5. Denitrification losses in flooded rice fields*

KR REDDY[1] and WH PATRICK Jr[2]

[1] Professor, University of Florida, Institute of Food and Agricultural Sciences, Central Florida Research and Education Center, P.O. Box 909, Sanford, FL 32771 and [2] Boyd Professor, Center for Wetland Resources, Louisiana State University, Baton Rouge, LA 70803, USA

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Introduction

Nitrogen transformations in a flooded rice soil are much the same as N transformations in drained soil systems, though the special soil/environmental conditions prevailing in flooded rice soils alter the rate at which these processes occur. The key N transformations in a flooded soil system include (1) mineralization of organic N; (2) nitrification of NH_4^+; (3) NH_3 volatilization; (4) denitrification; and (5) N_2 fixation (Figures 1a, b). Agronomic and ecological significance of these processes in the gain or loss of N from a flooded soil and sediment system has been studied by several researchers. The objective of this paper is to review recent research findings on the significance of nitrification-denitrification in flooded rice soils.

Soil/environmental conditions

Flooding of a soil results in displacement of soil O_2 with water, with any dissolved O_2 present in the pore water being readily consumed during microbial respiration, thus making soil profile devoid of O_2 [29, 30, 7, 65]. Supply of O_2 to the flooded soil is renewed in two ways: i.e. (1) diffusion of O_2 through the overlying floodwater and consumption at the soil-water interface, and (2) transport of O_2 through the stems of rice and other wetland plants to the roots and subsequent diffusion of O_2 into the rhizosphere. The greater potential consumption of O_2 compared to the renewal rate results in the development of two distinct soil layers: (1) an oxidized or aerobic soil layer which ranges from a few millimeters in thickness in soils of high microbial activity to 1 to 2 cm in soils of low biological activity, and (2) an underlying reduced or anaerobic soil layer in which no free

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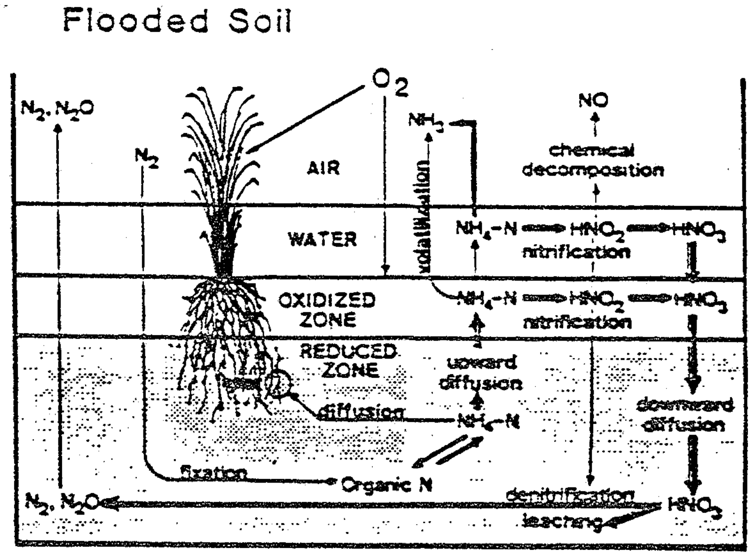

Figure 1(a). Schematic presentation of the N transformations functioning in the oxidized and reduced soil layers of flooded lowland soil.

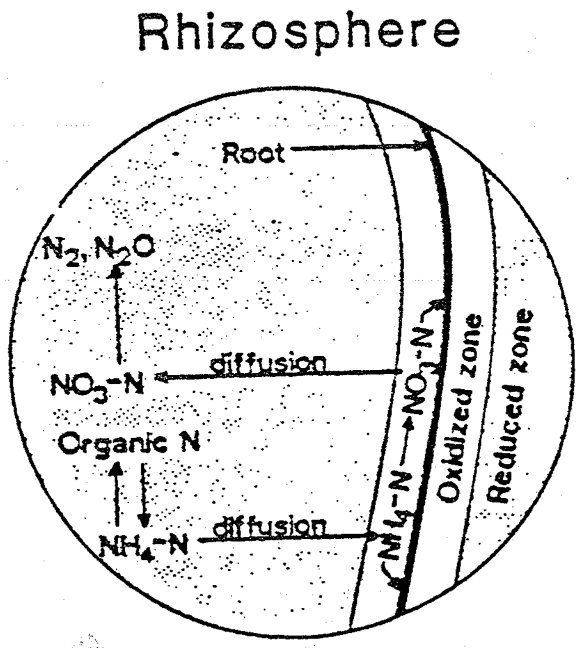

Figure 1(b). Schematic presentation of the N transformations functioning in the oxidized and reduced soil layers of rice rhizosphere.

