EFFICIENT USE OF FERTILIZER NITROGEN BY CROPS

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ABSTRACT

The efficient use of fertilizer N is discussed. The various processes of N loss are described, and the factors controlling the rate of loss. The paper then reviews various management practices to reduce loss, such as fertilizer formulations, and appropriate rates and methods of application. The basic strategy is to match the fertilizer supply to the changing nutrient requirements of the crop.

INTRODUCTION

Most agricultural soils are deficient in nitrogen (N) for the growth of crops. This deficiency can be overcome by the use of fertilizers, but fertilizer N is not being used efficiently (Peoples *et al.* 1995). Because of the relatively low manufacturing cost of urea, and its low transportation cost per unit of N, there has been a widespread move to urea as the major form of N produced and used. However, there is concern about the efficiency of using urea-N for agricultural crops, especially for flooded rice, since farmers' practices in Asia commonly result in recoveries of <40% of the N applied.

Fertilizer N can be lost by leaching, erosion and runoff, or by gaseous emissions. The relative importance of these processes can vary widely, depending on the agricultural system and the environment. For example, the N may be leached wherever the rainfall or water supply from other sources exceeds evapotranspiration. Water and wind erosion or runoff can be sources of fertilizer loss where bare soil is left fallow, and in irrigation systems where water is allowed to flow down slopes from one field to another, or where overflows occur following heavy rainfall. In general, however, gaseous emissions of N via ammonia (NH_3) volatilization, and denitrification have been identified as the dominant mechanisms of fertilizer N loss in many different agricultural systems (Peoples *et al.* 1995).

During the past few years, new approaches have been developed for the direct measurement of gaseous loss in a range of agricultural systems. These techniques have made it possible to assess losses accurately, and give us a better understanding of the timing of the losses and the chemical, biological and physical factors involved. This knowledge can be utilized to develop strategies to maximize profit to the farmers and to decrease losses to the environment. This bulletin discusses some of the options available to reduce the losses and increase the efficiency of fertilizer N.

FACTORS CONTROLLING LOSS

Our investigations have shown that the predominant loss process and the amounts lost are influenced by the ecosystem, soil characteristics, cropping procedure, fertilizer techniques and prevailing weather conditions. Thus, NH_3 volatilization is of paramount importance in sugarcane fields when urea is applied to the surface of cane residues left on the soil surface (Freney *et al.* 1992b). However, denitrification is the main loss process in irrigated cotton when fertilizer is drilled into a heavy clay (Freney *et al.* 1993b), while both NH_3 volatilization and denitrification are important when urea is broadcast into flooded rice fields (De Datta *et al.* 1989;

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Freney *et al.* 1990).

Ammonia Loss

Large losses of NH_3 from applied fertilizer have been detected from soil, floodwater, and irrigation water in many agroecosystems (Freney and Black 1988; Peoples *et al.* 1995). Losses of NH_3 measured from different upland and lowland cropping systems have ranged from negligible amounts to >50% of the fertilizer N applied, depending upon fertilizer practices and environmental conditions (Bacon *et al.* 1986; Keller and Mengel 1986; Black *et al.* 1989; Freney *et al.* 1992b). In flooded rice, NH_3 volatilization can account for 20% to >80% of the total N lost from fertilizer sources. (Simpson *et al.* 1984; De Datta *et al.* 1989; Freney *et al.* 1990; Mosier *et al.* 1989; Zhu 1992).

