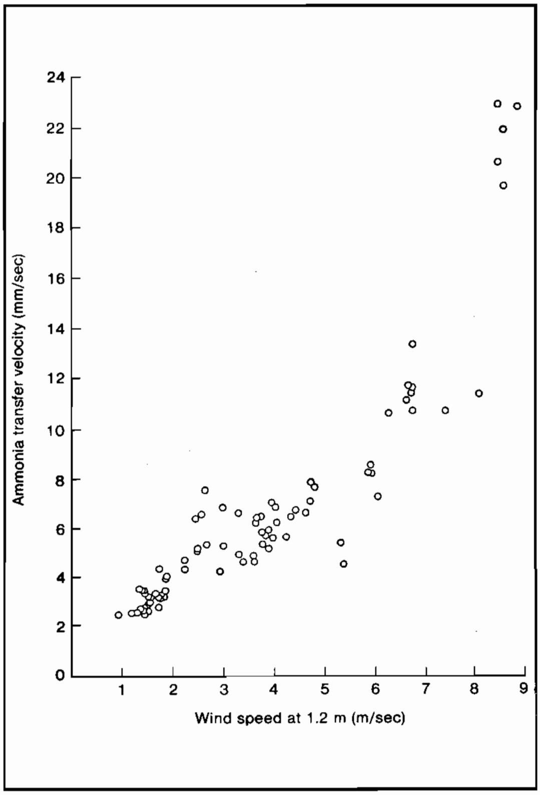

Fig. 1. Effect of wind speed on calculated ammonia transfer velocities from 1.2 m diameter evaporation pans buried in a farmer's field sown to pasture.

Experiments were therefore conducted in evaporation pans to assess the importance of wind speed on the use of the bulk aerodynamic method. The relationship between ammonia transfer velocity from 1.2 m diameter evaporation pans and windspeed is reasonably linear for wind speeds up to 6 m/sec; $y = 1.68 + 1.09x$, $r = 0.864$, $n = 71$ (Fig. 1). However, above 6 m/sec the transfer velocity increased at a greater rate as wind speed increased. Overall, an equation of the form, $\ln y = 0.79 + 0.249x$ gave a better description of the relationship between transfer velocity and wind speed ($r = 0.946$; $n = 88$).

The enhanced velocity in high winds was probably due to better mechanical mixing of the ammonia solution, which would have reduced the liquid phase resistance, and increased vertical transport in the air, which would have reduced the gas phase resistance.

Wanninkhof et al. (1985), in a study of sulfur hexafluoride emission from a shallow lake, also found a similar relationship between transfer velocity and wind speed. However, the threshold value, above which transfer velocity increased dramatically, was lower at about 2.4 m/sec. The data indicate that it is reasonable to expect a linear relationship at low wind speed. The presence of rice plants in flooded fields markedly attenuates wind speeds and thus it is most unlikely that wind speeds in excess of 2.4 m/sec would be experienced near the floodwater surface. Thus it seems reasonable to use a bulk aerodynamic formula with linear dependence on wind speed (Eqn 1) to calculate ammonia loss from small plots planted with rice.

Freney et al. (1985) noted the lack of a universal relationship for the bulk aerodynamic formula (Eqn 1) and pointed to the need to calibrate the method for each study site. The existence of a significant but, to date, unpredictable aqueous phase resistance to ammonia transfer is no doubt partly responsible for the lack of universality. Results at Griffith and Dan Yang showed that substantial temperature gradients may be present at the water surface. Observations in the evaporation pans showed that there were gradients in ammoniacal nitrogen concentration and pH as well (Fig. 2 and 3). These differences were significant at $P < 0.001$. It seems likely that a formula similar to Eqn 1, but employing the surface rather than the bulk ρ_o, should be more successful. Unfortunately the necessary measurements of surface temperature, ammoniacal nitrogen concentration and pH will be more difficult to obtain than the corresponding bulk properties.

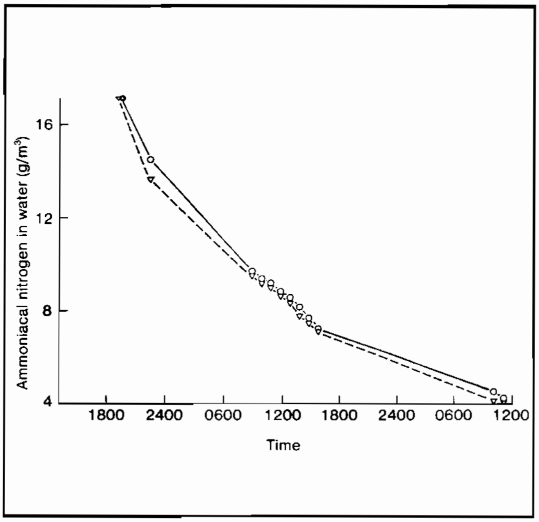

Fig. 2. Change in surface and bulk water ammoniacal nitrogen concentrations in an ammonium sulfate solution, contained in 1.2 m evaporation pans, during periods of ammonia loss. (o———o bulk water; ∇———∇ surface water).