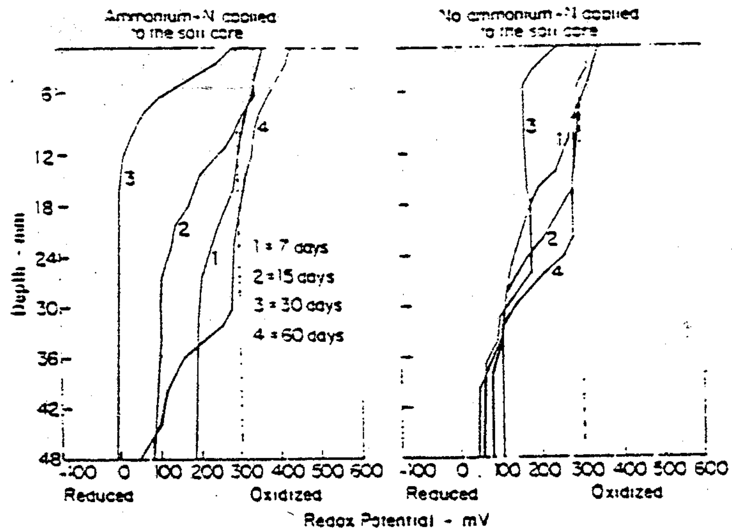

Figure 2. Thickness of oxidized soil layer of a flooded Crowley silt loam soil treated with ammonium fertilizers.

O_2 is present (Figure 1a). This profile differentiation has been characterized for flooded soils and for lake and ocean sediments, by several research workers [58, 42, 1, 22, 34].

The thickness of the oxidized soil layer can be characterized by measuring the oxidation-reduction potential of the soil profile. It is well established by earlier research [32] that O_2 disappears from a flooded soil system at Eh values of 300 mv or less. An Eh value of 300 mv (at pH 7) can be assumed to be the breakpoint between oxidized and reduced zones (Figure 2).

The oxidized soil layer is characterized by a reddish brown color formed as a result of Fe^{2+} oxidation to Fe^{3+}. The grey color of the underlying reduced layer is due to Fe^{2+}. The thickness of the oxidized soil layer is determined both by O_2 concentration of the floodwater and O_2 consumption potential of the underlying soil. Howeler and Bouldin [22] have shown that the thickness of the oxidized layer is influenced by O_2 concentration in the atmosphere above the floodwater. Increased algal activity in the floodwater of a rice field can increase the O_2 concentration of the floodwater as a result of imbalance between respiration and photosynthetic activity of the algae. These conditions can in turn increase the thickness of the oxidized soil layer. Thickness of the oxidized soil layer was found to be inversely related to carbon content of the soil. As the soil O_2 demand was increased by organic matter decomposition, the thickness of the oxidized soil layer was decreased significantly. Application of inorganic fertilizers (e.g., ammonium sulfate) was found to increase the thickness of the oxidized soil layer [45].

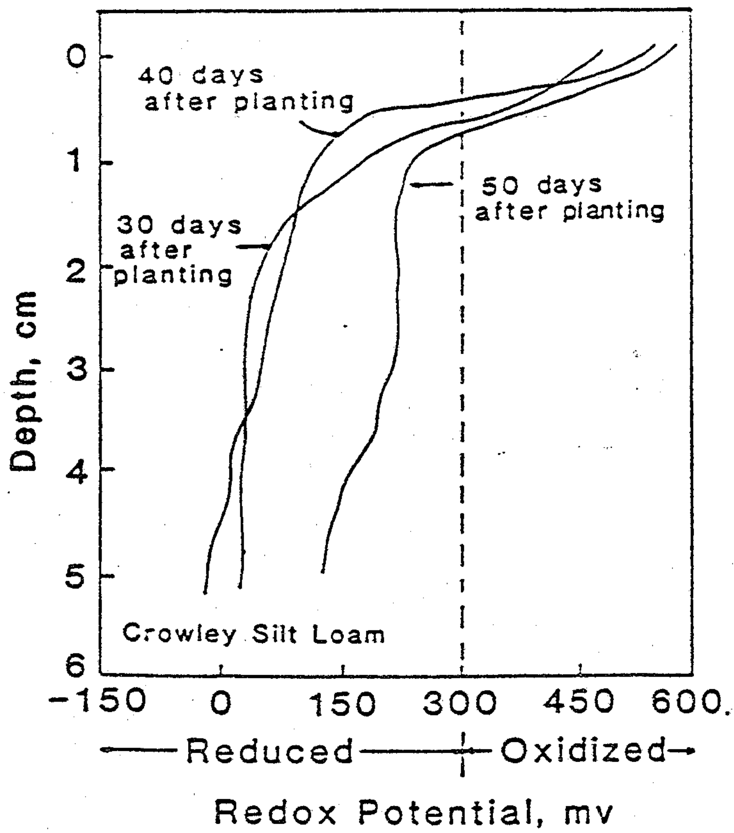

Figure 3. Thickness of oxidized soil layer of a flooded Crowley silt loam planted with rice.

Rice plants have a unique feature of transporting atmospheric O_2 through the stem to the roots, and some of this O_2 subsequently diffuses from the root into the adjacent soil layer [5, 6]. This condition creates a thin oxidized layer in the rhizosphere which can support aerobic microbial populations (Figure 1b). The development of two distinct soil layers in the rhizosphere can favor the simultaneous occurrence of nitrification in the oxidized layer and denitrification in the reduced soil layer. Thickness of the surface oxidized layer of an undisturbed soil column obtained from rice paddies was found to be less than one cm (Figure 3). At 50 days after planting, however, Eh of the soil profile had increased, indicating the oxidizing power of the rice roots.

