Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems

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Abstract

Research and extension work to improve nitrogen (N) management of irrigated rice has received considerable investment because yield levels presently achieved by Asian farmers depend on large amounts of N fertilizer. Most work has focused on placement, form, and timing of applied N to reduce losses from volatilization and denitrification. In contrast, less emphasis has been given to development of methods to adjust N rates in relation to the amount of N supplied by indigenous soil resources. As a result, N fertilizer recommendations are typically made for districts or regions with the implicit assumption that soil N supply is relatively uniform within these domains. Recent studies, however, document tremendous variation in soil N supply among lowland rice fields with similar soil types or in the same field over time. Despite these differences, rice farmers do not adjust applied N rates to account for the wide range in soil N supply, and the resulting imbalance contributes to low N-use efficiency. A model for calculating N-use efficiency is proposed that explicitly accounts for contributions from both indigenous and applied N to plant uptake and yield. We argue that increased N-use efficiency will depend on field-specific N management tactics that are responsive to soil N supply and plant N status. N fertilizer losses are thus considered a symptom of incongruence between N supply and crop demand rather than a driving force of N efficiency. Recent knowledge of process controls on N cycling, microbial populations, and soil organic matter (SOM) formation and decomposition in flooded soils are discussed in relation to N-use efficiency. We conclude that the intrinsic capacity of wetland rice systems to conserve N and the rapid N uptake potential of the rice plant provide opportunities for significant increases in N efficiency by improved management and monitoring of indigenous N resources, straw residues, plant N status, and N fertilizer. © 1998 Elsevier Science B.V.

Keywords: Cropping systems; Fertilizer management; Nitrogen accumulation; Nitrogen-use efficiency; Nutrient-use efficiency; Soil organic matter; Rice

1. Importance of nitrogen supply in irrigated rice

1.1. Purpose and goals

This paper critically evaluates our knowledge of nitrogen (N) cycling, availability, and plant acquisition in irrigated lowland rice systems, and the appli-
cation of this knowledge to improved crop management and the conservation of natural resources. The goal is to identify gaps in our understanding of key processes and to identify key research issues that will have the greatest potential to increase N-use efficiency for rice farmers in the developing countries of Asia. The review concentrates on intensive, irrigated lowland systems of the tropics and subtropics where the rice crop is grown in submerged soil.

1.2. Current and projected requirements and use

Average rice yield on 74 Mha harvested in Asia was 4.9 t ha\textsuperscript{-1} in 1990, which accounted for about 75% of global rice supplies (IRRI, 1991). About 7 Mt of elemental N was applied as fertilizer to this irrigated rice area (Cassman and Pingali, 1995a). Long-term experiments in the Philippines and India clearly show that N is the most limiting nutrient in irrigated rice systems (Nambiar and Ghosh, 1984; De Datta et al., 1988b). Significant yield responses to applied N are obtained on nearly all lowland rice soils when irrigation is adequate and weeds or pest problems do not limit growth. In large part, plant N status determines rice yield potential through effects on leaf area development and canopy photosynthesis (Kropff et al., 1993a), and N drives the demand for other macronutrients in irrigated rice systems (Dobermann et al., 1997).

Although N supply drives productivity, poor N fertilizer-use efficiency is characteristic of irrigated rice systems. Low efficiency is largely attributed to rapid losses of applied N from NH\textsubscript{3} volatilization and denitrification. Fertilizer N losses are estimated to range from 10 to 65% of the applied N (Vlek and Byrnes, 1986; De Datta and Buresh, 1989). In farmers' fields of Central Luzon, Philippines, apparent N fertilizer recovery was only 36 to 39% in two favorable irrigated rice domains (Cassman et al., 1993; Cassman et al., 1996c). At present levels of efficiency, total N fertilizer applied to irrigated rice will have to increase nearly threefold in the next 25 to 30 years to achieve the 60% increase in rice production that is required to meet demand from population growth (Cassman and Harwood, 1995). Reduced profit, greater emission of greenhouse gases, and groundwater contamination are possible consequences of such a massive increase in fertilizer-N requirements. Improved crop and soil management practices are needed to avoid these problems, but their development will depend on technologies that can sustain increases in both grain yield and N-use efficiency achieved by rice farmers.

2. Quantifying N-use efficiency

2.1. Contributions from indigenous and applied N

Farmers are mostly concerned with total profit and the return from investment in labor and inputs. Partial factor productivity (PFP) from applied nutrients is a useful measure of nutrient-use efficiency because it provides an integrative index of the total economic output relative to utilization of all nutrient resources in the system—including indigenous soil nutrients and applied inputs. The PFP from applied N (PFP) is the ratio of grain yield to the amount of applied N:

\[ PFP = \frac{Y}{N_r} \quad (1) \]

where \( Y \) is the grain yield obtained with an applied N rate of \( N_r \). Because the grain yield at a given N rate represents the sum of the yield without N inputs \( (Y_0) \) plus the incremental increase in grain yield that results from N application \( (\Delta Y) \), PFP can be expressed as:

\[ PFP = \frac{Y_0 + \Delta Y}{N_r} \quad (2) \]

or,

\[ PFP = \frac{Y_0}{N_r} + \frac{\Delta Y}{N_r} \quad (3) \]

The incremental efficiency, \( \Delta Y/N_r \), is proportional to the benefit–cost ratio from purchased N inputs. It is often called the agronomic efficiency (AE, Novoa and Loomis, 1981), and it represents the product of uptake efficiency from applied N, or recovery efficiency (RE):

\[ RE = \frac{\Delta N_p}{N_r} \quad (4) \]

and the physiological efficiency (PE) with which the plant utilizes the N acquired from applied inputs to produce more grain:

\[ PE = \frac{\Delta Y}{\Delta N_p} \quad (5) \]
where $\Delta N_p$ is the increase in plant N accumulation that results from N application. Thus, AE can be estimated by:

$$AE = \frac{\Delta Y}{\Delta N_p} \left( \frac{\Delta N_p}{N_c} \right)$$

(6)

and, PFP can be expressed as:

$$PFP = \left( \frac{Y_0}{N_c} \right) + \left( \frac{\Delta Y}{\Delta N_p} \right) \left( \frac{\Delta N_p}{N_c} \right)$$

(7)

or,

$$PFP = \left( \frac{Y_0}{N_c} \right) + AE$$

(8)

It is, therefore, possible to increase PFP by increasing the amount, uptake and utilization of indigenous N resources, and by increasing the efficiency with which applied N is taken up by the crop and utilized to produce grain. While AE, RE and PE are efficiency parameters with biological significance, $Y_0/N_c$ is a mathematical term derived from separating the contribution of grain yield supported by indigenous N resources from the yield response to applied N in the estimation of PFP. Making this distinction helps to identify whether constraints to increased PFP in farmers’ fields involve low $Y_0$, poor AE or both (Cassman et al., 1996c). These distinctions are important for evaluating research opportunities on crop and soil management to increase N-use efficiency of irrigated rice for several reasons. First, we have recently come to recognize that variation in $Y_0$ is unpredictable in seemingly similar soils and environments (see Section 3.3). Second, changes in $Y_0$ have a tremendous influence on PFP, and adjusting the timing and rate of applied inputs in response to $Y_0$ is crucial for optimizing AE (see Sections 6.2 and 6.4). Finally, as farmers strive to achieve higher rice yields, the margin for error in oversupply of N becomes much smaller because of the increased problems from lodging and diseases (see Section 6.1).

2.2. Measurement of N fertilizer uptake and losses

The most relevant estimate of $\Delta N_p$ is obtained by the ‘nutrient difference’ method based on the measured difference in total plant N in treatment plots with and without applied N. Plant-N in both cases is measured in aboveground biomass at physiological maturity. When $\Delta N_p$ is measured by N difference, it includes plant N directly acquired from the applied N as well as any increase in N uptake caused by the effects of the applied N on the availability or acquisition of indigenous N resources (Jenkinson et al., 1985). Because both direct and indirect contributions from applied N contribute to the marginal benefit that a farmer obtains from application of N fertilizer, $N_p$ is an important estimate of AE.

Although $^{15}$N-labeled fertilizer has been used to estimate RE from applied fertilizer in many field studies with rice grown in flooded soil, $^{15}N_p$ based on uptake of labeled fertilizer is typically much smaller than the $\Delta N_p$ calculated by N-difference (Westcott and Mikkelsen, 1985; Bouldin, 1986; Diekmann et al., 1993). Use of $^{15}$N fertilizer to estimate plant uptake of applied N frequently gives values that are only 40 to 60% of the actual increase in plant N that results from N application. Underestimation can occur regardless of N source, including $^{15}$N-labelled inorganic fertilizer and labelled organic N sources such as green manures (Fig. 1). Low estimates of RE result primarily from rapid pool substitution (Schnier, 1994) caused by biotic and abiotic immobilization of the applied $^{15}$NH$_4$-N in the soil microbial biomass (SMB), labile soil organic matter (SOM) fractions, and perhaps by phenolic compounds released from decomposition of crop residues in the low oxygen environment of reduced soil (see Section 4.2). Abiotic immobilization would be less likely in aerated soils where NO$_3$-N is the predominant form of available inorganic N.

Although rapid pool substitution can result in underestimation of RE, $^{15}$N-labelled fertilizer can be used to monitor the fate of applied N by mass balance (Craswell et al., 1985; De Datta et al., 1987a,b; Schnier et al., 1988), and to measure abiotic and biotic immobilization of the added fertilizer in clay minerals, microbial biomass or specific SOM fractions (Keerthisinghe et al., 1984; Inubushi and Watanabe, 1986; Schnier et al., 1987). These processes govern the rates of immobilization and remineralization, which in turn have a large influence on the amount of applied N available for plant uptake. It is also possible to measure denitrification from labelled fertilizer by direct measurement of N$_2$ and N$_2$O efflux after accounting for pool substitution (isotopic dilution) of the inorganic N pool in the soil (Siegel et al., 1982; Buresh and Austin, 1988). In contrast, measurement of NH$_4$ volatilization from
applied N fertilizer application using micrometeorological methods does not require the use of labelled N fertilizer (Fillery and De Datta, 1986), and thus avoids the potential confounding effects of added N interactions.

3. Retrospect: research on management of N fertilizer

3.1. Nitrogen in the soil–floodwater system

A unique feature of irrigated lowland rice culture is crop growth in submerged soil. In transplanted rice, fields are flooded before planting and soil is puddled to reduce percolation. Rice can also be planted by direct seeding, using either wet seeding, with pre-germinated seed broadcast on a puddled soil surface, or dry seeding after normal soil tillage with flooding after the seedlings are established. In all cases, soil redox potential rapidly decreases within 14 to 28 d after flooding to a steady-state level determined by the amount of readily decomposable organic matter, temperature, and the availability of electron acceptors such as NO$_3^-$, Mn$^{+4}$ and Fe$^{+3}$ (Ponnamperuma, 1972).

