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Plot-Specific N Fertilizer Management for Improved N-Use Efficiency in Rice-Based Systems of Bangladesh

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ABSTRACT

Rice is the principal cereal and the main staple food crop in Asia. Wheat comes second due to its role as alternative to rice for breakfast (unleavened bread) in the majority of the households in Bangladesh. Mineral N fertilizer is the major input to rice and wheat. The development of a simple technology to improve the low N-use efficiency by both crops and reduce the N losses is an important challenge in agronomic research.

The use of chlorophyll (soil plant analysis development, SPAD) meter and leaf color chart (LCC) were evaluated in N fertilizer management to achieve the synchrony of N supply and demand, and to improve fertilizer N-use efficiency in rice-based systems. To estimate the native soil N supply by using SPAD and LCC, N omission plots on 40 farmers' fields were established in three districts (Meherpur, Kushtia and Chuadanga) of Bangladesh during the T-Aman (wet), Boro (dry) and Rabi (cold dry) seasons of 2001-02. A field trial in one farmer's field was conducted for a comparative evaluation of the three leaf color charts (IRRI-LCC, China-LCC and California-LCC) in the T-Aman season. Four farmers' fields, two each in two districts, were selected for two experiments to estimate the critical LCC values in the T-Aman season, each of which consisted of three rice varieties and five N managements based on IRRI-LCC. Another experiment comparing six rice varieties and six N managements based on the SPAD meter was carried out in three farmers' fields during the Boro season. Furthermore, two experiments were conducted with three wheat varieties and six N levels and ten N managements in two farmers' fields during the Rabi season.

The findings reveal that the linear relationship of grain yield and SPAD reading at an early growth stage could explain 69% and 62% of variation in rice and wheat, respectively. The LCC, however, was less efficient and explained only 41% of the rice and 54% of the wheat variation. A multiple linear regression, additionally including the parameters such as tiller number and plant height, did not improve the poor correlation observed with LCC readings.

Due to the relatively low accuracy of yield estimates from N omission plots with the IRRI-LCC, a range of LCCs with varying color intensities and critical values for plot-specific N fertilizer management regarding yield and N-use efficiency was compared. The IRRI-LCC-3, China-LCC-4 and California-LCC-4-based N management resulted in 90%, 85% and 70% yield increase over the yield of N-control plot in the T-Aman season. IRRI-LCC-3-based N management produced similar yield levels to the recommended-N rate in rice with a lower rate of N applied in some cases. High yields were obtained when N application was based on IRRI-LCC-4 with relatively high N rates. Agronomic efficiency (AE) values ranged from 14.0 to 29.6 in the LCC-based N managements, and recovery efficiency (RE) from 36.2 to 70.7%.

The SPAD-35-based N management resulted in significantly higher yields with 3-12% lower N application rate than that of recommended-N in the Boro season. However, highest yields resulted from the SPAD-39-based N management with relatively higher N applied. AE values range from 24.9 to 39.6 in both treatments, and the RE from 41.0 to 57.0%.

In wheat varieties, 120 kg N ha^{-1} (the split application of 48-48-24 kg N ha^{-1} at basal, crown root initiation, and maximum tillering stage, respectively) resulted in the highest yield increase of 200-900 kg grain ha^{-1} over the yield of the recommended-N rate in the Rabi season. Maximum yields were obtained from the 50-50-20 application

(with critical SPAD value 44 for N fertilization at maximum tillering stage). The high AE of wheat was found at 120 kg N ha^{-1} levels. The critical SPAD values 44 and 48 resulted in higher AE values in 40-40-20 and 50-50-20 N managements. The RE values ranged from 38.4% to 64.6% in the SPAD-based N managements.

The correlation between SPAD readings and rice leaf N on area basis (r=0.59) was better than that on dry weight basis (r=0.42). The better correlation of SPAD reading at the maximum tillering stage was also observed with wheat leaf N on area basis (r=0.91 and 0.84) than that on dry weight basis (r=0.85 and 0.72).

The present study indicates that the SPAD meter is a reliable tool to estimate the native soil N supply at an early growth stage in rice and wheat, whereas the LCC could only provide rough estimations. While LCC-based N management appears more promising in wheat than in rice, it is not as reliable as SPAD-based approaches and can rarely contribute to higher yields through increased N-use efficiency. The critical LCC values of the IRRI-LCC color reduction below which mineral N needs to be applied were determined to be 3.5 for rice and 4.5 for wheat.

Parzellenspezifisches N-Düngermanagement für die verbesserte N-Nutzungseffizienz in Reisanbausystemen in Bangladesh

KURZFASSUNG

Reis ist das wichtigste Getreideanbauprodukt und Hauptgrundnahrungsmittel in Asien. An zweiter Stelle kommt Weizen wegen seiner Rolle als Alternative zu Reis zum Frühstuck (ungesäuertes Brot) in den meisten Haushalten in Bangladesh. Mineralischer N-Dünger ist der Hauptzusatz im Reis- und Weizenanbau. Die Entwicklung einer einfachen Technologie zur Verbesserung der niedrigen N-Nutzungseffizienz bei beiden Anbauprodukten und zur Reduzierung der N-Verluste ist eine wichtige Herausforderung in der agronomischen Forschung.

Der Einsatz von Chlorophyll-(‚soil plant analysis development' SPAD)-Meter und Blattfarbentafel (leaf color chart, LCC) wurden im N-Düngermanagement bewertet, um die Synchronisierung von N-Versorgung und –Bedarf zu erreichen, und um die N-Nutzungseffizienz von Dünger in Reisanbausystemen zu verbessern. Um die natürliche N-Versorgung mit SPAD und LCC zu ermitteln, wurden Parzellen ohne N-Düngung auf 40 Farmfeldern in drei Distrikten (Meherpur, Kushtia und Chuadanga) in Bangladesh während der T-Aman- (nass), Boro- (trocken) und Rabi- (kalt-trocken) Jahreszeiten 2001-02 eingerichtet. Ein Feldversuch in einem Farmfeld in Meherpur wurde in der T-Aman-Jahreszeit für eine vergleichende Bewertung der drei LCC (IRRI-LCC, China-LCC und Kalifornien-LCC) durchgeführt. Um die kritischen LCC-Werte zu bestimmen, wurden vier Farmfelder, je zwei in den Distrikten Meherpur und Kushtia, unter einem Reis-Reis- bzw. Reis-Weizensystem während der T-Aman-Jahreszeit für zwei Versuche ausgewählt, wobei sich jeder Versuch aus drei Reissorten und fünf N-Anwendungen auf der Grundlage von IRRI-LCC zusammensetzte. Ein weiterer Versuch mit sechs Reissorten und sechs N-Behandlungen auf der Grundlage des SPAD-Meters wurde auf drei Farmfeldern während der Boro-Jahreszeit durchgeführt. Außerdem wurden zwei Versuche mit drei Weizensorten und sechs N-Mengen bzw. zehn N-Behandlungen auf zwei Farmfeldern während der Rabi-Jahreszeit 2001-02 durchgeführt.

Die Ergebnisse zeigen, dass die lineare Beziehung zwischen Körnerertrag und SPAD-Messung im frühen Wachstumsstadium 69% bzw. 62% der Variation bei Reis bzw. Weizen erklären können. Das LCC war jedoch weniger effizient und erklärte nur 41% der Reis- und 54% der Weizenvariationen. Eine multiple lineare Regression, zusätzlich mit Parametern wie Anzahl der Bestockungstriebe sowie Pflanzenhöhe, führte nicht zu einer Verbesserung der bei den LCC-Messungen beobachteten Korrelation.