Some of the most important factors regulating NH_3 loss are the concentration of ammoniacal N, the temperature, and the pH of the soil solution or irrigation water, since all three variables markedly affect the partial pressure of NH_3. The pH in particular affects the equilibrium between ammonium and NH_3, so that the relative concentration of NH_3 increases from 0.1, to 1, 10 and 50% as the pH changes from 6 to 7, 8 and 9, respectively (Freney *et al.* 1983). As temperatures rise, the relative proportion of NH_3 to ammonium present at a given pH increases, while the solubility of NH_3 in water decreases. This increases the diffusion of NH_3 through the soil, and affects the rate of microbial transformations. Wind speed is another major determinant, controlling volatilization through its effect on mixing in the liquid phase, and the rate of transport of NH_3 away from the air-water or air-soil interface (Freney *et al.* 1981; Denmead *et al.* 1982; Fillery *et al.* 1984). Other variables which influence NH_3 volatilization include the pH-buffer capacity and cation exchange capacity of the soil, levels of urease activity, the availability of moisture, soil texture, nitrification rate, and the presence of plants or plant residues (Freney and Black 1988). In rice systems, factors such as fertilizer composition, rate, time and method of application, floodwater depth, and algal growth, exert their influences through the primary variables — ammoniacal N concentrations, the pH and temperature of floodwater, and wind speed (Peoples *et al.* 1995)

Nitrification - Denitrification

Since most of the fertilizer used all over the world is ammonium based (urea, ammonium sulfate, etc.) the release of gaseous products from the overall nitrification-denitrification process needs to be considered. Nitrification is the oxidation of ammonium to nitrate. In soils, the process is mediated by autotrophic and heterotrophic bacteria. The nitrification process is controlled primarily by ammonium and oxygen concentrations. The oxygen supply is moderated by the soil moisture content. In the normal soil moisture range, the effect of soil water content on N transformations probably reflects its effect on oxygen diffusion.

In flooded rice systems, nitrification can occur in the water column above the soil, or in a thin aerobic zone in the surface soil layer and around the plant rhizosphere. The supply of oxygen to the flooded soil is renewed by diffusion through the floodwater and by transport through rice stems and roots. Nitrification is dependent upon the movement of ammonium into the oxidized zone, to be processed by nitrifying organisms. The transport of ammonium by diffusion is influenced by the organic matter status and cation exchange capacity of the soil, the presence of reduced iron and manganese, the bulk density, and the rate of nitrification in the oxidized soil layer and rice rhizosphere. In some rice growing areas, management practices require alternate draining and flooding cycles. Ammonium accumulated during flooding can be nitrified rapidly as the soils dry and become aerated (Buresh and De Datta 1991).

Biological denitrification is the dissimilatory reduction of nitrate and nitrite to produce NO, N_2O and N_2. Soil factors that strongly influence denitrification are oxygen (which is controlled primarily by soil water content), nitrate concentration, pH, temperature, and organic carbon (Peoples *et al.* 1995). Soil water tends to moderate oxygen diffusion in soil and, generally speaking, denitrification occurs only when the soil water content is >60% of the air-filled pore space (Linn and Doran 1984). Soil organic matter provides energy for denitrifier growth, as well as supplying protons and electrons for the reduction process.

In lowland rice, large denitrification events occur when the soil is reflooded, and then proceed during flooding in the reduced soil layer (Buresh and De Datta 1991; Aulakh *et al.* 1992).

Efforts to predict loss of N by denitrification have had limited success because of the interaction of the various factors controlling denitrification (Rolston 1990). It is presumed that denitrification occurs in soil aggregates and anaerobic microsites which are heterogeneously distributed in the soil (Parkin 1987). This may explain the large variation in rates of emission often detected in field studies (von Rheinbaben 1990). The two other important variables which regulate denitrification, pH and temperature, are generally not the principal constraints in soils where crops are growing because all plants have a similar pH and temperature requirements. However, these two parameters may be responsible for limiting maximum rates of denitrification (Aulakh *et al.* 1992).

The potential for high denitrification losses appear to be greatest under wet conditions, with very high rates of fertilizer application, or high organic C and N inputs (Nieder *et al.* 1989; von Rheinbaben 1990).

