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Managing native and legume-fixed nitrogen in lowland rice-based cropping systems*

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Key words: biological nitrogen fixation, denitrification, fallow, flooded soil, leaching, legume, nitrate, nitrogen balance, nitrogen loss, *Oryza sativa,* rice, weeds

Table of contents

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* IRRI-NitTAL-IFDC joint contribution.

Abstract

Lowlands comprise *87%* of the 145 M ha of world rice area. Lowland rice-based cropping systems are characterized by soil flooding during most of the rice growing season. Rainfall distribution, availability of irrigation water and prevailing temperatures determine when rice or other crops are grown. Nitrogen is the most required nutrient in lowland rice-based cropping systems. Reducing fertilizer N use in these cropping systems, while maintaining or enhancing crop output, is desirable from both environmental and economic perspectives. This may be possible by producing N on the land through legume biological nitrogen fixation (BNF), minimizing soil N losses, and by improved recycling of N through plant residues. At the end of a flooded rice crop, organic- and NH_4-N dominate in the soil, with negligible amounts of NO_3. Subsequent drying of the soil favors aerobic N transformations. Organic N mineralizes to NH_4, which is rapidly nitrified into NO_3. As a result, NO_3 accumulates in soil during the aerobic phase. Recent evidence indicates that large amounts of accumulated soil NO_3 may be lost from rice lowlands upon the flooding of aerobic soil for rice production. Plant uptake during the aerobic phase can conserve soil $N0_3$ from potential loss. Legumes grown during the aerobic phase additionally capture atmospheric N through BNF. The length of the nonflooded season, water availability, soil properties, and prevailing temperatures determine when and where legumes are, or can be, grown. The amount of N derived by legumes through BNF depends on the interaction of microbial, plant, and environmental determinants. Suitable legumes for lowland rice soils are those that can deplete soil NO_3 while deriving large amounts of N through BNF. Reducing soil N supply to the legume by suitable soil and crop management can increase BNF. Much of the N in legume biomass might be removed from the land in an economic crop produce. As biomass is removed, the likelihood of obtaining a positive soil N balance diminishes. Nonetheless, use of legumes rather than non-legumes is likely to contribute higher quantities of N to a subsequent rice crop. A whole-system approach to N management will be necessary to capture and effectively use soil and atmospheric sources of N in the lowland rice ecosystem.

Introduction

Rice *(Oryza sativa)* is the major staple food crop of the tropical world and rice-based cropping patterns are prevalent in much of the tropics. Rice is grown on 145 M ha, *87%* of which is in wetland (lowland) culture, with the remaining grown on dry lands. The annual cultivation period for rice is determined by the distribution of rainfall, availability of irrigation water, and temperatures. Upland crops are typically grown during the nonflooded period, particularly in the transition seasons either at the end of the rains or before the onset of heavy rainfall. Cool season crops, such as wheat and winter legumes, are grown during the nonflooded season in areas where cool temperatures limit rice production.

Lowland rice is grown in bunded fields and is surface-flooded during most of the growing season. Rice soils are typically flooded and puddled, and rice seedlings are then transplanted. Alternatively, germinated seeds are broadcast onto flooded soil that is either puddled or nonpuddled. Dry seeding, where seeds are dibbled or broadcast onto aerobic soil, is also practiced. The soil is flooded when there is sufficient water to be impounded.

Nitrogen is the input required in largest quantities for lowland rice production. Soil N and biological nitrogen fixation (BNF) by associated organisms are major sources of N for lowland rice. More than *50%* of the N used by flooded rice receiving fertilizer N is derived from the combination of mineralization of soil organic N (Bouldin, 1986; Broadbent, 1984) and BNF by free-living and rice plant-associated bacteria (Roger and Ladha, 1992). The remaining N requirement is normally met with fertilizer. However, the efficiency of fertilizer N uptake by rice is low due to large N losses from flooded soil (De Datta and Buresh, 1989; De Datta and Patrick, *1986;* .Savant *et al.*, 1982). Further, declining or stagnating yields have recently been noticed with flooded rice culture receiving fertilizer N (Flinn and De Datta, 1984). An additional concern is that the capacity of soil to supply N may decline with continuous intensive rice cropping necessitating the application of successively larger quantities of fertilizer N to maintain yields (Bacon, 1990). On the other hand, large amounts of soil NO_3 may be lost from rice lowlands upon the flooding of aerobic soil before the establishment of rice (Buresh *et al.*, 1989).

Reducing N fertilizer use while maintaining the native soil N resource and enhancing crop N output is desirable from both environmental and economic perspectives. This may be possible by obtaining more N on the land through biological nitrogen fixation (BNF), reducing losses of N, and by recycling the N captured in vegetation during the off-season. Buresh and De Datta (1991) recently reviewed the dynamics and management of N in rice-legume cropping systems. Their review indicates that soil N losses may be reduced by fallow management, and legumes can partially contribute to the N requirement of a succeeding rice crop. Thus, the management of indigenous soil N and N derived in situ through legume BNF poses potentials for enhancing the N nutrition and N use efficiency of crops and the total N output from a lowland rice-based cropping system. The integrated application of possible N management tactics will require detailed knowledge of the N dynamics of the cropping system as influenced by variation in hydrological characteristics and diversity of cropping practices.

In this paper, we address the N dynamics for a range of major tropical rice-growing ecosystems. We attempt to define the major lowland rice-based cropping systems, and to document their hydrological, climatic and management effects on soil N dynamics. We then discuss the use of legumes in the capture and use of indigenous soil nitrogen and fixed atmospheric nitrogen in major rice-based cropping systems.

Major lowland rice-based cropping systems

Rice-based cropping patterns are prevalent in those tropical areas with 1500 mm or more annual rainfall with at least three consecutive months of 200 mm per month. The amount and duration of rainfall normally determine the number of crops possible. The rates of onset and decline of rainfall determine the type of rice culture, other crops in the pattern, and difficulty in tillage (Harwood and Price, 1976). Growing upland crops after paddy rice requires soil conversion from an anaerobic puddled state to an aggregated aerobic condition. This is often difficult in soils high in montmorillonite clays. These soils are often left fallow during the dry months even when irrigation water is available (Palaniappan, 1985).

The number of rice crops grown in lowlands varies with supplemental water availability and prevailing temperatures. The type of upland crops that can be grown are influenced by the durations and timing of non-flooded periods. For purposes of this discussion, we distinguish three broad classes of tropical lowland rice culture in terms of the annual period in which the soil is not flooded: (1) continuously flooded or saturated year-round (Fig. lA), (2) short nonflooded (Fig. 1B), and (3) long non-flooded (Fig. 1C). The three classes may be further subdivided on the basis of other important determinants of N dynamics and upland crop adaptation, such as temperature and water availability.