The chemistry of the soil–floodwater system relevant to management of N has been described in detail elsewhere (Ponnamperuma, 1972; Bouldin, 1986; De Datta, 1987). Briefly, oxygen diffusion through the floodwater maintains a thin, superficial, aerobic soil layer of 1 to 20 mm, below which soil is in a reduced state. Nitrate in the floodwater or aerobic soil layer is rapidly lost to dissimilatory denitrification because it diffuses into the reduced soil, where it serves as an electron acceptor for microbial anaerobic respiration. Likewise, NH$_4^+$-N in the reduced soil layer can diffuse into the aerobic layer where it undergoes nitrification, followed by diffusion back into the reduced zone and denitrification. Ammonium can also diffuse into floodwater and be lost to volatilization. Recent evidence based on direct measurement of N$_2$, N$_2$O and NH$_3$ emissions from applied N fertilizer indicate that most gaseous losses result from NH$_3$ volatilization while losses from denitrification are relatively small (Buresh and De Datta, 1990).

Prilled urea and ammonium sulfate are the least expensive and most common N fertilizer sources used on rice. In Asia, fertilizer is applied mostly by hand. On rice, it is broadcast and incorporated in puddled soil just before planting or broadcast as a topdressing into floodwater during the cropping period. Urea is rapidly hydrolyzed within 1 to 2 d, when incorporated in soil, or within 2 to 4 d when topdressed into floodwater (Fillery et al., 1986a; De
Datta et al., 1987a). The residence time of inorganic \( \text{NH}_4^- \) from fertilizer incorporated in soil is much longer than in floodwater because \( \text{NH}_4^- \) is adsorbed on soil colloids and losses from percolation are generally small. Losses from incorporated N fertilizer occur from diffusion of \( \text{NH}_4^- \) into floodwater and subsequent volatilization. Relative losses of applied N fertilizer occur from diffusion of \( \text{NH}_4^- \) into floodwater and subsequent volatilization. Relative losses of applied N broadcast in floodwater are larger than losses when the applied N is incorporated in soil (Schnier et al., 1988; Schnier et al., 1990a). The rate of \( \text{NH}_3 \) volatilization losses is mostly determined by floodwater, depth, pH, temperature, \( \text{NH}_4^- \) concentration, and windspeed (Jayaweera and Mikkelsen, 1990; Jayaweera et al., 1990; Rachhpal-Singh and Kirk, 1993a,b).

3.2. Fertilizer management to reduce N losses

Most research concerned with improving N-use efficiency of irrigated rice has focused on the reduction of N losses from applied fertilizer. The rationale for this emphasis came from large numbers of field studies in which the fate of \( ^{15} \text{N} \)-labelled fertilizer was monitored. Total losses typically ranged from 13 to 64% of the applied N, with a mean loss of 43% in 13 experiments conducted in the Philippines (Buresh and De Datta, 1990). Recent examples of research to reduce N losses include studies on improved timing and placement of conventional urea and ammonium sulfate fertilizers (De Datta, 1986; Fillery et al., 1986b; De Datta et al., 1988a; Schnier et al., 1990a), fertilizer formulations such as urea supergranules (USG), slow-release, and controlled release N fertilizers (Craswell et al., 1985; Buresh, 1987; De Datta et al., 1987a; Shoji and Kanno, 1994; Stutterheim et al., 1994), interactions of N fertilizer and floodwater depth (De Datta et al., 1987b), and fertilizer amendment with nitrification or urease inhibitors (Buresh et al., 1988a,b,c; Chaiwanakupt et al., 1996).

Although these studies and many others have contributed to our knowledge of N dynamics in the soil–floodwater system and the relative importance of different loss mechanisms, they have had little impact on N fertilizer management practiced by rice farmers. For example, the increase in grain yield from modified urea products, such as nitrification or urease inhibitors, is generally too small to offset increased costs compared to split applications of conventional urea (Buresh and Baanante, 1993). Although use of algacides along with modified urea may further improve performance by reducing diurnal fluctuations in floodwater pH (Chaiwanakupt et al., 1996), environmental issues associated with increased pesticide load have not been evaluated. Moreover, algal photosynthesis contributes significant amounts of organic carbon to the soil–floodwater system (Saito and Watanabe, 1978; Vaquer, 1984), and a reduction in algal growth would have an impact on the carbon balance of lowland rice soils (Cassman et al., 1995) and on floodwater biology.

Economic considerations have also hindered the adoption of controlled release fertilizers, USG, and band or deep urea injection, although each of these technologies can reduce N losses and increase rice yields. Controlled release fertilizers are presently much too expensive and are primarily used on high-value ornamental and nursery plants. Manual application of USG requires about 40 h ha\(^{-1}\), which is approximately equivalent to the labor required for pneumatic urea injection (Scholten, 1992). Urea top-dressings require less than half the labor so that even ‘risk-adjusted’ cost-benefit analysis indicates that deep placement is not an economic proposition on small farms (Van Noordwijk and Scholten, 1994). Moreover, the cost of labor in most Asian countries has increased much faster than the cost of N fertilizer and this trend is expected to continue (Pingali et al., 1997), which further dims prospects of these options. For USG, long-term experiments indicate that the actual yield increase is small compared to a standard split application of urea (Table 1).

The research emphasis on the reduction of N losses estimated by \( ^{15} \text{N} \)-labelled fertilizer during the 1980s and early 1990s seems to have diverted attention from the more relevant issue of optimizing yield and PFP through the direct effects of management on \( Y_0 \), AE, RE and PE. In a number of studies, large treatment differences in \( ^{15} \text{N} \) fertilizer losses and plant \( ^{15} \text{N} \) uptake were not reflected in total plant N or grain yield, and this discrepancy received little discussion (De Datta et al., 1988a; Schnier et al., 1990a,b; Rosenani and Azizah Chulan, 1992). Also during this period, scant attention was paid to the relatively large differences among soils or between seasons in the effective indigenous N supply (EINS) of the soil–floodwater system, which governs \( Y_0 \).
Table 1
Mean grain yield (t ha\(^{-1}\)) as affected by N-source treatments in long-term experiments at the IRRI research farm (1982–1993) and in a farmer’s field in Victoria, Laguna (1982–1991). Data from Cassman et al., 1996a

<table>
<thead>
<tr>
<th>N-source(^{1})</th>
<th>IRRI</th>
<th>Victoria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DS ((n = 10)^{2})</td>
<td>WS ((n = 11))</td>
</tr>
<tr>
<td>Control</td>
<td>3.79 d(^{3})</td>
<td>3.39 c</td>
</tr>
<tr>
<td>USG</td>
<td>6.40 a</td>
<td>4.39 a</td>
</tr>
<tr>
<td>PU</td>
<td>5.99 b</td>
<td>4.24 a</td>
</tr>
<tr>
<td>Azolla</td>
<td>5.63 c</td>
<td>4.02 b</td>
</tr>
<tr>
<td>Sesbania</td>
<td>5.72 c</td>
<td>3.90 b</td>
</tr>
<tr>
<td>PU + FRS</td>
<td>5.73 c</td>
<td>3.99 b</td>
</tr>
</tbody>
</table>

\(^{1}\)USG, urea supergranules; PU, standard split application of prilled urea, FRS = fresh rice straw. Except for the control treatment without applied N, all N sources provided 116 kg N ha\(^{-1}\) in the dry season (DS) and 58 kg N ha\(^{-1}\) in the wet season (WS).

\(^{2}\)Number of cropping seasons included in the analysis of variance.

\(^{3}\)Means within columns followed by the same letter do not differ significantly \((P < 0.05)\) by Duncan’s Multiple Range Test.

3.3. Limitations of present recommendations for N fertilizer management

Present N fertilizer recommendations for irrigated lowland rice in most Asian countries are typically provided on a regional or national level or for certain soil types (PhilRice, 1991; Pillai and Kundu, 1993). For irrigated transplanted rice in the Philippines, present recommendations call for 50 to 67% of total fertilizer-N inputs to be broadcast-incorporated before transplanting and the remainder topdressed at 5 to 7 d before panicle initiation. Total recommended application rates are higher in the dry season and lower in the wet season, and higher on ‘high N-requiring soils’ and lower on ‘low N-requiring soils’. Methods used to determine high and low N-requiring soils are not specified, and we believe that it is presently not possible to estimate the soil N supply (see Sections 5.1 and 6.4). Justification for these recommendations comes from many of the papers cited in Section 3.2.

Despite these recommendations, few farmers apply basal N to irrigated rice in the Philippines (Fujisaka, 1994; Cassman et al., 1996c). Instead, farmers broadcast one or more N fertilizer applications into floodwater. Fujisaka suggested that this is a reasonable strategy in response to uncertainty about crop establishment as a consequence of concern about (1) initial availability of irrigation or rainfall for puddling, and (2) seedling damage from the golden snail.

Even without uncertain crop establishment or pest problems, the requirement for a basal N application needs to be re-examined. Soil in most intensive, irrigated rice domains can support grain yields of 3 to 5 t ha\(^{-1}\) without N application when weeds and insect pests do not limit rice growth. For example, mean yield in unfertilized plots from 11 long-term experiments in five Asian countries was 3.9 t ha\(^{-1}\); it was 3.9 and 4.4 t ha\(^{-1}\) from replicated plots without applied N established in farmers’ fields of Central Luzon in the 1992 and the 1994 dry seasons, respectively (Cassman et al., 1996c). Despite these relatively high mean yields, there was an enormous variation in \(Y_0\) among the long-term experiment sites that had very different soil types and a comparable range in \(Y_0\) (Fig. 2) and N uptake (Fig. 3a) among farmers’ fields with similar soil types in one municipality (Cassman et al., 1996b). A similar magnitude of variation in \(Y_0\) and N uptake was found in the same field over time and among different fields at the IRRI farm. Most evidence points to dynamic fluctuations in the EINS of the soil–floodwater system as the primary cause of these differences under otherwise favorable growth conditions (see Section 5).

The existence of large field-specific variation in the starting point of the yield response to applied N has important implications for research on N man-
agement. For example, if the yield target is 7.5 t ha\(^{-1}\) and \(Y_0\) is 3.0 t ha\(^{-1}\) in one farmer’s field and 5.4 t ha\(^{-1}\) in another, then total applied N of 250 kg ha\(^{-1}\) is required on the former but only 133 kg ha\(^{-1}\) on the latter, if both farms achieve an AE of 18 kg grain kg\(^{-1}\) applied N. Moreover, it is likely that the optimum timing of N application would also differ. Blanket-N fertilizer recommendations would not be very effective given this magnitude of field-to-field variation. Initial results from four other irrigated rice domains in Vietnam, Thailand, India, and Indonesia indicate a similar range in \(Y_0\) among farms within relatively small rice-growing domains and on similar soil types.