Aufgrund der geringen Genauigkeit der Schätzungen der Erträge von den Parzellen ohne N-Düngung mit dem IRRI-LCC, wurde eine Auswahl LCCs mit unterschiedlichen Farbintensitäten und kritischen Werten für parzellen-spezifisches N-Düngermanagement hinsichtlich Ertrag und N-Nutzungseffizienz verglichen. Die IRRI-LCC-3, China-LCC-4 bzw. Kalifornien-LCC-4-basierten N-Behandlungen ergaben Ertragssteigerungen von 90%, 85% bzw. 70% verglichen mit der N-Kontrollparzelle in der T-Aman-Zeit. Das IRRI-LCC-3-basierte N-Management ergab ähnliche Erträge wie die empfohlene N-Menge bei Reis mit, in manchen Fällen, einer niedrigeren N-Menge. Hohe Erträge wurden bei der N-Anwendung auf der Grundlage von IRRI-LCC-4 bei

einer relativ hohen N-Menge erzielt. Die Werte der agronomischen Effizienz (AE) lagen zwischen 14.0 und 29.6 bei den LCC-basierten N-Anwendungen, und die N-Aufnahme-Effizienz (RE) zwischen 36.2 und 70.7%.

Die SPAD-35-Anwendung zeigte einen signifikant höheren Ertrag mit einer 3-12% niedrigeren N-Menge als die mit der empfohlenen N-Menge in der Boro-Jahreszeit. Die höchsten Erträge ergaben sich aus dem SPAD-39-basierten N-Management mit einer relativ höheren N-Menge. Die AE-Werte betrugen zwischen 24.9 in 39.6 in beiden Anwendungen und die RE zwischen 41.0 und 57.0%.

Bei den Weizensorten ergaben 120 kg N ha^{-1} (verteilte Gabe 48-48-24 kg N ha^{-1} bei der Grunddüngung, Beginn der Kronenwurzelbildung bzw. Hauptbestockung) höchste Ertragszunahmen von 200-900 kg Körner ha^{-1} gegenüber der empfohlenen N-Menge in der Rabi-Jahreszeit. Die höchsten Erträge wurden durch die 50-50-20-Anwendung erzielt (mit einem kritischen SPAD-Wert 44 für N-Düngung in der Hauptbestockungsphase). Die hohe AE von Weizen wurde bei 120 kg N ha^{-1} erzielt. Die kritische SPAD-Werte 44 und 48 ergaben höhere AE-Werte bei den 40-40-20 und 50-50-20 N-Anwendungen. Die RE-Werte lagen zwischen 38.4% und 64.6% in den SPAD-basierten N-Anwendungen.

Die Korrelation zwischen SPAD-Messungen und N-Gehalt des Reisblattes auf der Grundlage der Blattfläche (r=0.59) war besser als die Korrelation auf der Grundlage der Trockenmasse (r=0.42). Die bessere Korrelation der SPAD-Messung in der Hauptbestockungsphase wurde auch beim N-Gehalt des Weizenblattes auf der Grundlage der Blattfläche (r=0.91 und 0.84) verglichen mit der Korrelation auf der Grundlage der Trockenmasse (r=0.85 und 0.72) beobachtet.

Die vorliegende Studie zeigt, dass das SPAD-Meter ein zuverlässiges Instrument zur Ermittlung der natürlichen N-Versorgung des Bodens in einem frühen Wachstumsstadium bei Reis und Weizen darstellt, während das LCC nur eine grobe Schätzung erlaubt. Während LCC-basiertes N-Management bei Weizen vielversprechender als bei Reis erscheint, ist es nicht so zuverlässig wie die SPAD-basierten Ansätze und trägt selten zur Erhöhung der N-Nutzungseffizienz in Form von Erträgen bei. Die kritischen LCC-Werte der IRRI-LCC unter denen mineralische N-Düngung erforderlich wird, wurden mit 3.5 für Reis bzw. 4.5 für Weizen ermittelt.

TABLE OF CONTENTS

LIST OF APPENDICES

1 INTRODUCTION

It has been estimated that by 2050 the world's population will have increased by a factor of 1.4 - 1.5 over the present level. This projected demographic increase will occur mostly in Asia, which is home to 60% of the world's population and where people depend on rice as their staple food. The rice-consuming population grows by 2% annually. It is, therefore, crucial to increase rice production within a relatively short period (Mae, 1997). Rice is grown on 150 million hectares, comprising more than 10% of the Earth's arable land and accounting for about 30% of the global cereal production (FAO, 1999). Ninety-five percent of the world's rice is grown in less developed countries, primarily in Asia (IRRI, 1995). In Asia, both rice and wheat contribute substantially to regional food security. These two crops are frequently grown in an annual double-crop (rice-wheat) rotation, providing food for millions of people. Of the 24 million ha occupied by rice-wheat rotation systems, 10.5 million ha are found in China and 13.5 million ha in the Indo-Gangetic flood plains of South Asia (10 million in India, 2.2 million in Pakistan, 0.8 million in Bangladesh, and 0.5 million in Nepl). In these four countries, the rice-wheat system covers about 32% of the total rice and about 42% of the total wheat-growing area, accounting for a quarter to a third of the total rice and wheat production (Ladha et al., 2000).

Rice and wheat are the only cereals grown in Bangladesh and provide 94% of the national caloric intake (Timsina and Connor, 2001). Rice is the principal cereal and the main staple food crop. Wheat comes second due to its role as principal replacement or alternative to rice. Thus, it has become customary to have wheat-made "Chapati" (unleavened bread) for breakfast in the majority of the households in Bangladesh. With the introduction of modern varieties of rice and wheat, Bangladesh achieved near self-sufficiency in cereal production in the early 1980's. However, agricultural production has not been able to keep pace with the annual demographic growth rate of 2.6% (Badaruddin and Razzaque, 1995) and severe food shortages are predicted for the near future.

The relatively low yield level around 2.0 t ha^{-1} in both rice and wheat is associated with many production constraints of which the most important are low soil fertility, poor crop management, and a limited availability of labor and credit (Bhuiyan et al., 1993). In recent years, an increased cropping intensity without the matching increase in fertilizer inputs has caused an accelerated depletion and imbalances of both macro- and micro-nutrients (Ahmed and Eilas, 1986; Saunders, 1990). The constant removal of crop residues from the fields further enhances the observed soil fertility decline.

While the agro-climatic conditions of Bangladesh are suitable for growing a number of different crops, almost all cropping systems are rice-based since rice is the country's staple food. The dominant cropping systems are rice-rice-wheat, fallow-rice-wheat, and jute/ green manure-rice-wheat (Badaruddin and Razzaque, 1995). Nearly 80% of the annual rainfall occurs during the monsoon season between June and September. The period is used for the cultivation of autumn rice, locally called T-Aman. Some rainfall occurs during the cold and dry season between November and March. This season is locally called "Boro" when used for growing lowland rice and "Rabi" when used for growing upland crops such as wheat. With the recent introduction of irrigation facilities, farmers tend to favor Boro rice over Rabi wheat cultivation. About 85% of the total wheat is preceded by a crop of rice (Bhuiyan et al., 1993).