Year-round lowland rice culture

Continuous rice production systems were rare prior to the introduction of photoperiod-insensitive rice cultivars. However, they have become increasingly common. At the most intensive limit, three rice crops are successively cultivated

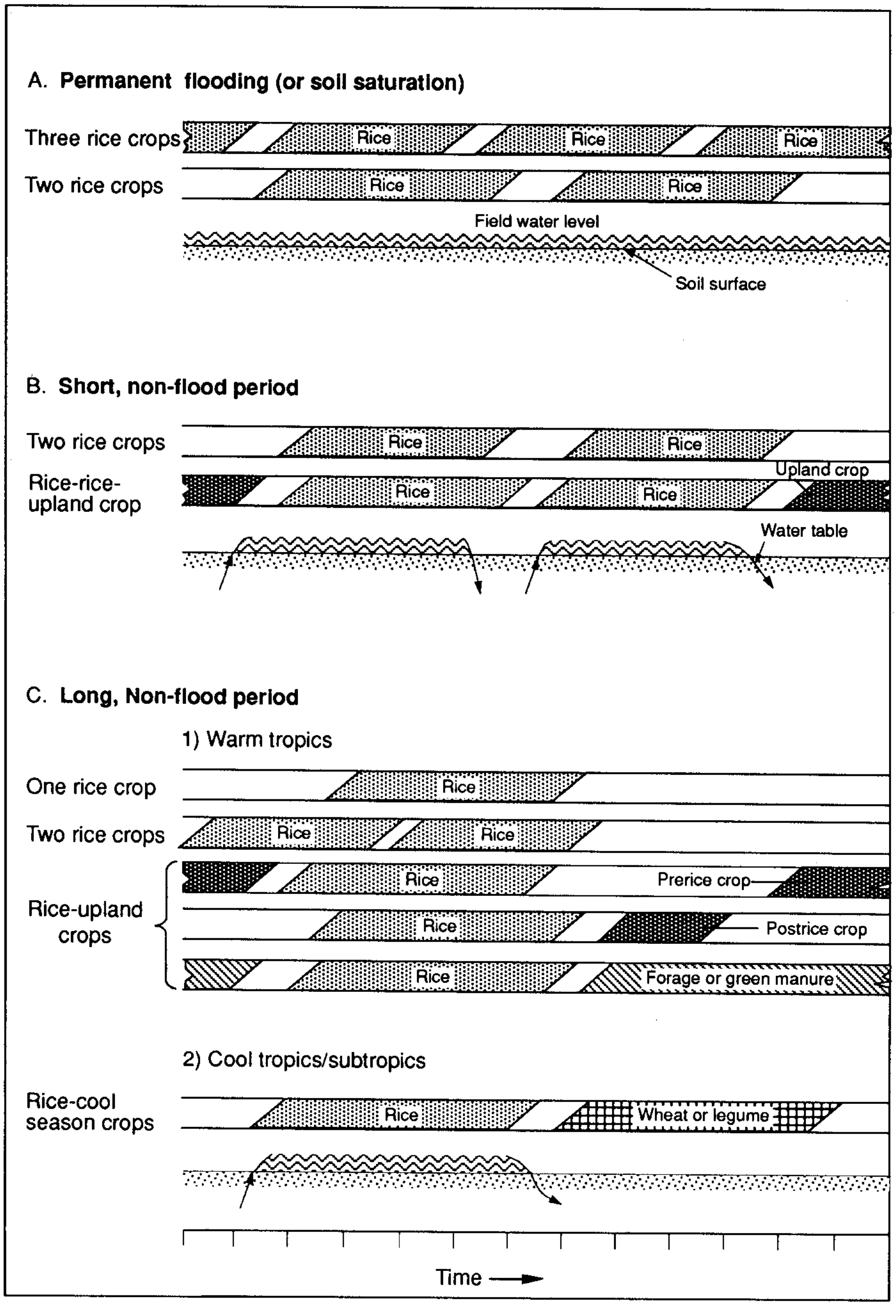

Fig. 1. Major lowland rice-based cropping systems from a soil nitrogen dynamics perspective. (**A**) permanent flooding (or soil saturation), (**B**) short, non-flood period, (**C**) long, non-flood period; (i) warm tropics and (ii) cool tropics/subtropics.

per annum under full irrigation, and the fields remain constantly saturated or flooded. The total area is not large, but this system is locally prominent in such areas as north Java and Bali, Indonesia.

Much more important are the irrigated double-crop ricelands, which are very common in countries at latitudes within 14° of the equator. Huke (1982) estimated double-cropped ricelands at 8.8 M ha or 13% of the total irrigated rice area worldwide. Much of the double cropped land remains flooded or saturated virtually year-round. An example is the double-cropped pump irrigated areas in Central Luzon, Philippines. Some very poorly drained rainfed and deepwater ricelands also experience year round waterlogging.

Lowland rice culture with short non flooded season

In much of Asia's irrigated double-cropped riceland there is a short dry period of one to two months between rice crops. This generally occurs in the late wet season before the dry-season crop is established, and/or after the dry-season crop is harvested.

Some rain fed areas that experience long wet seasons support two successive rice crops, leaving a short dry soil period of two to three months. The fields are usually left fallow due to lack of water or difficulty in tillage. In some areas legumes are produced on residual soil moisture, or established as relay crops on supplemental irrigation. Examples of this cropping system are rice-rice-grain legumes in southern India and Philippines, rice-rice-soybeans in Indonesia and rice-rice-Astragalus sp. in China.

Lowland rice culture with long non flooded season

Single-crop rice production is the dominant rice cultural system. The soil remains non-flooded from four to eight months of the year. This is the dominant case in the tropics because most riceland is rain fed, or can be irrigated only in the wet season (Garrity *et al.*, 1986). It is also dominant in the subtropics because although the land is fully irrigated, rice is constrained by cool temperatures during the winter season. Temperature also affects the soil N dynamics. Therefore, we recognize two subcategories of single crop lands, those in the warm tropics, and those with cool winters.

In single-crop ricelands, the rice crop may occupy the field from 90 to 210 days. There is great diversity in the rainfed rice ecosystems. They range from favorable rainfed conditions, to drought or submergence-prone shallow (0 to 25 cm), medium deep (25 to 50 cm), or deep water (>50 cm) flooding regimes. The highly variable surface hydrology has a profound influence on the nature of the N dynamics. Particularly significant is the unpredictable occurrence of aerobic or dry soil surface conditions during the growing season, alternating with surface flooding.

During the off-season, rainfed ricelands are typically fallowed (De Datta, 1981). The straw and fallow weed vegetation are subject to grazing by farm livestock. In a minor fraction of the area with conducive residual soil water-holding capacity, and/or a high groundwater table, upland crops, including legumes, are grown in the post-rice season. This practice is most common where the soil textures are loamy and exhibit superior tillage properties.

In well-drained ricelands with a gradual onset of rainfall in the dry-to-wet transition period, upland crops are grown prior to rice. Very early duration is advantageous, to permit maturity before the soil waterlogs. Mungbean is a very common grain legume in the pre-rice niche.

At latitudes above 14°N rice may experience significant cool-temperature stress during the coolest periods of the year. The establishment of dry-season rice crops is deliberately delayed to avoid this damage. Above 20° N dry-season rice cultivation is generally not feasible due to cold stress. Winter cereals or legumes are often grown in rotation with rice. The rice-wheat cropping pattern is dominant, occupying some 18 M ha in South Asia and China. Rice-legume patterns are also common. These often include chickpea, lentil, or soybean.

Soil nitrogen dynamics in rice lowlands

Fertilizer N transformations in flooded rice fields have been researched extensively (De Datta and Buresh, 1989; De Datta and Patrick, 1986). However, little attention has been paid to N transformations during the dry season when the soil is usually aerated (Buresh and De Datta, 1991). Knowledge is particularly lacking on the dynamics of soil N during the transition periods between dry and wet seasons.

A conceptualization of the dynamics of soil mineral N in a lowland, rice-growing soil undergoing a flooded-nonflooded sequence is pre-

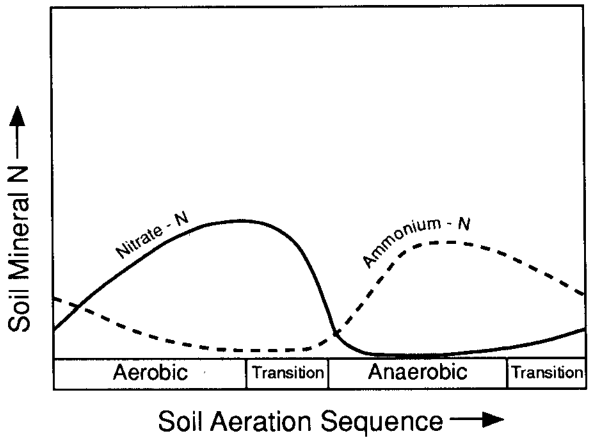

Fig. 2. Dynamics of soil mineral nitrogen in a lowland rice soil.

sented in Figure 2. Under saturated or flooded conditions, nitrification is restricted by a limited O_2 supply and NH, accumulates in the soil. At the end of a flooded rice crop, organic N and NH_4-N dominate and NO_3 present is typically negligible. Subsequent drying of the soil favors aerobic N transformations. Organic N mineralizes to NH_4, which is rapidly nitrified into NO_3. As a result, $N0_3$ accumulates in the soil during the aerobic phase, but is rapidly lost upon soil flooding.

