

In: Advances in Nitrogen Cycling in Agricultural Ecosystems. Edited by: J. R. Wilson. Proc. Symposium on Advances in Nitrogen Cycling in Agricultural Ecosystems, Brisbane, Australia, 11-15 May 1987. C.A.B. International, U.K. pp. 239-256.

NITROGEN CYCLING IN WETLAND RICE SOILS

I. Watanabe, S.K. De Datta and P.A. Roger

ABSTRACT

Nitrogen cycling in wetland rice soils is unique : (a) wetland rice is more dependent on soil N than dryland crops, (b) N accumulates at the soil surface through the activities of the photosynthetic aquatic biomass, and (c) inorganic nitrogen is not stable at the soil surface and in the floodwater due to denitrification and ammonia volatilisation.

Factors stimulating soil organic N mineralisation are known. However, methods of predicting soil N release to rice need improvement. Soil microbial biomass is an important source of N to wetland rice in mineral N-deficient conditions. Photosynthetic biomass in the floodwater causes N accumulation at the soil surface by immobilisation and N₂-fixation, but stimulates ammonia loss by increasing floodwater pH. Fauna in soil and floodwater play a role in recycling of N. Aerodynamic measurement of ammonia volatilisation loss accompanied by ¹⁵N balance in the field revealed that some loss is mediated by a mechanism other than ammonia volatilisation, probably denitrification. Point placement of granular urea, use of urease inhibitors, and proper timing of N fertiliser application reduce fertiliser N losses and increase N fertiliser efficiency.

INTRODUCTION

About 75% of the 143 M ha of rice land are lowlands (wetlands), where rice grows in flooded fields during part or all of the cropping period.

Flooding favours rice environments by : (1) bringing the soil pH near to neutral; (2) increasing availability of nutrients, especially P and Fe, (3) maintaining soil N ; (4) stimulating N₂-fixation; (5) depressing soil-borne diseases; (6) supplying nutrients from irrigation water; (7) suppressing weeds, especially those of C₄ type, and (8) preventing water percolation and

soil erosion.

By 1950's most of the unique characteristics of nitrogen transformations in wetland rice soils were described by Mitsui (1954). They are:

- (i) N fertility is higher in the flooded rice soils than in the upland soils.
- (ii) The surface of the flooded soil and the floodwater accumulate N by recycling or by biological N_2 -fixation.
- (iii) Surface-applied ammonium-N is unstable due to nitrification-denitrification. NH_4^+ is stable in reduced soil.

The recent proceedings of the symposium "Nitrogen Economy of Flooded Rice Soil" (De Datta and Patrick 1986) contains a wealth of updated knowledge on N transformations in flooded rice soils and several reviews are available (Anon. 1979 ; Watanabe et al. 1981a ; Patrick 1982 ; Savant and De Datta 1982). Knowledge and technology of biological nitrogen fixation have also recently been reviewed (Watanabe and Roger 1984 ; Roger and Watanabe 1986 ; Watanabe 1986). Therefore, to avoid repetition, this review focuses on recent knowledge of the N cycle in wetland rice soils, and introduces some untranslated Japanese work.

RELEASE AND MAINTENANCE OF AVAILABLE SOIL NITROGEN

Factors affecting the release of soil N

N balance studies in long-term fertility trials have demonstrated that N supplied by the soil is an extremely important component of rice production (Watanabe et al. 1981a). Despite this importance, very little research effort is expended on studying how to use soil N more effectively (Bouldin 1986). Early research, however, identified most factors favouring soil N mineralisation. It was shown that drying of soil stimulates ammonia formation and renders soil organic N more decomposable (Shioiri et al. 1941 ; Harada 1959). Other factors reported to stimulate soil N mineralisation were temperature elevation from 30°C to 40°C, liming, solubilisation of soil colloids by NaF, Na_2HPO_4 and Na oxalate (Harada 1959), mechanical destruction of soil aggregates (Harada et al. 1964 ; Hayashi and Harada 1964), and root growth (Hayashi and Harada 1964).

Drying of fallow soil has long been practiced by Chinese and Japanese farmers. Soil desiccation during the dry season in the tropics may stimulate soil N mineralisation the following wet season. Ventura and Watanabe (1978, 1984) showed that air-drying the soil during the dry season temporarily depressed N uptake at early stage, probably due to the accumulation of toxic substances, but increased total N uptake of rice measured at harvest. Flooding of dried soil for 2-4 weeks before transplanting eliminated the growth retarding effect, and the increase in soil N supply due to previous drying was not affected. The stimulation of N mineralisation was more than

denitrification loss of the nitrate accumulated during the dry period.

Puddling of the wet fields is a characteristic of land preparation in South and Southeast Asia. It incorporates weeds, prevents water seepage and may also stimulate soil organic matter breakdown. Soil N uptake by rice at early growth stages was faster in a transplanted, wet-puddled field than in a direct-seeded, uncultivated field (Ooyama 1975 ; Nonoyama and Nishi 1981). This was ascribed to the stimulation of soil N decomposition by mechanical destruction of soil aggregates, an effect observed under laboratory conditions by Hayashi and Harada (1964). However, Yoshino and Onikura (1980) found no difference in soil N mineralisation between soils collected before and after puddling and incubated under anaerobic conditions. Sharma and De Datta (1985) observed differences in chemical changes of puddled and non-puddled soils after flooding and the N uptake by rice, but no difference was found in the inorganic N content of soil between the two methods.

The effects of various farming practices on soil N mineralisation need to be re-examined.

Microbial biomass as a source of available N

Harada (1959) found that the soil N fractions that are made decomposable by air-drying, liming, temperature elevation and other factors, were included in labile fractions solubilised in sodium chloride. Further studies showed that microbial cell walls are major constituents of the soil organic matter that becomes decomposable by air-drying (Kai and Wada 1979). Microbial biomass is now regarded as a major channel through which organic nutrients are transferred to crop plants (Jenkinson and Ladd 1981).

The chloroform fumigation method has added significantly to the knowledge of the role of the microbiomass in cultivated soils (Jenkinson and Ladd 1981). Marumoto (1984) found that in oven-dried and rewetted rice soils, 66% of the N mineralised during 28 days of incubation came from the newly killed (chloroform fumigated) microbial biomass. In soils where ^{15}N -labelled ammonium N was newly immobilised due to the addition of glucose, ^{15}N abundance in the N mineralised from dried and rewetted soils was smaller than that from chloroform fumigated soils, indicating that air-drying made older immobilised N more mineralisable than chloroform fumigation (Inubushi and Watanabe 1987). The contributions of microbial biomass to the organic fractions rendered decomposable by methods other than drying are not known.

The ^{15}N abundance in the N absorbed by rice at late growth stages (when ammonium N in soil was almost depleted), or by rice in non-fertilised N plots was similar to that of flush N after chloroform fumigation (Inubushi and Watanabe 1986). This suggests that microbial biomass in flooded rice soil is the N source for rice when mineral N is deficient.

