# Nitrate Dynamics during the Aerobic Soil Phase in Lowland Rice-Based Cropping Systems

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## ABSTRACT

**In tropical rice (Oryza sativa L.) lowlands, soil $N0_3$ is lost during the transition from the dry to the wet season. To understand how soil and crop management influences $N0_3$ loss, we examined $N0_3$ dynamics during a 2-yr period in an Alfisol in the Philippines: weedy, weedfree, and frequently tilled main plots during the February to May dry season (DS), and Sesbania rostrata (Brem. & Oberm), mungbean [Irgna radiata (L.) R. Wilczek var. radiatal, weedy, and weed-free subplots during the May to July dry-to-wet transition (DWT). Weed-free plots were maintained by removing weeds as they emerged. Soil $NH_4$ (0-60 cm), which was not affected by management, averaged only 9 kg N ha'. While soil $N0_3$ increased under frequent tillage and weed-free fallowing, it decreased rapidly under weedy fallowing. On most sampling dates, $N0_3$ was the highest in DS tilled main plots. The widest range of $NO_3$ during the DS or DWT was 14 to 110 kg N ha $^{-1}$ in the first year, and 12 to 155 kg N ha$^{-'}$ in the second. During the second half of the DWT, $N0_3$ declined in all plots, but more markedly when plants were present than when not, indicating plant N uptake. Aboveground plant N prior to permanent flooding ranged widely from 31 kg N ha$^{-'}$ in weeds to 222 kg N ha$^{-'}$ in $N_2$-fixing *S. rostrata* plants in the first year, and 37 to 193 kg N ha$^{-'}$ in the second. The data also indicate $NO_3$ leaching following heavy rains. Further, the high waterfilled pore space, exceeding 0.7 L L$^{-'}$ in the second half of the DWT and approaching 1 L L' with permanent flooding, is presumed to have favored denitrification. Regardless of DS management or DWT plant N accumulation, the soil was virtually depleted of $N0_3$ soon after permanent flooding; $N0_3$ rarely exceeded 10 kg N ha$^{-'}$ when measured after 9 d (first year) and 11 d (second year) of permanent flooding. Our data indicate the immense capacity of this lowland soil to accumulate $NO_3$ and the marked effect of DS and DWT management on the amount of $N0_3$ that actually accumulates. In tropical rice lowlands, soil and crop management during the DS should be designed to limit $N0_3$ buildup so as to reduce $N0_3$ that is prone to loss during the DWT.**

O NE OR TWO CROPS of wet-season rice grown in flooded or saturated soil is characteristic of most tropical rice lowlands. The land is, however, reverted to upland condition during the dry season, with weedy fallowing as the least intensive and high-input cropping as the most intensive management practices. The soil, which is anaerobic for most of the rice crop period, dries and becomes aerobic during the DS. The duration of this aerobic soil phase ranges from a few to several months. In most of the rainfed lowlands of tropical Asia where a single crop of rice is grown, the soil can be aerobic for up to 8 mo during the year (George et al., 1992).

In most tropical rice lowlands, the transition from DS aerobic to wet-season anaerobic soil condition occurs approximately during a 1- to 2-mo period, depending on the onset of rain. Even with sufficient water from early rains, this DWT is too short for production of most upland crops. Additionally, the soil can be intermittently flooded from heavy rains. Hence, weedy fallowing is the dominant practice during DWT, but green manure and short-duration grain legumes, especially those capable of withstanding brief periods of flooding, are sometimes grown (Buresh and De Datta, 1991; Garrity and Flinn, 1988; George et al., 1992). The DWT ends when the soil is permanently flooded for rice culture.

After soil flooding, $NO_3$ is lost by leaching or by denitrification to $N_2$ and $N_2O$ gases. Buresh et al. (1989), based on $NO_3$ data from three Philippine lowland sites, reported the likely loss of 39 to 91 kg $NO_3N$ ha$^{-1}$ from the top 60-cm layer following flooding for rice production. The potential for buildup of $NO_3$, avenues of its loss, and ways to conserve it in rice lowlands have been conceptually addressed (Buresh and De Datta, 1991; George et al., 1992). Data reported subsequently (Buresh et al, 1993) showed that potential $NO_3$ losses were reduced when flooded rice was preceded by either weedy fallow or *Sesbania ros*trata green manure, compared with a bare fallow. Apart from these reports, $NO_3$ dynamics during the aerobic soil phase in tropical rice lowlands are relatively unexplored.

It is likely that, for a given soil under a given climate, the $NO_3$ that is present during the DWT is primarily a function of management during the DS preceding it. As cropping during the DS becomes more intensive, soil is subjected to increased tillage and irrigation, and often N inputs. An example is input-intensive vegetable production during the DS in Philippine rice lowlands. Nitrate buildup is likely to vary widely depending on these management practices (Dowdell et al., 1983; El-Haris et al., 1983; Lamb et la., 1985; Seneviratne and Wild, 1985).