Mineral nitrogen fertilizer is the major input to rice, and high grain yields can be obtained when the rice crop assimilates adequate amounts of nitrogen in the course of the growing season. Nitrogen absorbed by rice during the vegetative growth stage contributes to determine the number and size of the reproductive organs of rice (Ntamatungiro et al., 1999). However, the use efficiency of applied mineral N fertilizer to rice (NUE) is generally low and ranges from 15 to 25 kg grain produced per kg of fertilizer N applied (Cassman et al., 1996a). The NUE varies with the yield potential of the variety and the growth environment (Ladha et al., 1998a), but is largely determined by the extent of N losses via ammonium volatilization and denitrification. Fertilizer N losses are estimated to range from 10 to 65% of the applied N (Cassman et al., 1998). Thus, the N recovery by rice is low, ranging from 20 to 40% depending on source and timing of fertilizer N, crop and water management, and the agro-ecological conditions (Vlek and Crasswell, 1981). Low N fertilizer recovery is reportedly a major limitation in rice-wheat systems (Adhikari et al., 1999). Proper timing of the N applications has been shown to be crucial to minimize N losses and increase crop N recovery (Becker et al., 1994). Improving the synchrony between crop N demand and the N supply from soil and/or the applied N fertilizer is likely to be the most promising strategy to increase N use efficiency in these cropping systems. The N requirement by rice is closely related to the yield level, which in turn is determined by climate, particularly solar radiation, by the supply of nutrients other than N, and by crop management practices. Fertilizer N management strategies must thus be responsive to temporal variations in crop N demands and soil N supply in order to achieve supply-demand synchrony and to minimize N losses.

In the past, the timing of fertilizer to best match demand with supply has been based on regional recommendations. However, a growing body of evidence indicates large farm-to-farm and plot-to-plot variations in native soil N supply and thus in the soil's capacity to meet crop N demand (Cassman et al., 1996b and c; Stalin et al., 1996; Adhikari et al., 1999). In the developed world, the concept of precision farming is rapidly gaining importance. The question arises to what extent this principle of crop demand-driven, site-specific fertilizer application can add to farmers’ profits and enhance N use efficiency in the rice-based systems of Asia (Ladha et al., 2000). A group of scientists at the International Rice Research Institute (IRRI) in the Philippines has developed a simple tool for identifying crop N demand and soil N supply and thus for adapting the application of additional fertilizer N to meet the demand-supply gap.

Two potential solutions have been proposed to improve the timing of N application to rice and wheat. These comprise: (1) estimation of the amount of fertilizer N application based on the yield target and the soil N supplying capacity, and (2) the proper timing of the application of this amount of N through the use of a chlorophyll meter or leaf color chart.

The chlorophyll meter or SPAD (Soil Plant Analysis Development) meter is a small hand-held device that can within seconds determine the greenness of leaves corresponding to the leaf chlorophyll content. It has been shown that a close link exists between leaf chlorophyll content and leaf N content. Thus, the SPAD meter has become a quick, reliable, and nondestructive tool for diagnosing the N status of crops and thus for determining the right time of N topdressing (Peng et al., 1996; Ladha et al., 1998b; Balasubramanian et al., 1999). However, the cost (US$ 1200-1800 per unit) of the SPAD meter restricts its widespread use by farmers.

Since the SPAD meter measures the green leaf color as a proxy for leaf N content, a simplification is to use the green leaf color as an indicator for the N nutrition status of the crop. Farmers generally use leaf color as a visual and subjective indicator of the rice crop's nitrogen status and thus the need for N fertilizer application. In collaboration with PhilRice, the Philippines national agricultural research program for rice, the leaf color chart (LCC) was developed (CREMNET, 1999) based on a Japanese prototype. It is a simple and inexpensive tool for efficient N management in rice farming. The chart (IRRI-LCC) contains six shades of green from yellowish green (No. 1) to dark green (No. 6) and has been calibrated with the SPAD meter. It is 19 x 7 cm in size and can be easily taken in the pocket to the field. Other LCCs have also been developed at Zheijiang Agricultural University, China (China-LCC) with 8 shades of green and a larger size (38 x 9 cm) and at the University of California, USA (California-LCC), which also has 8 shades of green and a size of 38 x 10 cm. The California-LCC can be not only used for single leaf measurement but also for estimating the greenness of a whole field by looking through a viewer at the top of the chart and matching the color of the field with shade of green displayed at the border of the viewer.

SPAD / LCC thresholds or critical values indicate chlorophyll contents and/or N concentrations in the leaves below which the crop suffers from N deficiency, and yield will decline if N fertilizer is not applied immediately. However, these tools cannot be used universally as several factors affect SPAD / LCC values: radiation differences between seasons, plant density, varietal group, nutrient status other than N, and biotic and abiotic stresses that cause leaf discolorations (Peterson et al., 1993; Turner and Jund, 1994). Thus, the critical values of a healthy crop vary with environments and crop varieties. The N status of a crop and hence the fertilizer N input requirements further depend on the N supply from the soil. This soil N supplying capacity depends on the soil type (mineralizable N content) and is subject to temporal variations as a function of environmental and crop management. Similar to the readings of leaf greenness (SPAD, LCC), a precise estimation of the expected soil N supply will improve the amount and the timing of supplementary fertilizer N application for a desired target yield.

The soil N supply is best determined from crop N uptake in N omission plots where other nutrients are supplied in sufficient amounts so that plant growth is limited only by N supply (Witt and Dobermann, 2002). Since N fertilizer recommendations in flooded rice based on soil tests have not been successful (Stalin et al., 1996; Adhikari et al., 1999), the "omission plot technique" provides a useful tool to quantify soil N supply. The N fertilizer application rate is estimated using the recommendation model "QUEFTS" (Quantitative Evaluation of the Fertility of Tropical Soils), developed at Wagenigen University, the Netherlands (Janssen et al., 1990) and further refined at IRRI (Dobermann and White, 1999). The application of the QUEFTS model involves five steps (Witt and Dobermann, 2002):

1. Yield goal selection - The yield target is usually set to 70-80% of the variety - and environment-specific potential yield (simulated with Oryza-1 or similar crop growth simulation models).
2. Estimation of crop N requirements - The N uptake requirements of a rice and wheat crop depends on the target yield and follows a sigmoid uptake pattern.
3. Estimation of indigenous N supply - The amount of N that is supplied by the soil during the cropping cycle is estimated by measuring plant nutrient uptake in an N omission plot.
4. Calculation of fertilizer rate - Fertilizer recommendations are determined based on the plant nutrient requirement for the selected target yield, the estimate of the indigenous nutrient supply, and the expected fertilizer recovery efficiency.
5. Dynamic adjustment of fertilizer N applications - The total required N application is split and timed in relation to crop growth stages (sigmoid N uptake curve).

The enormous plot-to-plot and farm-to-farm variability in soil nutrient supply does not allow for general recommendations. The solution has to be field-specific. Strategies to quantify nutrient-supplying capacity based on soil tests and nutrient omission plots would restrict their widespread use, as farmers may be reluctant to establish nutrient omission plots. For a nutrient management strategy to be successful, it should be simple and involve farmers' knowledge and experience. Farmers may try to visually assess the deficiency (or toxicity) of the nutrient responsible for low yields. Although LCC is a simple tool to manage N topdressing, it does not take into account the indigenous soil N supply and, therefore, does not allow estimation of the basal fertilizer rate. In the absence of information with regards to the inherent soil N status, it is also difficult to set a target yield and subsequently calculate total N requirements. There is a need to develop a simple strategy that considers the initial soil N fertility and provides guidance for further N application rates and timing. A probable approach may be the combined use of QUEFTS to determine the total N requirements and a leaf chlorophyll-based option (SPAD, LCC) to optimize the timing of top-dressed N with the aim to reach the target yield with a minimal N application.