There are few estimates of microbial biomass in flooded soils. The

limited data obtained from wetland soils before or after flooding (Marumoto 1984 ; Hasebe *et al.* 1985) show higher ratios of microbial biomass C to total soil C (4-8%) than reported for upland arable lands (Jenkinson and Ladd 1981). Total microbial biomass may be larger in flooded soil because of the aquatic microbial community, especially microalgae.

Replenishment of microbial biomass and mineralisable N

If an energy source is not added to soil and new biomass is not synthesized, microbial biomass must decline after releasing nutrients. Watanabe and Inubushi (1986) observed that microbial biomass measured by chloroform fumigation (flush N + mineralised N without fumigation) increased at the soil surface and decreased in the puddled layer during flooding. Microbial biomass N in planted plots declined slightly more than that in fallow plots. The difference was, however, smaller than the absorption of soil N by the rice plant. This suggests that the replenishment of microbial biomass is related to the activity of the rice root. Inubushi and Watanabe (1986) estimated the residence time of microbial biomass N (or available N) to be 33 days, which suggests that the turnover of microbial biomass is much faster in tropical-wetland soils than in temperate upland soils (Jenkinson and Ladd 1981).

The significance of the microbial biomass accumulation at the soil surface and the corresponding enrichment in mineralisable N is discussed later.

Predicting mineralisation of soil N

The heavy dependence of rice on N mineralised from soil organic matter emphasizes the need for methods to assess N supply. There are two aspects of the prediction of available (mineralisable) N : (1) the estimation of the total amount of soil N available to the rice crop, and (2) the rate of supply of the mineralisable N. The first is necessary to determine the amount of fertiliser N for a given rice yield and the second to determine the timing of its split applications.

The amount of ammonium-N released during incubation of air-dried or wet soil under flooded conditions at 30°C for 2-4 weeks has been widely used as a biological index of N availability. Incubation of wet samples is preferable to the incubation of air-dried soil, because the N release pattern of moist-soil is closer to that observed in field. After air-dried soil is flooded, N mineralisation usually exhibits a very active phase followed by a slow phase. The mineralisation rate during the slow phase is not necessarily proportional to that of non-dried soil (Inubushi *et al.* 1985a, b). Two to four times more N is released by incubation of air-dried samples as compared with wet samples (Yoshino and Dei 1977 ; Inubushi *et al.* 1985a).

Total N content of the soil could be the simplest estimate of its

mineralisable N. Sahrawat (1983a) reported a high correlation coefficient between mineralisable N and total N in Philippine soils ($r = 0.94$). However, much lower values were reported for soils from Japan (Shioiri 1948, $r = 0.52$) China (Zhu *et al.* 1984, $r = 0.56$) and South and Southeast Asia (Kawaguchi and Kyuma 1977, $r = 0.58$), indicating that total N is not an accurate index of mineralisable N. In addition to total N, various chemical methods have been proposed to replace incubation methods (Sahrawat 1983a,b; Keeney and Sahrawat 1986), but none is widely used.

Flooded incubation of wet soils collected before transplanting has been used to predict the N release pattern during rice growth (see review by Dei and Yamasaki 1979).

Yoshino and Dei (1977) proposed the following equation for calculating mineralised N as a function of incubation period and temperature:

$$Y = K[(t-15).D/a]^n \quad (1)$$

where $Y = N$ mineralised after D days of incubation ; $K = Y$ at the end of the incubation ; $t =$ temperature in $^{\circ}\text{C}$; $a = (t-15) \times$ total number of days of incubation. The parameter n is related to the pattern of N release.

Yoshino and Onikura (1980) used 13 non-N fertiliser field plots to examine the validity of Yoshino and Dei's equation. N uptake of rice and ammonia present in the soil were summed to calculate soil N mineralisation in the field. Samples of the puddled layer collected before flooding and transplanting were incubated under flooded conditions at 30°C to estimate the parameters of N release. N release in the field was predicted by applying the measured soil temperature in the field to the equation. The time-sequence patterns of estimated soil N mineralisation fairly represented the N uptake pattern in the field. The amounts of N taken up by rice at the harvest, however, differed from the estimated values which were 72 to 148% of the N actually mineralised in the field up to harvest. Cai and Zhu (1983) also reported discrepancies between the predicted amount of mineralised N and N uptake by the plant.

Shiga and Ventura (1976) compared the N uptake pattern of rice grown in the field or in pots in the greenhouse with the N release pattern during the flooded incubation of wet soil samples at 30°C . The greenhouse results agreed well with the N release pattern of flooded incubation. During the early dry season, there were large discrepancies between N release estimated from Yoshino and Dei's equation (1977) and the actual N uptake by rice in the field, probably due to lower soil temperature during the dry season. Gao *et al.* (1984) applied Yoshino and Dei's method to estimate N release in the field and the response of early rice to N fertiliser. Soils were divided into 3 groups according to parameters K and n . Rice yield and response to N-fertiliser were correlated with the pattern of N mineralisation during flooded incubation.

Konno and Sugihara (1986) and Sugihara et al. (1986) developed another approach in which the parameters are: decomposable N, the kinetic constant of soil N mineralisation, and temperature change of the kinetic constant (expressed as apparent activation energy in Arrhenius's law) as shown in the equation:

$$N = N_0[1 - e^{-k \cdot t}] \quad (2)$$

where N = N mineralised at time t ; N_0 = N mineralised at infinite time = decomposable N; k, kinetic constant = $A^{-E_a/R \cdot T}$; E_a = apparent activation energy; R = gas constant; T = temperature in °K.

Yamamoto et al (1986) applied this equation in two sandy loam gley wetland soils in Kyushu, Japan. The estimate of soil N mineralisation fit well to the sum of N uptake in rice and ammonium N in soil.

Both approaches excluded the contribution of subsoil and available N derived from photoautotrophic organisms on the soil surface. Yoshino and Onikura (1980) ascribed the discrepancy between actual values and predicted values to higher N fertility of subsoil. Although Ventura and Watanabe (1984) showed the importance of N contributed from subsoil to N uptake, the role of subsoil in supplying N to rice has not been recognised in most predictions of N supply. Still, prediction methods of soil N mineralisation need improvement and field verification.

Part of the non-exchangeable ammonium is released during rice growth and absorbed by rice (Keerthisinghe et al. 1984, 1985) but the quantity of N absorbed by rice from this fraction is not yet known.

Varietal difference in the ability to absorb soil N

Research on the genotypic differences in soil N utilisation by rice is limited. Collaborative research between IRRI and University of California (Broadbent et al. 1987) has identified rice varieties that consistently

Table 1: Rice varietal differences in nitrogen utilisation efficiency (adapted from Broadbent et al. 1987).

