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Legumes as Nitrate Catch Crops during the Dry-to-Wet Transition in Lowland Rice Cropping Systems

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ABSTRACT

In tropical rice (*Oryza sativa* L.) lowlands, NO_3^- assimilation by plants during the transition from the dry to the wet season can preclude NO_3^- loss upon soil flooding and permit recycling of this N. In a 2-yr field study in an Alfisol in the Philippines, we examined the role of legume crops and weeds during the dry-to-wet (DTW) transition in conserving and/or recycling soil NO_3^- that accumulated under varied dry-season fallow management. During the May-to-July DTW transition, *Sesbania rostrata* (Bremek. & Oberm.), mungbean [*Vigna radiata* (L.) Wilczek], weedy, and weed-free treatments were subplots in the February-to-May dry-season mainplots of weedy, weed-free, and frequently tilled fallows. Legume biological N_2 fixation (BNF) was measured by ^{15}N dilution. Depending on dry-season management, the maximum extracted N (top 60-cm layer) in the DTW transition ranged from 38 to 164 kg ha^{-1}; this N was 62 to 96% NO_3^-. Soil N uptake by weeds ranged from 31 to 46 kg N ha^{-1}, that by mungbean from 29 to 80, and by *S. rostrata* from 46 to 125. The minimum estimates of DTW transition NO_3^- loss varied from none when plants were present to 107 kg N ha^{-1} in weed-free fallows. Legume BNF partially offset NO_3^- loss, although increased soil NO_3^- decreased BNF-N. Nitrogen fixed ranged from 37 to 63 kg N ha^{-1} by mungbean and 68 to 154 by *S. rostrata*. Harvest of mungbean caused negative BNF-N contribution to the succeeding rice crop in a few cases. In lowland rice-based cropping systems, weeds are effective in conserving soil N during the DTW transition, but legumes are more suitable nitrate catch crops because they allow the harvest of an economic product or the recycling of more N to a subsequent flooded rice crop.

LOWLAND RICE-BASED CROPPING SYSTEMS are common in the tropics in areas having ≈ 1500 mm annual rainfall with at least three consecutive months of 200 mm mo^{-1}. Rice is produced in flooded soil in the wet season, and during the dry season only when there is sufficient irrigation to flood the soil. Without continuous irrigation, weedy fallows and upland crops become important during the dry season. Green manure or other short season crops are sometimes grown during the transition from the dry to the wet season. Traditionally, legume green manures have been promoted during the DTW transition because of their ability to accumulate N from BNF.

Soil is aerobic during the dry season and during most of the DTW transition. Nitrate is the predominant form of plant available N in aerobic soils because NH_4^+ is rapidly nitrified. Rice lowlands accumulate NO_3^- during the dry season in varying amounts depending on management (George et al., 1993). Legumes assimilate this NO_3^- with consequent decrease in BNF. Thus, the greater the soil NO_3^-, the lesser the value of legumes as BNF crops (George and Singleton, 1992). However, in rice lowlands where soil NO_3^- will otherwise be lost by leaching or denitrification during the DTW transition (Buresh et al., 1989; George et al., 1992), decreased BNF is not necessarily a disadvantage.

Plant N uptake prior to and during the DTW transition may conserve soil NO_3^- from potential loss. A role for plants in minimizing NO_3^- loss in rice lowlands has been proposed (Buresh and De Datta, 1991; George et al., 1992). Buresh et al. (1993) reported that *S. rostrata* green manure and weeds prevented the loss of NO_3^- by assimilating it into biomass. They used the lower NO_3^- in *S. rostrata* plots compared with weed-free plots as an indication of NO_3^- assimilation by *S. rostrata*, but it is not known how much soil N was actually assimilated by *S. rostrata*, since the amount of N derived from BNF was not determined.

Growing of plants may not only reduce NO_3^- loss, but may also permit the N conserved in plant biomass to be removed in a crop produce or recycled to a subsequent flooded rice crop by incorporating the residues back into soil (George et al., 1992). Nitrogen in weed biomass in traditionally weedy fallows in rice lowlands may, thus, represent a saving of NO_3^- that might otherwise be lost. There are, however, no data on how varying levels of soil NO_3^- influence soil N uptake by weeds, and soil N uptake and BNF by grain and green manure legumes. It is possible that in many instances the amounts of N gained through BNF are minimal. With reduced BNF, grain legumes may not contribute additional N to a succeeding rice crop, since N is removed in pods.