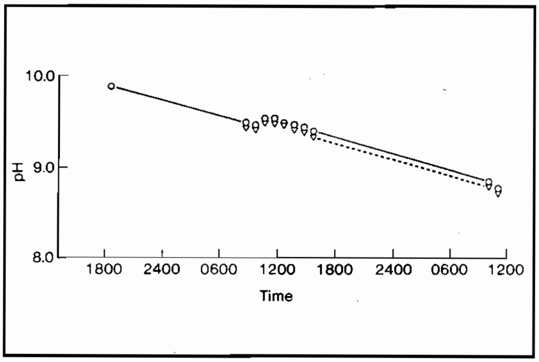

Fig. 3. Change in surface and bulk water pH values in an a ammonium sulfate solution, contained in 1.2 m evaporation pans, as a result of ammonia loss. (o———o bulk water; ∇———∇ surface water).

Factors Affecting Loss

Experiments were conducted in Australia and Asia to determine the influence of various factors on ammonia loss. Factors studied included fertilizer type, amount, timing and method of application, floodwater depth, turbidity and pH, algal growth, plot size, wind speed and temperature stratification in the floodwater.

Fertilizer Type

The two main fertilizers used in China, ammonium bicarbonate and urea, were compared for efficiency of use at two sites in China when each was applied by a typical farmer's method. Losses of ammonia followed the expected temporal patterns, with initially very rapid rates of volatilisation from the ammonium bicarbonate treatments and low rates of emission from the urea treatments. Ammonia emission from the areas fertilised with ammonium bicarbonate diminished rapidly and had virtually ceased by 75 hours after application. Ammonia emission from the urea treatments did not reach the highest rate until 4 or 5 days after fertilizer application and losses were sustained until day 7 or 8.

Ammonia losses from the calcareous site (Fenqiu) were much larger than those from the acidic site (Dan Yang). At Fenqiu the ammonia losses from the ammonium bicarbonate and urea treatments were 39 and 30% of the applied nitrogen, respectively, compared with only 18 and 9%, respectively, at Dan Yang. At Dan Yang the floodwater pH values were generally much lower, between 6.4 and 7.8, compared with 8.0–10.5 at Fenqiu. Differences between sites involved not only the soils, but at Dan Yang the solar radiation was lower and no algal growth was evident.

Denitrification losses were important at both sites with 33 and 41% of the applied nitrogen being lost at Fenqiu and Dan Yang, respectively. Denitrification losses from ammonium bicarbonate and urea were not significantly different. There was no evidence of leaching losses at either site.

Fertilizer Rate

In other experiments with different rates of urea application, ammonia and total nitrogen loss were each a constant proportion of the urea applied. Ammonia loss was 17% and total nitrogen loss was 24%.

Time of Application

Ammonia loss from urea applied to rice varied considerably depending on the time of application. Ammonia volatilisation was negligible, before and after flooding, when urea was applied to the dry soil surface 2 days before permanent flood. Before flooding, the urea prills remained undissolved and urea hydrolysis could not proceed. Thus there was no source of fertilizer-derived ammonia for volatilisation to occur. Upon flooding the urea prills were washed into cracks in the soil which subsequently closed. Therefore the movement of soluble nitrogen into the floodwater was prevented, and again there was no ammonia source for the volatilisation process.

When urea was broadcast into the floodwater a few days after permanent flood, ammonia losses were high and varied from 11 to 21% of the nitrogen applied. These losses were associated with high floodwater pHs and high wind speeds near the water surface.

However, when urea was applied into the floodwater at panicle initiation, ammonia losses were low (3-8% of the applied nitrogen). At this stage of growth the plant canopy shaded the floodwater, inhibiting algal photosynthesis and consequent pH elevation, thus resulting in low ammonia gas concentrations at the floodwater surface. In addition, the plant canopy restricted air movement at the water surface, thereby reducing ammonia transport away from the air-water interface.

Method of Application

The effect of method of application was studied at two sites in China, four sites in the Philippines, three sites in Malaysia, two sites in Thailand and two sites in Indonesia. Ammonia was lost at high rates following the broadcasting of urea into the floodwater 10 days after transplanting rice seedlings. At one of the sites in the Philippines with this method of application a mean of 52% of the applied nitrogen was volatilised as ammonia during the first 8 days after urea application. Total nitrogen loss was 60%. Ammonia loss was reduced slightly (to a mean of 43% of the applied nitrogen for two application rates) by broadcasting the fertilizer into 0.05 m deep floodwater and incorporating it into the soil with a rotary harrow before transplanting. Removal of the floodwater before application of the urea onto the saturated soil and incorporation by harrowing considerably reduced ammonia loss (to 9%) and total nitrogen loss (to 33%). Similar effects on ammonia loss were obtained at the other sites but a reduction in ammonia loss did not always result in reduced total nitrogen loss.