Depending on DS $NO_3$ buildup, the effect of DWT crops on $NO_3$ loss is also likely to vary. The ability of DWT crops to deplete soil $NO_3$ before flooding would depend on their N requirements. Nitrogen up

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Abbreviations: DS, dry season; DWT, dry-to-wet transition; WFPS, water-filled pore space.

take by DWT weed biomass in rice lowlands is not large; weed N prior to flooding for rice at several Philippine sites ranged from 15 to 42 kg N $ha^{-1}$ (Buresh et al., 1989, 1993). In contrast, legumes such as S. rostrata can accumulate in excess of 200 kg N $ha^{-1}$ in about 50 to 60 d in the Philippines (Becker et al., 1990; Buresh et al., 1993), and if soil N supply is sufficient to meet this N requirement, most N is likely to be derived from soil, not biological $N_2$ fixation (George et al., 1992).

Understanding $NO_3$ dynamics of rice lowlands is important not only from the perspective of $NO_3$ loss and its probable negative impacts on the environment, but also from the point of retaining this N on land and using it effectively. While the limited data available (Buresh et al., 1993) indicate the role of DWT vegetation in limiting $NO_3$ loss, the consequence of varied soil and crop management during the DS, possibly resulting in a range of $NO_3$ prior to the DWT, has not yet been addressed. Data on $NO_3$ dynamics under a range of management are necessary to devise practices to conserve and effectively use soil N in lowland ricebased cropping systems.

To achieve a wide range of soil $NO_3$ at the end of DS, we included repeated tillage and water application (as a proxy to intensive cultivation) as the most intensive and traditional weedy fallow as the least intensive management practice. Plant N accumulation during the DWT was varied by using weeds, mungbean (for grain), S. rostrata (for green manure), or by having no plants. We illustrate the case for variable loss of $NO_3$ in a Philippine rice lowland depending on varied management during the DS and growing of plants of varied N requirements during the DWT.

## MATERIALS AND METHODS

### Experimental Plan

Experiments were conducted in 1990 and 1991 at the research farm of the International Rice Research Institute, Los Banos, Philippines. The soil is a Tropudalf (Wopereis et al., 1993) and contained 276 g clay $kg^{-1}$, 365 g silt $kg^{-1}$, 345 g sand $kg^{-1}$, 14 g organic C $kg^{-1}$, 1.2 g total N $kg^{-1}$, and 0.022 g Olsen P $kg^{-1}$ in the 0- to 20-cm layer. The top 20 cm soil layer had a saturated hydraulic conductivity of 127 cm $d^{-1}$ (Wopereis et al., 1993), pH (1:1 w/v in $H_2O$) of 6.6, and cation-exchange capacity of 28 $cmol_c$ $kg^{-1}$. There were three DS (February-May) and four DWT (May-July) treatments set up in a randomized complete block design with treatments assigned in a split-plot arrangement. The treatments were replicated four times and repeated in the same plots in the second year. At the start of the DS, weedy, weed-free, and tilled wet-dry (alternating tillage and watering) fallows were established as main plots. During the subsequent DWT, *S. rostrata* and mungbean crops, and weedy and weed-free fallows were established as subplots of DS treatments. The setup was such that each of the DS treatments also continued as one of the four subplot treatments during the DWT. Thus, the weed-free subplot in the weed-free main plot provided continuity for the DS weed-free fallow. Similarly, the weed-free subplot in the tilled wet-dry main plot and weedy subplot in the weedy main plot provided continuity for their respective DS treatments.

### Field Management

The main plot treatments were initiated on 31 Jan. 1990 after the harvest of a previous rice crop and removal of all straw except 5-cm stubble bases. Subplots of 5 by 5 m were established with 15-cm-high soil levees separating the plots. All plots were rototilled to 20-cm depth at the start. From the weed-free plots, weeds were removed by hand as they emerged, and discarded. Native weeds were allowed to grow in the weedy fallow treatment. Weed establishment was uniform across replicates. The dominant weeds were spiny amaranth (*Amaranthus spinosus L.),* horse purslane (*Trianthema portulacastrum* L.), southern crabgrass [*Digitaria ciliaris* (Retz.) Koeler], and itchgrass [*Rouboellia cochinchinensis* (Lour.) W. Clayton]. The tilled wet-dry plots were subjected to alternating tillage (20cm depth) and water application during the DS to maximize NO, buildup. These plots were watered approximately to field capacity (4.5 g $kg^{-1}$) each time the soil water (20-cm depth) decreased to approximately 50% of field capacity based on tensiometer and gravimetric soil water measurements. Soil was tilled 3 to 5 d after each water application. The tilled wet-dry plots received five additional tillage and water applications (45 cm each time) until 27 Apr. 1990.