Soil NO_3^- under crop or weeds is normally lower than in bare soil (Buresh et al., 1989, 1993; George et al., 1992). We previously reported large variation in soil NO_3^- buildup depending on type of vegetation and soil management in a Philippine rice lowland (George et al., 1993). In this paper, we report the effects of the differing soil NO_3^- levels on N uptake and BNF by *S. rostrata*, mungbean, and weeds grown in the DTW transition and on N harvested in mungbean pods, and the effects of recycled plant residues on the early growth and N accumulation of a subsequent flooded rice crop. The major objective was to determine whether legumes, both green manure and grain types, are suitable nitrate catch crops during the DTW season transition in rice lowlands.

MATERIALS AND METHODS

Experimental Plan

The details of the experimental plan have been in part described previously (George et al., 1993). Field experiments were con-

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Abbreviations: DS, dry season; DTW, dry-to-wet (season transition); BNF, biological N_2 fixation.

ducted in an Alfisol in the Philippines at the research farm of the International Rice Research Institute (IRRI). The experiment contained three DS (February to May) mainplot treatments and four DTW (May to July) subplot treatments replicated four times in a split plot arrangement. Weedy, weed-free, and tilled-wet/dry (alternating tillage and watering) fallows were established in the dry season. During the DTW transition, green manure legume *S. rostrata* and grain legume mungbean, as well as weedy and weed-free fallows were established as subplots of the DS treatments. Additionally, ^{15}N microplots were established within legume and weed plots to measure N derived by legumes from soil and BNF.

Nitrogen-15 Microplots

Microplot areas of 1.2 by 1.2 m were established at the start of the dry season in 1990 in all plots that were to have *S. rostrata*, mungbean, or weed during the DTW transition. The microplot was 40 cm away from the levees at a corner of each plot and was isolated from the rest of the plot area by a galvanized iron frame (30 cm wide) pushed 15 cm down into soil. Nitrogen-15 isotope in the form of 98% ^{15}N enriched ammonium sulfate was applied at one or five kg ha^{-1} rates to microplots once at the beginning of the dry season in 1990. The five kg N ha^{-1} rate was used in the tilled-wet/dry treatment which, as part of another study, was also used to monitor soil ^{15}N enrichment and to produce ^{15}N-enriched plant biomass in situ.

Field Management

Field management during the dry season has been given in detail elsewhere (George et al., 1993) and, hence, only briefly described here. The DS management was initiated on 31 Jan. 1990 after the harvest of a previous rice crop and removal of all straw. Plots of 5 by 5 m were established, with 15-cm high soil levees separating the plots. All plots were tilled to 20-cm depth at the start. From the weed-free plots, weeds were pulled out by hand as they emerged, and were discarded. In the weedy fallow treatment, native weeds were allowed to grow. The tilled-wet/dry plots were subjected to alternating tillage (20 cm deep) and water application during the dry season to maximize NO_3^- buildup. These plots received five additional tillage and water applications (4 to 5 cm each time) until 27 Apr. 1990. Nitrogen-15 microplots in this study were managed like their whole plots.

At the end of the dry season, all plots were tilled to the 20-cm depth on 27 and 28 April in both years. Nutrients were applied each year before final tillage at 50 kg P ha^{-1}, 15 kg Zn ha^{-1}, and 1 kg Mo ha^{-1}. Furrows were made 30 cm apart and *S. rostrata* and mungbean (Taiwan Green, 70 d) were seeded in excess of 12 seeds m^{-1}. Mungbean seeds were coated with peat-based rhizobial inoculant prior to seeding. No seed inoculation was done to *S. rostrata*, because sufficient effective rhizobia were already present in the soil. The seeding was on 2 May in both years, except for *S. rostrata*, which was seeded 5 d later on 7 May in 1991. Plots were lightly irrigated to aid germination. *Sesbania rostrata* had to be reseeded on 8 May in 1990 and on 12 May in 1991 because of poor emergence.

Seven days after emergence, plants were thinned to achieve a final population density of 400 000 plants ha^{-1}. After 2 wk, *S. rostrata* and mungbean plots were hand weeded and the uprooted weeds were left on the soil surface. Weeds were allowed to grow in the weedy plots, but in weed-free plots, weeds were hand-pulled as they emerged. The dominant weed species in the weedy fallow were *Amaranthus spinosus* L., *Trianthema portulacustrum* L., *Digitaria ciliaris* (Retz.) Koel, and *Rottboellia cochinchinensis* (Lour.) W.D. Clayton. In 1990, *S. rostrata* spontaneously nodulated on their stems. Because of minimal rainfall, a water suspension of rhizobial inoculant had to be sprayed onto stems 4 wk after seeding in 1991.