Philippine rice farmers do not appear to recognize differences in soil N supply because no relationship exists between the amount of N fertilizer they apply and crop N uptake in plots established within their fields that did not receive applied N (Fig. 3a). Moreover, the yield response to applied N was not related to the quantity of applied N fertilizer, a result that indicates considerable variation in AE (Fig. 3b). We conclude that the key leverage points for research on crop and soil management to increase N-use efficiency of irrigated rice are: (1) understanding the reasons for such large differences in \(Y_0\), (2) development of management practices that sustain and opti-

![Fig. 2. Frequency distribution of mean rice grain yield (\(Y_0\)) from replicated plots without applied fertilizer-N established in farmers’ fields in the Guimba Municipality, Central Luzon. Three replicate plots were established in each farmer’s field, and differences in \(Y_0\) among farms were highly significant \((P < 0.001)\). Modified from the work of Cassman et al. (1996c).](image)

![Fig. 3. (a) The N fertilizer rate applied by farmers in relation to the EINS estimated by total plant N at physiological maturity in plots without applied N and (b) the yield increase from applied N fertilizer achieved by farmers in relation to the rate of applied N. Values shown are means from 42 farmers’ fields. Modified from the work of Cassman et al. (1996c).](image)

4. The indigenous N supply

4.1. Sources of indigenous N

Indigenous N sources include atmospheric deposition and irrigation water, incorporated plant residues, biological N fixation (BNF), N mineralization from SOM in surface soil, subsoil N, and the release of nonexchangeable NH\(_4\)-N from illite, vermiculite, and other minerals that fix NH\(_4\)-N. In general, N inputs from irrigation and atmospheric deposition are
relatively small except where pollution is severe near large urban centers. Kawaguchi and Kyuma (1977) concluded that N inputs from surface water sources were 'negligibly small' based on their analyses of river water sources in tropical Asia. More recent data are lacking. Inputs of N from deep wells is also usually quite low: in Bangladesh it was about 1 kg ha\(^{-1}\) yr\(^{-1}\) (Abedin Mian et al., 1991) and at the IRRI Research Farm it was less than 3 kg ha\(^{-1}\) per rice crop (Cassman et al., 1996b). Shallow-well water may contain more N (Handa, 1988), although most of this N is NO\(_3\) and much of it would be lost to denitrification in submerged rice paddies.

Estimates of N inputs from rainfall in irrigated rice areas include: 0.6 to 2.5 kg N ha\(^{-1}\) yr\(^{-1}\) between 1978–1981 at the IRRI Research Farm (App et al., 1984), 13.6 kg ha\(^{-1}\) yr\(^{-1}\) in Bangladesh (Abedin Mian et al., 1991), and 3 to 10 kg N ha\(^{-1}\) yr\(^{-1}\) more generally (Patnaik, 1978). These reports indicate that N from atmospheric inputs and irrigation water represent only a small component of the overall N balance in most rice-growing areas, and cannot account for the large differences among fields in the indigenous N supply. Although adsorption and release of fixed NH\(_4\)-N occur in some lowland rice soils (Keerthisinghe et al., 1984; Schnier et al., 1987; Cheng et al., 1989), we suspect that the contribution of these abiotic processes to differences in indigenous N supply are relatively conservative among fields with these fixation properties because rice uptake of available N is rapid (see Section 6.2), and rapid uptake maintains available NH\(_4\)-N at very low concentrations during crop growth. Instead, processes controlling SOM formation and decomposition, N inputs from BNF, N immobilization-mineralization dynamics, incorporated crop residues, soil moisture regime, tillage, and possibly N acquisition from subsoil appear most likely to account for differences in the indigenous N supply of the soil–floodwater system.

### 4.2. Soil organic matter

Indigenous N sources in irrigated lowland rice paddies are similar to those of upland cropping systems on well-drained soils. There are important differences, however, in the processes governing the transformation, retention, and losses of N inputs. One distinction is the conservation of soil organic carbon (SOC) and total soil N (TSN) in lowland soils that remain submerged for much of the year under annual double and triple rice-crop systems (Nambiar and Ghosh, 1984). This conservation or even increase in SOC and TSN can occur despite complete removal of all aboveground crop residues (Table 2). In treatments that receive N fertilizer, there is often a further increase in SOC and TSN concentration although the magnitude of this increase on a mass basis is sometimes reduced by a decrease in bulk density in the N-fertilized plots (Kundu and Ladha, 1995).

Knowledge of the processes governing the formation and degradation of SOM is required to develop management practices that conserve SOM and optimize the N contribution from it. In general, the chemical complexity of SOM has prevented a full understanding of these issues because it has not been possible to isolate the labile SOM–N pools most active in mineralization from more recalcitrant SOM–N pools. Furthermore, the structure and function of SOM in submerged soils and lowland rice systems have received less attention than SOM in aerated soils from upland systems.

In the absence of isolation methods, attempts have been made to correlate the quantity of available organic N in aerated soils with surrogate parameters.
such as the quantity of hydrolyzable amino acids (Bremner, 1965), but consistent relationships have not been found (Ottow, 1978; Stevenson, 1982). Chemical digests have been used to estimate concentrations of various SOM components (Kumada, 1987). This approach has revealed associations between patterns of in vitro N mineralization and ratios of specific organic N fractions, such as hydrolyzable \( \alpha \)-amino-N (Yonebayashi and Hattori, 1986a,b). In general, however, studies of N dynamics in both aerated and submerged soils have been restricted to measuring the effects of crop or soil treatments on chemical indices of available organic N without explaining the underlying chemical and biological processes.

More recently, the study of SOM structural components in aerated soils has been facilitated by new digestion procedures, such as cupric oxide oxidation (Kögel and Bochter, 1985), and advanced instrumental analysis, such as Fourier transform infrared spectroscopy (Baes and Bloom, 1989), pyrolysis (Schulden, 1993), gas–liquid chromatography (Katase, 1993) and, especially, nuclear magnetic resonance (NMR) spectroscopy (Wilson, 1987). These new methods of analysis give more detailed information about subunit structure of large heterogeneous molecules like humic substances. For example, Ye and Wen (1991) reported an accumulation of lignin products in SOM formed under submerged soil conditions based on NMR analysis. Still lacking, however, is an understanding of how the identified sub-units are arranged into three-dimensional structures, and how the chemical structure of SOM affects N immobilization–mineralization and other processes.

There is general agreement that young, labile SOM fractions contribute much more to N mineralization and immobilization than older, more stable SOM fractions (Chichester et al., 1975; Janssen, 1984; Powlson, 1990). Hence, simulation models of SOM dynamics rely on hypothetical SOM fractions for which pool sizes and transformation rates are empirically estimated (Parton et al., 1987; Nicolardot et al., 1994). The reasonable predictive capacity of these models for aerated soils provides evidence that these functional SOM fractions exist although they have not been clearly identified. Several chemical and physical fractionation procedures also indicate the existence of labile SOM fractions. Lefroy et al. (1993) found relationships between cropping history in upland soils and amounts of labile SOM oxidized by increasing concentrations of KMnO\(_4\). This procedure is destructive, however, so that identification of discrete labile SOM pools is not possible. Physical separation of SOM fractions by shaking and sieving or sonication isolates a ‘light fraction’ containing partially decomposed plant and microbial tissues (Janzen et al., 1992). Although the light fraction appears to reflect the recent effects of tillage on physically protected SOM in aerated soils, it may be less appropriate for intensively cultivated wetland-rice soils where repeated puddling completely destroys aggregation.

By differentiating SOM on the strength of its chemical binding to Ca\(^{2+}\) and other polyvalent cations, the extraction method of Olk et al. (1995) isolates SOM fractions that differ in their activity in nutrient cycling (Olk and Cassman, 1995a,b). Together, the mobile humic acid pool (MHA) and calcium-bound humic acids (CaHA) extracted by this method account for 18 to 24% of SOC and TSN in a wide range of soils with different parent material and texture, and from different cropping systems and climates. With continuous double- and triple-cropped rice, lignin degradation products such as phenolic compounds accumulated in the young, less humified MHA pool (Fig. 4). A similar but less pronounced effect was seen in slightly older, more humified CaHA fraction (data not shown). A trend toward increased phenolic humus with increased irrigated rice-cropping intensity is consistent with reduced rates of lignin decomposition under anaerobic soil conditions (Colberg, 1988). Hence, phenol accumulation in MHA and CaHA appears to result from predominantly reduced soil conditions (Olk et al., 1996); it occurs in soils with different parent material and texture as well as under different climatic regimes (D.C. Olk, unpublished data).

Lignin content of soil-incorporated crop residues and green manures has a strong effect on the subsequent rate of decomposition and N mineralization from these materials in both aerobic upland (Palm and Sanchez, 1991; Tian et al., 1992) and reduced lowland soils (Watanabe et al., 1991; Becker et al., 1994a,b). In plant residues with similar N content, higher lignin or polyphenol content reduces N mineralization. One explanation for this inverse relation-
ship is that N compounds are abiotically immobilized by lignin (Grabbe and Haider, 1971) and phenols (Flaig et al., 1975; Verma et al., 1975). Accumulation of lignin degradation products in SOM of submerged soils may therefore slow the rapid N cycling between SOM and inorganic forms, causing a decreased net N mineralization per-unit organic N in microbial biomass and labile SOM fractions. At issue is whether (1) the MHA and CaHA pools represent discrete, biologically active N pools in lowland rice soils and (2) increased lignin content of labile SOM fractions affects the indigenous soil N supply available to the rice crop (see Section 5.2).

4.3. Contributions of biological N fixation

In lowland rice fields that receive little or no applied N, the conservation of soil N is assumed to result from relatively large N inputs from BNF and relatively small losses of indigenous N through leaching, NH$_3$ volatilization or denitrification. These assumptions are consistent with gross N balances measured in unfertilized plots of long-term experiments. These studies indicate a net accretion of N after one allows for removal of harvested plant N and inputs of N from irrigation water and rainfall (Table 3). In each study, estimates of BNF inputs were based on indirect measures of plant N removal, and N losses were assumed to be negligible. Thus, N inputs from BNF–N to irrigated rice systems are in the range of 28 to 51 kg N ha$^{-1}$ per crop cycle, and these estimates are conservative because losses, though probably small, are ignored.

Husbandry practices that influence the contribution of BNF to the indigenous N supply include use of crop residue, fertilizer, and pest management. Heterotrophic N$_2$ fixation in bulk flooded soil is enhanced by incorporation of straw, which immobilizes available N, provides carbon substrate, and increases microbial activity (O'Toole and Knowles, 1973; Ladha et al., 1986; Santiago-Ventura et al., 1986; Roper et al., 1995). Phosphorus application stimulates growth and BNF of cyanobacteria (Wilson and Alexander, 1979; Cholitkul et al., 1980), as does pesticide control of grazing organisms, such as ostracods, and surface application of straw (Grant et al., 1983, 1985).