Plant growth can influence the magnitudes and forms of soil mineral N (Fig. 3). Nitrate, the predominant form of soil mineral N during the nonflooded season, will be assimilated by plants growing during the dry season and dry-to-wet transition periods. Buresh *et al.* (1989) found that soil NO_3 during the dry season in a lowland rice soil correlated inversely with the amount of N accumulated in weeds. Legumes grown during this season additionally accumulate atmospheric N through BNF. Part or all of the N in the plant biomass is removed from the land through the harvestable products of an economic crop. The remaining plant N can be returned to the soil as residues.

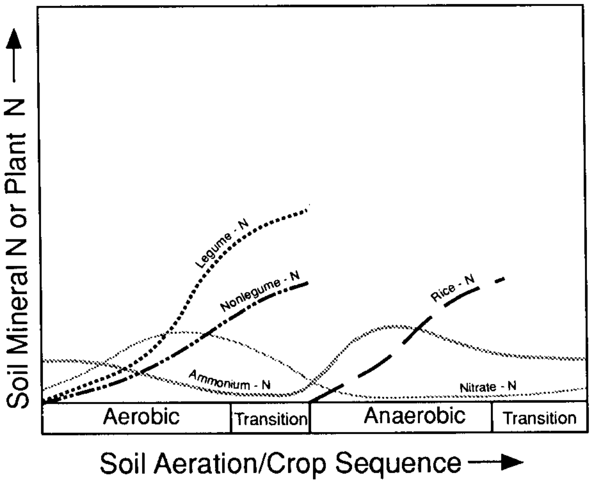

Fig. 3. Conceptual role of plants in conserving soil mineral and atmospheric nitrogen in a lowland rice-based cropping system.

Decomposition of plowed-under dry-season plant residues releases NH_4 into the flooded soil. Rice uptake decreases NH_4 the predominant N form in the flooded soil. Declining NH, level in flooded soil during the later part of rice season is partly replenished through BNF in flooded soil (Eskew *et al.*, 1981; Yoshida and Yoneyama, 1980) and from decomposition of rice roots and stubbles in addition to mineralization of soil N.

Soil nitrate accumulation

Nitrate-N accumulates when lowland rice soils become dry and aerated (Patrick and Wyatt, 1964, Ventura and Watanabe, 1978). Nitrate-N levels prior to flooding for wet season rice in several Philippine lowland rice soils ranged from 5 to 39 mg kg-' soil (Ponnamperuma, 1985). Buresh et al. (1989) measured 39 to 91 kg soil NO_3-N ha-' in the top 60 cm layer at the end of the dry season at three Philippine sites.

The production of $N0_3$ depends on the amount of organic N available for mineralization. Organic N varies considerably in lowland rice soils, depending on the level of native organic matter, and the history of cropping and organic amendments. The amount of N mineralized is increased by higher soil organic N levels (Broadbent, 1984; Hadas et al., 1986; Sahrawat, 1983). Bacon (1990) reported that successive soil incorporation of rice stubble gradually increased the N mineralization potential.

Residual soil water from the preceding wet-season rice crop, intermittent rains, and irrigation cause fluctuating soil water conditions. Soil water fluctuation generally results in a large production of NO_3 (Birch, 1960; Herlihy, 1979;

Sahrawat, 1980; Seneviratne and Wild, 1985). In a greenhouse study, continuous soil flooding during the dry season prevented NO_3 accumulation (Ventura and Watanabe, 1978). Drying, as well as alternate drying and wetting treatments resulted in the accumulation of soil NO_3.

Dry-season fallows are subjected to tillage for upland crop establishment or for weed control. Tillage increases soil aeration and tends to enhance the nitrification of mineralized NH_4 into NO_3 (Dowdell *et al.*, 1983). Herridge (1986) reported more. NO_3 in a cultivated fallow compared with a non-tilled fallow in a rainfed environment in Australia.

Loss of nitrate from soil

Flooding of aerated soil has generally been accepted as a major factor of NO_3 loss from rice soils (Bacon *et al.*, 1986; Buresh *et al.*, 1989; Janssen and Metzger, 1928; Patrick and Wyatt, 1964; Strickland, 1969; Wallihan, 1938; Yamane, 1957). With the use of ^{15}N microplots, Bacon et al. (1986) reported 90% reduction in NO_3 concentration after flooding of a rice soil. Loss of up to 91 kg ha^{-1} of native NO_3-N after flooding of fallow rice fields in the Philippines has been reported by Buresh *et al.* (1989).

Soil flooding can promote leaching losses of NO_3. Downward water flow carries NO_3 to lower soil layers (White, 1988). Two direct determinants of NO_3 leaching are the net downward flux of water and the concentration of NO_3 in the leaching water. Measuring these variables presents considerable problems because of difficulty in sampling and spatial and temporal variability in water flux and NO_3 concentration (Keeney, 1986; White, 1988). Large NO_3 losses through leaching occur generally from aggregated soils and from soils under bare fallow (Legg and Meisinger, 1982; White, 1988). These conditions exist in lowland soils during the aerobic phase before puddling for rice culture.

Soil saturation depletes soil of its O_2, thus creating favorable conditions for denitrifying organisms to reduce NO_3. Denitrification results in the production of N_2 and N_2O (Knowles, 1982). The rates of N_2 and N_2O evolution from soils will be higher under conditions of fluctuating redox potentials (wetting and drying cycles) than when the redox potential is continuously high (aerobic condition) or continuously low (anaerobic condition) (Letey *et al.*, 1981; Reddy and Patrick, 1975). Mosier *et al.* (1986) measured large fluxes of N_2 and N_2O from both fallow and cropped aerobic soils following water applications. Conditions favorable for N_2 and N_2O emissions may occur during the dry-to-wet transition period in lowland rice-based cropping systems.

Bacon et al. (1986) attributed rice soil NO_3 loss primarily to denitrification. An incubation study with the use of ^{15}N-labeled $N0_3$ by Buresh *et al.* (1989) indicated that NO_3 completely disappeared after 9 days of flooding, and 5% or less of the added NO_3 remained in the soil as either NH4 or organic N. Since conversion of NO_3 to NH_4 was negligible, either denitrification or leaching appeared to be the major loss mechanism.

Nitrogen dynamics of *major lowland rice-based cropping systems*

Soil N is essentially conserved under year-round flooded rice culture. Maintaining flooding between and during rice crops increases the soil N supply (Ponnamperuma, 1985; Santiago Ventura *et al.*, 1986; Ventura and Watanabe, 1978). Nitrate does not accumulate in the soil since soil drying between rice crops is minimal. Therefore, soil NO_3 losses associated with flooding events are not experienced. Rice field-associated BNF contributes to the maintenance of available soil N in these soils (Koyama and App, 1979).

In warm, tropical single-crop rice lowlands, large quantities of NO_3 might accumulate in soil over the prolonged aerated soil phase, then be lost during the dry-to-wet transition period. The quantity of NO_3 accumulated will depend on how the fallow is managed. Tillage and occasional rains might increase soil NO_3.

In intensively cultivated rice-wheat lowlands, fertilizer N application in excess of wheat crop requirements may lead to large quantities of residual mineral N after wheat harvest. Chaney (1990) observed significant increases in residual soil NO_3 levels after winter wheat at several sites in England when the N applications rates exceeded the optimum. Soil NO_3 after wheat in a sandy loam soil in India averaged 82 kg N ha^{-1} (Sharma *et al*., 1985), but the portion originated from fertilizer might have been low (Macdonald *et al*., 1989). Sharma *et al*. (1985) also found that NO_3 accumulation during a mungbean crop following wheat was substantial. Prior to the start of the wet season, the soil contained 223 kg NO_3-N ha^{-1}.