Sesbania rostrata plants and mungbean stover (after picking of pods) were cut at soil level on 13 and 14 July in 1990 and on 7 and 8 July in 1991. The biomass was chopped into small pieces, and spread onto the soil in their respective plots.

Plots were flooded and wet-tilled from 18 to 20 July in 1990 and from 10 to 13 July in 1991. Puddling was done with a hydrotiller, which also incorporated the plant residues. Twenty-one-day-old seedlings of rice ('IR 72') were transplanted on 20 July in 1990 and on 13 July in 1991.

Soil and Plant Sampling

Soil samples were collected periodically from the 0- to 20-cm and 20- to 60-cm depths in 1990 and from the 0- to 20-cm, 20- to 40-cm, and 40- to 60-cm depths in 1991. Each sample was a composite from four locations.

Mungbean pods from a 2- by 3-m area at the center of the plot were picked for yield determination. Fresh weights were determined on a subsample of ≈15 plants and also on all remaining plants cut from the 2- by 3-m sampling area. Whole-plot plant dry weight was determined from dry weights of subsamples dried at 65°C for 48 h. After drying at 65°C for 48 h, mungbean pods were threshed for seed, and dry weights of both seeds and pod walls were recorded.

Legume and weed samples for ^{15}N analysis were collected from 50-cm lengths of the two central rows in microplots. These plants were dried at 65°C for 48 h. Mungbean plants were hand threshed for seed and then separated into stover, seeds, and pod walls. Dried plant samples were ground for later ^{15}N and total N analyses.

Rice plants were sampled 7 wk after transplanting in 1990 and 6 wk after in 1991. Twelve to 16 hills each were cut at the soil surface from a previously designated row in each plot. The dry weights were determined and samples ground for total N analysis.

Laboratory Analyses

Soil samples were extracted with 2 *M* KCl and filtered extracts were analyzed for NO_3^- by the Cd reduction method and for NH_4^+ by steam distillation (Keeney and Nelson, 1982). Total N in plant samples was determined by the micro-Kjeldahl method (Bremner and Mulvaney, 1982). Kjeldahl digests of samples were steam-distilled with 10 *M* NaOH and the distillates were collected in 1 mL of saturated boric acid. In the case of ^{15}N samples, 15 mL of ethyl alcohol was distilled between treatments to avoid ^{15}N contamination. Nitrogen-15 samples were analyzed in a mass spectrometer (Buresh et al., 1982).

Data Analyses

Nitrogen derived from N_2 fixation and from soil were calculated using the equations of ^{15}N dilution method (IAEA, 1983). Nitrogen-15 excess in weeds was used as the non-N_2-fixing reference. Data sets were subjected to *F*-test. When found appropriate, data in different years were subjected to a combined analysis of variance. Means were separated by LSD (0.05) when *F*-tests were found significant.

RESULTS AND DISCUSSION

In a 2-yr study, we examined the role of legume crops and native weeds in conserving and/or recycling soil NO_3^- during the transition from the dry to the wet season in tropical lowland rice-based cropping systems. We illustrate here how varying N requirements and BNF capac-

Table 1. Maximum value of extracted N (NO_3^- + NH_4^+) from soil among the sampling dates prior to permanent flooding and soil N uptake by legumes (determined by ^{15}N dilution) and weeds during the dry-to-wet season transition in a rice lowland subjected to varied soil management during the preceding dry season.

Management		Maximum extracted N					
		1990		1991		Soil N uptake	
Dry season (DS)	Dry-to-wet (DTW) transition	Total	NO_3^-	Total	NO_3^-	1990	1991
						kg ha^{-1} ———	
Weedy fallow	*S. rostrata*					46aA	57aB
	Mungbean					33aA	29bA
	Weeds					34aA	37bA
	Weed-free					–‡	–
Weed-free fallow	*S. rostrata*					59aA	94aB
	Mungbean					46aA	54bA
	Weeds					31bA	42bA
	Weed-free					–	–
Tilled-wet/dry fallow	*S. rostrata*					97aA	125aB
	Mungbean					66bA	80bA
	Weeds					35cA	46cA
	Weed-free					–	–
LSD (0.05)¶						25	18

† Within columns and dry season management, means followed by the same lowercase letter are not significantly different by LSD (0.05); within rows, soil N uptake means followed by the same uppercase letter are not significantly different by LSD (0.05).