Rice variety	Growth duration	N utilisation efficiency Rank in 3 seasons ¹
	<i>days</i>	
IR13429-150-3	110	1, 1, 3
IR18349-135-2	110	2, 3, 5
IR8608-167-1	100	21, 23, 24
IR42(check)	130	9, 13, 17

1. Out of 24 rice varieties tested.

produce maximum grain yield with minimum fertiliser input (Table 1). Some are substantially better than IR42, an established variety with a reputation for good performance in poor soils. This study also suggests that varieties that mature in less than 100 days depend primarily on fertiliser N whereas late-maturing varieties depend primarily on soil N. The consistent performance of outstanding genotypes demonstrate that genetic improvement in N utilisation efficiency is practical.

Differences in soil N uptake among rice varieties were demonstrated by either the N uptake in non N-fertilised plots or the uptake of unlabelled N in plots where labelled fertiliser was applied. The ^{15}N technique suggests that rice genotypic differences in soil N uptake are not associated with varietal differences in ability to promote nitrogen fixation (Watanabe *et al.* 1987).

ROLE OF AQUATIC PHOTOSYNTHETIC COMMUNITIES IN N TRANSFORMATION

After flooding, particularly when N and P fertilisers are applied, there is an upsurge in growth of photoautotrophic organisms in the floodwater and at the soil surface. Shioiri and Mitsui (1935) suggested four roles for these organisms: (1) supplying organic matter to the soil surface; (2) immobilising N (reservoir effect); (3) supplying O_2 ; and (4) fixing N_2 (at that time, N_2 -fixation was regarded as symbiosis between N_2 -fixing bacteria and algae).

In 1943, Shioiri and Harada briefly reported the possible effect on ammonia loss of high floodwater pH resulting from algal activity, but they detected no ammonia loss. It is only recently that the role of the photosynthetic aquatic biomass in stimulating ammonia volatilisation by increasing pH has been demonstrated and extensively studied (Mikkelsen *et al.* 1978); Fillery and Vlek 1986).

The role of aquatic biomass in N transformations was not covered in most early reviews, except for N_2 -fixation. Recent reviews (Roger and Watanabe 1984; Roger 1986; Roger *et al.* 1987) cover this subject more fully. Ecology of the floodwater was reviewed by Watanabe and Furusaka (1980) and Watanabe and Roger (1985). The transformations and transfers of N as affected by the photosynthetic aquatic biomass are shown schematically in Figure 1.

Aquatic biomass productivity

The photosynthetic aquatic biomass in flooded rice fields is composed of prokaryotic and eukaryotic algae, and vascular macrophytes (aquatic cormophytes) free-floating or growing on soil, plants, and organic debris. Roger (1986) showed that the photosynthetic aquatic biomass is usually a few hundred kg dry weight/ha and rarely exceeds 1 t dry weight/ha. At 2.5% N content, an average aquatic biomass of 200 kg dry matter/ha would correspond to only 5 kg biomass N/ha. Biomass N rarely exceeds 10-20 kg/ha.

Daily productivity at early growth is approximately 1 g C/m² (Yamagishi

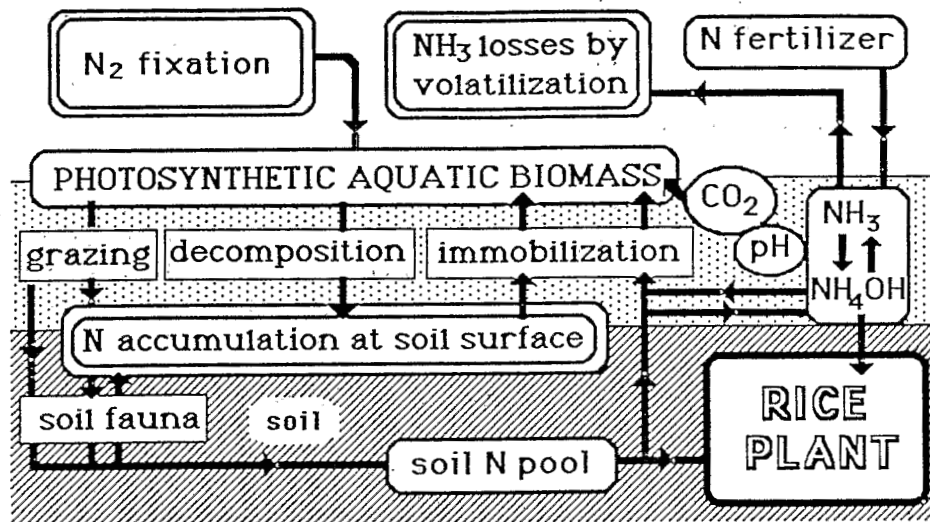


Fig. 1: Nitrogen dynamics in relation to the activity of the photosynthetic aquatic biomass in a rice field (after Roger 1986).

et al. 1980b; Vaquer 1984). Productivity decreases as the canopy density increases except when macrophytic algae emerge (Vaquer 1984). Recorded productivities are 50–60 g C/m² in 90 days (Saito and Watanabe 1978) and 70 g C/m² in 144 days (Yamagishi et al. 1980b). These values are similar to those encountered in eutrophic lakes.

Surface accumulation of N

Accumulation of total N at the soil surface was observed only when the surface was exposed to light. Reported values range from a few kg N/ha (App et al. 1984) to 35 kg N/ha per crop (Ono and Koga 1984).

Nitrogen may come from the atmosphere through biological fixation, from the floodwater through the trapping of N by aquatic biomass, and from the soil through absorption by plants or ingestion by invertebrates. A decrease of N accumulation from 35 to 26 kg N/ha occurred when the surface soil was isolated from the deeper soil by placing it in a Petri dish (Ono and Koga 1984). This means that the recycling of soil N to the surface is equivalent to 1/3 of the N originated from the photosynthetic aquatic biomass.

Watanabe and Inubushi (1986) and Inubushi and Watanabe (1986) determined the accumulation of microbial biomass N by chloroform fumigation (N mineralised without fumigation was not subtracted). Surface accumulation of microbial biomass N was demonstrated only in soils exposed to light. Microbial biomass N in the 0–1 cm soil layer accounted for 10–20% of that in

the 0-15 cm layer. This percentage may be underestimated, because algal debris are brought down to a deeper layer by soil fauna (Grant and Seegers 1985b).

Chlorophyll-like substances also accumulated at the surface in parallel with microbial biomass N (Watanabe and Inubushi 1986). A correlation between chlorophyll-type compounds and mineralisable N was reported by Inubushi *et al.* (1982) and Wada *et al.* (1982), indicating that photosynthetic biomass contributes significant quantities of available N and has an important role to play in maintaining the fertility of wetland soils. The ^{15}N abundance in surface-accumulated microbial biomass N was similar to that in aquatic weeds, but higher than that in floodwater blue-green algae (Inubushi and Watanabe 1986), suggesting that recycled soil N was the major source of the surface enrichment in available N in this small plot experiment.