Impacts of nitrate loss from rice lowlands

It is well understood that the loss of NO_3 via leaching and denitrification has undesirable environmental consequences. Leaching leads to NO_3 pollution of ground-water and N_2O emission from denitrification poses a threat to the stability of the ozone layer (Pretty and Conway, 1989). The significance, if any, of NO_3 loss from rice lowlands on the environment, and the negative impacts of NO_3 loss on the long-term N fertility of lowland rice soil, have thus far been largely ignored by researchers.

Available reports suggest possible high losses of NO_3 during soil flooding for rice production, but do not account for the cumulative loss that can occur during the entire dry and dry-to-wet transition periods. Lowland rice soils undergo short-term wetting or flooding, especially from intermittent early rain near the end of the dry season. During short-term wetting of the soil, NO_3 can be lost through denitrification (Mosier *et al.*, 1986). Heavy rain would cause substantial downward water flow, especially in sandy soils, leading to NO_3 loss through leaching (White, 1988). It is likely that the total NO_3 loss is greater than the reported disappearances of NO_3 after soil flooding for rice production.

Legumes in lowland rice-based cropping systems

Legumes are grown in rice lowlands primarily for food, and to a lesser extent for green manure and forage. The importance of legumes in rice lowlands is enhanced by their ability to meet part of their N requirements from the atmosphere through BNF and their potential to enhance soil N fertility. The major food legumes grown include cowpea *(Vigna unguiculata),* mungbean *(Vigna radiata),* peanut *(Arachis hypogaea),* pigeon pea *(Cajanus cajan),* chick pea *(Cicer arietinum),* and soybean *(Glycine max).* Major green manure legumes include milk vetch *(Astragalus sinicus)* and *Sesbania* spp. in China, *Sesbania spp.,* sunnhemp *(Crotalaria juncea)* and berseem clover *(Trifolium alexandrinum)* in India; and indigo *(Indigofera tinctoria)* in the Philippines (Garrity and Flinn, 1988; Singh *et al*., 1991; Yost and Evans, 1988). The most promising forage legumes include siratro *(Macroptilium atropurpureum),* lablab bean *(Lablab purpureus),* sunnhemp, and clitoria *(Clitoris ternatea)* (Carangal *et al*., 1988). Several of the green manure legumes such as berseem clover (T. *alexandrinum)* are also suitable as forages.

The length of the non-flooded season, water availability, soil properties and climate primarily determine when and where legumes can be grown. These together with socio-economic factors determine whether food, forage, or green manure legumes are grown on ricelands. Under continuous rice culture, the periods between rice crops are too short to include legumes. In lowlands where two rice crops are taken, the nonfiooded fallow may be long enough to grow a short-duration legume. Green manure legumes could be planted during a 40-to-60 day transition period between rice crops (Garrity and Flinn, 1988). Relay cropping of pulse crops such as mungbean after the second rice crop is common in parts of India (Palaniappan, 1985).

In single rice crop lowlands of the warm tropics with a long nonflooded season, there are two niches for short-duration legumes. They are the post-rice dry season for grain or forage types and the pre-rice dry-wet transition for grain or green manure types (Garrity and Flinn, 1988). Long-duration forage, green manure and cover crop legumes are grown sometimes as well. They may occupy most of the non-flooded season. In single rice crop lowlands of the cool tropics/ subtropics, short- and long-duration winter legumes are grown for food, forage or green manure.

Biological nitrogen fixation by legumes in rice lowlands

The determinants of BNF by legumes have been dealt with in detail in other recent papers (Bohlool *et al.*, 1992; Peoples and Craswell, 1992; Peoples and Herridge, 1990). The coverage here will be limited to general principles and to specific determinants that are applicable to legume production in lowland rice-based cropping systems. In general, BNF can supply N to a legume as long, as a factor other than N is not limiting plant growth and an effective Rhizobium symbiosis is ensured (Bohlool et al., 1992). Abundant mineral N supply, however, inhibits or replaces BNF as a N source for legumes (Munns, 1977; Streeter, 1988). The interplay of *Rhizobium,* plant, and environment determines the proportions of legume N derived from atmospheric and soil sources.

Rhizobial determinants

Indigenous soil rhizobia are often ineffective or partially effective in BNF, but are quite successful in competing for nodule sites with introduced elite strains. This frequently results in no observed increase in BNF from rhizobial inoculation (Dowling and Broughton, 1986; Ham, 1980; Meade *et al.*, 1985; Weaver and Frederick, 1974). Nonetheless, a response to inoculation may not be obtained if the number of native effective soil rhizobia exceeds 20 to 50 cells g^{1} soil (Singleton and Tavares, 1986; Thies *et al.*, 1991 a) .

Soil flooding during the rice season decreases rhizobial numbers, but strains differ in survival ability (Boonkerd and Weaver, 1982), and often sufficient numbers of rhizobia for effective nodulation thrive (Weaver *et al.*, 1987). Ladha et al. (1989a) reported survival in high numbers of rhizobia of the aquatic legume *Sesbania rostrata* in flooded rice rhizosphere. Rain splash and flooding often promote stem nodulation by S. *rostrata;* however, stem inoculation is probably beneficial under dry conditions (Ladha *et al.*, 1991). Upland legumes following prolonged soil flooding may require inoculation to ensure effective symbiosis establishment. With proper characterization of native soil rhizobia and soil N supplying capacity, the inoculation requirements of legumes may be predicted for various environments using the models developed by Thies *et al.* (1991b). One model which incorporates the numbers of indigenous rhizobia and soil N mineralization potential is presented in Figure 4. The model input variables can be obtained through soil analysis prior to legume planting.

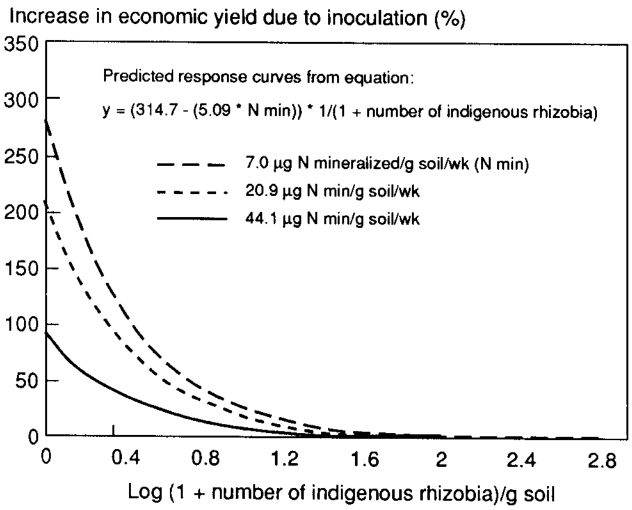

Fig. 4. Model describing legume inoculation response. Model inputs are numbers of indigenous rhizobia and soil N mineralization potential. Adapted from Thies et al. (1991b).

Plant determinants

The potential BNF capacity may be defined as the aggregate of the per-day deficits in mineral N uptake during the legume growth cycle (George and Singleton, 1992). Therefore, the higher the N yield potential of a legume for a given growth duration and soil N supply, the higher would be the proportion and amount of plant N derived through BNF (Fig. 5). For the sake of simplicity, it is assumed that the soil N uptake rate remains constant throughout the growth period which is unlikely in field environments.