‡ No plants were present.

§ Maximum extracted N was measured in the mainplot prior to the initiation of subplot treatments and therefore, is the same across subplots. The values are averages of four replicate mainplots.

¶ Comparing two DTW transition subplot means across different DS mainplots.

ities of DTW vegetation of weeds, mungbean, and *S. rostrata* interacted with variable levels of soil mineral N, primarily NO_3^-, that result from varied soil management. Imposition of weedy, weed-free, and frequently tilled fallows during the dry season generated a broad range of soil NO_3^- levels at the start of the DTW transition.

As an approximation to the extent of N mineralization that occurred in the various DS–DTW treatment combinations, the maximum values of KCl-extracted N (NO_3^- plus NH_4^+) among the sampling dates are presented in Table 1. The maximum extracted N ranged widely (38 to 164 kg N ha^{-1}) between DS–DTW treatment combinations, with the DS mainplot having the major influence. Nitrate was the dominant mineral N form in soil constituting up to 96% of the maximum extracted N values. As the amounts of NH_4^+ were low across treatments and relatively unchanged across sampling dates (George et al., 1993), the maximum NO_3^- values coincided with the maximum extracted N values. Therefore, the differences in maximum extracted-N amounts essentially reflected the differences in the amounts of soil NO_3^-.

The maximum extracted N values were measured just prior to or within ≈ 1 mo of seeding of DTW crops, and therefore, these may be considered to approximate the minimum amounts of N that were available for plant uptake. It is likely that N mineralization continued and the cumulative amounts of mineral N (primarily NO_3^-), that were available for plant uptake during the entire DTW transition were much greater than these observed maxima. However, the actual amounts accumulated by plants were less than the maximum extracted N values (Table 1).

Nitrogen derived from soil increased with both increased amounts of extracted N and increased N requirement of the plants, i.e., from weeds to *S. rostrata* (Table 1). The differences among plant species in soil N accumulation were magnified at increased mineral N supply (Table 1; Fig. 1). Thus, soil N uptake by weeds (= total weed N) ranged only narrowly (31–46 kg N ha^{-1}) while that by *S. rostrata* (= total N minus BNF-N) ranged widely (46–125 kg N ha^{-1}). Consequently, only at low extracted N did weed N tend to approximate soil N uptake by legumes.

Unlike soil NH_4^+, the low levels of which tended not to fluctuate between sampling dates (George et al., 1993), the built up soil NO_3^- disappeared in large proportions from the top 60-cm soil layer (Tables 1 and 2). This decline in NO_3^- levels occurred during the DTW crop period and also during the subsequent period of permanent soil flooding. At least part of the decline during the DTW crop period could be attributed to plant uptake (Table 1), but NO_3^- also declined in large quantities from weed-free plots where plant assimilation was not a factor. There were intermittent rains during the DTW crop period, and NO_3^- leaching was evident (George et al., 1993). During the later part of the DTW crop period and the subsequent period of permanent soil flooding, water-filled porosity (which exceeded 0.7 L L^{-1} and approximated 1 L L^{-1}) might have favored denitrification (George et al., 1993). Consequently, regardless of prior management or NO_3^- quantity, most of the NO_3^- was unaccounted for when measured at 9 or 11 d of flooding.

A negative difference between the maximum amount of NO_3^--N measured at the beginning of the DTW transition and the sum of soil N uptake by DTW plants and NO_3^--N remained in soil shortly after initiation of permanent flooding could be attributed to NO_3^--N loss (Table 2). This is assuming that negligible amounts of NO_3^- had reverted to NH_4^+ or organic N (Buresh et al., 1989) and plants had assimilated little NH_4^+. The apparent change in NO_3^- tended to be increasingly negative when high amounts of soil NO_3^- were associated with low amounts of soil N uptake by plants (Tables 1 and 2). Thus, NO_3^- loss was the greatest when soil was bare during the DTW transition