Nitrogen immobilisation and recycling

Nitrogen immobilisation by the photosynthetic biomass reduces N losses and N pollution of the environment. Shioiri and Mitsui (1935) measured an immobilisation rate of 10-26% of N applied in pots. Using a gas lysimeter, Vlek and Craswell (1979) estimated immobilisation at 18-30% for surface-applied urea and 0.4-6% for ammonium sulfate in 3 weeks. Immobilisation at 18-41% was recorded using ^{15}N -labelled urea (Vlek *et al.* 1980). When ^{15}N ammonium sulfate was mixed with the soil of the puddled layer, only 5% or less was immobilised (Inubushi and Watanabe 1986). Aquatic weeds greatly stimulated the removal of N from N-contaminated (NO_3^- , NH_4^+ , and organic N) irrigation water (Ito and Masujima 1980).

Recycling of N in the floodwater community is mediated by grazing invertebrates (Grant *et al.* 1986; Roger 1986). Ingestion and excretion rates of *Heterocypris luzonensis* (Ostracoda) were determined in the laboratory and used to estimate N ingestion and excretion in a field population. The calculated ingestion rate of 190 g N/ha per day (of which 120 g was excreted as NH_3) is much smaller than the estimated assimilation rate (1 kg N/ha per day) by the photosynthetic aquatic biomass. Burrowing of soil fauna such as tubificids facilitates the downward movement of surface-accumulated organic debris (Grant and Seegers 1985 a,b). This may explain the low difference in ^{15}N recovery between surface-applied or incorporated blue-green algae observed in the field (Tirol *et al.* 1982) and low total N accumulation at the soil surface (App *et al.* 1984). The roles of soil fauna in N cycling in floodwater and puddled soil needs to be re-examined.

Availability of photosynthetic biomass N to rice

Experiments on N recovery from ^{15}N -labelled algae and aquatic macrophytes were summarised by Roger (1986).

Recovery of blue-green algal N varied from 13 to 50% depending on the nature of the algal material (fresh vs. dried), the method of application

(surface-applied vs. incorporated), and the presence or absence of soil fauna. Highest recovery (50%) was obtained when fresh material was incorporated into a soil depleted of fauna (Wilson *et al.* 1980). Lowest recovery was obtained when dried material was spread on the surface of a soil rich in tubificids. Their activity made soil N available to rice through mineralisation and thereby reduced the recovery of algal N (Grant and Seegers 1985a). A residual effect of algal N was observed in the second rice crop in which 4 to 7% of algal N was recovered (Tirol *et al.* 1982; Grant and Seegers 1985a).

The ^{15}N recovery from Azolla and aquatic macrophytes ranged from 12 to 34% (Roger 1986), averaging 29% when incorporated. Just as rice absorbs more inorganic N when the fertiliser is incorporated into the soil, it absorbs more N from the photosynthetic aquatic biomass when the biomass is incorporated into the soil, than when it decomposes on the soil surface.

Experiments with soil labelled with ^{15}N fertiliser also provide data on N available from the photosynthetic aquatic biomass. Ventura and Watanabe (1983) showed that when the soil surface was exposed to light, ^{15}N in the rice plant was more diluted by unlabelled N. Nitrogen gains in the soil-plant system were higher than when the soil surface was not exposed to light. The contribution of photodependent N_2 -fixation on N uptake, estimated by ^{15}N dilution method, accounted for 20% of total N gains.

Effect of the photosynthetic aquatic biomass on N losses by ammonia volatilisation

Photosynthetic CO_2 depletion by aquatic communities increases floodwater pH and stimulates NH_3 volatilisation. The suppression of algal growth by Cu^{++} (Mikkelsen *et al.* 1978) and deep-placement of N-fertiliser (Cao *et al.* 1984) decreases diurnal variation of pH and N losses.

Fillery *et al.* (1986) estimated the photosynthetic biomass in fields where N losses were evaluated. One week after fertiliser application, a limited and uneven growth of algae (about 100 kg fresh weight/ha) was observed and pH at noon ranged from 7.8 (no visible algal growth) to 10.5 in the vicinity of algal colonies. Despite the low algal biomass, N losses were 30-40%. Although this high loss may be related to the natural alkalinity of the floodwater at the site, it indicates that large algal populations are not required to increase floodwater pH to levels that promote rapid N losses.

Various factors affect dissolved carbon dioxide (DIC) concentration, which determines the pH at a given temperature, as shown by the following equation (Yamagishi *et al.* 1980a):

$$d(\text{DIC})/dt = -P_g + R + \text{CER} + F_2 \quad (3)$$

where P_g = photosynthetic activity; R = respiration activity; CER = carbon exchange rate (positive when CO_2 is absorbed from atmosphere); and F_2 =

CO₂ transfer from soil to floodwater. All are expressed in g C/m².

CER decreases with temperature increase (Yamagishi *et al.* 1980a). This may be another parameter that increases ammonia volatilisation at higher temperature.

Azolla, floating on water, absorbs CO₂ from the atmosphere and inhibits photosynthesis of phytoplankton in the water by hindering light penetration. The pH of floodwater under Azolla is, therefore, stable and frequently below 8. These results indicate a potential for combined use of Azolla and chemical N to reduce losses by volatilization.

FATE OF FERTILISER NITROGEN

Many reviews are available on the fate of fertiliser N applied to wetland rice and the inefficiency of surface-applied N fertilisers (see De Datta *et al.* 1983; Vlek and Byrnes 1986). Figure 2 summarises recent ¹⁵N balance studies on N losses and recoveries by the plant in field microplots. The variation of soil recovery was smaller than the variations of plant recovery and loss. Recoveries of N in plant higher than 60% were obtained only by deep placement of urea supergranules in flooded soils (Craswell *et al.* 1985; De Datta *et al.* 1983; Cao *et al.* 1984, Chen and Zhu 1982). When N fertilisers were applied at panicle initiation or maximum tiller number stage, N