Floodwater Depth

Initially ammonia was lost at a faster rate from the shallow (0.05 m) than from the deep (0.14 m) floodwater; this was due to higher ammoniacal nitrogen concentrations and higher temperatures in the shallow water. Emission rates were more nearly comparable later in the experiment, but overall, 26% of the applied nitrogen was lost as ammonia from the shallow pond and only 18% from the deep pond.

Even though changes in water depth markedly affected ammonia emission rates and the amounts of ammonia lost, they did not significantly affect total nitrogen loss. The results suggest that management practices based only on changes in water depth may not result in increased efficiency of fertilizer nitrogen for flooded rice.

Turbidity, Algae and pH

Turbidity of the floodwater had a marked effect on ammonia loss because it reduced the amount of light penetrating the floodwater. This in turn restricted the growth of photosynthetic organisms (algae) in the floodwater which resulted in low floodwater pH values and low ammonia loss rates. Overcast conditions in the atmosphere, such as existed at Dan Yang during the field experiment, also restrict the growth of photosynthetic organisms and result in low floodwater pH values and low ammonia loss rates. These results suggest that ammonia loss can be reduced by the use of treatments to control the growth of photosynthetic organisms in the floodwater. The use of algicides, biocides and shading markedly reduced the growth of photosynthetic algae, restricted the elevation in pH values, and reduced ammonia loss (from 20.5 to 1.2% of the applied nitrogen). Total gaseous nitrogen loss was affected similarly by the individual treatments suggesting that if ammonia loss can be reduced then total losses will be similarly reduced.

The growth of algae can also *restrict* ammonia loss. At Fenqiu there was a prolific growth of algae on the floodwater surface and this acted as a barrier for ammonia loss until broken up by the strong winds.

Plot Size

The effect of plot size on ammonia transfer and total nitrogen loss was studied in cylindrical tanks, with internal diameters 0.33, 0.69, 1.2, 3 and 6 m and height 0.30 m, inserted in a flooded field at Griffith.

The relationships obtained between transfer velocity and tank diameter for three runs on one day are shown in Fig. 4. The results show that transfer velocity decreased slightly as the tank diameter increased from 0.33 m to 1.2 m and then increased markedly as the tank diameter increased to 3 m. There was little further change in transfer velocity as the size of the tank was increased from 3 m to 6 m. The same pattern occurred at all time intervals (Fig. 4), but the transfer velocity increased during the day. Maximal values were obtained between 1600 and 1800 hours. Similar results were obtained on other days.

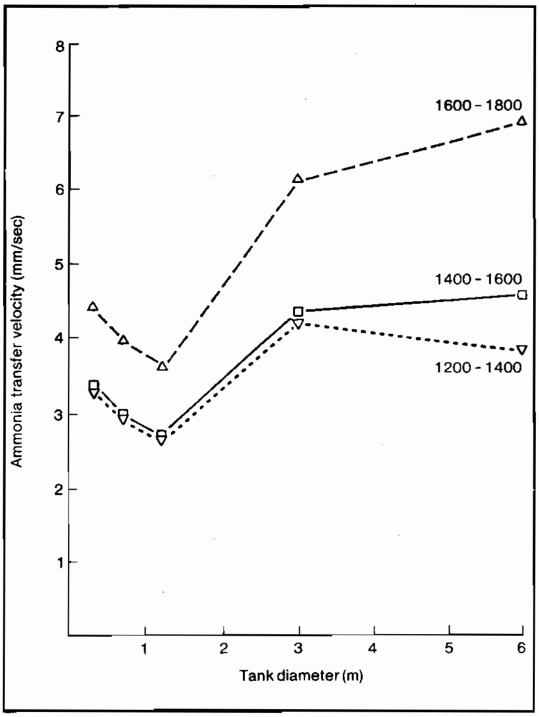

Fig. 4. Effect of tank size on ammonia transfer velocities from ammonium sulfate solutions.

The results are probably caused by the height of the wall above the water surface. This would affect wind flow across the water in the tanks and the effect should be more marked for the small tank. The higher transfer velocity in the very small tank may be due to the extra turbulence above the tank caused by the walls. This suggestion is supported by the observation that water loss from the 0.33 m diameter tank was greater than that from the 1.2 m diameter tanks (10.5 mm/day compared with 6.3 mm/day).