Results from long-term fertility experiments indicate that N fertilizer broadcast into floodwater suppresses growth and BNF of cyanobacteria (Latorre et al., 1986; Ladha et al., 1989), while deep placement of N fertilizer had little effect (Roger et al., 1981). Likewise, surface application of N fertilizer did not decrease BNF by heterotrophic bacteria in the rhizosphere and bulk soil, and sometimes resulted in greater rates of associative BNF (Ladha et al., 1989). Therefore, despite the inhibitory effects of surface applied N fertilizer on BNF by cyanobacteria, the net
Table 3
Estimates of N inputs to irrigated lowland rice systems based on N balance studies conducted under field conditions

<table>
<thead>
<tr>
<th>Site</th>
<th>Estimation period (years)</th>
<th>Annual cropping system</th>
<th>Parameters measured (kg N ha⁻¹)</th>
<th>BNF input per rice crop (kg N ha⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Thailand</td>
<td>2</td>
<td>R</td>
<td>Y⁺⁺ Y⁺⁺ E⁺⁺ E⁺⁺ E⁺⁺ N⁺⁺ N⁺⁺</td>
<td>28</td>
<td>Firth et al., 1973</td>
</tr>
<tr>
<td>Laguna, Phil.</td>
<td>12</td>
<td>R-R</td>
<td>E⁺⁺ Y⁺⁺ E⁺⁺ E⁺⁺ E⁺⁺ N⁺⁺ N⁺⁺</td>
<td>51</td>
<td>App et al., 1984</td>
</tr>
<tr>
<td>Central Luzon, Phil.</td>
<td>8.5</td>
<td>R-R</td>
<td>E⁺⁺ Y⁺⁺ E⁺⁺ E⁺⁺ E⁺⁺ N⁺⁺ N⁺⁺</td>
<td>40</td>
<td>App et al., 1984</td>
</tr>
<tr>
<td>Laguna, Phil.</td>
<td>14</td>
<td>R-R-R</td>
<td>E⁺⁺ Y⁺⁺ E⁺⁺ E⁺⁺ E⁺⁺ N⁺⁺ N⁺⁺</td>
<td>35</td>
<td>Cassman et al., 1995</td>
</tr>
</tbody>
</table>

¹R, single annual dry season rice crop; R-R, annual double-crop rice; R-R-R, annual triple-crop rice.
²P_N, N removed in harvested plant material; S_N, changes in total soil N content; I_N, A_N, N inputs from irrigation or rainfall, respectively; L_N, G_N, N losses from leaching or gaseous losses from denitrification/volatilization, respectively.
³Y, measured directly; N, not measured; E, estimated.
effects of N fertilization on total BNF in the soil–floodwater system appear to be relatively small. Increased SOC and TSN in treatments that receive N fertilizer in long-term experiments (Table 2) indicate that any decrease in BNF caused by N fertilizer application is more than compensated by greater amounts of N recycled in roots and crop residues, and by immobilization of N fertilizer in SMB and SOM.

Much less is known about the longer-term effects of continuous double or triple rice cropping in submerged soil on the ecology and population structure of the microbial, mesofauna, and mesoflora communities of the soil–floodwater system, and whether such changes affect BNF inputs or N cycling processes more generally. For example, blooms of green algae that lack the capacity to fix N₂ are stimulated by high rates of fertilizer-N application and they can increase NH₃ volatilization losses of applied N (Roger and Kurihara, 1991). Although these algal blooms are of short duration, longer lasting effects on biodiversity of eukaryotic phototrophs have not been examined. Green algae blooms may also increase the number of ostracods that graze on cyanobacteria. Increased biodiversity and activity of N₂-fixing bacteria may also provide other benefits related to the production of plant growth-promoting hormone-like substances (Frankenberger and Arshad, 1995). The potential to increase BNF through genetic manipulation of the rice plant is discussed by Ladha et al. (1997).

4.4. Soil biology and the indigenous N supply

The crucial role of prokaryotic microorganisms in N transformation applies to virtually all components of the indigenous N supply that are covered in other sections of this review, even though not always explicitly stated. This brief section focuses on recent progress and new approaches in analyzing and interpreting microbiological contributions, other than BNF, to the indigenous N supply of intensive lowland rice systems.

The role of microeukaryotes, including fungi, is not covered in this review, although these microbes are presumably constituents of microbial biomass in paddy soils. Except for vesicular–arbuscular mycorrhizal fungi and their effects on nutrient uptake by wetland rice (Secilia and Bagyaraj, 1992), these organisms have received little attention. Specific biomarkers now permit their quantification (Zelles et al., 1992; Hill et al., 1993), but they have not been used in submerged rice soils. Likewise, soil fauna and floodwater zooplankton are consumers of particulate organic matter, and are considered key recycling agents of ricefield fertility. A few recent studies provide measurements of microflora and mesofauna populations in intensive rice systems (Simpson et al., 1993a,b), but systematic studies of their contribution to soil N availability have not been undertaken. Given this lack of information, the following review will focus on prokaryotic processes with the greatest impact on the indigenous N supply.

4.4.1. Biological immobilization–mineralization

Available inorganic and soluble organic N compounds in soil can be assimilated through the following steps: incorporation into microbial biomass (immobilization), remineralization, transformation by oxidative or reductive processes, and transfer within the microbial food web. During catalysis, the soil microbiota generate polysaccharides, proteins and lipids that contribute to the formation and decomposition of SOM. At the same time, inorganic N can be lost as N₂ or N₂O via denitrification or as NH₃ from volatilization. Together, these processes have a major influence on the indigenous N supply of the soil–floodwater system.

For methodological rather than conceptual reasons, most research addressing the role of microorganisms in N supply of tropical rice soils has considered only the total SMB. The SMB is usually defined operationally—for example, extraction by chloroform fumigation. Further differentiation of microbiota into either specific microhabitats, such as the rhizosphere, or functional groups related to N-cycling, such as denitrifying or nitrifying bacteria, has hardly been considered (see Section 4.3).

Living SMB–N accounts for only 1 to 15% of TSN, with an average of 5% based on data from upland or well-drained agricultural soils (Anderson and Domsch, 1980) and submerged lowland rice soils (Inubushi and Watanabe, 1986). Although relatively small in size, the SMB–N pool is considered the largest source of endogenous N supply because it
turns over rapidly. Inubushi and Watanabe (1986, 1987) suggested that the amount of total SMB–N provides a reflection of soil N availability for plant uptake, based on concrete-microplot and pot experiments. More recent measurements from field experiments indicate a decrease in SMB after panicle initiation when peak crop N demand occurs (Reichardt et al., 1995). Whether this trend reflects increased N mineralization from the SMB caused by increased plant competition for a limited N supply remains to be determined. In contrast, increased inorganic N supply from urea, topdressed before panicle initiation, did not provoke a large increase in SMB, although nitrifying and denitrifying bacteria were stimulated.

These results, though preliminary, suggest plausible explanations for a shrinking SMB during the later stages of the rice growth cycle. Transition from aerobic to anaerobic conditions causes major changes of the soil microbial community in favor of obligate anaerobes (Reichardt et al., 1995). Furthermore, at times of high crop-N demand, competition between the roots and the microbiota for available N may cause increasing starvation and unbalanced growth of major components of the soil microbiota. These processes can finally lead to enhanced excretion of starvation proteins (Groat et al., 1986), which may account for a considerable peak of available N. Severe limitation of nutrients is likely to trigger an uncoupling of anabolic and catabolic microbial metabolism (Russel and Cook, 1995). Consequently, the physiological status of the microbial community members may determine whether or not they contribute to the N supply by ‘sacrificing’ biomass N or by engaging in biocatalytic functions.

In summary, although the size, C/N ratio, biodiversity, and physiological status of the SMB seems to be dynamic in both time and space, the influence of these observed phenomena on N-use efficiency in lowland rice soils has not been evaluated.

4.4.2. Biological N losses

In contrast to N fixation, the adequate measurement of other microbe-driven processes tends to be hampered by a lack of specificity. Nitrification or denitrification rates are often measured by \(^{15}\)N mass balances, which are unable to define single microbe-driven processes (Buresh et al., 1982). Moreover, if rapid pool substitution occurs (see Section 2.2), the active substrates from which the \(^{15}\)N evolves would be in doubt. As a result, reliable field data are lacking on rates of nitrification, nitrate reduction and denitrification.

Denitrification rates from labeled fertilizer have usually been estimated indirectly as the difference between \(^{15}\)N not recovered in the soil or plant at maturity and NH\(_3\) losses determined by micrometeorological techniques (Freney et al., 1985, 1990; Fillery et al., 1986a; Buresh and Austin, 1988). Recognizing the need for direct measurement of N\(_2\) and N\(_2\)O fluxes, an electric arc analysis was developed, and denitrification rates measured by this method ranged only from 0.2 to 1.1% of the applied \(^{15}\)N–urea in an irrigated rice field of Nueva Ecija, Philippines (Craswell et al., 1985; Buresh and Austin, 1988; Avalakki et al., 1995). In contrast, total loss of applied \(^{15}\)N estimated by the \(^{15}\)N balance method amounted to 26 to 40% in one study (Buresh and Austin, 1988), which indicates that NH\(_3\) volatilization was the dominant loss pathway.

It is also noteworthy that the metabolic pathways of N-cycle bacteria are quite diverse. For example, NO\(_3^–\) reduction to NH\(_4^+\), an N-conserving alternative to N\(_2\) losses via denitrification, is a true respiratory process. It is carried out by sulfate-reducing bacterial isolates from rice paddies. With an extremely high affinity for NO\(_3^–\) (i.e., low \(k_M\)), these N-preserving microorganisms outcompete ordinary denitrifiers at low nitrate levels (Dalsgaard and Bak, 1994). In this regard, claims that growth of certain types of sulfate-reducing bacteria is favored in the rhizosphere of rice deserve particular attention (Quattara and Jacq, 1992). Other primarily S-cycle bacteria can also play a role in N cycling, such as the S-oxidizing bacteria \(Thiomicrospira\) \(denitrificans\) or \(Thiosphaera\) \(pantotropha\). There are well-documented examples for not only heterotrophic nitrification, but also aerobic denitrification (Robertson and Kuenen, 1988; Robertson et al., 1989). Likewise, denitrification is not the only pathway causing losses of N\(_2\) to the atmosphere. That can also be achieved by anaerobic oxidation of ammonia to N\(_2\) gas with NH\(_4^+\) serving as an electron donor for nitrate reduction (Van de Graaf et al., 1995). The contribution of these pathways to N cycling in lowland rice soils is unknown,
and it would be premature to speculate about any implications.

4.5. Residue management, tillage, subsoil N, and soil moisture regime

4.5.1. Rice straw management

Straw accounts for about 40 to 50% of total aboveground biomass in modern high yielding rice cultivars. It represents a higher proportion of total biomass in later-maturing cultivars than in earlier maturing ones (Akita, 1989), and a smaller proportion in the dry season than in the wet season. The N concentration of rice straw typically ranges from 0.5 to 1.0%. With an average grain yield of 5.0 t ha−1 on 74 Mha of harvested irrigated rice in Asia, and assuming a harvest index of 45% and an average N concentration of 0.65% N, 452 Mt of rice straw containing about 3 Mt of N are produced annually. This amount of N is equivalent to about 40% of the total N fertilizer applied to irrigated rice in Asia. Root biomass and stem bases account for another 0.6 Mt of N, assuming root dry matter and stem bases represent 10% of aboveground biomass at maturity and have an N concentration of 0.8%.