While biological denitrification may represent one of the major pathways for gaseous N loss, there is evidence that nitrite produced by nitrifying or denitrifying microorganisms can also react chemically to form gaseous N compounds via "chemodenitrification" (Chalk and Smith 1983). In well-aerated soils, oxidation of nitrite to nitrate by *Nitrobacter* spp. generally proceeds faster than the conversion of ammonium to nitrite by *Nitrosomonas* spp., and normally only trace levels of nitrite are present (<1 μg N g soil^{-1}). However, high nitrite concentrations can be found (>250 μg N g soil^{-1}, Chalk *et al.* 1975) when ammonium-based fertilizers which form alkaline solutions upon hydrolysis, are banded in soils. Initially, at the centre of a fertilizer band, soil pH may be as high as 10 and concentrations of inorganic N may be >2000 μg N g soil^{-1} (Chalk *et al.* 1975). The high pH adversely affects both *Nitrosomonas* and *Nitrobacter*. However, it appears that the activity of *Nitrobacter* is inhibited to a greater extent, and nitrite accumulates. The nitrite formed in the inner alkaline zone diffuses into a more acidic region on the periphery of the fertilizer band, where it is chemically reactive and unstable.

MANAGEMENT PRACTICES TO REDUCE LOSS

Special problems arise with crops such as rice, cotton and sugarcane which receive large applications of N, but which also lose large amounts of N by denitrification and NH_3 volatilization (Peoples *et al.* 1995). When the economic situation is good, farmers are unconcerned about applying excess amounts of N. However, the environmental consequences of this wasteful practice need to be considered.

Fertilizer Form, Rate and Method of Application

It has been demonstrated that plant uptake of fertilizer N can be improved, and total N losses reduced from levels achieved with surface broadcasting, by various methods of application such as deep placement (Youngdahl *et al.* 1986) and banding (Malhi and Nyborg 1991). Relative recoveries and levels of N loss can also be influenced by fertilizer composition, and the rate or timing of application (Stevens and Laughlin 1989, Malhi and Nyborg 1991, Strong *et al.* 1992, Diekmann *et al.* 1993). Each of these factors will specifically affect ammonium volatilization and loss by denitrification.

The rate of NH_3 volatilization or denitrification, and the pattern of N loss, can be greatly affected by the choice of N-carrier, although there may be an interaction with soil type or environment. The amount of N lost as NH_3 from urea, for example, is usually less than that lost from ammonium bicarbonate, while it is frequently much higher than that lost from ammonium sulfate or ammonium nitrate.

Different rates of fertilizer application can influence losses, since ammoniacal N or nitrate usually accumulates in soil (or floodwater in lowland rice) in amounts roughly proportional to the amounts applied. Whether this markedly changes the proportion of fertilizer N lost may depend on the agricultural systems under study. Increasing the amounts of ammonium nitrate applied to corn, for instance, did not greatly affect the proportion of fertilizer N lost by NH_3 volatilization or denitrification, yet when urea application to rice was doubled from 30 to 60 kg N ha^{-1}, total N loss rose from 37 to 54% (Diekmann *et al.* 1993). In absolute terms, however, the amount of N lost in gaseous emissions will increase when fertilizer rates are raised, even where there is little change in the extent of fertilizer loss.

Decreasing NH_3 loss by alternative methods of application to surface broadcasting (eg. incorporation, burying at depth) is related to the provision of a physical barrier in the form of a layer of soil to trap the NH_3 liberated, and the influence of these methods on the ammoniacal-N concentrations in surface soil solution or floodwater. Delaying the supply of fertilizer until a substantial canopy has developed can also result in lowered emissions. The developed plants

(a) provide a sink for the mineral N released (ie. low ammonium concentrations are maintained in soil or floodwater),

(b) shade the soil or water and thus reduce soil or water temperatures,

(c) restrict air movement at the soil or water surface, thereby reducing NH_3 transport away from the air-soil or air-water interface, and

(d) in the case of lowland rice inhibit the growth of cyanobacteria and consequent pH elevation.

In upland crops, the effect of timing of fertilization on N loss by denitrification may be more related to rainfall or irrigation events affecting soil moisture content than to strategic applications of N during critical periods of plant growth (Bacon and Freney 1989).

In lowland rice, incorporation of urea into soil in the absence of floodwater presumably lowers NH_3 volatilization, because of greater reaction of the NH_3 and ammonium ions produced on urea hydrolysis with organic matter and cation exchange sites, and the lowering of ammoniacal-N in floodwater (Freney and Denmead 1992). Unfortunately, this strategy may also lead to increased nitrification and result in greater loss through denitrification (Freney *et al.* 1990).