All plots were tilled (20-cm depth) on 27 and 28 Apr. 1990 and the four subplot DWT treatments were initiated. Seeds of *S. rostrata* and mungbean were sown on 2 May 1990 in furrows 30 cm apart to achieve a final population density of 400 000 plants $ha^{-1}$. Mungbean seeds were preinoculated with peatbased rhizobial inoculant. Plots were lightly irrigated to aid germination. In weedy fallow subplots, native weeds were allowed to grow as in the DS weedy fallow main plot. The weed population was the same as during the DS, but produced greater biomass. On 8 May 1990, *S. rostrata* was reseeded to fill gaps left from earlier seeding. No subsequent tillage or irrigation was given to any plots, but there were intermittent rains.

On 13 and 14 July 1990, *S. rostrata* and mungbean were cut at soil level, chopped into small pieces, and spread on the soil in their respective plots. Plots were subsequently flooded and puddled. Rice (cv. IR 72) was transplanted on 20 July 1990. A second crop of rice was transplanted in early November 1990 after the harvest of the first crop in late October.

In 1991, all treatments were repeated in the same plots. Field operations were identical to those in 1990 except for differences noted below. Main plot treatments were initiated on 5 February after the harvest of the second rice crop of 1990 on 29 Jan. 1991. All plant materials except rice stubble bases (5cm height) were removed at the start. No tillage was done except in the tilled wet-dry plots, which received five additional tillage and four more water applications until 27 Apr. 1991. Subplot treatments were initiated by tilling all plots on 28 Apr. 1991. Mungbean was seeded on 2 May 1991 and *S. rostrata* on 7 May 1991. Due to germination failure, *S. rostrata* was reseeded on 12 May 1991 in new furrows made after a light tillage. On 7 and 8 July 1991, *S. rostrata* and mungbean aboveground biomass were cut and spread on the soil. Subsequently, the plots were flooded and puddled, and rice was transplanted on 13 July 1991.

### Field Sampling

Soil samples were collected at 2- to 4-wk intervals. In 1990, samples were collected from 0- to 20- and 20- to 60-cm depths. Sampling depths were 0 to 20, 20 to 40, and 40 to 60 cm in 1991. From each plot, four locations were sampled each time using a 5-cm-diam. auger. The samples from the four locations were immediately composited by depth, mixed thoroughly, and subsamples were transferred to a plastic bag for later KCl extraction. Another subsample was placed in a preweighed aluminum can for field soil water determination. All samples were placed immediately in an ice box and transported to the laboratory for further processing.

Using a bulk density core (5-cm-diam) sampler, soil samples were collected periodically from the same depths as those for KCl extraction for bulk density determination. Soil particle density was determined once and found to average 2.55 for the 0- to 40-cm layer and 2.58 for the 40- to 60-cm layer.

**Table 1. Soil $NH_4$ (0–60 cm) as influenced by fallow management† during the dry season and the dry-to-wet transition in a Philippine rice lowland.**

| Year 1990 | | | | Year 1991 | | | |
|---|---|---|---|---|---|---|---|
| Date | Weedy | Weed-free | Tilled | Date | Weedy | Weed-free | Tilled |
| | kg N ha⁻¹ | | | | kg N ha⁻¹ | | |
| 1 Feb. | 14 | 14 | 14 | 5 Feb. | 7 | 8 | 6 |
| 26 Feb. | 9 | 10 | 23 | 5 Mar. | 7 | 7 | 7 |
| 22 Mar. | 5 | 10 | 9 | 26 Mar. | 7 | 9 | 7 |
| 26 Apr. | 10 | 11 | 9 | 16 Apr. | 7 | 9 | 3 |
| 23 May | 10 | 12 | 16 | 6 May | 21 | 25 | 14 |
| 13 July | 5 | 7 | 9 | 21 May | 6 | 4 | 5 |
| 27 July‡ | 17 | 12 | —§ | 4 June | 5 | 7 | 6 |
| | | | | 18 June | 6 | 2 | 3 |
| | | | | 5 July | 7 | 5 | 4 |
| | | | | 22 July¶ | 18 | 11 | 14 |

† Fallow management initiated on 1 Feb. 1990 and on 5 Feb. 1991.
‡ 9 d after initiation of permanent flooding of all plots and incorporation of weed residues in weedy fallow.
§ Not measured.
¶ 11 d after initiation of permanent flooding of all plots and incorporation of weed residues in weedy fallow.

To determine aboveground N accumulation, weeds from DS weedy fallow were sampled prior to the initiation of the DWT subplot treatments and DWT legume and weed subplots were sampled prior to permanent flooding.

### Laboratory Analyses

The field subsample for soil water content was immediately weighed for total wet eight. From the sample for KCl extraction, 40 to 60 g of fresh soil were transferred to a plastic bottle and extracted with 150 mL of 2 M KCl for 1 h. The soil suspension was then filtered through Whatman no. 1 filter paper and the filtrate stored in a refrigerator for later analysis. Simultaneously, another subsample was weighed in a pre-weighed aluminum can for determination of soil water content at the time of KCl extraction.