There was a greater loss of labelled nitrogen from the larger diameter plots than from the 0.33 m and 0.69 m diameter plots and this difference was significant in two cases. These results are consistent with the ammonia loss results which suggested a greater loss of ammonia from large rather than small plots.

The type and size of enclosure can also retard urea hydrolysis and suppress the maximum day-time pH values (an effect which is cumulative over a number of days). These effects are the consequence of lowered light and heat penetration in the enclosed area due to shading of the floodwater by the enclosure walls. The magnitude of the effects varied with plot size and shape, and the material used for the construction of the plot wall.

It is apparent that the size of the plot used for comparing fertilizer treatments can have an effect on the ammonia transfer velocity and thus on ammonia loss. These effects were demonstrated in the absence of rice plants. Rice plants would be expected to modify the effect of plot size; they would attenuate the wind speed thus reducing the effect of microplot walls on ammonia transfer. The results suggest that plots should be at least 7 m^2 in area for the effects of plot size to be negligible.

Wind Speed and Temperature Stratification

These factors were studied in detail at a number of sites and their effects on ammonia loss have been mentioned above through their effects on the bulk aerodynamic method.

Importance of Different Loss Processes

Ammonia Loss

Evidence from all of the experiments indicates that gaseous emission was the only pathway for N loss under the prevailing conditions; runoff was prevented and leaching of N through the clay soils was not detected beyond about 0.10 m depth. The significant losses occurred quickly, and appeared to be almost entirely in the form of NH_3 and N_2; losses of N_2O and NO_X were minor (<< 1 kg N/ha).

Ammonia losses were closely linked to pH fluctuations, temperature and ammoniacal N concentrations in the floodwater (which together determine the equilibrium ammonia concentration at the water surface) and windspeeds. A model, predicting vertical flux densities of NH_3 from floodwater parameters and windspeeds, could thus be developed.

The pH of the floodwater frequently rose to values >9 during the afternoons and maxima of pH > 10 were noted occasionally during experiments in Australia, China and Malaysia. High floodwater pH values occurred over soils with an acidic surface layer as well as over calcareous soils. The diurnal rise in floodwater pH was associated with microbial photosynthetic activity. The fluctuations in pH were small when solar radiation was low.

Ammonia losses usually continued for ~ 10 days after the aplication of urea (40-90 kg N/ha) into the floodwater, with maximum rates of emission occurring on days 2-4. The cumulative amounts of N lost as NH_3 varied widely, from 2 to 56% of the urea N applied, according to whether solar radiation, windspeed and floodwater pH favoured the loss. Rainfall, low radiation, plant cover and low windspeed all suppressed NH_3 loss.

Total Gaseous N Loss

Despite the wide range in amounts of NH_3 lost, the total gaseous N loss from the soil-plant-water system, as determined by ^{15}N balance, did not vary as greatly between experiments in different seasons and locations. The loss was large, usually amounting to 40-60% of the applied N, when urea was applied to recently transplanted or young (4-6 leaf stage) direct-seeded rice. This generalisation appears to apply equally to locations in tropical, subtropical and temperate regions under the cultural conditions imposed.

Nitrogen (^{15}N) balance measurements at 2-day intervals after urea application, together with data on nitrite and nitrate fluctuations in the floodwater, suggest that nitrification and denitrification proceed concurrently with NH_3 volatilisation throughout a 10-day period. Because leaching losses and emissions of N_2O and NO_X were found to be negligibly small, it was concluded that the difference between total N loss and NH_3 loss could only be due to loss of N_2 by denitrification.

Denitrification

The importance of denitrification as a loss process at Griffith was determined directly by measuring emission of $^{15}N_2$ and $^{15}N_2O$ after addition of highly labelled urea to flooded rice at the panicle initiation stage. The results indicated that N_2 was emitted soon after the urea was added. The mean daily N_2 gas flux was greatest during the second day after urea addition (> 700 g N/ha/day) and decreased to ~ 100 g N/ha/day 6 days after fertilizer addition.

Of the urea nitrogen added, 0.02% was lost to the atmosphere as nitrous oxide, 0.9% was lost by ammonia volatilisation and 3% was lost as dinitrogen gas during the 7 days of measurement. At the end of this period, 0.028% and 0.002% of the added nitrogen was retained as dinitrogen gas in the floodwater and soil porewater, respectively.

The small retention of $^{15}N_2$ in the porewater and floodwater is interesting because of the belief that gases are not rapidly transported across a flooded field. It seems that there is a mechanism for the rapid transport of N_2 from the flooded soil to the atmosphere and this may be through the rice plants.