In some rice growing areas of the world, water management practices in rice fields sometimes require draining and reflooding. This can create oxidized (drained) and reduced flooded conditions in the soil. In the rice growing areas of the United States, rice soils are maintained under flooded conditions during the rice growing period, drained at harvest, and left without flooding until the next growing season. In poorly drained soils, heavy rainfall can result in temporary flooded conditions and upon draining, oxidized conditions are restored.

Special soil and environmental conditions in a flooded rice field support two redox N processes, i.e., nitrification (oxidation of NH_4^+ to NO_3^-) and denitrification (reduction of NO_3^- to N_2). Potentially, these reactions occur in (1) continuously flooded lowland rice fields, and (2) upland rice fields which are subjected to alternate flooding and draining cycles.

Nitrification

Nitrification is a microbially mediated reaction involving the oxidation of NH_4^+ to NO_3^-. In recent years, several reviews have appeared in the literature [17, 31, 8, 57] on the microorganisms involved and the factors influencing the process in soils. To some extent, the significance of nitrification in flooded soils and sediments was also reviewed by De Datta [13], Savant and De Datta [55], and Reddy and Patrick [49]. This review will primarily focus on the role of this biochemical process in regulating forms of native soil N and applied fertilizer N in flooded soils. In flooded rice soil, nitrification can potentially occur in (1) the water column above a soil; (2) the surface oxidized soil layer; and (3) the oxidized rhizosphere of rice. Nitrification is also active in intermittently drained flooded soils.

In a flooded rice soil, the substrate for nitrification is provided from (1) ammonification (organic N to NH_4^+), and (2) application of inorganic fertilizers. In lowland rice soils, ammonification is predominantly mediated by facultative and obligate anaerobes. The characteristic features of anaerobic microbial oxidation of organic matter in lowland soils; therefore, comprise: (1) incomplete decomposition of carbohydrate into carbon dioxide, organic acids, methane, and hydrogen; (2) low energy of fermentation, resulting in the synthesis of fewer microbial cells per unit of organic carbon oxidized; and (3) low N requirements of the anaerobic metabolism.

Net release of NH_4^+ in lowland soils is determined by the ammonification and immobilization balance which is controlled by the N requirements of the microorganisms involved, nature of the organic matter, and soil and environmental factors. Agronomically, accumulation of NH_4^+ supports about 60% of the N requirements of rice. A fairly good estimate of the amount of NH_4^+ available to the rice crop can be obtained by measuring the amount of NH_4^+ accumulated during anaerobic incubation. Ammonium N accumulation in lowland rice soils was found to be rapid during the first two weeks after submergence [43]. Ammonium formed during mineralization is rapidly partitioned into (1) NH_4^+ adsorbed on the cation exchange complex, and (2) equilibrium NH_4^+ in the soil solution. Data in Figure 4 show the relative

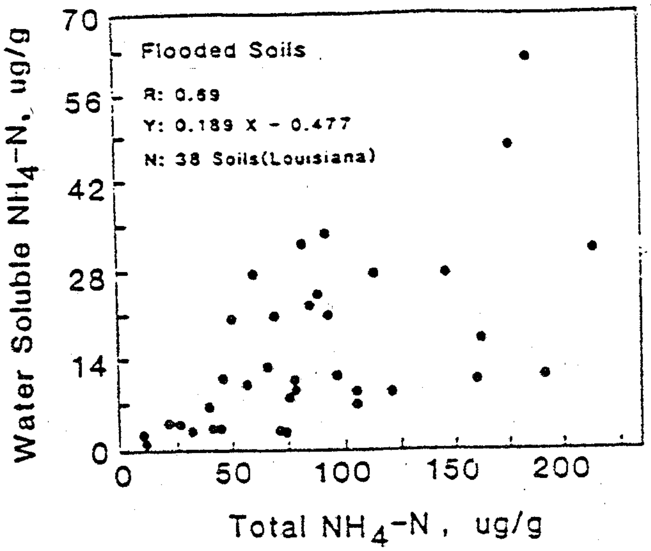

Figure 4. Relationship between water soluble NH_4^+ and total NH_4^+ of 38 flooded soils of Louisiana.

ratio of NH_4^+ in the soil solution to the total NH_4^+ present in 38 flooded soils of Louisiana. About 20% of the NH_4^+ was found to be in water-soluble form, while the remaining NH_4^+ was adsorbed on the exchange complex. Application of external sources of NH_4^+ can offset the equilibrium between these two fractions. The adsorptive capacity was found to be the most influential factor in the movement of NH_4^+ in flooded lowland soils [3].