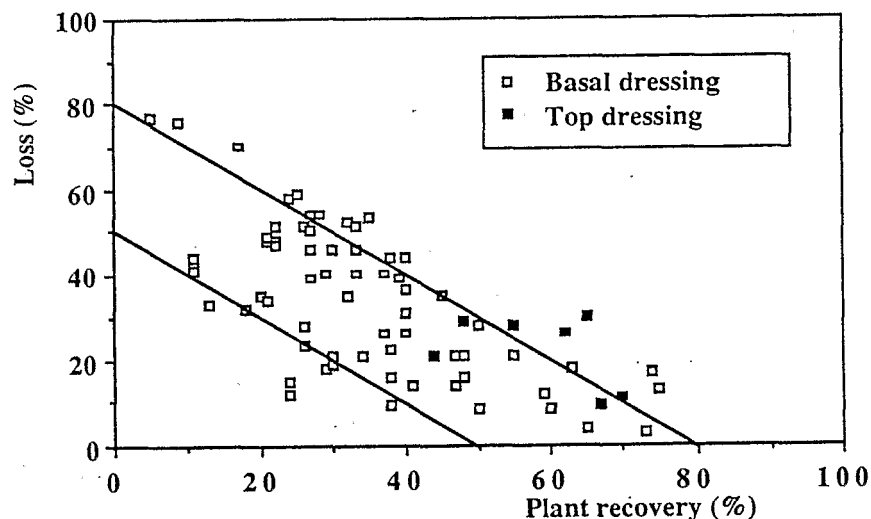


Fig. 2: Distribution of ¹⁵N recovery to plant and loss. Basal dressing: ¹⁵N applied before transplanting or just after seedling establishment. Top dressing: ¹⁵N applied at panicle initiation. From Chen and Zhu (1982), Craswell *et al.* (1985), Mo and Qian (1983), Yamamuro (1986), Fillery *et al.* (1986), Katyal *et al.* (1985), Cao *et al.* (1984), and De Datta *et al.* (1983).

recoveries by the rice plant were larger and losses smaller than with early application (Fig. 2).

N losses from surface-applied fertiliser

Two pathways of gaseous losses of N from flooded soil are known; viz. ammonia volatilisation, which has been quantified by direct measurements, and denitrification, which has been primarily estimated by indirect methods.

The extent of NH_3 volatilisation loss following urea application to flooded rice and the problems of relating loss measurements in chambers to the field, prompted many researchers to measure this loss by micrometeorological techniques. In the Asian tropics, Freney *et al.* (1981) were the first to use these techniques to assess field NH_3 volatilisation loss following fertiliser application. However, they used ammonium sulfate, which is not now a common fertiliser for rice. Studies on NH_3 volatilisation were summarised by Mikkelsen and De Datta (1979) and Fillery and Vlek (1986).

A recent study in the Philippines, of N losses following application of urea to rice (De Datta *et al.* 1986) determined total N loss by ^{15}N balance techniques and NH_3 loss by measuring NH_3 concentration in the floodwater and windspeed in the atmosphere 0.8 m above the floodwater (Table 2). NH_3 loss was 31% when N fertiliser was applied onto floodwater 10 days after transplanting — a common practice for many Asian rice farmers. The NH_3 loss occurred during the first 8 days after fertiliser application.

Table 2: Relation between total N loss and NH_3 volatilisation. Mabitac, Laguna, Philippines, 1985 late dry season. (De Datta *et al.* 1986).

Application method	Fertiliser rate	Water depth	Total N loss	NH_3 loss	Estimated denitrification ¹
	kg/ha	cm	%	%	%
Researchers' split ²	53	0	33	6	27
Researchers' split ²	53	5	54	22	32
Farmers' split ³	53	5	60	27	33
Researchers' split ²	80	0	32	7	25
Researchers' split ²	80	5	58	27	31
Farmers' split ³	80	5	59	31	28
LSD (0.05)	—	—	13	8	—
Farmers' split in circle ^{3,4}	80	5	55	31	24

1. Total N loss minus NH_3 loss; 2. 2/3 basal incorporated without standing water + 1/3 at 5-7 days before panicle initiation; 3. 2/3 at 10 days after transplanting into standing water + 1/3 at booting stage; 4. Unreplicated treatment where NH_3 loss was directly measured in the circle.

The estimated total N loss after 30 days was 55% of applied N (Table 2). No ^{15}N was detected in the soil below 15 cm and no overflow of floodwater from microplots was allowed so losses by leaching and runoff were negligible. Therefore, the 24% difference in the loss (Table 2) was probably due to denitrification. This needs to be confirmed by direct measurement.

Because nitrification is much slower than denitrification, the rate of loss by denitrification is determined by the nitrification rate. Focht (1979) assumed that nitrification in the oxidized soil is controlled by the O_2 supply to the soil surface and calculated a maximum nitrifying activity of 500 g N/ha per day. In situ soil core measurement of the nitrification rate by ^{15}N dilution (Watanabe *et al.* 1981b) showed a maximum of 1200 g N/ha per day, which is much lower than the potential NH_3 loss. The measurement of N_2 or N_2O evolved from the ^{15}N labelled fertiliser probably would be the best method to estimate denitrification loss. Data show that denitrification loss should not be underestimated. Ammonia or ammonium in the floodwater and at the soil surface could be lost by denitrification if NH_3 volatilisation was blocked.

Cultural practices to improve fertiliser N efficiency in flooded soil.

In recent years, a deeper understanding of the mechanisms causing poor N utilisation has helped to develop cultural practices to improve N fertiliser use efficiency in lowland rice. De Datta *et al.* (1987) suggested that applying N onto the floodwater between transplanting and early tillering, a common practice of Southeast Asia farmers, is wasteful. Appropriate timing of

Table 3: Effects of N source and application method on grain yield of transplanted rice in farmers' fields. Nueva Ecija, Philippines, 1986 dry season. (S.K. De Datta, IRRI, unpublished data).

Treatment ¹	Fertiliser applied	Grain yield ²
	kg N/ha	t/ha
Control	0	4.3
Farmers' split, PU ³	58	5.6
Researchers' split, PU ⁴	58	6.0
Point-placement, USG	58	6.1
Press wedge, USG	58	5.3
Plunger auger, PU	58	5.7
Farmers' split, PU	87	5.7
Researchers' split, PU	87	6.3
Standard error		0.1

1. PU = prilled urea, USG = urea supergranules. 2. Average of 3 farms.
 3. One half topdressed at 15 days after transplanting + 1/2 topdressed at post panicle initiation. 4. Two thirds basal broadcast and incorporated without standing water + 1/3 topdressed 5-7 days before panicle initiation.

N application and proper water management minimizes N loss and maximizes N use efficiency in lowland rice. In 1986 dry season trials in three farmers' fields in the Philippines, researchers' timing at two N levels increased grain yield by 0.4 - 0.6 t/ha over farmers' timing (Table 3).

Various urea and modified urea products are now available for extensive testing on lowland rice. These include urea of different granule sizes and slow-, and controlled-release fertilisers. The potential of urease inhibitors to reduce NH_3 volatilisation loss was also extensively tested. Results suggest that the urease inhibitor phenylphosphorodiamidate (PPD) can reduce NH_3 loss a little but seldom shows significant increase in grain yield (De Datta *et al.* 1983; Fillery and De Datta 1986).

Deep placement of fertiliser either by hand or machine was also promising. However, tests of machine deep placement have given inconsistent results.

CONCLUSION

Whereas N supply to rice by the soil is an extremely important component of rice production, little effort is expended in the tropics on studying how to use soil N more efficiently. A few predictive models for soil N mineralisation have been developed but have not yet been tested in the tropics.