Ammonia Loss from Rice Plants

The relative importance of ammonia loss from the floodwater and directly from rice plants in the period from anthesis to maturity was determined by a micrometeorological method on a large area of flooded rice at Griffith, NSW. Emissions from the floodwater at the same time were monitored by frequent floodwater sampling of pH, temperature and ammoniacal nitrogen concentration.

Ammonia loss from rice plants was observed during the whole of the period of observation but the rate of emission was very low (~60 g N/ha/day). These rates of emission were considerably lower than those observed from the floodwater immediately after urea application. For example on the third day after urea addition to the floodwater, rates of emission from the floodwater were of the order of 1 kg N/ha/day. The results show that ammonia emission from flooded rice plants is not an important avenue for nitrogen loss.

Reducing Ammonia and Total Nitrogen Loss

As mentioned above, ammonia loss can be reduced by increasing the floodwater depth before broadcasting the fertilizer into the floodwater (26 to 18%), by removing the floodwater completely and incorporating the fertilizer into the soil by harrowing (52 to 9%), by increasing the turbidity of the floodwater (26 to 16%) or by the use of algicides (21 to 11%). Other possible practices to control losses were studied. These include:

Surface Films

The effectiveness of additions of long chain alcohols in reducing ammonia volatilisation and total nitrogen loss after urea application was studied in evaporation pans and in a flooded rice field.

Preliminary experiments in evaporation pans, 1.2 m diameter, buried in an upland field of mown pasture, showed that ammonia volatilisation from water could be reduced by applications of surface films of long chain alcohols; the effect increased with increasing length of carbon chain.

The most effective way to add the film was to dissolve the long chain alcohol in ethanol, and to distribute the solution on the surface of the water.

In an experiment in a flooded rice field, additions of cetyl alcohol dissolved in ethanol significantly reduced the rate of ammonia emission (from 19 to 10% of the applied nitrogen) and total loss (from 31 to 7%). The effect was short-lived, probably due to microbiological decomposition of the cetyl alcohol and dispersion of the surface film by strong winds.

Urease and Nitrification Inhibitors

The effectiveness of phenylphosphorodiamidate (PPD) and N-(n-butyl) thiophosphorictriamide (BTPT) as urease inhibitors in moist and flooded soils was evaluated in laboratory, glasshouse and rice field experiments.

The effectiveness of the inhibitors varied markedly, depending on type of soil, cultural conditions and algal growth. In flooded soils in the dark, PPD was a more effective inhibitor than BTPT. However, in the presence of light and algae, BTPT was the more effective inhibitor of urea hydrolysis.

BTPT was completely ineffective in one flooded soil. Addition of ethylenediaminetetraacetic acid together with BTPT greatly improved urease inhibition in this soil.

Addition of BTPT increased the depth of penetration, immobilisation and retention of urea nitrogen in a flooded soil in the glasshouse, but these effects were not translated into yield increases in field plots at Griffith, NSW.

However, in a field experiment in Fuzhou, China, increases in grain yield as a result of inhibitor addition were obtained. The BTPT treatment reduced the rate of hydrolysis of urea but did not prevent hydrolysis. The nitrification inhibitor 2-ethynylpyridine (2EP) had no discernible effect on floodwater nitrite or nitrate concentrations, but this was not unexpected as nitrite and nitrate are only intermediates in the transformation process.

The inhibitors significantly increased tiller density, number of panicles per square metre, and spikelets per panicle and this was reflected in the final yield of grain (Table 1). The yield of straw was also significantly increased. BTPT and 2EP alone did not significantly increase grain nitrogen, but in combination significantly increased the uptake of nitrogen into grain. The 15% increase in grain yield due to the addition of the two inhibitors in combination was a very satisfactory result and is the first reported response of rice to a nitrification inhibitor.

Table 1. *Effect of urease inhibitor [N-(n-butyl)-thiophosphorictriamide] (BTPT) and nitrification inhibitor [2-ethynylpyridine] (2EP) on rice grain yield and nitrogen uptake.*

	Panicles /m^2	Spikes per panicle	Grain yield (kg/ha)	Straw yield (kg/ha)	Grain nitrogen (%)	Straw nitrogen (%)
PU	333	49.4	4740	4420	0.947	0.746
PU + BTPT	354	56.7	5300	5000	0.979	0.683
PU + 2EP	352	57.2	5150	4720	0.968	0.698
PU + BTPT + 2EP	371	57.5	5450	5100	1.012	0.774
l.s.d. ($P = 0.05$)	22	4.2	342	253	0.035	–
	*	**	*	**	*	N.S.