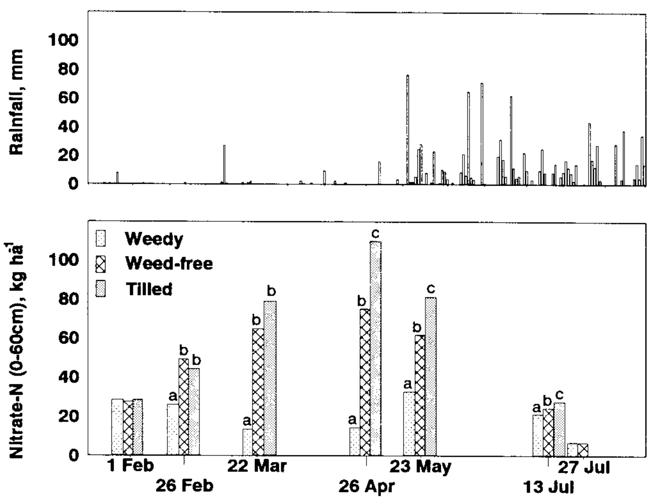


**Fig. 1. Soil $NO_3$ (0–60 cm) as influenced by management and rainfall during the dry season (DS) and the dry-to-wet transition (DWT) in a rice lowland, 1990. Dry season management was initiated on 1 February after tilling the soil uniformly to 20-cm depth. Soil $NH_4$ (0–60 cm) on 1 February was 14 kg N ha⁻¹. Tilled wet–dry fallow plots received five more tillage (20 cm) and five water applications (4–5 cm) until 27 April. All plots were tilled on 27 to 28 April. On 2 May, DWT treatments of mungbean and *Sesbania rostrata*, and weedy and weed-free fallow were established as subplots in all DS fallow plots. Nitrate values during the DWT are averages across subplot treatments. Bars with the same letter for a given date do not differ significantly by LSD(0.05).**

Samples for water content determinations were dried in an oven at 105 °C for a minimum of 24 h and then weighed. Water-filter pore space was calculated from gravimetric water content, bulk density, and particle density (Doran et al., 1990) and expressed in liters per liter.

Nitrate contents in the KCl extracts were determined by the Cd reduction method and $NH_4$ was determined by steam distillation with MgO (Keeney and Nelson, 1982). Both $NO_3$ and $NH_4$ were expressed on a dry-soil basis in kilograms of N per hectare.

Dry season weed and DWT legume and weed samples were oven dried (65 °C) and weighed. The N content was determined on ground samples by the micro-Kjeldahl method (Bremner and Mulvaney, 1982) and total N was expressed in kilograms of N per hectare.

### Data Analyses

Data from each year were separately subjected to analyses of variance. The data collected from weedy, weed-free, and tilled wet-dry treatments were analyzed as one set. The data collected during the DWT from subplot treatments were analyzed as a split plot in another set. Because of positive correlations between mean and variance at several sampling dates, $NO_3$ data were transformed to log (x + 1) before subjecting to analysis of variance.

## RESULTS AND DISCUSSION

Soil and crop management during both the DS and the DWT substantially influenced soil $NO_3$ but not soil NH4. Ammonium in the top 60-cm soil layer averaged only 9 kg N ha⁻¹ across 45 observations before permanent flooding in 1990 and 1991 (Table 1). The low $NH_4$ levels along with the substantially high $NO_3$ levels in the top 60-cm layer under certain management (Fig. 1 and 2) are indicative of the highly favorable soil environment during the DS and the DWT in rice lowlands for immediate conversion of mineralized $NH_4$ to $NO_3$.

The pattern of $NO_3$ buildup with time was the same in both years, but $NO_3$ at any given time varied widely depending on management and rainfall (Fig. 1 and 2; Tables 2 and 3). With the exception of weedy fallow, $NO_3$ continued to increase, reaching a maximum in the tilled main plot at the end of the DS in 1990 (110 kg N ha⁻¹ on 26 April) and in the *S. rostrata* subplot of the