The amount of N derived from BNF is also altered by the pattern of plant N assimilation (George and Singleton, 1992). The legume-Rhizobium symbiosis becomes functional in BNF only after the early rhizobial infection and nodule formation (Hardy *et al.*, 1971; Vincent,

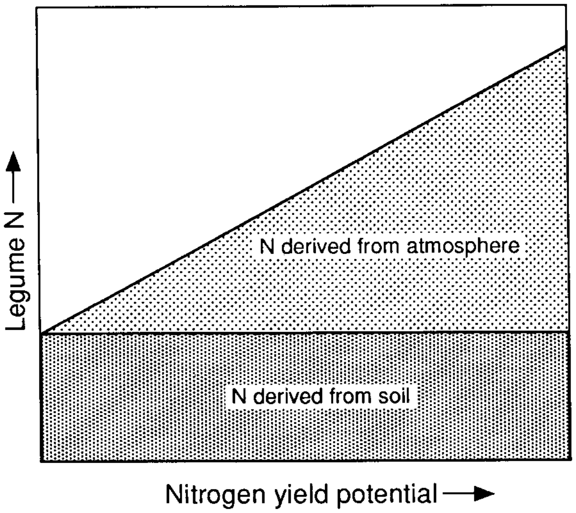

Fig. 5. Conceptual relationship between nitrogen yield potential and nitrogen derived from BNF under a constant soil nitrogen supply. It is assumed arbitrarily that the increasing nitrogen yield potential has no influence on the amount of nitrogen derived from soil.

1980). Therefore, during early legume growth, soil N is the major source of plant N. It is likely that a legume capable of meeting its early N requirement from the soil, but having a subsequent N requirement exceeding the soil N supply, will benefit from BNF. Consequently, soybean, which has a high N requirement during the podfill period, also has a high N_2 fixation rate during the same period (Afza *et al.*, 1987; George and Singleton, 1992; Imsande, 1988, 1989; Zapata *et al.*, 1987).

The efficiency of mineral N uptake by legumes further interacts with the N yield potential and the pattern of N assimilation in determining the amount of N derived from BNF. Under similar soil mineral N levels, legumes that are more efficient in extracting soil mineral N will benefit less from BNF. Using ^{15}N, George and Singleton (1992) determined in the field that common bean scavenges soil N much more efficiently than soybean, resulting in a lower proportion of N derived from BNF (Table 1). In their study, soybean derived 70% of its N from BNF compared to 23% by common bean at a similar flowering date, but the mineral N uptake efficiency of soybean was less than half that of common bean as determined by ^{15}N.. Consequently, KCl extracted mineral N in the soil under soybean was almost twice as high as that under common bean.

Environmental determinants

Major environmental determinants of optimal BNF performance are soil-related constraints and climatic stresses. The soil mineral N supply is of dominant importance. Increased soil mineral N supply invariably decreases the proportion of N derived from BNF (Deibert *et al.*, 1979; Eaglesham *et al.*, 1983; George *et al.*, 1988; George and Singleton, 1992; Gibson and Harper, 1985; Herridge and Brockwell, 1988; Thies *et al.*, 1991b). However, soil mineral N and BNF can be complementary in meeting the N requirement of the legume (Bergersen *et al.*, 1985; Deibert *et al.*, 1979; Eaglesham *et al.*, 1983; Herridge and Brockwell, 1988; Herridge *et al.*, 1984).

On the other hand, the supply of mineral N in early legume growth can enhance BNF, a phenomenon often referred to as the `starter N' effect. Insufficient soil N can restrict initial plant growth which limits subsequent plant growth and N demand, resulting in reduced need for BNF-supplied N. Alleviation of early N stress increases the amount of N derived from BNF (Table 2). Soybean plants receiving small amounts of mineral N formed a higher number

Table 1. Plant N, N derived from BNF, N uptake efficiency[a] and KCl-extractable soil N at flowering of field grown soybean and common bean (George and Singleton, 1992)

Legume	Plant N ($kg\,N\,ha^{-1}$)	N from BNF (%)	^{15}N uptake (%)	KCl-extr. N ($mg\,N\,kg^{-1}$ soil)
Soybean	58	70	5	17
Common bean	80	23	12	10

[a] N uptake efficiency is determined by using ^{15}N isotope as tracer and is the percent of applied ^{15}N fertilizer ($3\,kg\,N\,ha^{-1}$) assimilated by the plant.

Table 2. Mineral N effects on nodulation, total N, N derived through BNF and trifoliate leaf area by soybeans grown for 33 days in pots amended with 0.8% bagasse (Singleton P W, 1991; pers. commun.)

Nitrogen applied (μg N g^{-1} soil)	Nodule (no. pot^{-1})	Nodule weight (mg pot^{-1})	Total N	N from BNF[a]		Area of trifoliate[b] (cm^2)
				Amount	% of total	
0	148	440	189	168	99	30
50	173	651	316	280	95	41
100	144	667	343	251	78	53
200	87	459	541	219	42	51
400	66	147	593	0	0	42

[a] Determined by the N difference method.
[b] Area of trifoliate at 16 days of growth.

and weight of nodules and derived larger amounts of N from BNF than plants receiving either no N or large amounts of mineral N. The 'starter N' effect was due to increased plant growth as reflected by the increased area of the trifoliate at 16 days.

From the data presented in Table 2 and in other reports (Deibert *et al.*, 1979; Eaglesham *et al.*, 1983; George and Singleton, 1992; Herridge and Brockwell, 1988; Thies *et al.*, 1991a,b), a generalized conceptual relationship between soil N supply and N derived from BNF by legumes can be illustrated (Fig. 6). Initially, a 'starter N' effect tends to increase BNF but N from BNF approaches zero at the highest level of soil N supply. Increasing N supply, however, tends to increase total legume N.

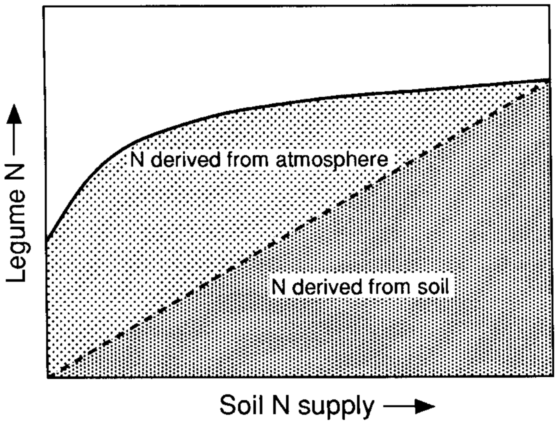

Fig. 6. A generalized conceptual relationship between soil N supply and nitrogen derived from soil or BNF. Data from Table 2 and data reported by Deibert et al. (1979); Eaglesham et al. (1983); George and Singleton (1992); Herridge and Brockwell (1988); Thies et al. (1991a,b) are considered in the proposed relationship.

Other soil constraints include acidity, salinity, nutrient toxicities, and nutrient deficiencies (Craswell *et al.*, 1987; Munns, 1977; O'Hara *et al.*, 1988; Singleton and Bohlool, 1983; Singleton et al., 1985). Application of P in soils of low P availability (Cassman *et al.*, 1981; Ssali and Keya, 1986) and liming acidic soils (Torres *et al.*, 1988) increases total N accumulation by legumes. Further, N_2-fixing legumes may have differing requirements of mineral nutrients compared to mineral N-dependent plants. Insufficient supply of mineral elements such as Ca, Mo, B and Fe can particularly limit N_2 fixation (O'Hara *et al.*, 1988; Robson, 1978). External P requirements of N_2-fixing legumes are higher than for mineral N-dependent legumes because of limited proliferation of the root system (Cassman *et al.*, 1980, 1981).

Likewise, waterlogging or water deficit negatively influences either plant growth or the symbiosis (Bennett and Albrecht, 1984; Chapman and Muchow, 1985; De Vries *et al.*, 1989a,b, Kucey et al., 1988; Minchin and Summerfield, 1976; Muchow, 1985; Sinclair *et al.*, 1987; Smith et al., 1988; Timsina, 1989). Water stress reduces total N accumulation (Chapman and Muchow, 1985) and, especially during late growth stages, limits pod addition and subsequent seed N demand in grain legumes (De Vries *et al.*, 1989b), thereby reducing N derived from BNF.