PU	Prilled urea
N.S.	Not significant ($P = 0.05$)
*	Significant at $P = 0.05$
**	Significant at $P = 0.01$

Associated Studies

Ammonia Loss From Urea Applied to Cabbages in China

Ammonia losses from soil were measured following applications of urea to cabbages growing in the eastern outskirts of Shanghai City, China. Urea was applied to two separate areas at 225 kg N/ha and two methods of addition were compared: surface application (100%) and split application (70% incorporated, 30% surface-applied). Ammonia emission was measured from each area by a mass balance technique using the newly developed ammonia sampler. Prior to an irrigation, hydrolysis of surface-applied urea was retarded by lack of moisture at the soil surface. Consequently, ammonia was emitted at very low rates before irrigation, and peaked at 24 μg N/m^2/sec after irrigation. Hydrolysis of incorporated urea proceeded steadily and was almost complete before the irrigation occurred. Total ammonia emission from both the surface and split treatments was similar prior to irrigation. Following irrigation, ammonia was lost at a faster rate from the surface treatment than from the split treatment, but the difference in rates of emission was much smaller than the difference between amounts of urea applied at the surface. Little ammonia was lost from the urea that had been incorporated.

Nitrogen Loss from Irrigated Wheat

Studies with ^{15}N were undertaken to assess the effect of duration of ponding on the nitrogen balance in an irrigated wheat crop near Griffith, NSW. The results indicated that the adverse effect of duration of ponding on wheat yield was not due to decreased availability of either fertilizer or soil nitrogen to the plants. These were collaborative studies with Professor Xi Zhen-bang of the Shanghai Academy of Agricultural Science.

Use of Results

Details of the simplified methods and information on the loss processes and improved management practices have been transferred to Asian scientists through the meetings of the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER). In addition, Ms W.N. Obcemea, who worked in Australia for 3 months, returned to the Philippines where she taught INSFFER trainee researchers the principles of the simplified methods.

Now that the loss processes are understood and management practices for reducing losses outlined, researchers and advisers in developing countries are in a sound position to recommend fertilizer practices to improve fertilizer efficiency and thus the project has met its aims.

The ammonia sampler has now been used in a number of different agricultural systems in New Zealand, Australia, Philippines, Thailand and Indonesia to assess ammonia loss from fertilizer applied to rice, wheat, cotton and sugar cane. The sampler has been produced and used by DARA in Victoria; NSW Department of Agriculture, Yanco; Riverina-Murray College of Advanced Education, Wagga; Department of Botany, University of New England, Armidale, NSW; International Rice Research Institute, Los Baños, Philippines; the Department of Soil Science, Lincoln College, New Zealand.

Summary

1. Three simplified methods for measuring ammonia loss after fertilizer application to flooded rice fields were developed. The specific advantages and constraints of each method were recognised and defined. Each method was evaluated under field conditions by direct comparison of its performance with a reference method (the full profile mass-balance micrometeorological method):

(a) The most accurate and reliable technique involves separate measurements of wind speed (u) and ammonia concentrations (c) in the atmosphere at 0.8 m above the rice crop. The rate of ammonia loss (F) is then calculated from the relationship

F = 0.09 uc. This method has been tested in the field at two sites in China, at three sites in the Philippines and at one site in Australia, and strong relationships have been obtained with negligible variation in the calibration slope.

(b) An integrative sampler was developed to give simple reliable measurements of the horizontal transport of ammonia. Using this device, total NH_3 loss can be obtained over widely-varying periods without any power source and with very little maintenance. The sampler was tested in the major experiments in Australia, China and the Philippines, plus some subsidiary use in Malaysia. It now performs satisfactorily under all conditions. Flux determinations made with this sampler are strongly correlated ($r > 0.90$) with those obtained by the laborious full-profile method.

(c) A bulk aerodynamic method was developed and found useful for assessing NH_3 loss from fertilizers applied to flooded rice in differently-treated small field plots. This technique enables valuable comparative NH_3 flux assessments to be made from simple measurements of floodwater parameters (ammoniacal N, pH and temperature) and windspeed. Such comparative measurements cannot be made by the large-circle, full-profile micrometeorological technique in most rice-growing areas in Asia because of the difficulty and expense of procuring sufficient land.

2. The results of many studies in Asia and Australia showed that NH_3 volatilisation from rice fields was controlled by floodwater temperature profiles, water depth, turbidity, air turbulence, evaporation, windspeed and the presence of algal films. A physical model of the loss process has been developed, based on calculated water surface temperature, dissolved NH_3 concentration and wind profiles. This model predicts NH_3 volatilisation with acceptable accuracy.

3. The extent of NH_3 loss from N fertilizers applied to rice has been determined in experiments in China, Malaysia, Philippines and Australia under realistic, undisturbed field conditions. In these experiments the most accurate micrometeorological technique available was used to determine NH_3 fluxes over 7–10-day periods and factors affecting NH_3 loss were studied. In every case the crop growth conditions and methods of fertilizer application were similar to those used by farmers in the local region. A large circular rice plot (0.2 ha) was used for the standard treatment and principal measurements. Weather and soil conditions varied greatly, resulting in a wide variation in NH_3 flux densities.