The applicability of such strategy is based on the following assumptions / hypotheses:

1. Determining a mathematical relationship between LCC at the early growth stage of rice and wheat with the grain yield in a N omission plot will allow a sufficiently accurate estimate of the inherent soil N fertility and thus of the total N requirement for a given target yield, as well as the rate and timing of N topdressing applications.
2. The application of this approach at field level will improve crop growth, N-use efficiency and ultimately the grain yield.

The present study was conducted with the general objective to develop and evaluate this simple N management strategy for rice and wheat in Bangladesh. The specific objectives were:

1. To evaluate LCC and SPAD for estimating the native soil N supply in farmers' fields under rice-rice and rice-wheat rotations.
2. To study the relationship of LCC and SPAD with yield and yield parameters of rice and wheat.
3. To compare three types of LCC for improving yield and N-use efficiency of rice and wheat, and determine the critical LCC values for N fertilization in predominantly grown rice and wheat varieties in Bangladesh.
4. To compare the plot-specific N fertilizer management based on LCC and SPAD, and recommended N management regarding yield and N-use efficiency in rice-rice and rice-wheat rotations.

2 LITERATURE REVIEW

Among cereal crops, rice and wheat are the two most important crops in the world. They contribute 45% of the digestible energy and 30% of the total protein in the human diet, and also contribute substantially to livestock feed (Evans, 1993). Nitrogen fertilization has an important influence on the yield of rice and wheat. The use of N fertilizer is increasing as a result of the increasing demand for dietary protein by the world's growing world population.

2.1 Role of rice-rice and rice-wheat cropping systems in Bangladesh

Rice is the predominant crop of the tropics and subtropics, while wheat has always been the predominant crop of temperate regions. However, wheat is now grown with moderate success in tropical and subtropical climates (Klatt, 1988; Saunders and Hettel, 1994). Most rice-wheat systems are located in South and East Asia in subtropical to warm-temperate areas characterized by cool, dry winters, and warm, wet summers (Timsina and Connor, 2001).

Bangladesh is a traditional rice country and produces wheat on only 5% of the rice lands, while approximately 85% of the much smaller wheat area also produces rice (FAO, 1999). It has been reported that the rice-wheat area in Bangladesh during the mid 1960s was only 0.054 M ha, representing 1% of the rice production area and 85% of the total wheat area. During the early 1990s, the rice-wheat area was 0.5 M ha, which was nine times larger than in the 1960s (Badaruddin and Razzaque, 1995).

Where temperatures are sufficiently warm in winter, farmers prefer to grow "Boro" rice over wheat provided adequate irrigation water is available. Boro rice gives more profit despite higher irrigation water requirements. Wheat (other non-rice crops such as oilseeds, pulses) is mostly grown where irrigation water and/or growing temperature are insufficient to grow boro rice (Morris et al., 1997).

Although there has been a general increase in wheat yields since 1960, there was evidence of a decline in yields in Bangladesh in the early 1980s. The present rates of increase in both rice and wheat yields are slower than they used to be (Timsina and Connor, 2001). A similar development was observed in intensive rice-rice systems that were also either stagnating or declining (Flinn et al., 1982; Flinn and De Datta, 1984).

Budaruddin and Razzaque (1995) also reported that sustainability of the rice-wheat system has become a critical issue for agricultural research in Bangladesh.

Ahmed (1995) suggested that priority in resource allocation for research and extension be given to the rice-wheat system for the following reasons:

- Rice and wheat are the staple food commodities of Bangladesh.
- The rice-wheat annual double cropping is major cropping system of Bangladesh.
- The demand for these cereals is projected to increase further in the future.
- The productivity of rice-wheat systems is low, and needs to be increased to reduce the countries dependence on imports and the growing spending of scarce foreign exchange, particularly for wheat.

2.2 Native soil nitrogen supply

The N demand of rice and wheat is met from native soil N supply and mineral fertilizer N application with fertilizer N filling the gap between crop demand and native soil N supply. Organic N via mineralization contributes to 50-80% of the total N uptake by a rice crop (Broadbent, 1979; Koyama, 1981). Thus, the native soil N supply is a crucial factor when determining and formulating N fertilizer requirements for a given target yield (Mingzhend and Zhumei, 1987; Smith et al., 1987; ten Berge et al., 1997). The assessment of the N fertilizer requirement for rice may be estimated as the difference between crop N demand (19-24 kg N uptake per ton of grain) and soil N supply (Ueno et al., 1988; Ueno et al., 1990; Kitada et al., 1991; Cassman et al., 1994).

Nutrients extracted by capsules containing a mixture of anion and cation exchange resin during anaerobic incubation of flooded soil from unfertilized plots were used as an index of the indigenous nutrient supply (Yang et al., 1991; Dobermann et al., 1994). The native soil N supply can be measured as plant N uptake at harvest in a small N omission plot located in a farmer's field, where P, K and other nutrients are applied in sufficient amounts so that plant growth is limited only by the native soil N supply (Witt and Dobermann, 2002).

It has been reported that nitrogen uptake by rice greatly varied between locations (Cassman et al., 1996b; Becker and Johnson, 2001), between crop growth stages (Stalin et al., 1996), and from year to year (Toriyama and Sekiya, 1991). However, total N uptake is closely correlated with grain yield with moderate variation (Cassman et al., 1998; Adhikari et al., 1999). Thus, the correlation with grain yield may provide a better tool for predicting native soil N-supply than soil tests (Stalin et al., 1996). The diagnostic measurement leaf chlorophyll has been proposed as an additional tool to define soil N supply with seasonal adjustments (Kitada et al., 1991; Cassman et al., 1994).

Cassman et al. (1996b) reported that the correlation between N uptake and grain yield is usually very high, because soil N supply limits N uptake in plots without applied N. Soil N supply can, therefore, be easily measured from grain yield measurements in N omission plots established in farmers' fields. Using well-calibrated functions, extension workers and farmers may reasonably estimate the native soil N supply in an individual field by only measuring grain yield from a small N omission plot (Dobermann et al., 1996).

2.3 Nitrogen supply and crop nitrogen demand

Nitrogen is the most critical nutrient element in crop production. It is vital for maintaining and improving crop growth and yield, and N-use efficiency to understand the mechanism by which crops respond to N (Lawlor et al., 1989; Sinclair and Horie, 1989; Bock and Hergert, 1991; Grindlay, 1997). Plants quickly and efficiently absorb nitrogen when their root systems come into contact with the required forms (NO_3^-, and NH_4^+), even in the micromolar range of concentrations in the soil solution (Lawlor et al., 2001). However, N absorption is much less efficient under conditions of cold drought water logging soils. Furthermore, the efficiency of N-use decreases with increasing amounts of N applied (Bock and Hergert, 1991).

Under favorable conditions, the estimation of N removal by rice or wheat is about 300 kg N ha^{-1} for 20 tons of dry matter accumulation (assuming a harvest index of 0.50), with an average of 1.5% N (Yoshida, 1981; van Duivenbooden et al., 1996; Lawlor et al., 2001). This N may be supplied from the soil and/or from N fertilizer applications. Deficiency symptoms may occur when N supply and N application are less than the amount of N removed. Many factors influence the N supply, such as N release from crop residues, soil-organic matter and soil-water content, temperature and the N content of rain (especially in industrial areas) and irrigation water (Lawlor et al., 2001). Because of a low and variable soil N supply and high N losses (i.e., by leaching and gaseous emissions from soils and plants), large applications of external N sources are required to obtain potential yields (Addiscott et al., 1991).