Matching Nitrogen Supply with Demand

The most efficient management practice to maximize plant uptake and minimize losses is to synchronize the N supply with the plant demand for this nutrient. This general concept of balancing supply and demand implies maintaining low levels of mineral N in soil when there is little or no plant growth, and providing sufficient N to meet plant requirements during periods of rapid growth (Peoples *et al.* 1995).

Nitrate accumulates in the soil during fallow periods between cropping seasons, as a result of mineralization of soil organic matter and nitrification of the ammonium so formed. The nitrate accumulated during fallow is more susceptible to loss by denitrification than nitrate which is produced when plants are present. Using interseasonal cover crops is one way of minimizing the accumulation of nitrate and its loss by denitrification.

It is generally agreed that more efficient use of fertilizer N results when the application of fertilizer coincides with the period of rapid plant uptake. Several applications of small amounts of fertilizer N during the growing season, therefore, may be a more effective means of supplying N for plant growth, than one large dose at the beginning of the season. Unfortunately, multiple applications of fertilizer are not always practical because of rainfall patterns and the difficulty of applying fertilizer within a maturing crop canopy (Doerge *et al.* 1991). However, split applications of N have proven useful in increasing crop production in some systems.

Fertilizer Supplied in Irrigation Water

Where irrigation is used, there is the opportunity of supplying fertilizer N along with the irrigation water. This allows the farmer to overcome some of the limitations in supplying multiple applications of fertilizer N to crops by conventional techniques, and to tune fertilizer N supply to crop requirements (Muirhead *et al.* 1985). Nitrogen can be supplied by dissolving fertilizer in the irrigation water applied to crops. This type of application has the advantages of simplicity, convenience and low cost. Urea dissolved in irrigation water has been found to be an efficient method of applying fertilizer N (Muirhead *et al.* 1985).

Foliar Applications

Foliar fertilization represents an alternative means of applying supplementary N during periods of rapid plant growth and N demand, or at times of critical physiological stress. It is most often used on high-value crops such as fruits and vegetables, although it has been successfully used for late applications of N to cereal, leguminous and fiber crops, to increase either grain protein or yield (Gray and Akin 1984). The effectiveness of foliar applications depends upon nutrient penetration of the cuticle and epidermal cells, and transport of N into the leaf.

As urea is rapidly absorbed, it is often used for foliar applications, of N. In wheat, around two-thirds of foliar applied urea-N was incorporated into plants within four hours of application, and almost 80% of the N applied was recovered in grain at the final harvest (Smith *et al.* 1991). Direct measurements of gaseous emission in such systems showed that very little N was lost by NH_3 volatilization from foliar applied urea, unless rain washed urea which had not yet been assimilated from the plant onto the soil (Smith *et al.* 1991).

Slow-Release Fertilizers

By using specific fertilizer formulations to release N in synchrony with plant requirements, it should be possible to provide sufficient N in a single application to satisfy the plant's needs, yet maintain very low concentrations of mineral N in the soil throughout the growing season. If this could be done, any gaseous loss event would be small because of the limited amount of N in the substrate.

Many different slow-release forms of N have been suggested, including

- coated fertilizers (Shoji et al. 1991),
- complex organic N compounds that are much less soluble in water than urea (Oertli, 1980; Allen 1984);
- urea supergranules (Youngdahl *et al.* 1986).

Many of these fertilizer formulations have been utilized for a number of different plant species growing in a range of diverse environments. The influence of slow-release forms on levels of soil mineral N, and the recovery of fertilizer N have been assessed for upland crops (eg. Mahli and Nyborg 1992), and lowland rice (Chauhan and Mishra 1989). The use of these formulations has generally decreased the total loss of fertilizer N.

Use of Inhibitors

Fertilizer use efficiency could be greatly increased if the hydrolysis of urea to ammonium by soil urease could be retarded by the use of urease inhibitors, or if nitrate accumulation during the cropping phase could be regulated by nitrification inhibitors.