The photosynthetic aquatic biomass plays a major role in N cycling in wetland soils. It stimulates NH_3 losses by increasing floodwater pH, but also enriches the soil surface with N by N_2 fixation, and N immobilisation and recycling. Quantitative data on the two last processes are still meagre. Soil microbial biomass is an important source of N to wetland rice in mineral N-deficient conditions.

NH_3 volatilisation loss from wetland rice soils has been quantified. Total N losses were measured by ^{15}N balance technique. Denitrification loss was estimated by the differences between total N and NH_3 losses as affected by various N fertiliser management practices. Future challenge is to directly measure both NH_3 volatilisation and denitrification losses in relation to total nitrogen losses using ^{15}N balance technique.

Based on these basic researches, cultural practices have been developed which minimise NH_3 and apparent denitrification losses and maximise fertiliser N use efficiency in wetland rice. Cultural practices to increase availability of soil nitrogen in wetland rice fields have to be developed.

REFERENCES

- Anonymous (1979). 'Nitrogen and Rice'. (Intern. Rice Res. Inst.: Manila, Philippines), p. 499.

- App, A., Santiago, T., Daez, C., Menguito, C., Ventura, W., Tirol, A., Po, J., Watanabe, I., De Datta, S.K., and Roger, P.A. (1984). Estimation of the nitrogen balance for irrigated rice and the contribution of phototrophic nitrogen fixation. Field Crops Res. 9, 17-27.
- Bouldin, D.R. (1986). The chemistry and biology of flooded soils in relation to the nitrogen economy in rice fields. In 'Nitrogen Economy of Flooded Rice Soils'. (Eds S.K. De Datta and W.H. Patrick, Jr.) pp. 1-15. (Martinus Nijhoff Publisher: Dordrecht.)
- Broadbent, F.E., De Datta, S.K., and Laureles, E.V. (1987). Measurement of nitrogen utilization in rice genotypes. Agron. J. In press.
- Cai, Gui-xin, and Zhu Zhao-liang (1983). Effect of rice growth on the mineralization of soil nitrogen. Acta Pedologica Sinica 20, 272-8.
- Cao Zhi-hong, De Datta, S.K., and Fillery, I.R.P. (1984). Nitrogen-15 balance and residual effects of urea-N in wetland rice field as affected by deep placement techniques. Soil Sci. Soc. Amer. J. 48, 203-8.
- Chen Rong-ye, and Zhu Zhao-liang (1982). Studies on fate of nitrogen fertilizer. 1. The fate of nitrogen fertilizer in paddy soils. Acta Pedologica Sinica 19, 122-30.
- Craswell, E.T., De Datta, S.K., Weeraratne, C.S., and Vlek, P.L.G. (1985). Fate and efficiency of nitrogen fertilizer applied to wetland rice. The Philippines. Fert. Res. 6, 49-63.
- De Datta, S.K., Fillery, I.R.P., and Craswell, E.T. (1983). Results from recent studies on nitrogen fertilizer efficiency in wetland rice. Outlook Agric. 12, 125-34.
- De Datta, S.K., Obcemea, W.N., Chen, R.Y., Calabio, J.C., and Evangelista, R.C. (1987). Effect of water depth on nitrogen use efficiency and nitrogen-15 balance in lowland rice. Agron. J. 79, 210-6.
- De Datta, S.K., and Patrick, W.H. (1986). 'Nitrogen Economy of Flooded Rice Soils'. (Martinus Nijhoff Publisher: Dordrecht.)
- De Datta, S.K., Trevitt, A.C.F., Obcemea, W.N., Frenay, J.R., and Simpson, J.R. (1986). Comparison of total N loss and ammonia volatilization in lowland rice using simple techniques. Annual Meeting American Society of Agronomy, New Orleans, USA, 30 Nov-5 Dec 1986, pp. 197.
- Dei, Y., and Yamasaki, S. (1979). Effect of water and crop management on the nitrogen supplying capacity of paddy soils. In 'Nitrogen and Rice'. (Intern. Rice Res. Inst.: Manila, Philippines.), pp. 451-64.
- Fillery, I.R.P., and De Datta, S.K. (1986). Ammonia volatilization from nitrogen sources applied to rice fields: I. Methodology, ammonia fluxes and nitrogen-15 loss. Soil Sci. Am. J. 50, 80-6.
- Fillery, I.R.P., Roger, P.A., and De Datta, S.K. (1986). Ammonia volatilization from nitrogen sources applied to rice field: II. Floodwater properties and submerged photosynthetic biomass. Soil Sci. Soc. Am. J. 50, 86-91.
- Fillery, I.R.P., and Vlek, P.L.G. (1986). Reappraisal of the significance of ammonia volatilization as an N loss mechanism in flooded rice fields. In 'Nitrogen Economy of Flooded Rice Soils'. (Eds S.K. De Datta and W.H. Patrick, Jr.) pp. 79-98. (Martinus Nijhoff Publisher: Dordrecht.)
- Focht, D.D. (1979). Microbial kinetics of nitrogen losses in flooded soils. In 'Nitrogen and Rice'. (Intern. Rice Res. Inst.: Manila, Philippines.), pp. 119-34.
- Frenay, J.R., Denmead, O.T., Watanabe, I., and Craswell, E.T. (1981). Ammonia and nitrous oxide losses following applications of ammonium sulfate to flooded rice. Aust. J. Agric. Res. 32, 37-45.
- Gao Jia-hua, Zhang Yun, Huan Dong-mai, Wu Jing-min, and Pan Zun-pu (1984). Nitrogen mineralization pattern and nitrogen efficiency in paddy soil. Acta Pedologica Sinica 21, 341-9.
- Grant, I.F., Roger, P.A., and Watanabe, I. (1986). Ecosystem manipulation for increasing biological N₂ fixation by blue-green algae (Cyanobacteria) in lowland rice fields. Biol. Agric. and Hort. 3, 299-315.
- Grant, I.F., and Seegers, R. (1985a). Tubificid role in soil mineralization and recovery of algal nitrogen by lowland rice. Soil Biol. Biochem. 17, 559-63.
- Grant, I.F., and Seegers, R. (1985b). Movement of straw and algae facilitated by tubificids (Oligochaeta) in lowland rice soil. Soil Biol. Biochem. 17, 729-30.
- Harada, T. (1959). The mineralization of native organic nitrogen in paddy soils and mechanism of its mineralization. Bull. Nat. Inst. Agric. Sci. B9, 123-200.
- Harada, T., Hayashi, R., and Chikamoto, A. (1964). Effect of physical pretreatment of soils on the mineralization of native organic nitrogen in paddy soils. J. Sci. Soil Manure, Jpn 35, 21-4.
- Hasebe, A., Kanazawa, S., and Takai, Y. (1985). Microbial biomass carbon measured by Jenkinson's fumigation method. Soil Sci. Plant Nutr. 31, 349-59.
- Hayashi, R., and Harad, T. (1964). Effect of cropping on mineralization of native organic nitrogen in paddy soils. J. Sci. Soil Manure, Japan 35, 123-6.
- Inubushi, K., Wada, H., and Takai, Y. (1982). Easily decomposable organic matter in paddy soils. II. Chlorophyll type compounds in Apy horizons. Jpn J. Soil Sci. Plant Nutr. 53, 277-82.