Lawlor et al. (2001) reported that the amount of N taken up by a crop and the efficiency with which it was used in crop production was not a constant, but changed with environmental factors and N supply. Even though excess N remaining in the soil for later absorption increases the chance of leaching, it releases gaseous forms of N, which are potential pollutants (Bacon, 1995). Therefore, the economic returns from N applications to crops and the risk to the environment are of the greatest importance.

2.4 Nitrogen losses from fertilizer applied to rice and wheat

Nitrogen can be lost mainly through runoff, leaching, denitrification and ammonia volatilization. Many ^{15}N recovery experiments have reported that the losses of 20-50% of fertilizer N in cereal production can be attributed to the combined effects of denitrification, volatilization, and/or leaching (Olson and Swallow, 1984; Sanchez and Blackmer, 1988; Francis et al., 1993; Karlen et al., 1996). It has been reported that the total unaccounted N from N fertilizer applied to rice and wheat was in the range of 60-80% and 22-30%, respectively (Vlek and Fillery, 1984; Vlek and Byrens, 1986; Cai et al., 1998; Cai et al., 2002).

2.4.1 Runoff loss

Annual N loss through erosion was 18.3 kg N ha^{-1} from upland rice fields in China (Peng et al., 1995). Ma (1997) also reported that the annual loss of N via drainage of surface water prior to transplanting rice seedlings and via runoff was 9.3 and 19.8 kg N ha^{-1}, respectively, in rice-wheat rotation in China. Those amounts were equivalent to 2.7% and 5.7% of the applied N, respectively. Vlek and Fillery (1984) showed that maintaining standing water in wetland rice fields can lead to the rapid leaching of nutrients in soils with moderate to high percolation rates or to runoff from one field to another in paddies with poorly developed or maintained bunds. Katyal et al. (1987) reported that surface runoff of fertilizer N was seldom a problem in wheat if uncontrolled movement of water from field to field was avoided.

Craswell and Vlek (1982) observed that the degree of outflow of water from rice fields was variable, depending on the site, season, and degree of water control and water management. They also reported runoff losses in the range of 4-16 kg N ha^{-1}, 19-30 kg N ha^{-1}, and 19-30 kg N ha^{-1} in Japan, the Philippines and California, respectively.

2.4.2 Leaching loss

The downward movement of NO^-_3 in the soil profile is called nitrate leaching. Zhu et al. (2000) reported a total leaching loss equivalent to 1.8% and 3.4% of applied N in the wheat and rice growth period, respectively, in a wheat-rice system in Jiangning, Jiangsu Province, China. It has been also reported that the annual leaching loss in a rice-wheat cropping system was in the range of 10-34 kg N ha^{-1}, which was equivalent to 2.5-6.1% of the mean annual N input (Ma, 1997).

Bauder and Montgomery (1980) found that no NO_3^--N accumulated below 20 cm when urea or ammonium sulphate was the sources of N, and low-volume high-frequency irrigations were applied. Using ^{15}N fertilizer, the amount of N moving beyond the 20 cm depth was negligible in a flooded Crowley silt loam under rice (Reddy, 1982). However, Singh et al. (1997) reported that leaching losses of N as urea, NH_4^+ and NO_3^-, beyond the 30 cm depth in a sandy loam soil over 60 days were about 6% of the total urea-N and 3% of the total ammonium sulphate-N applied in three equal-split doses in lysimeters planted with rice in India. Leaching losses of 3-9% in Russia were reported by Kudeyarov (1989).

Irrespective of the N source, the concentration of N in the leachate was higher where the entire N was applied as basal instead of split dressings (Mahajan and Tripathi, 1992). Katyal et al. (1985) indicated that leaching losses were largely responsible for the loss of N and poor performance of the urea supergranules placed below the soil surface of highly percolating soil with low CEC. Similar findings were reported by Vlek et al. (1980a) for a greenhouse experiment.

2.4.3 Denitrification

The anaerobic respiration of nitrate results in the formation of N_2 and N_2O gases that leave the soil (denitrification). Gaseous N losses due to denitrification from applied fertilizer N have been reported as being about 9.5% in winter wheat (Aullakh et al.,

1982) and 10% in lowland rice (De Datta et al., 1991). Substantial studies consistently showed negligible denitrification from submerged rice soil during the period of rice growth due to the limited rate of nitrification (Buresh and De Datta, 1990; Buresh et al., 1991). Cai et al. (2002) also reported that denitrificantion loss was not a significant pathway of N loss from N fertilizer applied to wheat or submerged rice during the rice growth period.

In some cases, a high mitigation rate of N_2O emission was observed when using slow-release fertilizers (Delgado and Mosier, 1996; Akiyama et al., 2000; Hou et al., 2000; Yan et al., 2000). It was found that the estimation of oxidized gaseous N species and their contribution to the overall atmospherical NO budget depend on their production and consumption via denitrification and nitrification (Williams et al., 1992; Granli and Bockman, 1994; Skiba et al., 1997). Hosen et al. (2002) reported that NO and N_2O emissions from soil columns were affected by the depth of urea application.

2.4.4 Ammonia volatilization

Ammonia volatilization is the shift from the NH^+_4 to the NH_3 form of N in flooded water under conditions of high pH and temperature. It has been noted that Indian scientists were probably the first to recognize the importance of ammonia volatilization, at least as an N loss mechanism in flooded alkaline soils (Vlek and Fillery, 1984). In the early studies, Boulding and Alimago (1976) and Vlek and Craswell (1979) have already shown high ammonia loss from N fertilizer applied to flooded soils as measured under natural or high air exchange rates under enclosures.

Ammonium loss was an important pathway of N loss from N fertilizer applied to rice (30-39% of the applied N) and to wheat (1-20% of the applied N) (Cai et al., 2002). Katyal et al. (1987) reported that the loss of applied ^{15}N in wheat was as much as 42%, which was most likely due to volatilization from the wet soil surface following irrigation. Cai (1997) also reported that ammonia loss was the dominant pathway of N loss from soils and accounted for up to 40% of applied N and 70% total gaseous loss under certain conditions with the micro-meteorological mass balance technique. Fillery et al. (1984) reported that NH_3 loss accounted for a 30-50% loss of the N applied to floodwater 2-3 days after transplanting. Ammonia loss from well-developed rice canopies occurred in the range of 11-13% N applied as urea and ammonium sulphate after panicle initiation (Freney et al., 1981; Fillery et al., 1984).

Vlek and Craswell (1981) concluded that alkalinity must be present in floodwater to sustain NH_3 fluxes, because NH_3 volatilization is an inherently acidifying process. They also indicated that urea hydrolysis provides a source of alkalinity (HCO_3^-) when urea is applied to flooded soil. This accounted for the higher NH_3 losses from urea than from NH_4^+-N sources applied to soil flooded with deionized or distilled water resembling the conditions in rainfed rice system (Vlek and Craswell, 1979).

2.5 Ways to minimize N losses and improve N use efficiency

Several techniques have been devised in the past to reduce N losses and improve N use efficiency in rice and wheat fields. Vlek and Fillery (1984) reported that the major problem with broadcast applications of N fertilizers was the development of high concentrations of urea and/or ammonium in the flooded water and surface layer of soil where the major loss mechanism - ammonia volatilization, nitrification-denitrification, and surface runoff - operated. They also suggested that the concentration of fertilizer N in the floodwater might be reduced by deep placement of the fertilizer, use of slow-release fertilizer, nitrification inhibitors or urease inhibitors, incorporation of the N into the soil, or split application of the fertilizer dose.