Additionally, climatic stresses such as low temperature, low solar radiation and unfavorable photoperiod can deleteriously affect plant and symbiotic performance (Becker *et al.*, 1990; George *et al.*, 1988, 1990; Hodges and French, 1985; Lawn and Williams, 1987; Muchow, 1985). Becker *et al.* (1990) reported that the number of days required to produce 100 kg N by *S. rostrata* was higher when the plants were grown during short days than during long days.

Nitrogen contribution from legumes in rice lowlands

Inclusion of legumes in the cropping pattern with rice can increase. the total N output from the cropping system but does not necessarily result in a positive soil N contribution. The amount of N derived from BNF, the net effect of the legume on N losses and the amount of N removed with harvested plant material will determine whether there is a positive net soil N balance.

Food and forage legumes

The amount of N removed from the land and the amount available for recycling will vary with the N harvest index (NHI), which is the fraction of total N removed in the harvested produce. To achieve a positive soil N balance after legume harvest, it is essential that the amount of N derived from BNF exceed the amount of N removed in the legume produce, i.e. the proportion of total N derived from BNF should exceed NHI. Nitrogen removal through grain or forage may deplete soil N. Of the 23 cases of grain legumes compiled by Peoples and Craswell (1992), N balances were positive in 17 cases and negative or unchanged in six cases.

Examples of soil N gain or depletion by grain legumes under varying N availability and yield potentials are presented in Table 3. The data demonstrate that even with a large N input from BNF, the net soil N balance may be negative. Despite a high soybean crop N value (404 kg N ha^{-1}) and high BNF input (290 kg N ha^{-1}) the net soil N balance was negative because NHI exceeded the proportion of N derived from BNF (Table 3, Chapman and Myers, 1987). In the above example, a slight reduction in NHI or a slight increase in N derived from BNF would have resulted in a large soil N gain since the N yield was large. Since NHI is an attribute less amenable to field management, obtaining a positive soil N gain may primarily depend on strategies to increase BNF.

As Peoples and Craswell (1992) have also argued, even when there is little or no net soil N gain, the depletion of soil N is still much less after a grain legume than a nonlegume. Nevertheless, grain legumes increase the N output of the cropping system that is economically usable. Management approaches to limit the amount of N removed in an economic produce to the amount of N derived from BNF will at least prevent depletion of native soil N. One approach which meets the purposes of both grain N harvest and residue N production is the use of dual-purpose food legumes (Buresh and De Datta, 1991; Kulkarni and Pandey, 1988).

The effect of cutting and removing plant residues as fodder for farm animals or of allowing farm animals to graze on legume cover-cropped fallows has a similar effect as exporting N through harvested grains (Myers and Wood, 1987). The amount of N returned to the land depends on how the animal residues are managed. Nevertheless, grazing by animals is likely to remove less N from land than cutting and removing plant residues because part of the forage ingested by grazing animals is returned to the land via urine and dung.

Stem-modulating aquatic green manure legumes

Stem-modulating aquatic green manure legumes are fast-growing and can accumulate large amounts of N in 45 to 60 days of growth (Ladha *et al.*, 1992). Data on the most frequently studied stem-modulating aquatic green manure legume, *S. rostrata,* show that it derives larger amounts of N from BNF than do root-modulating waterlogging-tolerant legumes, under either flooded or non-flooded conditions and it accumulates as much or more N under flooded conditions as do root-modulating legumes such as S. *cannabina* and S. *sesban* grown under drained conditions (Morris et al., 1989; Ndoye and Dreyfus, 1988; Pareek *et al.*, 1990). These features make stem-modulating legumes uniquely suitable for areas prone to flooding in the prerice season.

The reported tolerance of BNF by stem-nodulating aquatic legumes to mineral N under

Table 3. Net soil nitrogen gains due to BNF following cropping of legumes at varying yield-potential and soil N availability levels[a]

Legume	N status at planting			Total crop N	% total crop N derived from BNF	% total crop N in produce removed	Net soil N gain due to BNF	Reference
	Total N (%)	Miner. N ($\mu g\ g^{-1}$)	Fert. N					
			($kg\ N\ ha^{-1}$)		(%)		$kg\ N\ ha^{-1}$	
Cowpea	0.12	–[b]	30	84	19	67	− 40	Sisworo et al. (1990)[c]
	–	81	0	125	70	64	+ 7	Ofori et al. (1987)
	–	81	25	153	54	64	− 16	Ofori et al. (1987)
	–	–	25	100	70	49	+ 21	Eaglesham et al. (1982)[d]
	–	–	100	98	36	53	− 17	Eaglesham et al. (1982)
Mungbean	0.04	3.5	–	172	65	52	+ 23	Chapman and Myers (1987)
	0.16	–	0	60	67	52	+ 9	Suwanarit et al. (1986)
	0.16	–	20	62	56	53	+ 2	Suwanarit et al. (1986)
Peanut	0.16	–	0	241	60	48	+ 29	Suwanarit et al. (1986)
	0.16	–	20	250	62	47	+ 38	Suwanarit et al. (1986)
Soybean	0.04	3.5	–	404	72	73	− 6	Chapman and Myers (1987)
	0.12	–	30	90	33	62	− 26	Sisworo et al. (1990)[e]
	0.16	–	0	186	65	9	+104	Suwanarit et al. (1986)
	0.16	–	20	174	68	9	+103	Suwanarit et al. (1986)
	–	Low	0	246	68	62	+ 14	Thurlow and Hiltbold (1985)[f]
	0.30	–	33	222	46	73	− 60	Zapata et al. (1987)
	0.13	38	0	347	9	47	−132	Bergersen et al. (1989)[g]
	0.13	19	0	267	56	68	− 32	Bergersen et al. (1989)[h]

[a] Values derived from available data when originally not given. [b] Data not available. [c] Average for four crops. [d] Average for four cultivars. [e] Average for two crops. [f] Average for 'Lee' soybean at six sites. [g] Pre-fallowed soil; total N includes roots, nodules and fallen leaves. [h] Pre-cropped (oats) soil; total N includes roots, nodules and fallen leaves.

flooded conditions (Becker *et al.*, 1986, 1990; Dreyfus and Dommergues, 1980; Eaglesham and Szalay, 1983; Ladha *et al.*, 1992) may suggest that these legumes prefer N from BNF over soil N. Whether this characteristic leads to soil NO_3 accumulation in aerobic soil is yet to be determined. However, similar total N accumulation and similar or decreased N_2 fixation by S. *rostrata* in non-flooded compared to flooded soil (Morris et al., 1989; Ndoye and Dreyfus, 1988) may indicate a significant capacity for soil N uptake in aerobic soil.

Legumes in the post-rice as opposed to the pre-rice niche

Post-rice legumes with subsequent fallow periods before wet-season rice, and pre-rice legumes grown immediately before the wet-season rice, may have varied effects on native soil N and on N contribution to rice. It appears that soil NO_3 accumulation in fallows following legumes could be significant. Strong et al. (1986) presented data on soil mineral N (NO_3 and NH_4) accumulation during 6 months of fallow following several legumes, oil seeds, and cereals. Following harvest, crop residues were left in the field, and the soil was tilled to a depth of 8 cm. Soil mineral N accumulation during the fallow period was generally higher following legumes than following oilseeds or cereals. They attributed differences in soil mineral N to differences in N content and C:N ratios of the crop residues.

High quantities of mineral N following the legumes are not advantageous to rice. Nitrogen mineralization during the post-legume fallow, and subsequent N loss upon soil flooding will remove the mineral N from the system. There is evidence that, regardless of post-rice treatments, soil NO_3 may rapidly drop to uniformly low levels by the start of the wet-season rice crop. The higher soil NO_3 level following post-rice legumes compared to weeds reported by Buresh and De Datta (1991) in a Philippine soil persisted until the next sampling, 3 weeks later. However, NO_3 in all treatments declined to a low level before the start of the wet-season rice culture (Table 4, IRRI-NifTAL-IFDC collaborative research). Weed growth during the fallow period after the legume harvest probably assimilated some of the soil NO_3, but NO_3 loss was likely to have been large in the treatments.