Extensive research has been conducted on the utilization and benefits of rice straw in irrigated rice systems. Recycling of rice straw increases BNF in the soil-floodwater system (see Section 4.3), reduces total requirements for N fertilizer inputs, and increases SOC and TSN (Ponnamperuma, 1984). When used in combination with inorganic N fertilizer, the N contained in rice straw has a fertilizer-N equivalent of about 85% compared to a standard split application of prilled urea (Table 1), and it is comparable to that of green manures (Cassman et al., 1996a). Unfortunately, most rice farmers in the developing countries of Asia do not recycle rice straw. Because almost all rice is harvested manually, straw is removed from the field to facilitate threshing and subsequent tillage operations, or piled in the field at threshing stations and later burned or removed. In some areas, stubble is simply burned to facilitate subsequent tillage operations. Straw is also removed for use as forage, fuel, or building material. Whatever the reason, incorporation or removal of rice straw has a significant impact on both the short- and long-term PFP of irrigated rice systems.

4.5.2. Tillage, root distribution, and subsoil N

In most of Asia, whether straw is removed or not, rice crop residues are incorporated when the soil is puddled, usually 7 to 10 d before transplanting or sowing. Because incorporation of rice straw or other crop residues accelerates the rate of decrease in soil redox potential (Ponnamperuma, 1972), straw decomposition occurs under mostly anaerobic conditions, which may account for the increasing phenolic character of young SOM fractions in continuous rice cropping systems on lowland soils (see Section 4.4.2). In fact, there is very little dry tillage before planting of irrigated rice because of small farm size, weed problems, lack of large power equipment, and the high energy requirements for primary tillage of dry soil (De Datta, 1981). Puddling of saturated soil requires less energy and is achieved using draft animals or small hand-held tractors. Depth of puddling varies depending on equipment used and soil type. Although the soil puddling operation is similar before planting rice in rice–wheat systems, shallow dry tillage is practiced before sowing wheat.

Typically, the puddled soil layer in which soil is well-mixed ranges from 10 to 20 cm in depth. The rice root system in puddled soil is extremely fibrous and root development is highly concentrated in the top 0 to 20 cm of puddled soil layer, even in soils without a hardpan. For example, there is no hardpan in the Long-Term Fertility Experiment at IRRI where bulk density of the 0 to 20-cm and 20 to 30-cm layers was 0.63 and 0.75 g cm−3, respectively. In the same experiment at PhilRice, a slight hardpan is evident with a bulk density of 0.86 and 1.18 in the 0 to 20 and 20 to 30-cm layers, respectively. At both sites, 88 to 93% of total root length to 30-cm depth was found in the 0 to 20-cm puddled soil layer when sampled at flowering stage (Table 4). This pattern of root distribution was similar in different cultivars (data not shown), and it is similar to patterns found in other studies (Yoshida, 1981; De Datta et al., 1988a,b).

The issue of root growth and physiological activity below the puddled soil layer is important in defining the active rooting volume for N acquisition. Highly concentrated distribution of rice roots in the surface layer may result from diffusional limitations of oxygen supply to growing root tips in anaerobic soil. Armstrong and Beckett (1987) estimated a max-
Table 4
Profile distribution of root length density (cm cm\(^{-3}\)) of IR72 measured at flowering stage at two sites in the Long-Term Fertility Experiments at IRRI and PhilRice in two seasons\(^1\). Unpublished data of Cassman, Samson, and Redulla

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IRRI</td>
<td>PhilRice</td>
<td>IRRI</td>
<td>PhilRice</td>
</tr>
<tr>
<td>0–5</td>
<td>7.4 (±0.7)(^1)</td>
<td>11.0 (±0.2)</td>
<td>9.2 (±0.9)</td>
<td>9.0 (±1.2)</td>
</tr>
<tr>
<td>5–10</td>
<td>3.5 (±0.5)</td>
<td>3.1 (±0.1)</td>
<td>4.0 (±0.2)</td>
<td>6.3 (±0.5)</td>
</tr>
<tr>
<td>10–20</td>
<td>1.8 (±0.3)</td>
<td>1.3 (±0.1)</td>
<td>3.3 (±0.2)</td>
<td>2.8 (±0.1)</td>
</tr>
<tr>
<td>20–30</td>
<td>0.9 (±0.2)</td>
<td>0.6 (±0.1)</td>
<td>0.9 (±0.1)</td>
<td>0.8 (±0.1)</td>
</tr>
<tr>
<td>0–20 cm (% of total)</td>
<td>(88%)</td>
<td>(93%)</td>
<td>(92%)</td>
<td>(93%)</td>
</tr>
</tbody>
</table>

\(^1\)Root measurements taken from the + NPK balanced fertilizer treatment. Aboveground biomass at the time of sampling was 6.4 and 7.0 t ha\(^{-1}\) in the 1991 wet season (WS) and 8.6 and 13.9 t ha\(^{-1}\) in the dry season (DS) at IRRI and PhilRice, respectively.

\(^1\)Values in parenthesis are one mean standard error.

imum aerated root length of 22 to 30 cm for rice roots growing in an anoxic media. These estimates are consistent with the poor root development observed below 20 cm in soil without physical impediment (Table 4). Despite these theoretical considerations and direct measurements of root distribution, the N contribution from soil below 20 cm depth to total N uptake of irrigated rice is estimated to be 5 to 30% of total plant N (Sekiya and Shiga, 1977; Ventura and Watanabe, 1984; Suenobu et al., 1993). These estimates, however, are not likely to be representative of actual field conditions because they are based on microplot studies in which soil was disturbed to place a physical root barrier. Improved methods are needed to measure the actual N acquisition from subsoil in undisturbed plots, and the contribution of variation in subsoil N to large differences in the indigenous N supply of irrigated, lowland rice.

A recent study demonstrated the positive effects of dry deep tillage to 40 cm with a chisel plow on N uptake and grain yield in a lowland field with a well-developed hardpan (Kundu et al., 1996). When plowing depth was limited to 25 cm, the increase in grain yield was small. The benefits of one deep tillage operation to 40 cm depth were evident in three successive crops. Deep tillage increased extractable inorganic N in the 15 to 30-cm depth interval and root proliferation in the 13 to 25-cm layer. It had only small effects on root density at depths below 25 cm. Despite the potential benefits of deep tillage, the large energy requirements and heavy equipment needed for deep tillage of heavy lowland soils will restrict the potential use of this intervention by Asian rice farmers.

4.5.3. Effects of soil moisture regime and fallow management

Wetting and drying cycles have a large effect on soil N mineralization. The flush of N mineralization that occurs when dry soil is rewetted was originally described in tropical upland soils (Birch, 1958), but it also occurs in lowland rice soils when soil water potential falls below –1.0 MPa (Toriyama and Sekiya, 1991; Hasegawa and Horie, 1994). While the magnitude of this ‘drying effect’ is large enough to account for agronomically significant differences in the indigenous N supply of lowland paddy soils, two issues need clarification. First, only a small portion of surface soil dries below the –1.0 MPa threshold in lowland rice fields during fallow periods because self-mulching occurs in soils that were previously puddled. Even deep soil cracking only dries the sides and edges of the dense pads that are formed. Second, while soil drying has a large effect on the rapid phase of N mineralization in the 14- to 21-d period after rewetting, it has a much smaller influence (Inubushi and Wada, 1987) or negligible effect (Toriyama and Sekiya, 1991; Hasegawa and Horie, 1994) on the steady-state slow phase that governs soil N mineralization rates during the period of highest crop N demand (see Section 5.1).

Field management and moisture regime in the fallow period between rice crops can have a large impact on the indigenous N supply for a subsequent
rice crop (George et al., 1993a,b, 1994). The NO$_3$-N mineralized in the fallow period can be acquired by weeds, green manures, or a short-season grain–legume crop. Incorporation of the crop or weed residues when the field is puddled for a following rice crop results in greater N uptake and grain yield when compared with a dry-plowed weed-free fallow in which mineralized NO$_3$-N is leached or lost to denitrification. For the same reasons, it is likely that ratooning rice stubble left in the field would also serve to capture mineralized N and reduce N losses during fallow periods.

5. Optimizing N contributions from indigenous resources

5.1. The effective indigenous N supply (EINS)

The supply of N from both applied fertilizer and indigenous resources is most efficiently utilized when it is congruent with crop requirements for growth and yield formation because excess inorganic N in the soil–floodwater system is at risk from NH$_3$ volatilization and denitrification losses, and to a lesser degree from leaching. It is therefore important to distinguish the EINS as the fraction of total available N during the cropping season that is acquired by the rice plant when pests, non-N nutrient deficiencies, or other constraints do not limit crop growth. By this definition, total crop N accumulation in plots without applied N provides a reasonable estimate of the EINS if other factors are not limiting. Actual crop uptake provides a useful index of EINS because it is easily measured, tightly correlated with grain yield, and provides a quantitative indicator of system productivity (Cassman et al., 1996c). A similar approach was used by Janssen et al. (1990).

The contribution of N acquired during early vegetative growth to grain and total biomass production at maturity is considerably less important than the contribution of N uptake after midtillering when crop demand is greatest and reproductive growth begins (Cassman et al., 1996a; Peng et al., 1996a). For example, dry matter and N accumulation at 30 to 40 d after sowing (midtillering stage) were two to threefold greater in broadcast wet-seeded rice than in transplanted rice with or without applied N (Fig. 5). Despite this early advantage, final grain yield, dry matter and N accumulation were comparable or greater in transplanted rice. Similar results were reported in other studies (Schnier et al., 1990a,b). Increased early season N uptake and dry matter production without an increase in grain yield can also be achieved by increasing hill density in transplanted rice (Setter et al., 1994). In both cases, this early advantage results from greater plant density and more rapid leaf area and root development.

Present recommended practices and typical farmer-practiced N fertilizer management do not include N application after panicle initiation. Therefore, the N uptake rate during most of the reproductive growth phase is presumably governed by the rate of net N mineralization because the contribution from current BNF to N uptake is relatively small (Eskew et al., 1981), and available N from fertilizer applied before panicle initiation is rapidly depleted by plant uptake, gaseous losses, or immobilization (Buresh et al., 1988b; De Datta and Buresh, 1989; Schnier et al., 1990a; Cassman et al., 1993). Uptake of N in the vegetative growth stage that exceeds the requirement for maximum achievable yield determined by solar radiation and temperature results in greater tiller numbers and leaf area than needed (see

Fig. 5. (a) Dry matter and (b) N accumulation of transplanted (TR) or broadcast wet-seeded (BWS) rice in treatments without applied N ($N_0$) or with 220 kg N ha$^{-1}$ ($N_{220}$) applied in four split applications. The experiment was conducted in the 1993 dry season at the IRRI Research Farm. Modified from the work of Peng et al. (1996a).
the work of Ladha et al., 1997). This overreaction causes increased tiller mortality, dilution of N in a larger canopy biomass, and reduced canopy net assimilation rates after panicle initiation (Dingkuhn et al., 1990; Schnier et al., 1990b; Peng et al., 1996a). Although additional N could be applied to maintain canopy N status in the period from panicle initiation to heading, it often increases the severity of lodging and disease problems, particularly in direct-seeded rice.