Deep placement of urea can prevent the rapid conversion of ammonium to nitrate and, therefore, prevent denitrification N losses. It has been proved that deep placement of N fertilizer is an effective means to reduce ammonia concentration in the floodwater (Craswell et al., 1981) and to drastically reduce ammonia volatilizations (Vlek and Craswell, 1981). Similar findings of early studies have been reported for upland crops where the fertilizer was placed below the soil surface (Fenn and Kissel, 1976) and incorporated within the soil (Matocha, 1976). However, this method is not suitable for growing rice crops.

The objective of slow-release fertilizers is to match the release of N with the difference between the N needs of the plants and the N available from the soil. Although slow-release properties can be obtained by coating a soluble N source with a less-soluble compound such as sulphur, wax or both (Blouin et al., 1971), a universal release pattern for slow-release N sources is probably unrealistic in the case of great variability of the environmental conditions and varieties (Vlek and Fillery, 1984). Samosir and Blair (1983) reported that there was no difference in yields between sulphur-coated urea and control plot on S-deficient soil.

The inhibition of ammonium nitrification may be favorable for reducing nitrate leaching (Ball-Coelho and Roy, 1999). Chen et al. (1994) have demonstrated that using nitrification inhibitors (wax-coated calcium bicarbide and N-serve) could reduce 21-27% of the denitrification losses of applied N. Nitrification inhibitors, e.g., Dicyandimamide (DCD), and prevent the production of NO_3^-, i.e., the substrate in the denitrification process (Reider and Michand, 1980). However, the result of the DCD experiment in the Philippines showed no advantage with respect to yield (IRRI, 1983). The nitrification inhibitors have performed poorly in the tropics, because of the problem of degradation of DCD and tropical soil temperature regimes (Osiname et al., 1983).

Using urease inhibitors can delay the conversion of urea to ammonium (Vlek et al., 1980b). Vlek et al. (1980b) also reported that incorporation of 1% w/w of phenyl-phosphordiamidate (PPD) to urea was able to delay the appearance of ammonical-N in the floodwater by blocking the urease activity of the soil-water interface, which is the primary site for hydrolysis of urea in the floodwater. Similar findings were reported by Freney et al. (1993) and Chaiwanakupt et al. (1996). However, the anticipated cost of urease inhibitors is taken into consideration and the techniques may have limited the success in the field.

Multiple-split applications of mineral N fertilizer can reduce N losses (De Datta and Buresh, 1989) and increase N use efficiency (Cassman et al., 1994). Rao et al. (1995) indicated that the productivity of applied mineral N was improved by water control and split application of N fertilizer. Yield response to split application of N might be indicative of leaching losses resulting from the coarse-texture and relatively permeable soils (Becker and Johnson, 1999). In contrast, Singh et al. (1991) concluded that increasing the number of split doses of urea from 3 to 10 was not helpful in enhancing the efficiency of urea-N in permeable soil under lowland rice in India. Vlek and Fillery (1984) reported that split application and/or incorporating were widely recommended by research and extension agencies, but their use resulted in a relatively low utilization efficiency.

2.6 Nitrogen fertilizer management through crop demand

Nitrogen losses from the soil-plant system are large, leading to low fertilizer N use efficiency when N application is not synchronized with crop demand (Becker et al., 1994; Singh et al., 2002). It has been documented that synchrony between crop demand and the N supply from all sources throughout the growing season is needed for improving N use efficiency in crop production systems (Cassman et al., 1993; Appel, 1994; Campbell et al., 1995; Izaurralde et al., 1995; Robertson, 1997). A review by Vlek and Fillery (1984) stated that the efficiency could be improved if the timing and dosage of fertilizer were adjusted according to N-supplying capacity of the soil, morphological development of the plant, or growing-degree days.

Due to the large variability of the N supplying capacity of the native soil from farm-to-farm and plot-to-plot (Cassman et al., 1993; Stalin et al., 1996; Adhikari et al., 1999), the strategies of N-fertilizer management should be responsive to the large variation of crop nitrogen requirements and soil N supply (Peng et al., 1996) in order to achieve the synchrony of supply and demand and to improve N-use efficiency.

For diagnosing the N status of crops, two quick, reliable and non-destructive tools (chlorophyll meter and leaf color chart) have been successful for determining the right time of N application under field conditions (Turner and Jund, 1991; Smeal and Zhang, 1994; Garcia et al., 1996; Peng et al., 1996; Singh and Singh, 1997; Ladha et al., 1998a; Peng and Cassman, 1998; Adamsen et al., 1999; Balasubramanian et al., 1999; Vidal et al., 1999; Hussain et al., 2000).

2.7 Chlorophyll meter or SPAD (Soil Plant Analysis Development) meter and Leaf Color Chart (LCC)

The chlorophyll meter was developed by the Soil-Plant Analyses Development Section of the Minolta Camera Company, Japan. Since the cost of the SPAD meter restricts its widespread use by farmers, the first leaf color chart was developed in Japan (Furuya, 1987). Chinese researchers at Zheijiang Agricultural University developed a much-improved LCC and calibrated it for indica, japonica, and hybrid rice. It then became a model for the IRRI-LCC (Dobermann and Fairhurst, 2000). Cass Mutter from California University produced another type of leaf color chart (http://www.syix.com/rrb/newslet/Winter2001.htm).

2.7.1 Mechanism of SPAD meter

The SPAD meter is sensitive to photosynthetic pigments of individual leaves, or remotely with radiometers, which measure the reflectance of the entire plant canopy.

The SPAD meter measures the relative amount of chlorophyll in the leaf, which is related to leaf greenness, by transmitting light from light-emitting diodes (LED) through a leaf at wavelength of 650 nm (red) and 940 nm (near-infrared) (Minolta, 1989). It normalizes the index for variables such as leaf thickness and cuticle reflectance properties, which are not directly related to pigment concentration. The 650 nm light corresponds to peak chlorophyll attenuation of red light (R). The infrared (IR) 940 nm signal is not absorbed by chlorophyll. The signal from the silicon photo diodes used to detect the transmitted light is received by a microprocessor, which linearizes the signal and calculates a unitless SPAD value:

$$\mathbf{SPAD = A\ [\log (RC_0 / RC) - \log (IRC_0 / IRC)] + B}$$

where A and B are constants, RC and IRC are currents from red and IR detectors, respectively, with the sample in place, and RC_0 and IRC_0 are currents from the red and IR detectors, respectively, without a sample (Wood et al., 1993; Adamsen et al., 1999).

2.7.2 General guidelines for using SPAD meter

It is important to remember that SPAD threshold values indicating critical leaf N level may vary among plant types (semi-dwarf, tall local, hybrid varieties, etc.), systems of cultivation (transplanted vs. direct seeded), environmental conditions (temperate, tropical, sunlight intensity, moisture regime, etc.), etc. Therefore, SPAD readings have to be calibrated to plant types and systems of cultivation under local conditions to fix the correct SPAD threshold value for each situation. The steps to follow in SPAD-based N management trials are:

1. The SPAD-meter threshold for N topdressing is 35.
2. Chlorophyll meter readings are normally taken once a week, starting from 14 days after transplanting for transplanted rice, and 21 days after seeding for wet-seeded rice.

3. The top fully expanded leaf is chosen for N measurement and the SPAD reading is taken on one side of the midrib of the leaf blade, midway between leaf base and leaf tip. In the early growth stages, the leaf blade may be too narrow for SPAD measurements without touching the midrib. In such case, readings can be taken at the tip of the leaf even on the midrib. Ten random readings must be taken for each plot and the average noted.