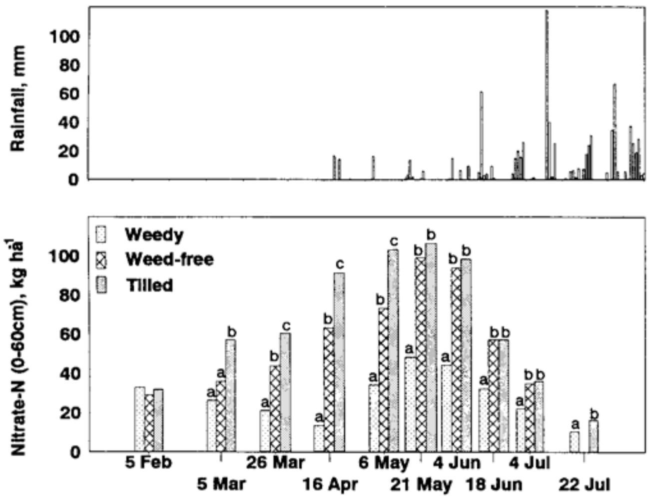


**Fig. 2. Soil $NO_3$ (0–60 cm) as influenced by management and rainfall during the dry season (DS) and dry-to-wet transition (DWT) in a rice lowland, 1991. Dry season management was initiated on 5 February after tilling the soil uniformly to 20-cm depth. Soil $NH_4$ (0–60 cm) on 5 February was 6 kg N ha$^{-1}$. Tilled wet–dry fallow plots received five more tillage (20 cm) and four water applications (4–5 cm) until 27 April. All plots were tilled on 28 April. On 2 May, DWT treatments of mungbean and *Sesbania rostrata*, and weedy and weed-free fallow were established as subplots in all DS fallow plots. Nitrate values during the DWT are averages across subplot treatments. Bars with the same letter for a given date do not differ significantly by LSD(0.05).**

**Table 2. Soil $NO_3$ (0–60 cm) as influenced by fallow or crop† management and rainfall during the dry-to-wet transition in a Philippine rice lowland, 1990.**

| Management | | | | |
|---|---|---|---|---|
| Dry season | Dry-to-wet transition | 23 May (160 mm)¶ | 13 July‡ (504 mm) | 27 July§ (142 mm) |
| | | kg N ha$^{-1}$ | | |
| Weedy | *Sesbania rostrata* | 38 | 21 | 9 |
| | Mungbean | 33 | 21 | 10 |
| | Weeds | 28 | 13 | 8 |
| | Weed-free | 32 | 28 | 9 |
| Weed-free | *S. rostrata* | 61 | 26 | 6 |
| | Mungbean | 68 | 25 | 7 |
| | Weeds | 58 | 13 | 6 |
| | Weed-free | 61 | 33 | 9 |
| Tilled wet–dry | *S. rostrata* | 89 | 23 | —# |
| | Mungbean | 74 | 22 | — |
| | Weeds | 59 | 9 | — |
| | Weed-free | 104 | 58 | 10 |
| *F* test | | | | |
| Main plot | | *** | NS | NS†† |
| Subplot | | ** | *** | ** |
| Interaction | | * | * | * |

*,**, and *** Significant at $P$ = 0.05, 0.01, and 0.001, respectively; NS = not significant at $P$ > 0.05.
† Fallow management initiated on 1 February; dry-to-wet transition subplot treatments were initiated on 2 May.
‡ Harvest of *S. rostrata* and mungbean.
§ 9 d after initiation of permanent soil flooding for rice culture.
¶ Cumulative rainfall since the previous sampling date.
# Not measured.
†† Only weedy and weed-free main plot treatments were included in the analysis.

tilled main plot at mid-DWT in 1991 (155 kg N ha$^{-1}$ on 4 June) The greatest $NO_3$ buildup in tilled wet-dry plots was expected since tillage and alternate drying and wetting are normally associated with increased $NO_3$ in aerobic soils (Linn and Doran, 1984; Radford et al., 1992; Ventura and Watanabe, 1978). But $NO_3$ levels increased also in the weed-free fallow, indicating substantial N mineralization even without tillage or drying and wetting.

While the measured $NO_3$ levels were as high as 155 kg $NO_3$ -N ha$^{-1}$, these high levels cannot approximate the cumulative amount of $NO_3$ that was mineralized under each management. It is likely that we have missed even the highest $NO_3$ buildup. Our measurements were at 2- to 4-wk intervals, but nitrification, de nitrification, and leaching are dynamic processes and can occur simultaneously. Soil water (or aeration) has a major influence on $NO_3$ levels (Linn and Doran, 1984; Doran et al., 1990; Rochester et al., 1991), and measurements just after heavy rains are likely to indicate lower $NO_3$ amounts than the ones just prior. For example, in 1991, rain was much less before the 21 May sampling (Fig. 2) when 155 kg $NO_3$ -N ha$^{-1}$ was measured (Table 3). But there were heavy rains just before the 23 May sampling in 1990 (Fig. 1); 77 mm of rain fell on 17 May and another 29 mm on 22 May. Thus, $NO_3$ amounts within treatments might have fluctuated with the intermittent rains (Fig. 1 and 2) and associated short flooding-drying cycles.