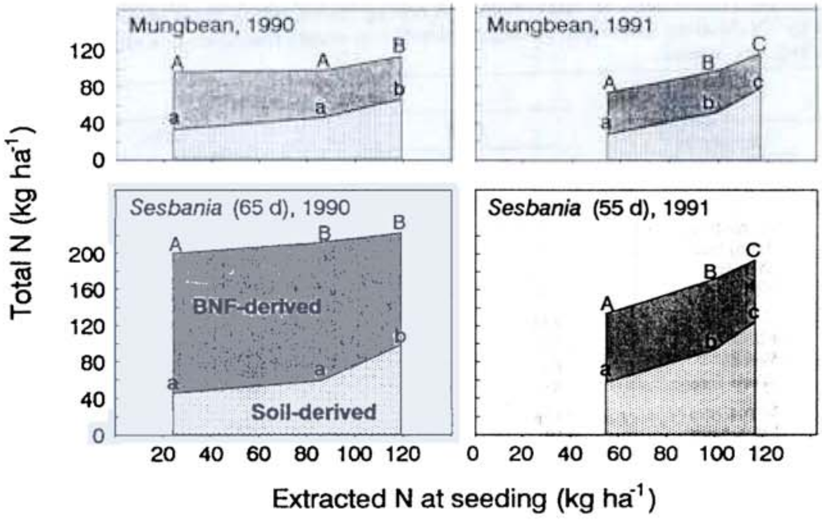

Fig. 1. Relationship between KCl-extracted N at seeding and total and biological dinitrogen fixation–derived N for *S. rostrata* and mungbean during the dry-to-wet season transition in a rice lowland subjected to varied fallow management during the dry season just preceding. Points on a given curve with the same lowercase letter for soil-derived N or uppercase letter for total N do not differ significantly by LSD (0.05).

following a DS tilled fallow, and the least when the DS weedy fallow was followed by the same during the DTW transition. These estimated NO_3^- losses would be the minimum that could be lost from the system, since loss prior to the time of maximum extracted-N and subsequent NO_3^- production were not accounted for.

Plant uptake competes with leaching and denitrification for soil NO_3^-, thus protecting NO_3^- from loss mechanisms. Reduction in NO_3^- leaching with growing crops compared with bare fallowing has been reported (Maidl et al., 1991; Martinez and Guiraud, 1990). Conceivably, only that portion of soil NO_3^- which is in excess of plant requirements or inaccessible to plant roots could be lost. However, soil conditions during the second half of the DTW transition in rice lowlands are highly conducive for both leaching and denitrification losses of NO_3^- (George et al., 1992, 1993). Further, NO_3^- loss is rapid upon soil flooding (Buresh et al., 1989). The aggregate NO_3^- loss would be the least if most of the soil NO_3^- could be depleted by plant uptake prior to permanent flooding.

It follows then that, under conditions favoring high NO_3^- production, plants best suited for NO_3^- conservation during the DTW transition ought to have high N requirements and be fast growing and tolerant to occasional flooding of the soil from intermittent rains. *Sesbania rostrata* green manure best fitted this description, compared with

Table 2. Decline in soil NO_3^- levels before and during 9 d (in 1990) or 11 d (in 1991) of permanent flooding and the apparent change in soil NO_3^- in a rice lowland subjected to varied soil and crop management during the dry-to-wet season transition and the dry season just preceding.

Management		NO_3^-, % of prior max. value†				Apparent change in NO_3^-‡	
		1990 flooding		1991 flooding			
Dry season (DS)	Dry-to-wet (DTW) transition	Before	After	Before	After	1990	1991
		%				kg ha^{-1}	
Weedy fallow	*S. rostrata*	56bc§	24a	15b	8c	+18a	−16b
	Mungbean	68b	32a	24b	14bc	+10a	−15b
	Weeds	44c	31a	25b	20b	+14a	+9a
	Weed-free	89a	28a	78a	31a	−23b	−49c
Weed-free fallow	*S. rostrata*	35ab	8a	13b	−¶	−9a	−
	Mungbean	34ab	9a	25b	−	−22ab	−
	Weeds	17b	8a	23b	−	−38b	−
	Weed-free	44a	12a	57a	31	−65c	−91
Tilled–wet/dry fallow	*S. rostrata*	21b	−	16b	5b	−	−23a
	Mungbean	20b	−	20b	7b	−	−31ab
	Weeds	8b	−	14b	6b	−	−51b
	Weed-free	52a	9	56a	28a	−100	−107c
LSD (0.05)#		24	ND†	12	ND	ND	ND

† Maximum NO_3^- value coincided with the maximum extracted N and can be calculated from data in Table 1.

‡ The difference between the maximum soil NO_3^--N measured at an earlier sampling date and the sum of soil N in legume or weed biomass and soil NO_3^--N remaining after permanent flooding.