Ammonium present in soil solution is subjected to movement in two directions, namely (1) upward movement into the surface oxidized soil layer and floodwater, and (2) movement toward plant roots. This movement of NH_4^+ is accomplished by mass flow and diffusion with rate of NH_4^+ movement in lowland soils being governed by the concentration gradient established as a result of (1) plant uptake; (2) loss mechanisms in the rhizosphere; and (3) loss mechanisms in the surface oxidized soil layer and the floodwater. Other factors influencing the movement of NH_4^+ include (1) NH_4^+ regeneration rate in the reduced soil layer; (2) concentration of NH_4^+ in the pore water; (3) cation exchange capacity of the soil; (4) types of other cations on the exchange complex; and (5) relative volume of the pore space, which is a function of the bulk density.

Results in Figure 5 (a, b) show the movement of NH_4^+ in a lowland soil without plants. The source of NH_4^+ in flooded Crowley silt loam (a predominant rice soil in Louisiana) was added fertilizer NH_4^+ plus mineralization of native soil organic N. The source of NH_4^+ in flooded organic soil (lowland rice soil in south Florida) was mineralization of soil organic N. In both cases,

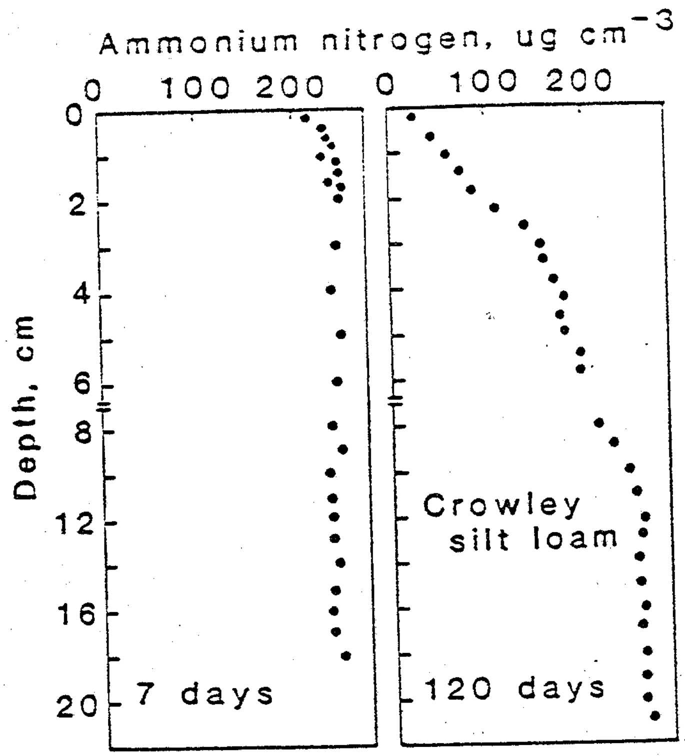

Figure 5 (a). Distribution of applied NH_4^+ in flooded Crowley silt loam with no plants (Reddy et al., 1976).

upward diffusion of NH_4^+ into the surface oxidized soil layer and the floodwater was demonstrated. Diffusion patterns of NH_4^+ will probably be different in lowland soils planted with rice and in soils where alternate flooding and draining are used as a management practice. In soils with no plants, rapid depletion of NH_4^+ in the surface soil layers was probably due to nitrification and ammonia volatilization. Results presented by Reddy and Rao [48] indicated that about 50% of the mineralized NH_4^+ was found to be lost from flooded organic soil as a result of diffusion from reduced soil to the overlying oxidized soil layer and the floodwater.

In a lowland soil planted to rice, Savant and De Datta [53, 54] and Savant et al. [56] have studied the movement of fertilizer N (prilled urea, urea supergranules, sulfur-coated urea, and urea placed in mudballs) placed in the root zone (10 cm deep). Their studies have indicated that NH_4^+ movement was downward > lateral > upward from the deep placement site. When $(NH_4)_2SO_4$ was surface applied, Bilal [9] observed appreciable concentrations of NH_4^+ in the floodwater and in the surface 1.2 cm of soil. However, when urea was surface applied, Savant and De Datta [54] measured a significant amount of NH_4^+ at the 12–14 cm depth, 4 weeks after application. Downward