- Inubushi, K., Wada, H., and Takai, Y. (1985a). Easily decomposable organic matter in paddy soils. V. Ammonification in the submerged soil as related with the mineralisable nitrogen. *Jpn J. Soil Sci. Plant Nutr.* 56, 404-8.
- Inubushi, K., Wada, H., and Takai, Y. (1985b). Easily decomposable organic matter in paddy soils. VI. Kinetics of nitrogen mineralization in submerged soils. *Soil Sci. Plant Nutr.* 31, 563-72.
- Inubushi, K., and Watanabe, I. (1986). Dynamics of available nitrogen in paddy soils. II. Mineralized N of chloroform-fumigated soil as a nutrient source for rice. *Soil Sci. Plant Nutr.* 32, 561-78.
- Inubushi, K., and Watanabe, I. (1987). Microbial biomass nitrogen in anaerobic soil as affected by N immobilization and N_2 -fixation. *Soil Sci. Plant Nutr.* 33, 213-24.
- Ito, A., and Masujima, H. (1980). Studies on the purification of polluted water in paddy fields. *J. Sci. Soil Manure, Japan* 51, 478-85.
- Ito, O., and Watanabe, I. (1985). Availability to rice plants of nitrogen fixed by *Azolla*. *Soil Sci. Plant Nutr.* 31, 91-104.
- Jenkinson, D.S., and Ladd, J.N. (1981). Microbial biomass in soil: measurement and turnover. In 'Soil Biochemistry 5'. (Ed. E. Paul) pp. 415-71. (Marcel Dekker: New York.)
- Kai, H., and Wada, K. (1979). Chemical and biological immobilization of nitrogen in paddy soil. In 'Nitrogen and Rice'. (Intern. Rice Res. Inst.: Manila, Philippines.), pp. 157-74.
- Katyal, J.C., Singh, B., Vlek, P.L.G., and Craswell, E.T. (1985). Fate and efficiency of nitrogen fertilizers applied to wetland rice. II. Punjab, India. *Fert. Res.* 6, 279-90.
- Kawaguchi, K., and Kyuma, K. (1977). 'Paddy Soils in Tropical Asia'. (Univ. Hawaii Press: Honolulu.)
- Keeney, D.R., and Sahrawat, K.L. (1986). Nitrogen transformation in flooded rice soils. In 'Nitrogen Economy of Flooded Rice Soils'. (Eds S.K. De Datta and W.H. Patrick.) pp. 15-39. (Martinus Nijhoff Pub.: Dordrecht.)
- Keerthisinghe, G., De Datta, S.K., and Mengel, K. (1985). Importance of exchangeable soil NH_4^+ in nitrogen nutrition of lowland rice. *Soil Sci.* 140, 194-201.
- Keerthisinghe, G., Mengel, K., and De Datta, S.K. (1984). The release of nonexchangeable ammonium (^{15}N labelled) in wetland rice soils. *Soil Sci. Soc. Amer. J.* 48, 291-4.
- Konno, K., and Sugihara, S. (1986). Temperature index for characterizing biological activity in soil. Its application to decomposition of soil organic matter. *Bull. Nat. Inst. Agro-Evn. Sci., Japan.* 1, 51-68.
- Marumoto, T. (1984). Mineralization of C and N from microbial biomass in paddy soil. *Plant Soil* 76, 165-73.
- Mikkelsen, D.S., and De Datta, S.K. (1979). Ammonia volatilization from wetland rice soils. In 'Nitrogen and Rice'. (Intern. Rice Res. Inst.: Manila, Philippines.), pp. 157-74.
- Mikkelsen, D.S., De Datta, S.K., and Obcemea, W. (1978). Ammonia volatilization losses from flooded rice soils. *Soil Sci. Soc. Amer. J.* 42, 725-30.
- Mitsui, S. (1954). 'Inorganic Nutrition, Fertilisation and Soil Amelioration for Lowland Rice'. (Yokendo: Tokyo.)
- Mo Shu-xun, and Qian Ju-fang (1983). Studies on the transformation of nitrogen of milk vetch in red earth and its availability to rice plant. *Acta Pedologica Sinica* 20, 12-22.
- Nonoyama, Y., and Nishi, H. (1981). Edaphological studies on non-tillage direct sowing cultivation of paddy rice. *Bull. Chugoku Nat. Agric. Expt. Stn.* E18, 1-55.
- Ono, S., and Koga, S. (1984). Natural nitrogen accumulation in a paddy soil in relation to nitrogen fixation by blue-green algae. *Jpn J. Soil Sci. Plant Nutr.* 55, 465-70.
- Ooyama, N. (1975). Nitrogen supplying patterns of paddy soils for rice plant in temperate area in Japan. *J. Sci. Soil Manure, Japan* 46, 297-302.
- Patrick, W.H. (1982). Nitrogen transformations in submerged soils. In 'Nitrogen in Agricultural Soils'. Agronomy Monograph No. 22, pp 449-65 (ASA-CSSA-SSSA: U.S.A.)
- Roger, P.A. (1986). Effect of algae and aquatic macrophytes on nitrogen dynamics in wetland rice fields. *Congr. Int. Soil Sci. Soc., Hamburg, Germany*, pp. 13-21.
- Roger, P.A., Grant, I.F., Reddy, P.M., and Watanabe, I. (1987). The photosynthetic aquatic biomass in wetland rice fields and its effect on nitrogen dynamics. In 'Efficiency of Nitrogen Fertilizers for Rice'. (Intern. Rice Res. Inst.: Manila, Philippines.), pp. 43-68.
- Roger, P.A., and Watanabe, I. (1984). Algae and aquatic weeds as source of organic matter and plant nutrients for wetland rice. In 'Organic Matter and Rice'. (Intern. Rice Res. Inst.: Manila, Philippines.), pp. 147-68.
- Roger, P.A., and Watanabe, I. (1986). Technologies for utilizing biological nitrogen fixation in wetland rice: potentialities, current usage, and limiting factors. *Fert. Res.* 9, 39-77.
- Sahrawat, K.L. (1983a). Mineralization of soil organic nitrogen under waterlogged conditions in relation to other properties of tropical rice soils. *Aust. J. Soil Res.* 21, 133-8.
- Sahrawat, K.L. (1983b). Nitrogen availability indices for submerged rice soils. *Adv. Agron.* 36, 415-51.