§ Within columns and DS management, means followed by the same lowercase letter are not significantly different by LSD (0.05).

¶ NO_3^- was not measured.

Comparing two DTW transition subplot means across different DS mainplots.

†† ND = Not determined.

Table 3. Nitrogen-15-based estimates of the amount and percent of total plant N derived from biological nitrogen fixation (BNF) by legumes grown during the dry-to-wet season transition in a rice lowland subjected to varied crop and soil management during the preceding dry season.

	Plant N from BNF			
	Amount		As % of total	
Management	1990	1991	1990	1991
	— kg N ha^{-1} —		— % —	
	Dry season (DS) mainplot†			
Weedy fallow	109aA‡	62aB	71aA	59aB
Weed-free fallow	103aA	62aB	63aA	46bB
Tilled-wet/dry fallow	86aA	52aB	48aA	34cB
	Dry-to-wet (DTW) transition subplots§			
S. rostrata	144aA	74aB	69aA	46aB
Mungbean	54bA	43bB	53bA	46aB

† Values averaged across DTW subplots.
‡ Within columns and DS mainplots or DTW subplots, means followed by the same lowercase letter are not significantly different by LSD (0.05); within rows, amount or percentage means followed by the same uppercase letter are not significantly different by LSD (0.05).
§ Values averaged across DS mainplots.

Table 4. Nitrogen exported in pods, N harvest index (NHI; N exported in pods as a fraction of total plant N), and N gain in situ due to biological nitrogen fixation (BNF) by mungbean grown during the dry-to-wet season transition in a rice lowland subjected to varied soil management during the preceding dry season.

Dry season management	N export		NHI		N gain†	
			1990	1991	1990	1991
	- kg N ha^{-1} -				— kg N ha^{-1} —	
Weedy fallow	30aA‡	45bB	0.31aA	0.60aB	33aA	1aB
Weed-free fallow	33aA	65aB	0.34aA	0.65aB	19aA	−19abB
Tilled-wet/dry fallow	37aA	71aB	0.32aA	0.60aB	11aA	−34bB

† Difference between N exported in pods and N derived from BNF.
‡ Within columns, means followed by the same lowercase letter are not significantly different by LSD (0.05); within rows and traits, means followed the same uppercase letter are not significantly different by LSD (0.05).

mungbean, which is sensitive to flooding and only moderate in its N requirement. However, the effectiveness of *S. rostrata* as a nitrate catch crop depends on a further step in N cycling, since the entire amount of plant N is recycled to the subsequent flooded rice crop. Mungbean, on the other hand, could prove to be a better nitrate catch crop, since a portion of its N was immediately harvested in pods. However, there exists the possibility that no pods could be harvested from mungbean if heavy rains, and associated flooding, in the DTW transition prevent the crop from reaching maturity.

Despite being nitrate catch crops, *S. rostrata* and mungbean derived additional N from BNF (Table 3; Fig. 1). In both years, *S. rostrata* fixed greater amounts of N compared with mungbean as a consequence of its greater total N requirement (George and Singleton, 1992) and due to its greater capacity for BNF from stem nodulation (Ladha et al., 1992). For both legumes, N derived from BNF decreased as soil-extracted N at seeding increased; the proportion of total N derived from BNF was the least in tilled fallow mainplots, which had the greatest NO_3^- buildup (Table 1). Greater tolerance to mineral N of BNF by stem nodules compared with root nodules of *S. rostrata* (Becker et al., 1991; Dreyfus and Dommergues, 1980; Ladha et al., 1992) and a possible shift in N_2-fixing activity from roots to stem cannot be verified, for lack of data on mass or activity of nodules. Stem nodulation by *S. rostrata*, however, did not appear to negatively influence N uptake from aerobic soil, since increased total N of *S. rostrata* was associated with increased soil N uptake (Fig. 1).

The effects of soil NO_3^- on BNF and total N were more pronounced in 1991 than in 1990 (Table 3; Fig. 1). In 1990, soil NO_3^- started to decline ≈1 mo earlier than in 1991 because of heavy rains (George et al., 1993), possibly diminishing a prolonged NO_3^- effect on plants and resulting in enhanced BNF (Table 3). Despite reduced total N (Fig. 1) in 1991, soil N uptake by *S. rostrata* (Table 1) was greater in 1991 than in 1990, evidence of a prolonged and significant NO_3^- effect. *Sesbania rostrata* accumulated less total N in 1991 than in 1990, mainly because harvest in 1991 was 10 d earlier.