5.2. SOM and the effective indigenous N supply

5.2.1. SOM, N uptake, and net N mineralization

There appears to be general agreement in the literature that the N supplying capacity of lowland rice soils is positively correlated with SOM content. Most studies investigating this relationship, however, draw conclusions based on correlations among laboratory-generated indices (Ponnamperuma, 1980; Mohapatra and Khan, 1983; Sahrawat, 1983a), or correlation of rice N uptake in greenhouse pot experiments with SOC or TSN (Sahrawat, 1982; Kai et al., 1984). Several authors have proposed SOC or TSN as indices of soil N supplying capacity for lowland paddy soils that can be used to estimate N fertilizer requirements (Ponnamperuma, 1980; Sahrawat, 1982; Kai et al., 1984; Neue, 1985). There is little direct evidence, however, documenting a significant association between SOC or TSN and the amount of plant N acquired from indigenous soil resources under field conditions in tropical lowland rice systems (Sahrawat, 1983b).

The relationship between EINS and SOC or TSN was evaluated in farmer’s fields in Central Luzon and in long-term experiments (Cassman et al., 1993; Cassman et al., 1996b). Grain yield and N uptake in plots without applied N were closely correlated (r = 0.91), but there was tremendous variation in both parameters among fields (Fig. 3a). There was no relationship between EINS and SOC or extractable NH$_4$-N, and only a weak correlation between EINS and TSN (r$^2$ = 0.1). A similar lack of association was found in plots without applied N in 11 Long-Term Fertility Experiments in five Asian countries. Moreover, in the Long-Term Continuous Cropping Experiment, there is also enormous year-to-year and season-to-season variation in grain yield and N uptake in treatment plots without applied N that cannot be attributed to changes in SOM content, temperature effects, solar radiation, variety, N inputs from irrigation water, pests, or nutrient limitations other than N.

At issue is the reconciliation of the close positive correlation of laboratory- or greenhouse-validated soil N supply indices with SOM content, and results from the on-farm studies and long-term experiments in which SOC, TSN or extractable NH$_4$-N explain little of the variation in EINS. We suspect that this discrepancy involves the degree of congruence between net N mineralization and crop demand, and the bias of most anaerobic incubation methods or soil-test indices to be dominated by soil N supplying capacity in the rapid phase of net N mineralization which corresponds to the early season soil N supply (see Section 6.4).

5.2.2. Yield decline in intensive rice systems

A rice yield decline of 50 to 200 kg ha$^{-1}$ yr$^{-1}$ has been documented in a number of long-term experiments on continuous, irrigated lowland rice systems in the tropics (Cassman and Pingali, 1995b). Declining yield trends occur at about the same rate in treatments that receive recommended inputs of inorganic fertilizer and in unfertilized control treatments. Thus, it is PFP that has declined from a decrease in $Y_0$ while the AE, RE, and PE have not changed (Cassman et al., 1995). In all cases where soil data are available, soil SOC and TSN have remained constant or have increased significantly—particularly in treatments that received complete fertilizer inputs (Table 2). Deficient tissue N levels measured at flowering stage in the 1991 dry season indicated that the yield decline phenomenon was associated with a decrease in the EINS despite the conservation or increase in SOC and TSN. At one site, grain yields were restored to the 9 to 10 t ha$^{-1}$ range by increasing the rate of N application (Cassman et al., 1995). At the other two sites, restoration of grain yield also required an increase in the rate of applied N, but sustaining these yield levels after the first 2 years required increased rates of P and K in addition to higher N rates (see Table 3, Dobermann et al., 1997) and prophylactic application of fungicide to protect against yield loss from sheath blight (Rhizoctonia solani) (Cu et al., 1996).
The lack of phenol oxidation and the strong phenolic character of MHA extracted from soil of several long-term experiments appears to be characteristic of labile SOM extracted from intensively cropped lowland rice soils. These properties may contribute to the conservation of SOM in flooded soils and to the decrease in the EINS by causing abiotic immobilization of available N (see Section 4.2). It is clear, however, that N inputs from BNF (Table 3) and carbon inputs from floodwater algae and zooplankton and recycled roots and stem bases are sufficient to maintain or even increase SOC and TSN despite almost complete removal of aboveground crop residues (Table 2).

5.2.3. Crop residue management and green manures

Before commercial fertilizers were widely available, use of green manures and recycled straw was common in traditional lowland rice systems of East Asia (King, 1911). Since the 1960s, use of inorganic N fertilizers has become widespread and use of green manures has declined (Ishikawa, 1988; Chen, 1994). Rising costs of land and labor are cited as the main reasons for this trend, particularly in those countries with rapid economic development (Rosegrant and Roumasset, 1988; Ali and Narciso, 1994). Other reasons include government fertilizer subsidies, and the time lost for production of rice or other cash crops. Continued interest in substitution of organic N sources for commercially produced inorganic N fertilizers is justified, however, by the magnitude of present and future N requirements in irrigated rice systems.

It is clear from a large body of published research that organic N inputs from legume green manures (Singh et al., 1991), Azolla spp. (Lumpkin and Plucknett, 1982), and rice straw (Ponnamperuma, 1984) can provide agronomically significant amounts of N to the rice crop and reduce N fertilizer requirements. Recent review articles summarize many of the agronomic issues and scientific challenges related to the goal of increasing the contribution of green manures to rice-based cropping systems (Ladha et al., 1992; Ladha and Garrity, 1994).

Although there is general agreement that the AE from green manure-N or Azolla-N is similar to equivalent inputs of inorganic N fertilizer, this conclusion is based on field studies that did not provide equal quantities of N inputs in treatments comparing organic and inorganic N sources (Ventura and Watanabe, 1993) or experiments of short duration (Westcott and Mikkelsen, 1987; Kundu et al., 1991; Rosenani and Azizah Chulan, 1992). The former confounds the comparison because rice yield response to applied N is curvilinear, and because immobilization–mineralization rates are sensitive to the source and amount of applied N (Westcott and Mikkelsen, 1985). Experiments lasting only 1 or 2 years may not allow sufficient time to assess the potential longer-term benefits on soil quality from use of organic N sources. Furthermore, the yield response to applied N from both fertilizer and organic N sources can be highly variable from year to year (Morris et al., 1986).

Because use of green manures and recycling of rice straw depends largely on the relative costs of inorganic N fertilizer, labor and land, two key issues are the relative AE of N from organic N sources and inorganic fertilizer, and whether long-term residual benefits accrue from use of organic N sources. In two long-term comparisons in which all N sources were applied at equivalent N rates, the AE from green manures was about 85 to 95% that of prilled urea with a standard split application (Table 1). Although use of green manures resulted in significantly higher SOC and TSN compared to treatments only receiving inorganic fertilizer, there was no evidence of greater EINS or Y0 from long-term use of green manures (Cassman et al., 1996a). Measurement of residual effects after 22 consecutive rice crops indicated an increase in extractable soil N during the early season from planting to midtilling in treatments that had previously received Azolla or rice straw. No differences were detected in extractable soil N at panicle initiation. Greater crop N uptake was also observed in the residual rice straw treatments at panicle initiation, but crop N accumulation after panicle initiation, final grain yield and total biomass were similar regardless of previous N-source treatment.

These results are consistent with the supposition that increased indigenous N supply in the early vegetative phase is less important for yield development than the N supply after midtilling (see Section 5.1). Also consistent with these results is the
hypothesis that the rate of rapid-phase net N mineralization is more sensitive to changes in SOM content caused by crop management than the slower linear-phase (see Section 6.3). Because NO$_3^-$ is the end product of N mineralization in aerated soil vs. NH$_4^+$ in reduced soil, mineralized inorganic N in excess of plant uptake capacity is less prone to gaseous losses in aerated soil than in a submerged soil. For these reasons, the contribution of green manures and legume rotations to the EINS may be larger for nonrice crops grown in aerated soil in rotation with rice. It is notable that significant residual benefits from green manures are often found in rice–wheat systems (Singh et al., 1991; Buress and De Datta, 1991), and, in contrast to continuous double-crop rice systems, SOM declines over time in conventional rice–wheat systems without green manures (Nambiar, 1995). Green manures and legume rotations may also play a role in the capture and recycling of mineralized soil N during fallow periods between rice crops (George et al., 1993a,b, 1994; Ladha et al., 1996). Use of green manures and recycled straw may also affect soil physical properties. Such effects are especially important in upland cropping systems where soil is prone to erosion or crusting, or where dry soil tillage is practiced. They are less important when primary tillage is accomplished by puddling and the crop is grown in submerged soil.

In conclusion, minimal use of green manures in intensive lowland rice systems appears to reflect higher costs of green manure-N, a similar or lower AE of green manure-N than fertilizer-N, and relatively small residual benefits from effects on EINS or other soil properties. For rice–nonrice cropping systems, however, the short and longer-term benefits from use of green manures or legume rotations may be larger than in rice double-crop systems. In all rice systems, recycling of straw in combination with inorganic N fertilizer would result in a significant reduction in total N fertilizer requirements. Recycling of straw also has a major influence on the potassium (K) balance and maintenance of soil K status of intensive rice systems (see the work of Dobermann et al., 1997). Trends of rising labor costs and increased mechanization of tillage and harvest operations may contribute to increased recycling of rice straw.

6. Towards field-specific management

6.1. N demand of the rice crop

Grain yields are closely associated with plant N accumulation in a curvilinear fashion, and this relationship is relatively conservative when the best-performing commercial varieties are evaluated in a given irrigated rice domain (Fig. 6). At a given site, however, yield potential varies from year-to-year due to normal variation in temperature and solar radiation. For example, there is a 80% probability that grain yield potential will fall between 8.0 to 10.0 t ha$^{-1}$ in the dry season and 6.0 to 8.2 t ha$^{-1}$ in the wet season at the IRRI Research farm based on long-term weather data (Kropff et al., 1994a).

Average irrigated rice yields are about 5.0 t ha$^{-1}$ today, but they must rise to 8.0 t ha$^{-1}$ by 2020 to meet projected demand for rice in Asia (Hossain and Fischer, 1995). This yield level is about 90% of the climate-adjusted mean yield potential of 68 sites in the major rice-producing areas of Asia (Mathews et al., 1995). Responsive N fertilizer management will

![Fig. 6. Relationship between grain yield and aboveground plant N at physiological maturity measured in farmers' fields in the Guimba Municipality of Central Luzon, 1992 dry season. Yields were measured in plots without applied N (N0) and in adjacent areas of the field-at-large that received the farmers’ N fertilizer management regime (FP). A total of nine cultivars were used by the 42 farmers with IR64 planted in 50% of the monitored fields and approximately equal use of the other cultivars. Modified from the work of Cassman et al. (1996c).](image-url)
be crucial for achieving higher yields, increased AE, and yield stability. The biophysical requirement for a high leaf area index with high N content to achieve rice yields of 5 to 6 t ha$^{-1}$ in the wet season and 7 to 8 t ha$^{-1}$ in the dry season makes the margin for error from 'overfertilizing' much smaller than at lower yield levels. Increased lodging and disease severity are associated with high yield levels and an N supply that exceeds crop demand (Setter et al., 1994). This association can result in a yield decrease despite increased N uptake, and often results in a parabolic fit of the yield response to plant N accumulation or applied N rate when disease severity is high or when lodging occurs before grainfilling is finished (Cu et al., 1996).