- Saito, M., and Watanabe, I. (1978). Organic matter production in rice field floodwater. Soil Sci. Plant Nutr. 24, 427-40.
- Savant, N.K., and De Datta, S.K. (1982). Nitrogen transformations in wetland rice soils. Adv. Agron. 35, 241-302.
- Sharma, P.K. and De Datta, S.K. (1985). Puddling influence on soil, rice development, and yield. Soil Sci. Soc. Amer. J. 49, 1451-7.
- Shiga, H., and Ventura, W. (1976). Nitrogen supplying ability of paddy soils under field conditions in the Philippines. Soil Sci. Plant Nutr. 22, 387-99.
- Shioiri, M. (1948). The effect of drying paddy soils during fallow period. Rep. Agric. Exptl. Stn. 64, 1-24.
- Shioiri, M., Aomine, S., Uno, Y., and Harada, T. (1941). The effect of drying of paddy soils. J. Sci. Soil Manure, Japan 15, 331-3.
- Shioiri, M., and Harada, T. (1943). Loss of N due to upward movement of ammoniacal nitrogen and its leaching by downward movement. Transformation of nitrogen in flooded soils. J. Sci. Soil Manure, Japan 17, 375-6.
- Shioiri, M., and Mitsui, S. (1935). Chemical composition and decomposition in soil of algae and some aquatic plants grown in paddy soils. J. Sci. Soil Manure, Japan 9, 261-7.
- Sugihara, S., Konno, T., and Ishii, K. (1986). Kinetics of mineralization of organic nitrogen in soil. Bull. Natl. Inst. Agro-Env. Sci. Jpn 1, 127-66.
- Tirol, A.C., Roger, P.A., and Watanabe, I. (1982). Fate of nitrogen from blue-green algae in a flooded rice soil. Soil Sci. Plant Nutr. 28, 559-70.
- Vaquier, A. (1984). La production algale dans des rizieres de Camargue pendant la periode de submersion. Ver Internatl. Verein Limnol. 22, 1651-4.
- Ventura, W., and Watanabe, I. (1978). Dry season soil conditions and soil nitrogen availability to wet season wetland rice. Soil Sci. Plant Nutr. 24, 535-45.
- Ventura, W., and Watanabe, I. (1983). ¹⁵N dilution technique for assessing the contribution of nitrogen fixation to rice plant. Soil Sci. Plant Nutr. 29, 123-31.
- Ventura, W., and Watanabe, I. (1984). Dynamics of nitrogen availability in lowland rice soils: the role of soil below plow layer and effect of moisture regimes. Philipp. J. Crop Sci. 9, 135-42.
- Vlek, P.L.G., and Byrnes, B.H. (1986). The efficacy and loss of fertilizer N in lowland rice. In 'Nitrogen Economy of Flooded Rice Soils'. (Eds S.K. De Datta and W.H. Patrick.) pp. 131-47. (Martinus Nijhoff Publisher: Dordrecht.)
- Vlek, P.L.G., and Craswell, E.T. (1979). Effect of nitrogen source and management on ammonia volatilization losses from flooded rice-soil systems. Soil Sci. Soc. Amer. J. 43, 352-8.
- Vlek, P.L.G., Stumpe, J.M., and Byrnes, B.H. (1980). Urease activity and inhibition in flooded soil system. Fert. Res. 1, 191-202.
- Wada, H., Inubushi, K., and Takai, Y. (1982). Relationship between chlorophyll-type compounds and mineralisable nitrogen. Jpn J. Soil Sci. Plant Nutr. 53, 380-4.
- Watanabe, I. (1986). Nitrogen fixation by non-legumes in tropical agriculture with special reference to wetland rice. Plant Soil 30, 343-57.
- Watanabe, I., Craswell, E.T., and App, A. (1981a). Nitrogen cycling in wetland rice fields in Southeast and East Asia'. In 'Nitrogen Cycling in Southeast Asian Wet Monsoon Ecosystems'. (Ed. R. Wetzel.) pp. 4-17. (Aust. Acad. Sci.: Canberra.)
- Watanabe, I., and Furusaka, C. (1980). Microbial ecology of flooded soils. Adv. Microb. Ecol. 4, 125-68.
- Watanabe, I., and Inubushi, K. (1986). Dynamics of available nitrogen in paddy soils. 1. Changes in available N during rice cultivation and origin of N. Soil Sci. Plant Nutr. 32, 37-50.
- Watanabe, I., Padre, B.C.P., and Santiago, S.T. (1981b). Quantitative study on nitrification in flooded rice soil. Soil Sci. Plant Nutr. 27, 373-82.
- Watanabe, I., and Roger, P.A. (1984). Nitrogen fixation in wetland rice field. In 'Current Developments in Biological Nitrogen Fixation'. (Eds N.S. Subba Rao) pp. 237-76. (Oxford and IBH: New Delhi.)
- Watanabe, I., and Roger, P.A. (1985). Ecology of flooded rice fields. In 'Wetland Soils: Characterization, Classification, and Utilization'. (Intern. Rice Res. Inst.: Manila, Philippines.) pp. 229-43.
- Wilson, J.T., Eskew, D.L., and Habte, M.H. (1980). Recovery of nitrogen by rice from blue-green algae added in a flooded soil. Soil Sci. Soc. Amer. J. 44, 1330-1.
- Yamagishi, T., Okada, K., Hayashi, T., Kumura, A., and Murata, Y. (1980a). Cycling of carbon in a paddy field and the atmosphere. Jpn J. Crop Sci. 49, 135-45.
- Yamagishi, T., Watanabe, J., Okada, K., Hayashi, T., Kumura, A., and Murata, Y. (1980b). Cycling carbon in a paddy field. II. Biomass and gross production of algae. Jpn J. Crop Sci. 49, 146-55.

- Yamamoto, T., Kubota, T., and Manabe, H. (1986). Estimation of soil nitrogen mineralization during growth period of rice plant by kinetic method. Jpn J. Soil Sci. Plant Nutr. 57, 487-92.
- Yamamoto, S. (1986). Nitrogen cycle in paddy fields (Part 4). The fate of ammonium N by surface application and incorporation in soil and mineralised soil nitrogen on assimilation, immobilisation, denitrification, and absorption by rice plants in semi-ill drained paddy fields. Jpn J. Soil Sci. Plant Nutr. 57, 13-22.
- Yoshino, T., and Dei, Y. (1977). Prediction of nitrogen release in paddy soils by means of the concept of effective temperature. J. Central Agric. Exptl. Stn., Konosu 25, 1-62.
- Yoshino, T., and Onikura, Y. (1980). Evaluation of nitrogen supplying capacity of paddy soils by an incubation method. J. Central Agric. Exptl. Stn., Konosu 31, 73-86.
- Zhu Zhao-liang, Cai Gui-xin, Yu Ying-hua, and Zhang Shao-lin (1984). Nitrogen mineralization of paddy soils in Tai-lake region and the prediction of soil nitrogen supply. Acta Pedologica Sinica 21, 29-36.