Urease Inhibitors

A large number of compounds have been proposed and tested for their ability to inhibit soil urease (Mulvaney and Bremner 1981), but most are ineffective or do not persist in soil (Austin *et al.* 1984, Byrnes *et al.* 1989). The phosphoroamides, such as phenylphosphorodiamidate (PPD) and N-(n-butyl) thiophosphorictriamide (NBPT), have shown promise for limiting the hydrolysis of urea in laboratory and greenhouse studies when either used singly (e.g. Chai and Bremner 1987, Byrnes and Amberger 1989, Christianson *et al.* 1990), or in combination (Qui-Xiang *et al.* 1994). However, relatively few studies have been done on their ability to reduce NH_3 volatilization and increase grain yield in the field.

Several studies using PPD and NBPT as urease inhibitors have been conducted in flooded rice fields (e.g. Simpson *et al.* 1985, Fillery *et al.* 1986, Buresh *et al.* 1988, Cai *et al.* 1989), but little reduction in NH_3 loss has been achieved by using these compounds. The main reasons for the lack of success of PPD in flooded soils seem to be its rapid hydrolysis under the alkaline conditions generated in the floodwater by photosynthetic algae (Austin *et al.* 1984), or its decomposition due to the high temperatures reached in the floodwater (Chai and Bremner 1987). The reasons for the failure of NBPT in flooded soils have not been completely explained, but the results of laboratory studies with non-flooded soils suggest that NBPT must be converted to the oxygen analogue before it will inhibit urease activity (Chai *et al.* 1988, Creason *et al.* 1990). Studies with another thiophosphorictriamide, thiophosphoryl triamide, showed that it too was a relatively weak inhibitor of urease activity. Appreciable inhibition was only achieved after it had been converted to its oxon analogue (McCarty and Bremner 1989, Bremner *et al.* 1991). These studies indicate that the thiophosphorictriamides do not inhibit urease activity, but that the phosphorictriamides are potent inhibitors of urease activity.

Field studies in Thailand show that the activity of PPD can be prolonged, and NH_3 loss markedly reduced, by controlling the floodwater pH with the algicide Terbutryn (Freney *et al.* 1993a). In addition, these workers found that a mixture of NBPT and PPD in the presence of Terbutryn was even more effective than PPD alone. It appears that during the time when the PPD was effective, NBPT was being converted to its oxygen analogue. This inhibited urease activity when PPD lost its capacity to inhibit urease activity. The combined urease inhibitor - algicide treatment reduced NH_3 loss from 10 to 0.4 kg N ha^{-1}.

Christianson *et al.* (1990), in a laboratory study, found that cyclohexylphosphorictriamide (CHPT) was a very effective inhibitor of urease activity. This finding was confirmed in a field experiment with flooded rice in Thailand (Freney *et al.* 1995). In this experiment, the oxon analogue of NBPT, N-(n-butyl) phosphorictriamide, was compared with CHPT. The two phosphorictriamides markedly reduced urea hydrolysis, but CHPT was more effective than N-(n-butyl) phosphorictriamide. Addition of CHPT maintained the ammoniacal N concentration of the floodwater below 2 g m^{-3} for 11 days, reduced NH_3 loss by -90%, and increased grain yield.

Nitrification Inhibitors

Since ammonia or ammonium-producing compounds are the main sources of fertilizer N, maintenance of the applied N in the ammonium form should mean that less N is lost by denitrification. One mechanism of maintaining added N as ammonium is to add a nitrification inhibitor with the fertilizer (Broadbent *et al.* 1957, Bundy and Bremner 1973, Sahrawat *et al.* 1987).