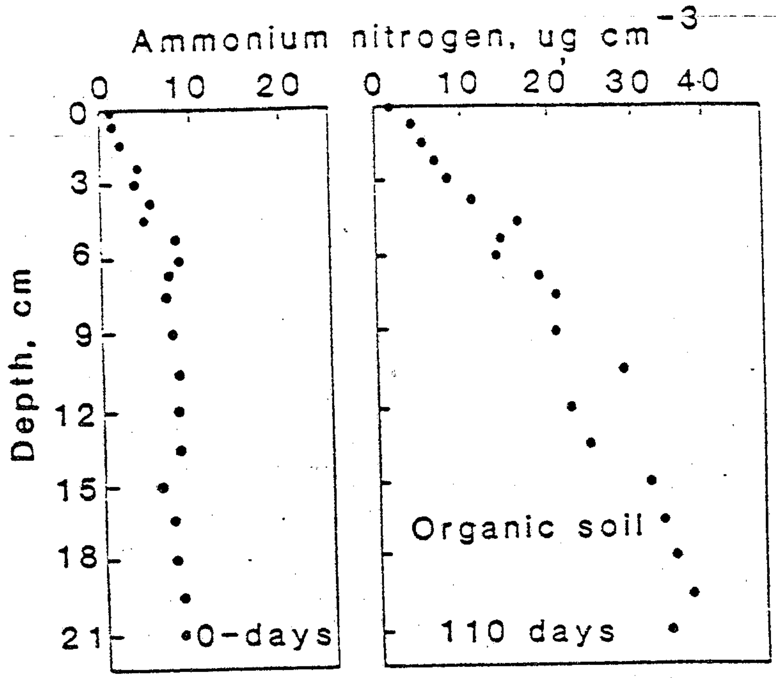

Figure 5 (b). Distribution of mineralized NH_4^+ in flooded organic soil with no plants (Reddy and Rao, 1983).

movement of plant available N can result in significant loss from coarse textured soils. Vlek et al. [69] measured serious loss in fertilizer N after placement of urea supergranules in lowland soils having a percolation rate of 5 mm day^{-1}.

Movement of NH_4^+ either upward or downward as a result of concentration gradients can decrease the amount of plant available N in the root zone, thus decreasing the fertilizer N use efficiency by rice. The transport of NH_4^+ by ionic diffusion from the reduced soil layer to the oxidized soil layer is influenced by organic matter status of the soil, presence of reduced Fe and Mn, bulk density, and rate of nitrification in the surface oxidized soil layer and in the oxidized rhizosphere.

Ammonium N diffusing into the floodwater and into the oxidized soil layer is highly unstable because of rapid oxidation to NO_3^-. Since the process of nitrification depends on the metabolism of nitrifying organisms, it is imperative that the organisms be present in adequate numbers to achieve rapid oxidation of NH_4^+. Generally, fertilized soils have larger populations of nitrifiers compared to unfertilized soils [4], and surface application of NH_4^+ fertilizers in lowland soils can potentially enhance the activity of nitrifying organisms. Nitrification rate was also found to be rapid in water containing dissolved CO_2, compared to CO_2-free water [47]. Under specialized conditions, a portion of NH_4^+ can be converted into aqueous NH_3 when pH of the floodwater is > 8.0. In the floodwater of a lowland soil, high pH conditions can exist when photosynthetic activity of algae is actively withdrawing the dissolved CO_2 from the water, thus increasing the pH at mid-day and decreasing pH at night when respiratory activities liberate free CO_2 into the water [28]. Aqueous NH_3 formation during photosynthetic periods of algae can decrease the activity of nitrifying bacteria. However, research has shown that most of the active nitrification occurs in the oxidized surface soil layer [10].

Nitrification of NH_4^+ in the floodwater and in the oxidized soil layer was observed by several research workers [11, 66, 64, 36, 9, 73, 50, 48]. Significant concentration of NO_3^- was observed in the oxidized soil layer of flooded Crowley silt loam (Figure 6). In soils with low organic matter content, the oxidized soil layer is usually thick, and most of the nitrification occurs in this zone such that no NH_4^+ diffuses into the floodwater. In soils with high organic matter content, the oxidized layer is thin, and under

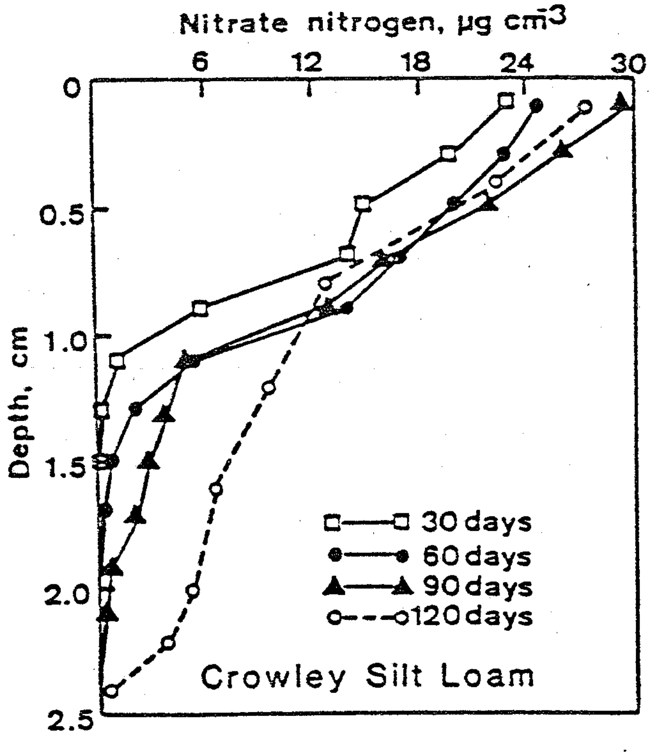

Figure 6. Distribution of NO_3^- in the oxidized and reduced soil layers of flooded Crowley silt loam soil (Reddy et al., 1976).

these conditions. NH_4^+ tends to diffuse into the floodwater. Nitrification is evidenced by the significant concentration of NO_3^- formed in the floodwater of an organic soil [48]. In a field study in California, surface application of NH_4^+ fertilizer significantly increased the NO_3^- levels in the floodwater, indicating rapid nitrification [9].