In all of the situations studied ammonia volatilisation and denitrification were the only important loss processes. Despite the large variation in NH_3 loss (2-56% of the applied N), total N loss in the standard urea treatment was always high, usually 40–60% of the applied N, and plant N recovery was only about 25%. Studies on the relationship between NH_3 volatilisation and denitrification showed that the two losses proceeded concurrently but that they were not always complementary, i.e. a reduction in NH_3 loss in response to a change in floodwater conditions or management did not necessarily affect the denitrification loss, as measured indirectly by ^{15}N balance. Ammonia loss from rice plants, rather than from the soil or floodwater, does not seem to be an important pathway of loss.

4. Changes in fertilizer and floodwater management allowed the loss of NH_3 from flooded rice to be substantially reduced. Most effective was a preplanting incorporation of broadcast urea fertilizer into soil from which the floodwater had been drained. The urease inhibitor N-butylthiophosphorictriamide delayed urea hydrolysis and in association with a nitrification inhibitor 2-ethynylpyridine was effective in increasing rice yields. A surface film of cetyl alcohol was effective in reducing ammonia and total nitrogen losses. Other observations, including effects of chemical form of fertilizer (e.g. ammonium bicarbonate versus urea), timing and rate of application on the extent of N loss, have helped our collaborators to assess the critical management factors dominating the N loss process.

5. The project has enhanced the research capacity of all of the scientists involved. The Asian collaborators have increased their knowledge of the mechanisms of N loss, gained training in specific techniques for use in future monitoring and experimental programs and participated in experiments where factors directly pertinent to the practices of their region were tested. The foundations were laid for future regional evaluation of N losses from fertilizers applied to rice and other crops. This will provide a sound base for recommendations of fertilizer use and ensure maximal efficiency of use by crop plants.

Publications

Twenty-seven papers have been produced from this study and five of these have been published in Chinese.

(i) In progress

1. Mosier, A. R., Chapman, S. L., and Freney, J. R. (1989). Determination of Dinitrogen Emission and Retention in Floodwater and Porewater of a Lowland Rice Field Fertilized with ^{15}N-Urea. (Submitted to *Fert. Res.*).

2. Melhuish, F. M., Humphreys, E., White, R. J. G. and Muirhead, W. A. (1989). Flood Irrigation of Wheat on a Transitional Red-brown Earth. I. Effect of Duration of Pondong on Plant Growth, Yield and N Uptake. (Submitted to *Aust. J. Agric. Res.*).

3. Humphreys, E., Melhuish, F.M., Xi Zhen Bang, and White, R.J.G. (1989). Flood Irrigation of Wheat on a Transitional Red-Brown Earth. II. Effect of Duration of Ponding on Availability of Soil and Fertilizer Nitrogen (Submitted to *Aust. J. Agric. Res.*).

4. De Datta, S. K., Trevitt, A. C. F., Freney, J. R., Obcemea, W. N., Real, J. G., and Simpson, J. R. (1988). Use of a Bulk Aerodynamic Method and ^{15}N Balance to Evaluate Management Practices for Reducing Nitrogen Loss from Lowland Rice. (Submitted to *Soil Sci. Soc. of Am. J.*

(ii) Completed

5. Simpson, J. R., Muirhead, W. A., Bowmer, K. H., Cai, G. X., and Freney, J. R. (1988). Control of Gaseous Nitrogen Losses from Urea Applied to Flooded Rice Soils. *Fert. Res.* (in press).

6. Zhu, Z. L., Cai, G. X., Simpson, J. R., Zhang, S. L., Chen, D. L., Jackson, A. V., and Freney, J. R. (1989). Processes of Nitrogen Loss from Fertilizers Applied to Flooded Rice Fields on a Calcareous Soil in North-central China. *Fert. Res.* (in press).

7. Zhu, Z. L., Zhang, S. L., Cai, G. X., Chen, D. L., Simpson, J. R. and Freney, J. R. (1989). Investigations on Nitrogen Losses from Fertilizers Applied to Flooded Calcareous Paddy Soil. A Summation of the Field Investigations Conducted in Dan Yang and Fenqiu, China. *Acta Pedol. Sin.* (in press).

(iii) Published

8. Simpson, J. R. and Freney, J. R. (1988). Interacting Processes in Gaseous Nitrogen Loss from Urea Applied to Flooded Rice Fields. Int. Symp. on Urea Technol. and Utilization (Malaysian Society of Soil Science: Kuala Lumpur) p. 281–290.