The data in Table 3 and Fig. 1 provide further evidence that N derived from BNF largely compensates for a deficit in soil N uptake in meeting the total legume N requirement (George and Singleton, 1992). This compensation by BNF in meeting legume N demand may provide yet another N benefit in rice lowlands. As alluded to earlier, some NO_3^- loss is inevitable during the DTW transition even when substantial amounts can be assimilated and held against loss by green manure crops such as *S. rostrata* (Tables 1 and 2). Except under a continuously maintained weed cover, NO_3^- builds up in soil (George et al., 1993), and not all of this could be intercepted and assimilated by crops regardless of their N demands (Table 1). Therefore, unlike nonlegumes, BNF by legumes could offset this NO_3^- loss.

While BNF by DTW legumes could partly offset NO_3^- loss, the BNF contribution to a post-legume rice crop depends on how much of the legume N is removed from the land. A net N contribution to the succeeding rice crop is achieved only when the proportion of N derived from BNF exceeds the fraction of N harvested, referred to as the N harvest index (Table 4). The net N contribution was negative after mungbean in 1991, when nitrogen harvest index and soil N uptake (Table 1) were high and N derived from BNF was low (Table 3); however, if NO_3^- loss (Table 2) were also accounted for, the net N contribution would likely be more with mungbean than with a potential alternate nonlegume crop. Adding also the N contained in roots, the N contribution could further increase. Thus, a grain legume rather than a nonlegume grain crop is likely to result in less immediate net depletion of N from the soil–plant system, while allowing export of N for human consumption. It should be noted that depletion of N from the system (by NO_3^- leaching or denitrification) would be greater in the absence of a DTW crop, whether legume or nonlegume.

Excepting the export of N for economic use, recycling of the plant residues to the next rice crop would be the most practical way of using the DTW N. The amount of DTW N available for recycling varied considerably between the years and among the plant species (Table 5). Plant biomass and N available for recycling, on average, were the highest for *S. rostrata* (9.4 t biomass ha^{-1} with 189

Table 5. Aboveground plant residues and N recycled to a wet season flooded rice crop in a lowland subjected to varied soil and crop management during the dry-to-wet season transition and the dry season just preceding.

Management		Plant residues		Residue N	
Dry season (DS)	Dry-to-wet (DTW) transition	1990	1991	1990	1991
		— Mg ha^{-1} —		— kg ha^{-1} —	
Weedy fallow	*S. rostrata*	11.7aA†	5.5aB	200aA	134aB
	Mungbean	3.9bA	1.2cB	66bA	30bB
	Weeds	3.2bA	3.3bA	34cA	37bA
Weed-free fallow	*S. rostrata*	12.3aA	6.7aB	213aA	172aB
	Mungbean	4.0bA	1.5cB	65bA	35bB
	Weeds	3.7bA	3.5bA	31cA	42bA
Tilled–wet/dry fallow	*S. rostrata*	12.9aA	7.0aB	222aA	193aB
	Mungbean	4.2bA	2.0cB	77bA	46bB
	Weeds	4.0bA	3.3bA	35cA	46bA
LSD (0.05)‡		1.15	0.73	12	14

† Within columns and DS management, means followed by the same lowercase letter are not significantly different by LSD (0.05); within rows and traits, means followed by a common uppercase letter are not significantly different by LSD (0.05).

‡ Comparing two DTW transition subplot means across different DS mainplots.

Table 6. The effects of soil and crop management during the dry season and the dry-to-wet season transition (DTW) and recycling of residues from DTW on dry matter and N accumulation by 9- or 10-wk-old flooded rice plants in a lowland.

	Plants, 9 or 10 wk old†			
	Dry wt.		Total N	
Management	1990	1991	1990	1991
	kg N ha^{-1}			
Dry season (DS), mainplots‡				
Weedy fallow	1.6a§	1.2a	28a	28a
Weed-free fallow	1.5a	1.3a	27a	28a
Tilled–wet/dry fallow	1.5a	1.3a	27a	29a
Dry-to-wet (DTW) transition, subplots¶				
S. rostrata	2.2a	1.8a	42a	45a
Mungbean	1.8b	1.5b	32b	35b
Weeds	1.2c	1.0c	19c	20c
Weed-free	1.1d	0.8d	15d	14d

† 10 wk after seeding (7 wk after transplanting) in 1990 and 9 wk after seeding (6 wk after transplanting) in 1991.

‡ Values averaged across DTW transition subplots.