Another potential active site of nitrification in lowland rice soil is the rhizosphere. The diffusive flux of O_2 from the rice roots to the adjacent soil can create an oxidized environment around the roots. This oxidized soil rhizosphere can potentially support nitrification of NH_4^+ diffused from surrounding reduced zones. However, no experimental evidence has been reported on the significance of this process in the rice rhizosphere.

Denitrification

Under O_2-free conditions, many microorganisms can utilize NO_3^- as a terminal electron acceptor, a process called NO_3^- respiration or dissimilatory NO_3^- reduction. The pathway involving the reduction of NO_3^- to gaseous end products ($NO_3^- \rightarrow NO_2^- \rightarrow HNO \rightarrow NO \rightarrow N_2O \rightarrow N_2$) is usually known as denitrification, and the pathway of reduction to NH_4^+ ($NO_3^- \rightarrow NH_2OH \rightarrow NH_4^+$) is known as dissimilatory reduction. The intermediate N oxides of this process can also be used as electron acceptors. In recent years, several reviews on this process have been reported [39, 14, 63, 24, 40, 16]. Dissimilatory reduction of NO_3^- to NH_4^+ can potentially occur in soils and sediments high in organic matter which are anaerobic for long periods, including sediments, anaerobic digestors and continuously flooded lowland soils [23, 25, 62]. Denitrification, on the other hand, can be a major pathway of NO_3^- loss from soils where temporary reduced conditions exist or soils which are less intensively reduced (soils with low organic matter content). Denitrification has been shown to be a dominant process in soils with Eh values of 200 to 300 mv, while NO_3^- reduction to NH_4^+ occurs in soils with Eh values of < -100 mv [32, 12].

In flooded rice soils, denitrification primarily occurs in the reduced soil layer devoid of O_2. In the absence of O_2, NO_3^- is used as an electron acceptor by the facultative anaerobes during the oxidation of soil organic matter and other organic substrates. Most of the denitrification in lowland soils probably occurs in the proximity of the oxidized-reduced interface, which is less intensively reduced. The significance of this process has been extensively studied by several researchers as evidenced in recent reviews.

The supply of NO_3^- in lowland soils is primarily derived by nitrification of added ammoniacal or urea fertilizers. The NO_3^- formed in the oxidized soil layer or in the oxidized rhizosphere is constantly supplied to the reduced layer by diffusion in response to the concentration gradient established across the interface. The rate of denitrification is dependent on the NO_3^- supplying capacity of the system, presence of available carbon substrate, and other soil and environmental variables. On the other hand, the flux of NO_3^- is governed by the denitrification rate in the reduced soil layer, thickness of the oxidized soil layer, floodwater depth, and NO_3^- concentration in the floodwater and in the oxidized soil layer. Loss of NO_3^- from the floodwater has been found to increase with increased availability of available carbon in the underlying anaerobic soil layer [15]. Nitrate diffusion rate in flooded lowland soils has been found to be in the range of 1.2 to 1.33 cm^2 day^{-1}, which is about 7 times faster than NH_4^+ diffusion. The high diffusion coefficient values for NO_3^- are expected, since NO_3^- is an anion, is not adsorbed on the exchange complex, and tends to move rapidly in the soil water.

Nitrogen loss due to denitrification in the presence of rice plants was also found to be significant; however, the magnitude of N loss was lower compared to that for systems without plants [46]. Garcia [19, 20] has demonstrated the positive effect of the rice rhizosphere on denitrification by measuring N_2O reductase activity. Woldendorp [72] suggested that plant roots can accelerate denitrification in the rhizosphere by taking up O_2 and excreting organic substances which can serve as an energy source. Denitrifying activity in the rice rhizosphere was found to be maximum in the early stages of rice growth [21] and to decrease progressively with the age of the plant. Mandal and Datta [27] observed decreased N_2 production during denitrification as the rice plant approached maturity. Smith and Delaune [60] measured significantly greater $N_2O + N_2$ production in the first 2 days after fertilization for lowland soil planted with rice as compared to nonplanted soil. In a lowland rice soil, NO_3^- may be limiting overall N losses due to nitrification-denitrification in the rhizosphere. The controlling factor of N loss from the rhizosphere is the competition for NO_3^- uptake between denitrifying bacteria and rice roots.

Nitrification-denitrification

Both nitrification and denitrification reactions are known to occur simultaneously in lowland rice fields where both oxidized and reduced zones exist. In flooded lowland soil these reactions potentially occur in (1) the surface oxidized soil layer and the underlying anaerobic soil layer, and (2) the rhizosphere. Nitrification-denitrification reactions can also occur in soils subjected to alternate flooding and draining conditions. Ammonium accumulates during flooding; then when soil is drained NH_4^+ is nitrified and NO_3^- accumulates. Upon reflooding NO_3^- can be potentially lost through denitrification.