On the other hand, weedy fallow greatly depressed $N0_3$ buildup during both the DS and the DWT (Fig. 1 and 2; Tables 2 and 3). Initial amounts of $NO_3$ in weedy fallow (26 kg N ha$^{-1}$ at the start of DS weedy fallow main plot and 13 to 110 kg N ha$^{-1}$ prior to the establishment of DWT weedy fallow subplots across the 2 yr) rapidly declined to a low level and then remained at that level. It may be noted that tilling the DS weedy fallow main plot as part of establishing the DWT subplot treatments temporarily increased $NO_3$ in the DWT weedy fallow subplot. Low $NO_3$ under weedy compared with weed-free fallowing during the DWT has been reported (Buresh et al., 1993). The results reported here show that weedy fallowing during the DS has an even greater depressing effect on $NO_3$ buildup than during the DWT. This is despite lower weed N accumulation (15 kg N ha$^{-1}$ in 1990 and 24 kg N ha' in 1991) during the DS compared with the DWT (Table 4). But more important is the fact that weedy fallowing drastically decreased $NO_3$ even when the initial $NO_3$ levels were high. This was the case when weedy fallow subplots in the DWT were preceded by weed-free or tilled main plots in the DS. Despite the differing initial $NO_3$ levels and minimal $NO_3$ effect on weed N accumulation, weedy fallow had a substantial and relatively rapid suppressing effect on $NO_3$ buildup.

Like weeds, *S. rostrata* and mungbean also decreased $NO_3$, but more slowly than weeds. Nitrogen accumulation by *S. rostrata* and mungbean significantly responded to soil $NO_3$ levels, more so in 1991 than in 1990 (Table 4). As expected *S. rostrata* accumulated the maximum N, and the weds the least. It may be noted, however, that $NO_3$ increased during the first 3 to 4 wk after seeding of legumes in 1991 and not in 1990. This increase in $NO_3$ is most likely due to current $NO_3$ production exceeding plant N uptake. Since all plots were tilled and irrigated at legume seeding, enhanced $NO_3$ production

**Table 3. Soil $NO_3$ (0–60 cm) as influenced by fallow or crop† management and rainfall during the dry-to-wet transition in a Philippine rice lowland, 1991.**

| Management | | 21 May (43 mm)¶ | 4 June (16 mm) | 18 June (100 mm) | 5 July‡ (85 mm) | 22 July§ (208 mm) |
|---|---|---|---|---|---|---|
| Dry season | Dry-to-wet transition | | | | | |
| | | kg N ha$^{-1}$ | | | | |
| Weedy | *Sesbania rostrata* | 78 | 56 | 24 | 12 | 6 |
| | Mungbean | 50 | 40 | 23 | 12 | 7 |
| | Weeds | 14 | 12 | 10 | 9 | 7 |
| | Weed-free | 51 | 69 | 71 | 55 | 21 |
| Weed-free | *S. rostrata* | 116 | 127 | 50 | 17 | —# |
| | Mungbean | 127 | 102 | 60 | 32 | — |
| | Weeds | 37 | 15 | 18 | 17 | — |
| | Weed-free | 114 | 132 | 101 | 75 | 41 |
| Tilled wet–dry | *S. rostrata* | 147 | 155 | 67 | 25 | 7 |
| | Mungbean | 119 | 75 | 35 | 23 | 9 |
| | Weeds | 38 | 15 | 20 | 14 | 6 |
| | Weed-free | 121 | 148 | 105 | 83 | 41 |
| *F* test | | | | | | |
| Main plot | | *** | *** | *** | ** | **†† |
| Subplot | | *** | *** | *** | *** | *** |
| Interaction | | NS | ** | NS | * | * |

*,**, and *** Significant at $P = 0.05$, 0.01, and 0.001 respectively; NS = not significant at $P > 0.05$.
† Fallow management initiated on 5 February; dry-to-wet transition subplot treatments except *S. rostrata* were initiated on 2 May; *S. rostrata* was seeded on 7 May.
‡ Harvest of mungbean and *S. rostrata*.
§ 11 d after initiation of permanent soil flooding for rice culture.
¶ Cumulative rainfall since the previous sampling date.
# Not measured.
†† Only weedy and tilled wet–dry main plot treatments were included in the analysis.

is likely during the first few weeks. In comparison, soil N uptake during the first few weeks of legume growth is not likely to be large. The net result will then be an increase in $NO_3$. A similar situation might have existed in 1990, but heavy rains during the early part of the DWT may have leached $NO_3$ beyond the 60-cm depth.

Regardless of the quantity of $NO_3$ accumulated, the amount of aboveground plant N, or the type of DWT vegetation, $NO_3$ declined rapidly in the second half of the DWT (Fig. 1 and 2; Tables 2 and 3). While part or all of this decline in vegetated plots is attributable to plant N uptake (Table 4), $NO_3$ declined also in weed-free fallow. However, increased soil water resulting from frequent rains was a factor common to all treatments (Table 5). Because of the high permeability of our soil (Wopereis et al., 1993), leaching following heavy rains might have been substantial. Rapid loss of flood water was observed, a situation conductive to $NO_3$ leaching (Bergstrom and Johansson, 1991), Additionally, WFPS in all treatments increased to above 0.7 L L$^{-1}$ by the second half of the DWT (Table 5), indicating the probable occurrence of denitrification (Aulakh et al., 1991; Linn and Doran, 1984; Doran et al., 1990).