Results of Hamid *et al.* (1984) show no difference in rice yields when rice is grown six weeks after legume harvest or after approximately 18 weeks of continuous fallow. However, when sorghum was the post-rice crop the rice yield was severely depressed. In a study by John *et al.* (1989), yield of rice immediately after cowpea cropping with all aboveground residues removed or after a weedy fallow were similar. The addition of pre-rice cowpea residues, however, did increase rice yield.

Maximizing total nitrogen capture by legumes in rice lowlands

Maximizing N gains through legumes in rice lowlands entails approaches that maximize BNF

Table 4. Soil-nitrate accumulation during the fallow period following post-rice legumes and weedy fallow in a lowland rice-based cropping system

Post-rice treatment	Sampling time for nitrate		
	Legume harvest[a] (0–80 cm)	3 wk after harvest (0–60 cm)	6 wk after harvest[b] (0–60 cm)
	(kg NO_3-N ha^{-1})		
Cowpea	53	47	8
Mungbean	53	52	9
Nodulating soybean	54	50	8
Nonnodulating soybean	47	40	8
Weedy fallow	32	28	7

[a] Data from Buresh and De Datta (1991).
[b] Start of wet-season rice culture.

while minimizing soil N losses. Soil and crop management should ensure establishment of an effective symbiosis, and prevent excessive accumulation and subsequent loss of soil NO_3. The quantity of mineral N present at planting and mineralized during the legume growing season will influence the amount of N derived from BNF.

Managing soil nitrate supply

Soil nitrate associated with the aerobic phase in ricelands can be a source of N for both legume and rice crop, if it can be managed effectively. A lack of response of legumes to external N application indicates that the initial N needs are generally met by native soil NO_3. Moreover, legume N needs may be limited by a reduced yield potential due to inadequate supplies of water and nutrients other than N. Nitrate-N assimilated by the legume is conserved in the system against possible loss due to subsequent soil flooding. The management objective then is to utilize soil NO_3 that might otherwise be lost, and to maximize BNF.

Allowing for increased nitrate uptake

The total amount of N that can be accumulated by a legume crop in a given environment is fixed by physiological and environmental determinants. Legume management aims to meet this potential by maximizing the plant demand for N and by optimizing the soil mineral N supply to maximize aggregate plant N accumulation through soil uptake and BNF.

Soil water deficits often limit legume growth and plant N demand in lowland rice-based cropping systems. Establishing a post-rice legume crop prior to or immediately after the rice harvest is crucial in maximizing the use of the entire residual soil water reservoir. Water deficits are likely during the late growth stages of a post-rice legume because of a receding water table (Senthong and Pandey, 1989; Timsina, 1989).

In areas with limited soil-water availability, drought-tolerant legumes such as pigeon pea and indigo are suitable post-rice legumes that accumulate N throughout the dry season. Peanut is reported to withstand relatively larger soil water deficits than most grain legumes because of a higher root density in the lower soil depths (De Vries et al., 1989a; Senthong and Pandey, 1989).

Early rains facilitate establishment of pre-rice legumes. However, intermittent waterlogging during this season is deleterious to crop growth and yield formation (Alam, 1989; Minchin et al., 1978; Timsina, 1989), thus limiting N derived from BNF. Alam (1989) observed that cowpea and mungbean are unsuitable in poorly drained soils where short-term flooding occurs during the pre-rice dry-to-wet transition period. Aquatic legumes can increase N input in these soils. Green manure legumes such as S. *rostrata* and *Aeschynomene afraspera* are adapted to flooded soil conditions (Ladha et al., 1992). Aquatic legumes can possibly conserve soil NO_3 during growth in nonflooded soil. Stem nodule BNF can additionally provide N to the plant when the soil is flooded.

Increased soil water availability not only enhances legume growth, but also promotes soil NO_3 production. Ideally, the previously accumulated NO_3 should be depleted during early legume growth, and NO_3 supply thereafter should be less than plant N demand. A reduced soil NO_3 supply combined with sufficient water for legume growth can result in enhanced BNF as the legume enters the reproductive phase.

Minimizing soil supply of nitrate

Management may play a role in influencing the amount of NO_3-N formed in aerobic soil and its subsequent assimilation by plants or loss from the soil-plant system. Planting legumes with notillage is a strategy to decrease soil NO_3, since tillage can increase soil NO_3 levels. Peoples and Craswell (1992) have presented data showing improved N_2 fixation by soybean under notillage. Therefore, relay seeding of legumes before harvest of the preceding rice crop might be suitable for maximizing residual water use and decreasing NO_3 accumulation.

Rice stubble management can influence the amount of NO_3 produced in soil. Incorporating the stubble rather than leaving it on the soil surface or burning it following harvest, significantly reduces soil NO_3 (Bacon, 1987, 1990). Bacon (1987) reported reduced soil NO_3 levels for up to 12 weeks, and reduced N uptake by the following wheat crop, when rice stubble

(15 t ha^{-1}) was incorporated soon after harvest. Nitrogen depletion by crops preceding the legume or competition for N in a legume-nonlegume intercropping system, influences the amount of NO_3 available to the legume crop. Soil NO_3 is low immediately after a flooded rice crop. Planting a legume immediately after the rice crop might maximize BNF provided soil water is adequate. Total N derived from BNF by several legumes increased to 93-95% when grown immediately after a dry-season rice crop, compared to 65-72% when grown after a prolonged fallow (Chapman and Myers, 1987). Legumes following cereals usually fix higher amounts of N than legumes following a fallowed soil (Bergersen *et al.*, 1985, 1989) because of decreased soil mineral N levels. Likewise, cereallegume intercropping can enhance N derived from BNF by the legume (Fujita *et al.*, 1992; Rerkasem *et al.*, 1988; Rerkasem and Rerkasem, 1988) due to mineral N depletion by

Managing inefficient nitrate uptake by legumes

Legumes that are inefficient in mineral N uptake might meet their N requirement through BNF because of a complementary relationship between soil N uptake and BNF. This might cause no substantial change in the amount of legume N accumulated but might lead to larger net NO_3 loss from lowland rice soils. While some reports indicate inefficient NO_3 uptake during the legume reproductive phase (Imsande, 1986; Imsande and Edwards, 1988) others indicate large N uptake from aerobic soil throughout the legume reproductive phase (Afza *et al.*, 1987; George and Singleton, 1992). Herridge and Bergersen (1988) described the "sparing" of soil NO_3 by N_2-fixing legumes, where more NO_3 remains in the soil after a legume compared to a nonlegume. Nonetheless, excess NO_3 may remain in a lowland soil after the growth of a legume. This NO_3 can be lost after soil flooding.

Larger amounts of residual soil mineral N have been reported after cropping of legumes than of other crops (Doughton and MacKeN2ie, 1984; McEwen *et al.*, 1989; Stong *et al.*, 1986). Reports on post-legume soil NO_3 levels in lowland rice soils are few. Buresh *et al.* (1989) reported 25 kg NO_3-N ha^{-1} in the top 60 cm soil layer at harvest of mungbean grown after lowland rice. Table 4 shows identical soil NO_3 levels (52 kg NO_3-N ha^{-1}) in the top 80 cm layer at harvest of soybean, cowpea, mungbean and a non-nodulating soybean isoline in a lowland rice soil, but a reduced NO_3 level (32 kg NO_3N ha^{-1}) under a weedy fallow. The corresponding NO_3 levels in the top 20 cm soil layer were 30 kg NO_3-N ha^{-1} for legumes and 12 kg NO_3-N ha^{-1} for a weedy fallow, indicating that the weeds were more effective than legumes either in depleting soil NO_3 or in maintaining low NO_3 levels by other mechanisms. Nitrogen fixation by the legumes, however, had not influenced the soil NO_3 levels, as the non-nodulating soybean and the N_2-fixing legumes maintained similar soil NO_3 levels.