Knowledge of the N uptake requirement at each stage of development to achieve a given yield level is fundamental for responsive management of N inputs. For a specified rice-growing domain, this relationship can be defined by straightforward measurements of dry matter and N content, and cumulative thermal units (Cassman et al., 1993; Cassman et al., 1994). Recent evaluation of this relationship in early maturing cultivars at two sites in the Philippines confirms the relative importance of the available N supply from midtillering to flowering at yield levels above 9 t ha$^{-1}$ (Fig. 7).

### 6.2. Congruence of N supply and crop demand

The goal of responsive N management is congruence of N supply and demand. Congruent N management requires prediction of the EINS and crop N uptake requirements to determine the need for a basal N application and the timing and rate of post-establishment N topdressings. In recent field studies, for example, grain yields of 9 to 10 t ha$^{-1}$ were achieved in the dry season without basal N application (Table 5). Yields without applied N in these experiments ranged from 4.5 to 5.6 t ha$^{-1}$. Although these yields represent relatively high $Y_0$ values, 30% of the farmers’ fields monitored in Central Luzon had $Y_0$ in this range (Fig. 2), and we are finding a similar range of $Y_0$ in intensive rice domains of Java, Indonesia, the Mekong Delta of Vietnam, and the Cauvery Delta of south India (K.G. Cassman, D.C. Olk, A. Dobermann, unpublished data). At issue is the need for basal application in fields with lower EINS. There is also a need to understand the reasons for such large variation in the EINS (see Sections 4 and 5).

Even if the crop N requirement and the EINS are known, maintaining adequate N supply in the soil-floodwater system is difficult due to rapid N losses and equally rapid N uptake. All else being equal, the

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**Fig. 7.** Aboveground N accumulation in two early maturing rice cultivars in relation to cumulative degree days (8°C threshold) from a total of four experiments in two dry seasons conducted at the IRRI Research Farm in Laguna and the PhilRice Experiment Station in Nueva Ecija. Data points are means of variety and N fertilizer treatments at each sample time. Fertilizer treatments include various timing and rates: a basal application incorporated in soil before transplanting, or broadcast applications into floodwater at midtillering (MT), before panicle initiation (PI), or flowering stage (FL). For each fertilizer treatment, mean grain yield and AE (AE) are shown at right (K.G. Cassman, M.J. Kropff, P. Peng, M.A. Dizon, S. Liboon, R. Torres, unpublished data).
Table 5
Grain yield and agronomic efficiency (AE) of irrigated lowland rice in treatments with and without basal N application. Data modified from Peng et al., 1996a

<table>
<thead>
<tr>
<th>Site/Yr (variety)</th>
<th>Establishment method</th>
<th>N fertilizer ($\text{kg ha}^{-1}$)</th>
<th>Grain yield (t ha$^{-1}$)</th>
<th>AE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>MT</td>
<td>PI</td>
</tr>
<tr>
<td>IRRI/1992 (IR72)</td>
<td>TPR</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td></td>
<td>0</td>
<td>60</td>
<td>60</td>
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<tr>
<td></td>
<td></td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>IRRI/1992 (IR72)</td>
<td>TPR</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td>BWS</td>
<td>0</td>
<td>0</td>
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<td></td>
<td>0</td>
<td>60</td>
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<td></td>
<td></td>
<td>0</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>TPR</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>BWS</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>PRRI/1993 (IR64616H)</td>
<td>TPR</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>60</td>
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<td></td>
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<td>60</td>
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<td>60</td>
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</tbody>
</table>

$^a$TPR, transplanted rice; BWS, broadcast wet-seeded.
$^b$Timing of N application: B, basal; MT, mid-tillering; PI, 5–7 days before panicle initiation; FL, flowering.
$^c$For each site-year, values followed by the same letter do not differ at < 0.05 by DMRT.
rate of loss is proportional to the concentration of NH$_4$-N in floodwater. Predicted NH$_3$ volatilization rates under typical field conditions from a topdressing of 40 kg N ha$^{-1}$ broadcast into floodwater are initially 4 kg ha$^{-1}$ d$^{-1}$, and would be more or less in proportion to the rate of applied N (Rachhpal-Singh and Kirk, 1993b). Plant uptake of applied fertilizer-N is also a cause of rapid N removal from the soil-floodwater system. In fact, plant N uptake rates are of the same magnitude as potential volatilization losses. Sustained uptake rates of 8 to 10 kg N ha$^{-1}$ d$^{-1}$ have been recorded in the field given an adequate supply of available N (Fig. 8). Together, rapid uptake and losses of applied N result in a ‘feast or famine’ pattern of N supply that is characteristic of irrigated rice systems and makes congruence of N supply and crop demand a difficult goal to achieve.

One approach to reduce the feast or famine dilemma is to increase the number of split applications using equal N rates in all splits but less N per application. There is some evidence from field studies that this approach increases fertilizer uptake efficiency and reduces N losses (De Datta et al., 1988a). A further refinement of this approach is to use more split applications with different N rates that correspond to the estimated crop demand at different growth stages.

6.3. Plant-based options for field-specific management

Plant-based strategies that rely on monitoring the N status of the rice crop have been used to improve fertilizer-N efficiency. Leaf N content is closely related to photosynthetic rate (Yoshida and Coronel, 1976; Peng et al., 1995a) and biomass production (Yoshida, 1981). The N concentration on a dry weight basis (N$_w$) of the most recent fully expanded leaf is considered an index tissue to determine the need for N topdressings (Wallihan and Moomaw, 1967). Use of this approach by farmers is limited by cost and turnaround time. The chlorophyll meter (SPAD) provides a simple, quick, and non-destructive method for estimating the N concentration of the index leaf, but the linear relationship between N$_w$ and SPAD readings differs markedly depending on growth stage and rice cultivar (Takebe and Yoneyama, 1989).

Peng et al. (1993) demonstrated that differences in leaf thickness are largely responsible for variations in the relationship between N$_w$ and SPAD values in rice. When leaf N concentration was measured on a leaf area basis (N$_a$), there was a similar linear correlation between SPAD values and N$_a$ for all stages of development and lines tested (Peng et al., 1995b, 1996b). Moreover, single leaf photosynthetic rates were more closely correlated with N$_a$ than with N$_w$, and grain yields approaching yield potential levels could be achieved when N$_a$ of the uppermost, fully expanded leaf was maintained at or above 1.4 g m$^{-2}$. Leaves with N$_a$ at this critical level give a SPAD reading of 35 regardless of development stage or genotype.
Fertilizer-N management guided by a chlorophyll meter was compared with farmer practices in 22 fields of Central Luzon. In large plots, a topdressing of 30 to 45 kg N ha\(^{-1}\) was applied when the SPAD value of the most recent fully expanded leaf fell below 35. On average, outside these plots, farmers applied 70% of total fertilizer-N in a first topdressing at 15 d after planting, and the remainder in a second topdressing at 30 d, which corresponds to mid- to late tillering. None of the farmers applied basal N, five applied only one N application, 14 applied two splits, and three made three applications. In contrast, the SPAD-guided N management used three to four split applications that were spread more evenly from 20 to 58 d after planting. Average grain yield was 12% greater and the N rate 11% less with SPAD-guided management than the farmers' N fertilizer practices (Table 6). Monitoring of leaf N status indicated N deficiency after panicle initiation in most fields under the farmers' N management (Peng et al., 1996a). Average RE of N applied by farmers was 34% vs. 62% in SPAD-guided plots.

While these preliminary results are promising, they require more widespread testing. Moreover, nutrient limitations other than N may reduce the expected response to applied N (see Dobermann et al., 1997), and the critical SPAD threshold for N topdressing. Therefore, research on field-specific N management must be coupled with a broader effort on alleviating nutrient limitations more generally. Results from the Philippines indicate that farmers apply too much N in the first topdressing and that more split applications given later in the season would improve AE. Although the current cost of the chlorophyll meter may limit use by individual farmers, it might be affordable for researchers, extension agents, and perhaps farmer cooperative groups or villages. A more detailed economic analysis of the chlorophyll meter as an N management tool is provided by Pingali et al. (1997).

6.4. Estimating the effective indigenous N supply

Although monitoring of plant N status can be used to determine the timing of N topdressings after the crop is established, the requirement for a basal N fertilizer application at planting and the amount of N fertilizer to apply both at planting and in subsequent topdressings depends on the indigenous N supply. Prediction of EINS during crop growth is therefore essential to optimize the efficiency of applied N. It is also an important research tool to help identify the reasons for the large field-to-field variation observed in EINS and to develop management strategies that optimize and maintain the EINS (see Section 3.3).

Net N mineralization rates of lowland paddy soils measured by anaerobic incubation of initially air-dried soil follow a generic pattern with a rapid phase lasting 14 to 28 d and a slow steady-state phase thereafter (Dei and Yamasaki, 1979). The pattern of NH\(_4\)-N release is best described by a two-pool additive model that infers a rapidly decomposable organic N pool from which release of NH\(_4\)-N follows first order kinetics, and a more recalcitrant organic N pool that releases N much more slowly in a linear fashion (Zahid, 1995). Most laboratory-derived indices are based on anaerobic incubation studies of relatively short duration, usually 14 to 28 d at 30°C. Based on thermal time, or cumulative degree days, this period of incubation is approximately equal

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### Table 6

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N rate (kg ha(^{-1})) ((N_c))</th>
<th>Grain yield (kg ha(^{-1})) ((Y))</th>
<th>Agronomic efficiency (\frac{\Delta Y}{N_r})</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fertilizer N</td>
<td>0</td>
<td>4460 ± 300</td>
<td>~</td>
</tr>
<tr>
<td>Farmer's practice</td>
<td>134 ± 10(^1)</td>
<td>6500 ± 210</td>
<td>15.3 ± 2.2</td>
</tr>
<tr>
<td>Chlorophyll meter</td>
<td>120 ± 3</td>
<td>7310 ± 230</td>
<td>23.7 ± 2.4</td>
</tr>
</tbody>
</table>

\(^1\)One standard error.
to or less than the early crop establishment growth phase, especially when transplanting or sowing occurs 7 to 10 d after puddling.