4. If the average SPAD reading is less than 35 at seven days after N application, topdress N without delay.

5. The amount of N to be applied at different growth stages of semi-dwarf rice varieties has been worked out as shown below:

Transplanted rice		**Dry season**	**Wet season**
Early growth stage	0-20 DAT	30 kg N ha^{-1}	20 kg N ha^{-1}
Rapid growth stage	20-50 DAT	45 kg N ha^{-1}*	30 kg N ha^{-1}*
Late growth stage	50-flowering	30 kg N ha^{-1}	20 kg N ha^{-1}

Direct wet-seeded rice		**Dry season**	**Wet season**
Early growth stage	0-30 DAS	30 kg N ha^{-1}	20 kg N ha^{-1}
Rapid growth stage	30-60 DAS	45 kg N ha^{-1}*	30 kg N ha^{-1}*
Late growth stage	60-flowering	30 kg N ha^{-1}	20 kg N ha^{-1}

* Apply the high N dose (45 kg N ha^{-1} in dry season and 30 kg N ha^{-1} in wet season) only once or twice during the rapid growth stage (CREMNET, 1995).

2.7.3 General guidelines for using LCC

1. Select the youngest fully expanded and healthy leaf of a single plant for leaf color measurement. The color of this leaf is highly related to the N status of the rice plant. From each field, select 10 leaves from 10 randomly selected plants representing the planted area. Be sure to select plants in an area where the plant population is uniform.

2. Measure the color of each selected leaf by holding the LCC and placing the middle part of the leaf on top of a color strip for comparison. Do not detach or destroy the leaf.

3. During measurement, shield the leaf being measured from the sun with your body, because leaf color reading is affected by the sun's angle and sunlight intensity. If possible, the same person should take leaf color measurements at the same time of the day.

4. If the color of a rice leaf seems to fall between two color shades, take the mean of the two values as the reading. For example, if the color of a rice leaf lies between number 3 and 4, the reading to be noted is 3.5.

5. The LCC readings are normally taken once every 7-10 days, starting at 14 days after transplanting for transplanted rice and at 21 days after seeding for direct wet-seeded rice. Continue taking readings at 7- to 10-day intervals until the first flower appears.

6. The critical leaf color reading for N topdressing may range from 3 to 4 for different varieties. For example, the critical value may be 3 for varieties with light green foliage and 4 for varieties with dark green foliage such as the high-yielding varieties and hybrids.

7. The leaf color scores also change with the method of rice planting. Generally, the critical reading is lower for direct-seeded rice than for transplanted rice. For the majority of the commonly grown semi-dwarf rice varieties, a critical reading of 3 for wet-seeded rice and 4 for transplanted rice is suggested.

8. Calculate the average of the 10 LCC readings. If the average leaf color reading falls below the set critical value, topdress N fertilizer immediately to correct N deficiency in rice crop.
9. Alternatively, if more than five leaves show readings below the set critical value, topdress N fertilizer immediately to correct N deficiency in rice crop.
10. The amount of N fertilizer to be applied at different growth stages for semi-dwarf indica varieties are as follows:

Transplanted rice		**Dry season**	**Wet season**
Early growth stage	14-28 DAT	30 kg N ha^{-1}	20 kg N ha^{-1}
Rapid growth stage	29-48 DAT	45 kg N ha^{-1}*	30 kg N ha^{-1}*
Late growth stage	49-flowering	30 kg N ha^{-1}	20 kg N ha^{-1}

Direct wet-seeded rice		**Dry season**	**Wet season**
Early growth stage	21-34 DAT	30 kg N ha^{-1}	20 kg N ha^{-1}
Rapid growth stage	35-55 DAT	45 kg N ha^{-1}*	30 kg N ha^{-1}*
Late growth stage	56-flowering	30 kg N ha^{-1}	20 kg N ha^{-1}

* Apply the high N dose (45 kg N ha^{-1} in dry season and 30 kg N ha^{-1} in wet season) only once or twice during the rapid growth stage (CREMNET, 1999).

3 MATERIALS AND METHODS

The following subchapters describe the materials and methods used in this study to meet the general objective, which is to develop and evaluate the simple N management strategy for rice and wheat in Bangladesh.

3.1 Experimental site

A study was carried out in farmers' fields in the Meherpur (23°36′-23°52′ N and 88°34′- 88°47′ E), Kushtia (23°41′-23°58′ N and 89°0′-89°12′E) and Chuadanga (23°29′-23°42′ N and 88°47′-89°01′) districts of Bangladesh (see experimental site map). The area receives an average annual rainfall of 2164 mm at mean annual maximum and minimum temperatures of 30.0°C and 22.8°C, respectively. Monthly meteorological data during the study period are shown in Figure 3.1. Field experiments were conducted during the wet season (T-Aman rice), the dry season (Boro rice), and the cold dry season (Rabi wheat) of 2001-2002.

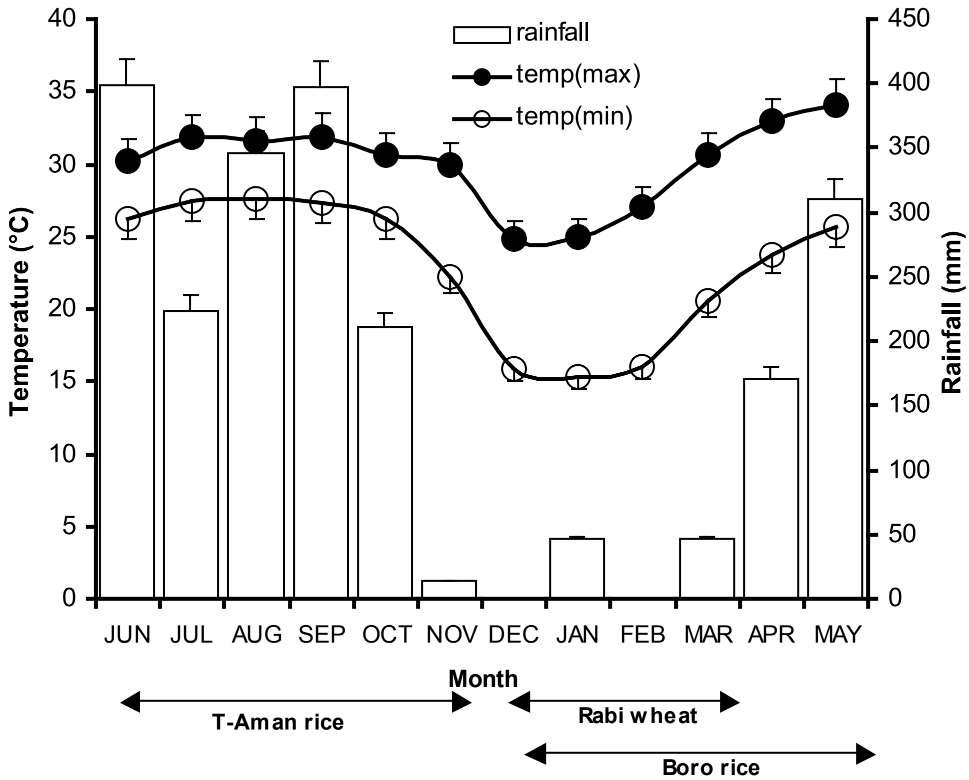

Figure 3.1. Mean monthly rainfall and temperature during the experimental period (June 2001- May 2002)