The significance of nitrification-denitrification reactions in flooded lowland soils had been recognized as early as 1935 [58]. Later this process was confirmed by several incubation experiments [41, 59, 2, 33, 11, 35, 64, 73, 44, 50, 37]. The extent of N losses through nitrification-denitrification reactions in flooded lowland soils is dependent on the supply of NH_4^+ to the oxidized zones of the soil profile where nitrification potentially occurs, and supply of NO_3^- to reduced zones of the soil where NO_3^- reduction is potentially active. An NH_4^+ concentration gradient is established across the oxidized-reduced soil interface as a result of nitrification, while NO_3^- concentration gradient is established as a result of NO_3^- reduction in the reduced zones. Both NH_4^+ and NO_3^- diffuse into the respective zones in response to the concentration gradient. The sequential processes involved in N loss from flooded lowland soil are ammonification, NH_4^+ diffusion, nitrification, NO_3^- diffusion, and denitrification. The ultimate conversion of NH_4^+ to N_2 gas by these processes was demonstrated in flooded Crowley silt loam soil using ^{15}N [37]. From the data reported in the literature, it can be concluded that NH_4^+ diffusion and nitrification appear to be limiting N loss from most flooded lowland soils, and that NO_3^- diffusion and denitrification usually occur at a rapid rate and are not likely to limit the overall process. Nitrification reactions both in the surface (oxidized) soil layer and in the rhizosphere are controlled by O_2 diffusion and the rate of O_2 consumption by nitrifying bacteria and heterotrophic bacteria involved in organic matter decomposition.

Although controlled experiments conducted in the laboratory demonstrate that gaseous losses of N_2 and N_2O occur as a result of nitrification-denitrification, there is no direct evidence available for field conditions. However, field studies have provided indirect evidence on the possibility of these processes occurring in lowland rice soils. Results of pot and field experiments (Table 1) using ^{15}N indicate that about 35% of added N (ammonium or urea) is recovered by the plant and about 26% of the added N remains unaccounted for. Recovery of N in the greenhouse experiments was found to be generally much higher than for field experiments. Loss of N in these systems was attributed to NH_3 volatilization, nitrification-denitrification, and leaching. However, few field studies strongly suggest the possibility of nitrification-denitrification as the loss mechanism functioning in a rice field. In a field study by Patrick and Reddy [38], about 30% of the added N was lost when $^{15}NH_4$ was applied at the 7.5 cm depth (Figure 7). Serious losses were observed 4 weeks after application of fertilizer, indicating the possibility of nitrification in the rhizosphere and in the surface oxidized zone, and subsequent denitrification in the reduced zone. In another study by Wetselaar [70], about 59% of the added N was unaccounted for from surface-applied fertilizer, and 45% of the added N was not accounted for in plots receiving fertilizer by deep placement. Ammonia volatilization accounted for only 4.3% of the added N when fertilizer was surface-applied, and for only 0.7% of the added N when fertilizer N was applied by deep placement. The unaccounted-for N showed a gradual increase with time, indicating the strong possibility of coupled nitrification and denitrification. When urea was incorporated into a flooded lowland soil under tropical field conditions [26], about 31% of the added N was not accounted for, while about 10% of the added N was lost through NH_3 volatilization and about 8% was lost through

Table 1. Fate of applied ammonium sulfate and urea fertilizers in flooded soils planted with rice (greenhouse and field studies)

	Added ^{15}N fertilizer (%)	Number of studies
Plant uptake	35.1 ± 16.5	40
Loss	26.7 ± 14.0	36
Soil & Roots	38.2	

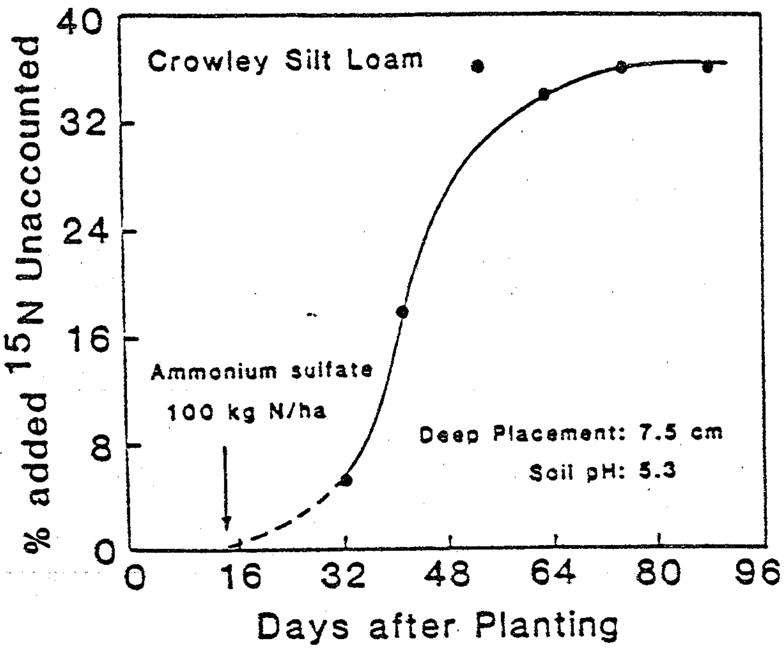

Figure 7. Percent of added $^{15}NH_4$ fertilizer unaccounted for at various times during rice growing season (Patrick and Reddy, 1976b).