Weed N accumulation during the dry season in lowland rice soils reported by Buresh and De Datta (1991) ranged from 11 to 29 kg N ha^{-1}. It is likely that most legumes that derived at least 50% of their N from BNF would have equal or larger amounts of N removed from soil compared to weeds; there might be other effects of weeds on soil NO_3 than uptake. Soil NO_3 levels are usually lower in grass and hay crop fields than in fields of row-planted crops such as maize (Magdoff, 1982).

It follows that strategies to develop or select legume-Rhizobium symbioses tolerant to soil $N0_3$ (Betts and Herridge, 1987; Carroll *et al.*, 1985; Hansen *et al.*, 1989; Herridge and Betts, 1988) or legumes with reduced ability to use NO_3 (Carroll and Gresshoff, 1986; Nelson *et al.*, 1983) might not be advantageous in lowland rice-based cropping systems unless methods other than plant uptake are found to prevent the buildup and subsequent loss of NO_3. Suitable legume genotypes for lowland rice soils might be those that can deplete soil NO_3 while still deriving large amounts of N from BNF. Part of the NO_3 could possibly also be assimilated by weeds either during a post-legume fallow period before rice or during the legume crop.

Use of legume nitrogen for lowland rice

Use of legume green manures and grain legume residues as a N source to rice has been well reviewed (Buresh and De Datta, 1991; Singh *et al.*, 1991). Soil incorporation of legume green manures (Ladha *et al.*, 1989b; Morris *et al.*, 1986a, 1989; Ventura *et al.*, 1987) and of legume harvest residues (Alam, 1989; John *et al.*, 1989; Norman *et al.*, 1990) in lowland rice culture generally results in increased N uptake and yield of rice. However, the efficiency of residue N use by rice might be exaggerated, because most reports attribute the positive influence exclusively to a N effect.

Belowground residues

Data compiled by Buresh and De Datta (1991) showed legume root N accumulation ranging from 3 to 50 kg N ha^{-1}. They assessed the contribution from belowground legume residues as a N source for rice to be negligible in most cases. This would be especially true with grain legumes grown to maturity because of the remobilization of N from roots and nodules to the grain. The belowground N contribution may be significant if legumes are incorporated as green manure during the flowering and early reproductive stages when root nodulation could be abundant. Nodule biomass at flowering of several grain legumes ranged approximately from 4 to 118 kg ha^{-1} (Table 5, Abaidoo *et al.*, 1990; George *et al.*, 1987; Thies *et al.*, 1991a). Assuming a maximum 7% N content, this nodule biomass contained approximately 0.3 to 8 kg N ha^{-1}. Adding the amount of N present in the roots, total belowground N could become significant in certain cases. However, the value of this N to lowland rice is questionable because N-rich nodule tissue would decompose and release N very rapidly. Morris *et al.* (1989) found no difference in rice N-gain between legume green manure grown in situ or that transported from a nearby field, suggesting no N contribution from belowground biomass. Nevertheless,, quantitative data on belowground residue N are required to understand N cycling in rice-based cropping systems.

Table 5. Nodule biomass at flowering of legumes in tropical soils

Legume	Nodule biomass (kg ha^{-1})	Reference
Common bean	4– 68	Abaidoo et al., (1990)[a]
	8– 65	Thies et al., (1991a)[b]
Cowpea	38–105	Thies et al., (1991a)
Lima bean	13– 67	Thies et al., (1991a)
Soybean	16– 75	Abaidoo et al., (1990)[a]
	24– 87	Thies et al., (1991a)[b]
	26–118	George et al., (1987)[c]

[a] Across two sites of differing mean temperature and three N application regimes.

[b] Across several sites of varying soil N status and yield potential.

[c] Across three sites of varying soil N status and mean temperature.

Aboveground residues

The amount of N that can be incorporated through some legume green manure crops (Ladha *et al.*, 1992) is larger than the N needs of rice. Buresh and De Datta (1991) compiled data on amounts of N incorporated with aboveground green manure and grain legume residues in lowland rice-based cropping systems. Green manure N ranged from 21 to 267 kg N ha^{-1}; N in aboveground residues of grain legumes from 17 to 101 kg N ha^{-1}. Nitrogen fertilizer substitution for lowland rice by incorporated green manures ranged from 24 to 137 kg N ha^{-1}, and by grain legume residues from 37 to 100 kg N ha^{-1}. Similar data are presented by Singh *et al.* (1991). Furoc and Morris (1989) suggested that the addition of N in S. *rostrata* green manure in excess of 100 kg ha^{-1} has limited value for increasing rice yield. Moreover, large application of N-rich legume residues has the potential to supply excessive N to rice, leading to crop lodging and yield reduction (Alam, 1989).

Nitrogen release from legume residues

Many studies demonstrate a rapid release of N, and an increase in soil NH_4, followed by a plateau or decline in NH_4 levels after green manure incorporation (Khind *et al.*, 1985; Nagarajah *et al.*, 1989; Palm et al., 1988). The release of NH_4 from green manure is, therefore, not matched by the N uptake by rice. Thus, NH_4 released may be subject to immobilization or loss. Morris *et al.* (1986b) reported that recovery of N from green manure was 33%, similar to that from N fertilizer. In contrast, Ventura *et al.*

(1987) reported up to 75% recovery of S. *rostrata* green manure N by rice. The differences in green manure N recoveries reported may be partly due to differences in the amount applied, in C:N ratio, and in timing and method of application. Recent data show that NH_4-N loss from green manure was lower than that with equivalent amounts of fertilizer N (Biswas, 1988). Rice recovery of green manure N is larger than from urea, and green manure increases the recovery of urea-N (Diekmann, 1991). Supplementing moderate amounts of basally applied green manure N with top dressed fertilizer N may maximize both green manure and fertilizer N recoveries (Morris *et al.*, 1986b).

Conclusions and research directions

The large amounts of NO_3-N, which accumulate in aerobic soil during the non-flooded season, can be lost for lowland rice upon flooding. Prevention of this loss might make a significant N contribution to crops in the dry-to-wet transition period or to a subsequent rice crop. In addition, the inclusion of legumes for grain, forage, and green manure production might increase the total N output from the cropping system and further add to soil N through BNF. The N derived from BNF by legumes can be increased by maximizing plant N demand and by minimizing soil NO_3 supply. A post-rice nonlegume crop followed by a pre-rice green manure legume or intercropping legumes with nonlegumes during both the post-rice and pre-rice seasons might maximize the conservation and effective use of both soil NO_3 and atmospheric N in lowland rice-based cropping systems. Legumes would be ideal crops for soils low in native N, where other upland crops may grow poorly without external N supply. Where soils are left fallow during the non-flooded season due to production constraints, increasing the legume component in the weed flora may be suitable for capturing both soil NO_3 and atmospheric N.

Our knowledge of the processes and factors regulating NO_3 accumulation and loss during the nonflooded season and the dry-to-wet season transition period and how legume BNF fits into this complex are still very limited. Research is needed to understand the mechanisms of N gains and losses and to identify and refine appropriate soil and crop management practices to maximize soil N and legume BNF use in lowland rice-based cropping systems.

So far, research on N dynamics and balances in legume-lowland rice sequences has been primarily with pre-rice legumes grown just prior to wet season rice. Because dry-season legumes are also an important post-rice crop in lowland rice-based cropping system, there is a need to ascertain the effects of post-rice legumes with subsequent fallow periods before wet-season rice on native soil N dynamics and N contribution to rice.

Maintaining soil N levels in the rice-based farming system is not the dominant objective of the farmer in the choice of cropping pattern and management practices. Overall profitability shall continue to dominate as the basic farmer objective. However, there is a major potential for directing research toward identification of management practices aimed at maintaining long term soil fertility while providing profitability in the short term. This will depend upon a more solid knowledge base of system-level N dynamics.

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