§ Within columns and DS mainplots or DTW transition subplots, means followed by the same lowercase letter are not significantly different by LSD (0.05).

¶ Values averaged across DS mainplots.

kg N ha^{-1}). While mungbean, on average, produced the least amount of residues (2.8 t ha^{-1}), its N content (53 kg N ha^{-1}) was significantly greater than in weed residues. Except in the case of weeds, residue biomass was significantly lower in the second year. The greater residue biomass of *S. rostrata* in 1990 than 1991 was because of its 10 d longer growth period in 1990. Mungbean residue biomass in 1990 was more than twice that in 1991, primarily due to a low harvest index in 1990 (Table 4). This was due to abortion of mungbean pods caused by heavy rains in 1990. Not only did the residue N amounts vary considerably, but also the N concentrations of the residues between plant species and between years, potentially causing varying N supplies to the succeeding flooded rice crop.

Depending on the DTW-extracted N levels (Table 1), the residue N consisted of varying proportions of soil N and BNF-N (Tables 3, 4, and 5). In the weedy fallow mainplots, N derived from BNF accounted for a major portion of the legume N recycled to rice. On the other hand, in the weed-free and tilled fallow mainplots, N derived from soil accounted for a substantial portion of the recycled legume N. Normally, the value of recycling soil NO_3^- by legume green manuring may not be apparent, since BNF could compensate for reduced uptake of soil N regardless of NO_3^- loss. With the ^{15}N-isotope-based BNF data and frequently measured soil NO_3^- data, it was possible to determine that the DS management had a major influence on NO_3^- loss and DTW vegetation-recycled soil NO_3^-. There is yet another advantage for recycling soil NO_3^- as DTW plant N to a flooded rice crop in a lowland as opposed to upland: the anaerobic N mineralization stops at NH_4 stage, preventing further loss of this N through NO_3^- leaching or denitrification. It should be noted, however, that depending on the N amount and flood water chemistry, the recycled N is still subject to loss as ammonia during the flooded rice crop (Buresh and De Datta, 1991).

Recycling in situ of soil NO_3^- or BNF-N, as opposed to harvesting of a crop product for human use, would be of merit only if this N is effectively used by the subsequent flooded rice crop. In both years, dry matter and N accumulation by 9- to 10-wk-old rice plants did differ significantly between the subplot treatments of the transition period, but not between the DS mainplots (Table 6) despite the differences in residue biomass and N amounts. Rice in plots that were maintained plant-free during the DTW transition and that, therefore, received no residues, accumulated the least dry matter and N. In *S. rostrata* plots, dry matter and N accumulation by rice was the highest, reflecting the high amounts of residue N recycled (Table 5); rice N accumulation was as much as three times higher in *S. rostrata* plots than in weed-free plots. However, N accumulation by rice crop at this early stage did not correspond with the amounts of residue N that were recycled. For example, *S. rostrata* residue N, which was 136 kg N ha^{-1} greater than that of mungbean residue N, coincided with only 10 kg N ha^{-1} increase in rice N. On the other hand, 16 kg N ha^{-1} greater mungbean residue N than weed N increased rice N by almost a similar amount (14 kg N ha^{-1}). These disproportionate relationships between residue N and rice N are likely due in part to a limited sink for N at this early stage in rice growth.

SUMMARY

In tropical rice lowlands, minimizing NO_3^- loss during the DTW transition may not only conserve soil N, but also avoid negative impacts on the environment of N_2O gas from denitrification and leached NO_3^-. By manipulating soil NO_3^- levels, soil N uptake, BNF, and residue N, we examined the role of weeds and legume crops in conserving and recycling soil NO_3^- during the DTW transition. Some NO_3^- loss may be inevitable in rice lowlands even when substantial amounts of soil N is held in biomass by green manure crops such as *S. rostrata*. Unlike weeds, legumes offset NO_3^- loss by BNF. Under conditions of high NO_3^- buildup, green manure legumes such as *S. rostrata* are likely to be more effective in utilizing soil NO_3^- and to recycle a greater quantity of N than weeds to a subsequent rice crop. If the total harvestable crop N is considered, however, it is likely that a grain legume such as mungbean might be a better nitrate catch crop. Whether it is for green manuring or harvest of an economic product (grain or forage), or whether land is left to weeds, it is obvious that plants growing during the DTW transition conserve soil NO_3^-. The results support the need for a whole-system approach to N management to conserve and effectively use N in the lowland rice ecosystem.

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