Numerous substances have been tested for their ability to inhibit nitrification, and several of these have been patented. Only a limited number of chemicals are available commercially for use in agriculture. These include 2-chloro-6 (trichloromethyl) pyridine (nitrapyrin), sulfathiazole, dicyandiamide, 2-amino-4-chloro-6-methyl pyrimidine, 2-mercaptobenzothiazole, thiourea and 5-ethoxy-3-trichloromethyl-1,2,4-thiadiazole (terrazole). Unfortunately, most of these compounds have limited usefulness (Keeney 1983). For example, the most commonly used nitrification inhibitor, nitrapyrin, is seldom effective because of sorption on soil colloids, hydrolysis to 6-chloropicolinic acid, and loss by volatilization (Hoeft 1984).

It has been established in laboratory studies that acetylene is a potent inhibitor of nitrification (Walter *et al.* 1979, Hynes and Knowles 1982). However, because it is a gas there are problems in introducing it into the soil in the field, and maintaining it during the growing period at the concentration required to limit nitrification. This problem may be overcome by the use of calcium carbide, coated with layers of wax and shellac to provide a slow-release source of acetylene (Banerjee and Mosier 1989). Addition of wax-coated calcium carbide to the fertilized soil has reduced nitrification and increased yield, or recovery of N, in irrigated wheat (Freney *et al.* 1992a), maize (Bronson *et al.* 1992), cotton (Freney *et al.* 1993b, Chen *et al.* 1994), and flooded rice (Banerjee *et al.* 1990, Keerthisinghe *et al.* 1993).

Another way of overcoming the problem of applying gaseous acetylene is to use substituted acetylenes such as 2-ethynylpyridine or phenylacetylene, which are liquids at ambient temperatures. These two compounds have proved to be effective inhibitors in laboratory studies (McCarty and Bremner 1986, 1990, Crawford and Chalk 1992). The use of 2-ethynylpyridine in irrigated cotton has resulted in greatly increased recovery of applied N (Freney *et al.* 1993b).

Water Management

Since maximum denitrification rates are commonly observed when the pore spaces in soil contain >90% water, minimizing the time during which soil is saturated should limit denitrification. However, maintaining a balance between limiting denitrification or nitrate leaching and appropriate water management is difficult. Rolston *et al.* (1982) showed that when the same amount of irrigation water was applied to fields in either one, two or six applications during a two-week interval, less N_2O was emitted from the less frequently irrigated soils. Unfortunately, irrigating only once or twice each two weeks increased nitrate leaching.

Trickle or drip irrigation systems allow the delivery of N to the area of maximum crop uptake, and match the rate of application to the plants' requirements. If trickle systems are operated carefully, they can reduce deep percolation, runoff and denitrification (Doerge *et al.* 1991).

Flood irrigation has been used to disperse the granules of surface-applied urea and wash the solubilized urea into the soil. When this technique was used to apply urea for a subsequently flooded rice crop, no ammonia was lost to the atmosphere (Humphreys *et al.* 1988).

Managing floodwater depth is also important for controlling NH_3 volatilization in lowland rice (Freney *et al.* 1988). Broadcast urea was hydrolysed at a faster rate in shallow (5 cm) water than in deep (14 cm) water, with the result that ammoniacal N concentrations were greater in the shallow water. In addition the shallow water heated up more quickly and attained a higher temperature than the deep water. Consequently, ammonia was lost at a faster rate from the shallow water.

Algicides and Surface Films

The pH of floodwater in lowland rice is markedly affected by the growth and metabolism of photosynthetic microorganisms (Roger *et al.* 1987). During daylight hours, these cyanobacteria fix carbon dioxide and excrete hydroxyl ions, and the pH of floodwater rises dramatically. At night, the cyanobacteria respire, carbon dioxide is emitted, and the pH of the floodwater decreases. Floodwater pH values in excess of 10 have been observed during daylight hours (Simpson *et al.* 1984), while the pH may decrease by 2 or 3 units overnight. Such diurnal fluctuations in floodwater pH are a common feature of rice-growing regions of the world (eg. Fillery *et al.* 1984, Humphreys *et al.* 1988, Chauhan and Mishra 1989). Changes of pH from 8 to 10 could be expected to increase the NH_3 volatilization rate by more than ten-fold (Freney and Denmead 1992). Additions of algicides or biocides to floodwater have been successful in suppressing these diurnal variations in pH, and NH_3 losses have been found to be reduced by up to 40 - 50% (Bowmer and Muirhead 1987, Simpson *et al.* 1988). Algicides such as Terbutryn have also been found to suppress photosynthetic oxygen production, and it has been speculated that this may contribute to a retardation of nitrification and so limit additional losses via denitrification (Bowmer and Muirhead 1987). However, subsequent field trials suggest that this may not always be the case (Simpson *et al*. 1988).