**Table 4. Aboveground plant N accumulation by dry-to-wet-transition crops as influenced by fallow management† during the preceding dry season in a Philippine rice lowland.**

| Management | | Aboveground plant N | |
|---|---|---|---|
| Dry season | Dry-to-wet transition | 1990 | 1991 |
| | | kg N ha$^{-1}$ | |
| Weedy | *Sesbania rostrata* | 200 | 134 |
| | Mungbean | 96 | 75 |
| | Weeds | 34 | 37 |
| Weed-free | *S. rostrata* | 213 | 172 |
| | Mungbean | 98 | 99 |
| | Weeds | 31 | 42 |
| Tilled wet–dry | *S. rostrata* | 222 | 193 |
| | Mungbean | 114 | 117 |
| | Weeds | 35 | 46 |
| *F* test | | | |
| Main plot | | * | *** |
| Subplot | | *** | *** |
| Interaction | | NS | ** |

*,**,*** Significant at $P = 0.05$, 0.01, and 0.001, respectively; NS = not significant at $P > 0.05$.
† Fallow management initiated on 1 Feb. 1990 and on 5 Feb. 1991; dry-to-wet transition subplot treatments were initiated on 2 May in both years except *S. rostrata* in 1991, which was seeded on 7 May.

**Table 5. Water-filled pore space during the dry-to-wet transition in a Philippine rice lowland under varied soil and crop management†.**

| Date | Water-filled pore space (0–20 cm)‡ | | |
|---|---|---|---|
| | Weedy | Weed-free | Tilled |
| | L L$^{-1}$ | | |
| Year 1990 | | | |
| 23 May | 0.79 | 0.81 | 0.85 |
| 13 July | 0.84 | 0.85 | 0.84 |
| 27 July | 1.03 | 1.04 | — |
| Year 1991 | | | |
| 21 May | 0.55 | 0.60 | 0.60 |
| 4 June | 0.49 | 0.52 | 0.54 |
| 18 June | 0.76 | 0.77 | 0.82 |
| 5 July | 0.69 | 0.67 | 0.72 |
| 22 July | 1.00 | — | 1.03 |

† Weedy, weed-free, and tilled fallow main plots were initiated after tilling soil uniformly to 20-cm depth on 1 Feb. 1990 and on 5 Feb. 1991. Weeds were allowed to grow in weedy fallow and were removed as they emerged in weed-free fallow. Tilled wet–dry fallow plots received repeated tillage and water applications.
‡ Values are averages across *S. rostrata*, mungbean, weedy fallow, and weed-free fallow subplot treatments during the dry-to-wet transition.

**Table 6. Depth distribution of soil $NO_3$ in the dry-to-wet transition weed-free plot subjected to periodic tillage and water application during the preceding dry season in a Philippine rice lowland.**

| Year 1990 | | | Year 1991 | | |
|---|---|---|---|---|---|
| Date | 0–20 cm | 20–60 cm | Date | 0–20 cm | 20–60 cm |
| | — kg N $ha^{-1}$ — | | | — kg N $ha^{-1}$ — | |
| 26 Apr. | 69a† | 41b | 6 May | 68a | 35b |
| 23 May | 18b | 82a | 21 May | 76a | 44b |
| 13 July | 11b | 46a | 4 June | 107a | 41b |
| 27 July | 3a | 7a | 18 June | 29b | 77a |
| | | | 4 July | 16b | 67a |
| | | | 22 July | 2b | 39a |

† Values followed by the same letter within a row do not differ significantly by LSD (0.05).

Data in Table 6 on the depth distribution of $NO_3$ in tilled wet-dry plots support the assumption of $NO_3$ leaching. Initially, the top 0- to 20-cm soil layer had significantly greater amounts of $NO_3$ than the bottom 20to 60-cm layer in both 1990 and 1991. Immediately after heavy rains, however, there was a significant increase in $N0_3$ in the lower 20- to 60-cm layer. Even though the total amount in the top 60-cm layer was declining, $NO_3$ in the 20- to 60-cm layer initially increased before subsequent decline, indicating movement of $NO_3$ down the soil profile.

Regardless of the mode of $NO_3$ disappearance, it is clear that the period of transition from the dry to the wet season in rice lowlands is greatly conducive to $NO_3$ loss. At the last measurement before permanent flooding, $NO_3$ in the weed-free subplots of both weed-free and tilled main plots had already decreased to 43 to 56% of the maximum values measured previously across the 2 yr of the study (Fig. 1 and 2; Tables 2 and 3). An equal or greater total decrease in soil $NO_3$ was also observed in *S. rostrata*, mungbean, and weed plots (Tables 2 and 3). Leaching might have been the major mode of $NO_3$ loss during this time, especially in the weed-free fallow (Maidl et al., 1991; Martinez and Guiraud, 1990). At the next measurement, 9 d into permanent flooding in 1990 and 11 d in 1992, $NO_3$ decreased to between 6 and 10 kg N $ha^{-1}$ in all except the 1991 weed-free plots. The WFPS approximated 1 L $L^{-1}$ during this time (Table 5). Denitrification may have contributed substantially to $NO_3$ loss during this time because soil puddling for rice may have reduced the leaching loss.