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Follow-Up

A handbook is being prepared for publication as an ACIAR Monograph to explain the principles of the three simplified methods, to provide details of the practicalities of measurement including experimental design, method of computation, accuracy, precision, suitability of localities and environments, constraints and limitations. This handbook is aimed at researchers in developing countries but will be useful for workers in developed countries who are being introduced to the techniques. More and more applications for the ammonia sampler and bulk aerodynamic method are being found and more interest in their use is now apparent.

Further research into the loss processes is underway in China, Philippines and Australia as a result of the findings of this ACIAR-financed project, especially with regard to the direct determination of denitrification and assessment of nitrification rates. This work commenced in Canberra and is now being carried out at the University of Melbourne, Institute of Soil Science, Nanjing, and at the International Rice Research Institute, Los Baños, Philippines.

Additional work is underway on the use of urease and nitrification inhibitors as a result of our studies in this project, and it is hoped that these studies can be further developed with the Fujian Academy of Agricultural Sciences in a new project.

Other Activities

Interactions with INSFFER Scientists

The International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) is organised jointly by the International Rice Research Institute and the International Fertilizer Development Centre. Our participation in the annual meetings of INSFFER has enabled us to inform rice researchers quickly of the important results of our work in this project. Papers were presented and discussed at the workshops of INSFFER in 1984

(Philippines), 1985 (Australia), 1986 (China) and 1987 (India).

A scientific meeting of INSFFER collaborators and other participants interested in nitrogen fertilizers for rice was held in Australia during 8–16 April 1985. It consisted of a workshop and site visit tour, funded by ACIAR through Project 8206, and the International Rice Research Institute and organised by J. R. Freney (Convenor), R. Wetselaar, J. R. Simpson, W. A. Muirhead and P. E. Bacon.

The workshop, which was held over 4 days, was concerned with the efficiency of nitrogen fertilizers for rice and was attended by 65 scientists representing 13 countries and three international centres. The meeting was generally acknowledged as being highly successful and enabled Asian scientists to learn of the results of project 8206, and to experience rice-growing techniques, problems and achievements in a more developed country — a unique opportunity for many of them.

Scientists Visiting Australia

Ms Cai Gui-xin from the Institute of Soil Science, Academia Sinica, Nanjing, People's Republic of China, worked on factors affecting ammonia loss from flooded soils and the processes controlling the use of urease inhibitors. Ms Cai worked successfully in Australia from January 1985 to November 1988, obtaining a Doctor of Philosophy degree from the University of Queensland as a result of her studies.

Mr Chen De-li, a soil chemist from the Institute of Soil Science, Academia Sinica, Nanjing, People's Republic of China, arrived in September 1985 to study techniques for assessing nitrogen loss by denitrification and ammonia volatilisation. He returned home on 17 March 1986 after a successful stay. He applied for, and was awarded a Postgraduate Scholarship to study for a Doctor of Philosophy Degree at the University of Melbourne. He completed his second year of study in 1988.

Mr Ren Zu-jian, Assistant Director of the Soil and Fertilizer Institute, Fujian Academy of Agricultural Sciences, Fuzhou, People's Republic of China, arrived in Australia on 25 January 1986 and spent 6 months learning simple techniques for assessing ammonia volatilisation.

Mr Xi-Zhen-bang from the Shanghai Academy of Agricultural Sciences arrived in Australia on 25 January 1986 and spent 4 months with the Centre for Irrigation Research. He also spent 3 weeks in Canberra, during a field experiment at Whitton, to learn techniques for assessing ammonia loss.

Mr Zulkifli Malik of the Malaysian Agricultural Research and Development Institute spent 10 weeks in Canberra from 10 January 1985, studying techniques for the assessment of ammonia loss from flooded rice.

Ms W. N. Obcemea of the International Rice Research Institute (IRRI) spent 4 months in Australia, from November 1984 to February 1985, studying techniques for the measurement of ammonia loss in the field. On her return to IRRI, Ms Obcemea taught the simplified field techniques for assessing ammonia loss to trainees from the INSFFER network.

Ms M. Samson from the Agronomy Department, International Rice Research Institute, Los Baños, spent 6 months in Canberra from November 1986 to April 1987 studying techniques for assessing ammonia and dinitrogen loss. On her return, she worked on a project funded by the Australian International Development Assistance Bureau to assess the importance of nitrogen loss from flooded rice in the Philippines, Indonesia and Thailand.

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No. 3. ACIAR Grain Storage Research Program: research report 1984–85, 85p., 1986.

No. 4. Coconut germplasm in the South Pacific islands, M.A. Foale, 23p., 1987.

No. 5. South Pacific agriculture: challenges and oportunities for ACIAR and its research partners, G.J. Persley and P. Ferrar, 87p., 1987.

No. 6. ACIAR Grain Storage Research Program: research report 1985–86, 96p., 1987.

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