Another strategy to restrict NH_3 volatilization from flooded rice is to spread monomolecular films of organic compounds on the surface of the floodwater. Investigations using long chain alcohols have demonstrated substantial reductions in nitrogen losses, despite the elevated floodwater temperatures under the surface films (Cai *et al.* 1987, Simpson *et al.* 1988). The principal difficulty encountered with this practice is maintaining a continuous film on the floodwater surface under windy conditions.

CONCLUSION

As can be seen from the discussion above, many approaches are available to control the gaseous losses of fertilizer N by NH_3 volatilization and denitrification. However, it is necessary to know whether the two processes in a particular agroecosystem are independent or complementary, so that simple cost-effective management strategies can be designed for that system. If they are independent, then it should be possible to increase the efficiency of fertilizer N use and reduce total N loss by applying management practices to limit loss by one mechanism. However, since ammonium is the common source of both nitrification-denitrification and NH_3 volatilization, the losses may well be complementary more often than independent. In such cases, a reduction in NH_3 volatilization would not necessarily lead to a reduction in total loss, because the N conserved would be nitrified and then be susceptible to denitrification. Experimental data shows that the two processes are independent in some systems, under certain treatments, but complementary in others (Simpson *et al.* 1988, Bacon and Freney 1989, Freney *et al.* 1990). These different responses probably arise from changes in the rate of nitrification of the NH_3 conserved, and/or changes in factors which specifically influence denitrification. Consequently, it may be necessary to apply several techniques to simultaneously restrict both loss mechanisms.

The management of N is of concern to farmers engaged in agricultural production, and to researchers and environmentalists concerned with the effects of the lost N on climatic change and the ozone layer (Peoples *et al.* 1995). The interests of each are not exclusive. Responsible management aimed at increasing the efficiency of N-fertilizer use by crop and forage species will ensure greater returns to the farmer, and provide an incentive for reducing the impact on the environment.

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DISCUSSION

Several participants were interested in Dr. Freney's evidence of a high rate of nitrification from deep placed fertilizer, since studies in Taiwan had shown a low rate of nitrification from deep placement of N fertilizer in paddy fields. Dr. Freney explained that there is an oxidized layer at the soil surface and also around the rice roots. This can mean quite a large oxidized zone in the soil which enables nitrification to continue after flooding. In all the cases he had studied, there had been no evidence of nitrogen losses by leaching from paddy soils - in every case, it had been gaseous losses which were most important. According to one model, ammonia may oxidize to nitrate at the soil/water interface. The nitrate them diffuses down into the anaerobic zone so that denitrification can occur. However, this process is a slow one, and in practice denitrification occurs very rapidly. Dr. Freney felt it more likely that denitrification takes place at the soil/water interface, although he was not sure whether this involved a single set of microorganisms which can both nitrify and denitrify. In the reduction and oxidation of methane, which could be seen as a comparable process, some scientists believe that a single organism can both produce and consume methane gas.

Farmers in Indonesia are being encouraged to use tablet forms of urea in paddy soils. Some of them are reluctant to do this, because of the extra work of application. Dr. Freney was asked how he viewed the losses from this practice. He felt that this would depend on the rate at which the urea tablets dissolved, and the competition between plant roots and microorganisms for the urea produced. He felt that there would probably be much the same situation as if granular urea was used.

One question was asked about the economic returns of using calcium carbide as a nitrification inhibitor. Dr. Freney felt that this is a major problem, because the cost of the wax and shellac coating material is fairly high. He had been trying to increase the concentration of carbide by reducing the thickness of the coating, and this had been quite successful, so that he hoped a commercial product would soon be on the market.