The large difference in soil $NO_3$ between weedy and weed-free fallow is of interest. While the lower $N0_3$ amounts in weedy than in weed-free fallow is partly due to weed N uptake (Table 4), as mentioned above, the N in aboveground weed biomass at the end of the DS was very low. On the other hand, soil $NO_3$ in the DS weedfree main plot (75 kg N $ha^{-1}$ on 26 April in 1990 and 63 on 16 April in 1990) is about two times greater than soil $NO_3$ plus weed N in the weedy fallow main plot. Further, during the DWT, *S. rostrata* and mungbean accumulated much more N than weeds (Table 4), yet the associated soil $NO_3$ levels remained higher than under weeds during most of DWT. Even during DWT, when conditions were more favorable to leaching or denitrification of $NO_3$, weed-free fallow maintained a higher level of $NO_3$ than weedy fallow.

Weedy fallow might have had effects other than N

**Table 7. Soil $NO_3$ (0–20 cm) and water-filled pore space (0–20 cm) as influenced by weedy and weed-free fallows† during the dry season in a Philippine rice lowland.**

| | Soil $NO_3$ (0–20 cm) | | Water-filled pore space (0–20 cm) | |
|---|---|---|---|---|
| Date | Weedy | Weed-free | Weedy | Weed-free |
| | — kg N $ha^{-1}$ — | | — L $L^{-1}$ — | |
| Year 1990 | | | | |
| 26 Feb. | 14b‡ | 27a | 0.55b | 0.61a |
| 22 Mar. | 8b | 45a | 0.54b | 0.62a |
| 26 Apr. | 6b | 48a | 0.51b | 0.64a |
| Year 1991 | | | | |
| 5 Mar. | 14a | 23a | 0.51a | 0.55a |
| 26 Mar. | 10b | 25a | 0.48b | 0.54a |
| 16 Apr. | 9b | 41a | 0.35b | 0.44a |
| 6 May | 18b | 52a | 0.52b | 0.58a |

† Weedy and weed-free fallow were initiated after tilling soil uniformly to 20-cm depth on 1 Feb. 1990 and on 5 Feb. 1991. Weeds were allowed to grow in weedy fallow and were removed as they emerged in weed-free fallow.
‡ Values followed by the same letter within a row do not differ significantly by LSD(0.05).

uptake on soil $NO_3$ because the relatively low weed N uptake alone cannot account for the substantially low $N0_3$. One cause for the large difference in soil $NO_3$ between DS weedy and weed-free fallow could be the difference in soil water content between them. During the DS, the WFPS (0-20 cm) in the weed-free fallow was significantly greater (Table 7) and was in a more favorable range for ammonification and nitrification (Linn and Doran, 1984; Doran et al., 1990) than weedy fallow. Weeds are likely to have increased water loss through evapotranspiration. On the other hand, water loss from the weed-free fallow could be less because capillary water flow through the dry topsoil layers would be slow. Our observation is consistent with that of Hundal and De Datta (1982), who reported substantial water loss during the dry season under weedy compared with bare fallowing.

It is unlikely, however, that the slightly reduced soil water content exerted such a substantial depressing effect on $NO_3$ in the weedy fallow. Nitrate in the top 20 cm in the weedy fallow was as much as eight times lower than in the weed-free fallow (Table 7). Such a large difference could result from increased denitrification or continuous microbial immobilization of mineralized N in the weedy fallow. Nitrate loss by denitrification in the proximity of weed roots cannot be ruled out (Lamb et al., 1985; Weier et al., 1991; Wheatley et al., 1991). Immobilization due to continuous weed residue turnover is also likely because continuous dying of old weeds and emergence of new weeds have been observed.

## SUMMARY

We examined $NO_3$ dynamics in a rice lowland in the Philippines subjected to contrasting management during the February to May DS and the May to July DWT in 1990 and 1991. Management that included tillage or weedfree fallow enhanced soil $NO_3$ buildup while growing of plants, legumes and weeds, decreased such buildup. Nitrate buildup was minimum when the soil was left to native weed growth. Native weed growth might have had other effects on soil $NO_3$ than assimilation into biomass;

for example, the associated decrease in soil water could also have decreased nitrification. Although the magnitude and range of $NO_3$ buildup observed in this particular soil may not represent all lowland rice-growing soils, the results clearly demonstrate the large potential of management to influence buildup of $NO_3$ and its subsequent dissipation. The impacts of $NO_3$ loss from rice lowlands on the environment and on long-term soil N fertility have thus far been explored only on a limited scale and in a few soils. Our results indicate that there is an urgent need to target soil and crop management to better conserve $NO_3$ in rice lowlands.

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