leaching. These results also suggest the possibility of nitrification-denitrification. Freney et al. [18] and Smith et al. [61] attempted to measure N_2O emission under field conditions to demonstrate direct evidence for nitrification-denitrification. Nitrous oxide emissions amounted to less than 0.1% of the applied $(NH_4)_2SO_4$ or urea-N. Because of great demands for electron acceptors in the reduced zones of lowland soils, N_2O produced during denitrification is rapidly converted to N_2 during microbial respiration. Since N_2O is only a minor end product of this process, the low rates of evolution do not represent the total loss of N due to denitrification.

Water management in lowland fields can also influence the extent of N losses as a result of nitrification-denitrification. In many rice growing areas of the world, continuous flooding is usually not maintained, probably due to a shortage of water. In the United States, rice is either water-seeded or drilled-seeded. When rice is directly water seeded, soils are usually drained subsequently to lower water depth in order to enhance seedlings and root development, whereas direct-seeded fields are only flooded after the seedlings are about 10–15 cm high. In either case, alternating flooded (reduced or anaerobic) and drained (oxidized or aerobic) conditions are created. In the tropics and the subtropic areas of the world, soils used for rainfed-lowland rice cultivation may also experience alternate flooding and drained cycles, often due to heavy rainfall events and poor soil drainage. Frequent flooding and draining cycles not only decrease the amount of residual fertilizer N, but also drastically affect reserves of soil organic N.

Organic N is converted to NH_4^+ under both flooded and drained conditions, but at different rates. Under drained conditions, NH_4^+ is oxidized to NO_3^-, and when the soil is reflooded, NO_3^- is denitrified. Wijler and Delwiche [71] noted that alternating oxidized and reduced conditions should result in greater total N loss from the soil than would be found under continuously reduced conditions. The length of each oxidized and reduced period in the soil may vary, depending upon soil/environmental conditions. Reddy and Patrick [44] observed a total N loss of up to 24% from Crowley silt loam soil which underwent alternating oxidized and reduced periods of 2 and 2 days during a 4-month incubation. Increasing the duration of the alternating aerobic and anaerobic periods decreased the amounts of N loss.

In a greenhouse study, Sah and Mikkelsen [51] observed significantly lower plant available N in a soil which underwent alternate flooded-drained conditions, as compared to continuous flooding or alternate flooding and drained conditions. Among the N sources evaluated, urea and $(NH_4)_2SO_4$ had similar effects, but sulfur-coated urea maintained significantly lower levels of plant available N in the soil. Nitrogen use efficiency by rice decreased from 67% under continuously flooded conditions to 35% when soil underwent two cycles of alternate flooded and drained conditions [52]. Nitrification inhibition can significantly prevent the loss of added and native N in rice soils managed under alternate flooded and drained conditions.

Conclusions

Extensive laboratory incubation studies reported in the literature clearly establish the role of nitrification-denitrification reactions in N loss from flooded lowland soils. Despite many greenhouse and field experiments conducted in serveral parts of the world to evaluate the fate of applied fertilizer ^{15}N in lowland soil, quantitative information identifying the key processes involved is still not available. None of the field studies using ^{15}N have documented direct evidence (measuring gaseous end products) of nitrification-denitrification. Mass balance of ^{15}N in the field studies attributes the unaccounted-for N to potential loss via nitrification-denitrification. NH_3 volatilization, and leaching.

Nitrogen loss due to nitrification-denitrification can potentially occur when fertilizer is either surface applied or placed in the root zone. Surface-applied fertilizer, if in ammoniacal form, can be rapidly converted to NO_3^-, since the applied fertilizer granules sink through the floodwater and settle on the surface oxidized layer. Slow-release fertilizers can reduce losses due to this process. However, when urea fertilizer is surface applied, significant amounts of N can be lost through volatilization, since hydrolysis of urea alters the alkalinity of the floodwater [67, 68]. Although NH_3 volatilization losses can be reduced by placing the fertilizer in the root zone [28], it is still unknown whether N loss due to nitrification-denitrification can be prevented. An active (aerobic) rhizosphere can potentially increase the rate of nitrification and subsequent denitrification, thus decreasing the amount of plant available N in the root zone. Future research in this area is urgently needed in order to design better management practices to increase the efficiency of N utilization by rice and to conserve the amount of fertilizer to be applied.

Nitrogen losses due to nitrification-denitrification reactions can be prevented if (1) nitrification is prevented, thus maintaining inorganic N in NH_4^+ form; (2) placing the fertilizer in the root zone; and (3) increasing the O_2 demand in the root zone by increasing the organic matter content of the soil. These are some of the potential management strategies that can be used to prevent N losses from rice fields.

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