Compared to the slow-phase linear net N mineralization rate, rapid-phase rates are much more sensitive to the effects of soil drying (Inubushi and Wada, 1987; Toriyama and Sekiya, 1991; Hasegawa and Horie, 1994) and differences in SOC or TSN content (Zahid, 1995). In 30 lowland rice soils from the Philippines, for example, the correlation between the estimated size of the rapidly decomposable organic N pool, which governs the rapid-phase net mineralization rate, and SOC content was $r = 0.84$ ($P < 0.001$), vs. $r = 0.65$ ($P < 0.001$) for correlation of the slow-phase linear rate constant with SOC. Despite the highly significant overall correlation, some soils with similar SOC and TSN content had slow-phase rate constants that differed by two to threefold.

Measurement of slow-phase rates by standard anaerobic incubation methods is confounded by abiotic fixation of mineralized NH$_4$-N in clay minerals and by losses of inorganic N that presumably occur in micro-niches where redox potential is higher than in bulk soil. Fixation of mineralized N would be greatly reduced by the presence of a strong sink such as the rice root system. In anaerobic incubations, use of a K-saturated cation exchange resin (K-R) mixed with soil provides such a sink and gave much higher estimates of slow-phase net N mineralization rates (Fig. 9). In all soils tested, even those without NH$_4$-N fixation properties, estimates of slow-phase net mineralization rates were 20 to 200% higher when measured by the K-R incubation system than with standard incubation methods without resin.

Because plant N uptake after midtillering has a greater influence on grain yield (Fig. 7), final dry matter and total plant N than early season uptake (Fig. 5), it seems likely that EINS would be more closely related to slow-phase N mineralization than N release in the rapid phase. Compared to the standard method, the K-R anaerobic incubation method should more accurately reflect slow-phase mineralization rates that occur under field conditions when the rice root system acts as a strong sink for mineralized N. If the K-R method provides an accurate reflection of slow-phase net N mineralization, it could be used to evaluate the influences of crop and soil management practices on EINS, and to study the processes controlling it. Whether the K-R method can accurately estimate the slow-phase contribution to crop N uptake under field conditions is under investigation.

Until new methods are developed, direct measurement of plant N uptake is the only option for estimating EINS of paddy soils. There is some evidence that EINS is similar in fertilized and unfertilized plots, which indicates that the indirect effects of applied N fertilizer on uptake of indigenous soil N are relatively small (Schnier, 1994). If true, EINS could be roughly estimated by grain yield from small plots without applied N, but with adequate supply of other nutrients, because grain yields are closely related to N uptake (Fig. 6). These estimates could be used by extension workers and farmers to monitor the stability of EINS, how management and season affect it, and to compute the total inputs of N fertilizer required to achieve a targeted yield level. The latter would require some knowledge of RE from applied N. The timing of split applications could be determined by a chlorophyll meter and estimated from the relationship between plant N accumulation and time (Fig. 7) or by user-friendly optimization models.

6.5. Simulation models

Several rice simulation models predict yield potential with reasonable accuracy based on genotype-specific developmental coefficients and climate data.
These include the SIMRIW (Horie, 1987), ORYZA1 (Kropff et al., 1993b), and CERES-Rice (Singh et al., 1993) models. Each of these models considers the N supply, as well as other nutrients and water, not limiting. For flooded soils with a standing rice crop, the fate of N fertilizer broadcast into floodwater has been simulated by Rachhpal-Singh and Kirk (1993a,b). Another model simulates only the process of NH₃ volatilization (Jayaweera and Mikkelsen, 1990). These soil–floodwater N models are extremely complex and have large requirements for input data on soil properties, N uptake by roots, crop growth rates, and climate. Such models are helpful in identifying key issues for further research, but they are not likely to be used directly for field-specific N management.

The CERES-Rice model (Godwin and Singh, 1991) is the only model that simulates both growth of the rice crop in relation to N supply, and N availability and uptake from the soil–floodwater system. The soil–floodwater submodel was adapted from the aerobic soil-N model of Godwin and Jones (1991). It has 12 subroutines accounting for N inputs, organic N pools of varying bioavailability, N movement, soil and floodwater transformations of inorganic N, N diffusion and equilibrium between floodwater and soil, ammonium sorption, N balance, and net N mineralization from the different organic N pools. The N balance component simulates the turnover of SOM and crop residues (mineralization–immobilization of N). Because the soil N component of the model is a modification of an aerated soil-N model, it does not account for the unique processes of N immobilization–mineralization in submerged soil.

Various components of the CERES-Rice model have been validated with data from IBSNAT experiments (Li, 1987), Department of Agriculture and Land Development Department, Thailand (Jintrawet, 1991), and from collaborative field research by IRRI and IFDC in the Philippines (Godwin et al., 1990; Buressh et al., 1991; Singh and Buressh, 1994; Kropff et al., 1994b). Whereas prediction of yield and total biomass compare well with other models when simulations are based on non-limiting N supply, its ability to predict the EINS estimated by plant N uptake from soil without applied N has not been validated. Two key issues under investigation are: (1) the contribution of initially available inorganic NH₄−N and NH₄−N released in the rapid phase of N mineralization after soil puddling to the EINS, and (2) the apparent disconnection between the EINS and SOM content documented in field studies (see Section 5.2). At present, the CERES simulation of the plant-available N supply from SOM assumes a proportionality between SOM and net N mineralization (Fig. 10) and EINS, a relationship that does not appear to hold true in field experiments (Cassman et al., 1996a,b), or in farmer’s fields (Fig. 3).

Use of complex simulation models that predict crop growth, N demand, and soil N supply as a N management tool is not likely in the next 10 years because knowledge about the processes governing the indigenous N supply of the soil–floodwater system is lacking. Simplified optimization models such as MANAGE-N appear to have more promise because they simulate only crop demand and require specification of the EINS and RE from applied N (Reithoven et al., 1995). In this model, demand is determined by a simplification of the ORYZA1 model (Kropff et al., 1993b), while the EINS and RE are provided as inputs based on data from field calibration.

Fig. 10. Cumulative net N mineralization from SOM as predicted by the CERES-Rice model using climate data and soil properties measured in a field at the IRRI Research Farm (circles), and with specifications for a two-fold increase (squares) or a 50% decrease (triangles) in organic carbon content. In each case the SOM is specified to have a C/N ratio of 10, which is typical for lowland rice soils at the IRRI farm. Rate constants are indicated for the mostly linear slow phase net N mineralization from 40 to 84 d after transplanting.
tions. Initial results indicate higher yields and greater AE with N fertilizer management predicted by the optimization model than from presently recommended practices at several research stations in five Asian countries (T.M. Thiagaranjan and H. ten Berge, personal communication). The advantage was greatest at sites where a recommended basal N application was eliminated as predicted by the optimization model. To be of widespread use, however, methods for estimating EINS will be required to accommodate the large field-to-field variability in this crucial parameter.

7. Summary and conclusions

Nitrogen dynamics in the soil–floodwater–rice system are perhaps one of the most complex biophysical systems in agriculture. Despite this complexity, new insights into constraints to improved N efficiency and system properties have helped define research objectives more clearly. The heavy emphasis of past research on reducing losses of applied N has been replaced with a more comprehensive approach that considers N losses to be a symptom of incongruent N supply and crop demand rather than a driving force. We now recognize the unique capacity of wetland rice systems to conserve indigenous N resources, the rapid N uptake capacity of the rice plant and, despite rapid N losses from floodwater, an apparent N fertilizer RE that is equal to or higher than for other cereal crops such as corn or wheat when also grown under irrigated conditions. The property of N conservation, however, is associated with tremendous variability in the indigenous N supply that is sensitive to relatively small changes in management and climate—a characteristic of irrigated lowland rice systems that presents both extraordinary challenges and opportunities to improve N-use efficiency.

These system attributes and the requirement of a 60% increase in average rice production highlight the need for N management strategies that optimize the contributions from both indigenous N resources and applied N inputs. Where constraints other than N do not limit crop performance, poor fertilizer-N efficiency presently achieved by rice farmers results primarily from a lack of congruence between EINS, applied N inputs, and crop demand. Assuming little change in trends of farmgate prices for rice, N fertilizer, and labor, the greatest opportunities for increased N-use efficiency in the short term will involve the development of field-specific N management strategies that better match the N supply from indigenous resources and applied N with the pattern of crop demand. For a targeted yield level, this approach would optimize AE in relation to $Y_0$ and thus minimize N losses. Although much of this research is adaptive because it depends on improving the timing and rate of conventional urea-N applications, strategic research is needed to optimize the contributions of indigenous N resources, to improve in-season responsiveness to changes in crop condition or yield potential, and to increase the efficiency with which recommendations on N management can be generated. Strategic research issues are given below.

- Development of on-farm participatory research approaches that help farmers integrate knowledge of EINS on a field-specific basis and plant-based strategies for determining the need for N topdressings. This approach would incorporate: (a) dynamic soil-tests to improve estimates of EINS such as the K–R anaerobic incubation method or use of small ‘N fertilizer omission plots’ to measure $Y_0$; (b) tools to provide real-time estimates of crop N requirements such as the chlorophyll meter, user-friendly optimization models, and expert systems; and (c) regular quantification of other constraints to efficient N-use such as deficiencies and balance of other nutrients, interactions between crop N status and diseases or insect pests, weed problems, shortage of irrigation water and time of water availability. Analyses of general constraints to help target research on N-use efficiency has been neglected in recent years. In the Philippines, for example, the last systematic analysis of constraints to rice production in farmers’ fields was conducted in the mid-1970s (De Datta et al., 1979).

In the medium- and long-term there appears to be considerable potential to increase the contributions from indigenous N resources of the soil–floodwater system. Success towards this objective will depend on increased knowledge in the areas stated below.

- What are the major controls on the contribution of SOM to EINS in relation to moisture regime and...
soil aeration? The key questions are: (a) Does the formation of humus and increased phenol content in reduced soil affect subsequent N mineralization from labile SOM fractions? (b) Does abiotic immobilization of available N occur as a result of changes in SOM structure in flooded soils? (c) Are MHA and CaHA discrete SOM pools that reflect the influence of recent of soil management and the bioavailability of N from young humus? (d) Can management of crop residues and soil aeration alter the chemical structure of SOM to increase EINS without forfeiting the capacity to conserve N and C?

- How can soil biology be managed to increase N-use efficiency and sustain soil quality? Progress towards this goal will require better understanding of soil ecology and functional biodiversity to address the questions: (a) What microbial processes control the slow-phase N mineralization rate which has the largest influence on EINS? (b) How does size and physiological status of SMB influence EINS? (c) Are alternate metabolic pathways of N-cycle bacteria important regulators of EINS? (d) Does intensification of irrigated rice production alter the structure of soil microbial communities, and if so, do these changes affect EINS and N cycling? (e) Is it possible to increase the contribution of current BNF to plant N uptake? (f) how much does variation in subsoil N and rooting patterns contribute to differences in EINS, and can this contribution be increased? Answering these questions will require more than a short-term effort, but the knowledge gained and its application are pivotal to achieving the dual goals of increased N-use efficiency and the preservation of natural resources in the tropical and subtropical lowlands of Asia.

References


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