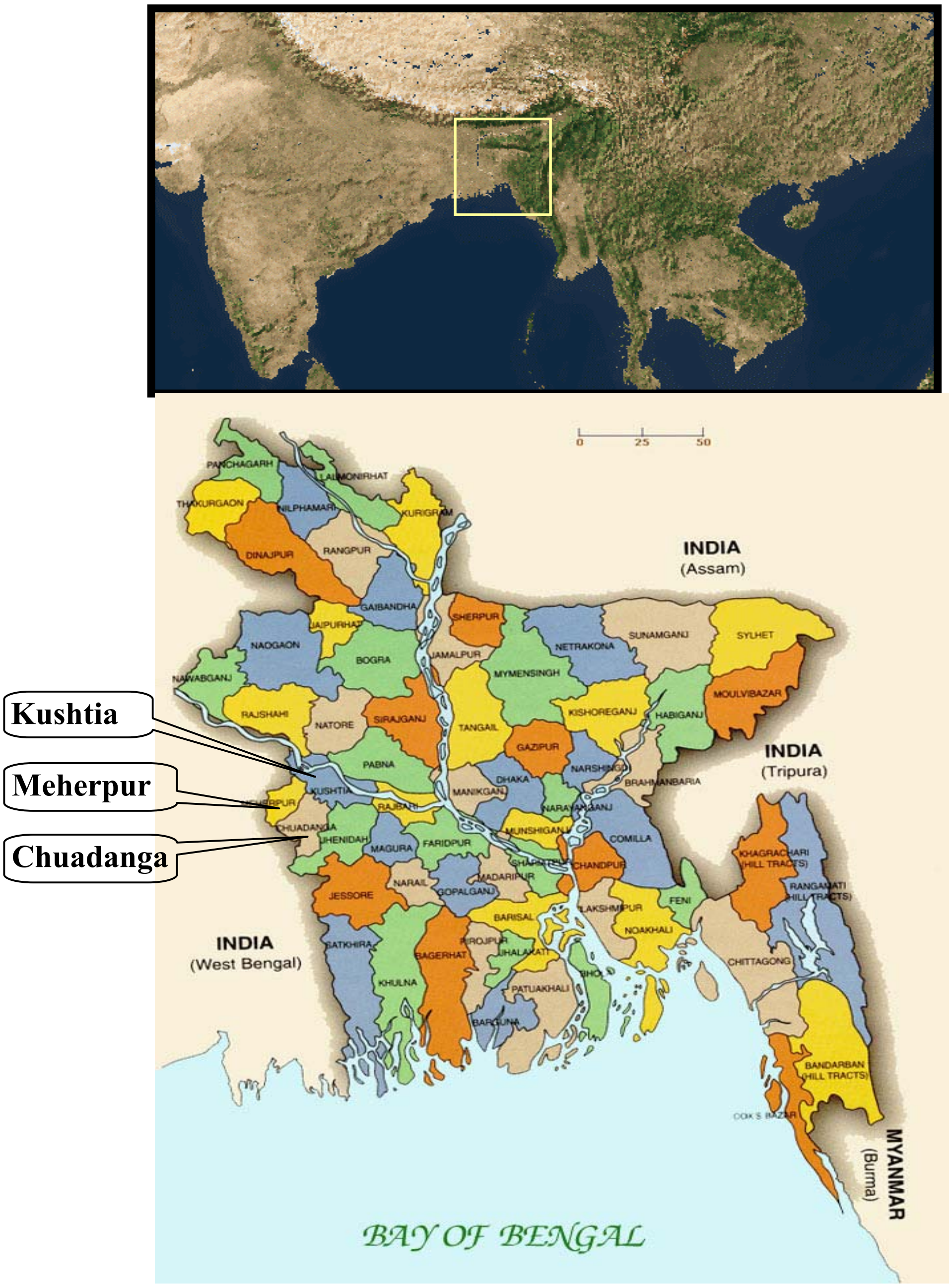

Figure 3.2. Location of the experimental sites in Bangladesh

3.2 List of experiments

Eight experiments were established for three different research activities during the study period (Table 3.1).

Table 3.1 Experiments conducted in the T-Aman rice-, Boro rice- and Rabi wheat-growing season of 2001-02 in Bangladesh

Research Activity	Expt. No.	Title	Cropping system	Season	Treatments	Number of fields
1	1.a	Evaluation of Leaf Color Chart (LCC) and chlorophyll meter (SPAD) for estimating native soil N supply	rice-rice	T-Aman & Boro	N-omission	20
	1.b	"	rice-wheat	T-Aman & Rabi	N-omission	20
2		Comparison of three types of LCC- based N managements in rice production	T-Aman rice	T-Aman	12 N-managements	1
3	3.a	Estimation of critical leaf color chart (LCC) values for different crops and seasons	rice-rice	T-Aman	3 var. x 5 N-managements	2
	3.b	"	rice-wheat	T-Aman	3 var. x 5 N-managements	2
	3.c	"	Boro-rice	Boro	6 var. x 6 N-managements	3
	3.d	"	Rabi-wheat	Rabi	3 var. x 6 N-managements	1
	3.e	"	Rabi-wheat	Rabi	3 var. x 10 N-managements	1

3.3 Experimental soils

Forty eight farmers' fields were used in three different research activities. The soil-texture classes comprised loam, sandy loam and clay loam at the Meherpur and Kushtia sites and silt loam and silt clay soils at the Chuadanga site. The physico-chemical soil properties (0-15 cm) are shown in Tables 3.2 (a) and (b). Mean pH values ranged from 7.3 to 7.6. Total soil N contents were generally less than 0.6%. Soil organic C contents were higher in soils under the rice-rice system than in those under the rice-wheat rotation. However, the availability of Zn was less in rice-rice than in rice-wheat rotation.

3.4 Plant material

The semi-dwarf high-yielding lowland rice varieties BR-11 (145 days) and BRRI dhan-39 (120 days) were used in N omission plots during the T-Aman season in the rice-rice and rice-wheat system, respectively. In the rice-rice system, BRRI dhan-28 (140 days) was used during the Boro season. The wheat variety Kanchan (115 days) as used during the Rabi season. In addition, BR-11 was used to compare different Leaf Color Charts during the T-Aman season of 2001.

In addition to the cultivars used in the research activities, the following rice and wheat varieties were commonly grown in the farmers' fields:

Wet season	<u>Rice-rice system</u>	<u>Rice-wheat system</u>
(T-Aman season)	BR-11 (145-d)	BRRI dhan-32(130-d)
	BRRI dhan-30 (145-d)	BRRI dhan-33(120-d)
	BRRI dhan-31 (140-d)	BRRI dhan-39(120-d)

Cold dry season	<u>Rice varieties</u>	<u>Wheat varieties</u>
(Boro and Rabi season)	BRRI dhan-28 (140-d)	Kanchan (115-d)
	BRRI dhan-29 (160-d)	Gaurab (108-d)
	BRRI dhan-36 (140-d)	Protiva (110-d)
	BRRI hybrid-1 (160-d)	Shatabdi (100-d)
	Alok (160-d)	
	Sonar Bangla-1 (140-d)	

Table 3.2.(a) Physico-chemical properties of soils (0-15 cm) used for estimation of the native soil N supply (Research activity-1) during the T-Aman rice-, Boro rice- and Rabi wheat-growing seasons of 2001-02 in Bangladesh

Farmer ID	Farmer's Name	Soil pH (water)	Total N g kg^{-1}	Organic C g kg^{-1}	Olsen P mg kg^{-1}	Exchange-able K Cmol$_c$ kg^{-1}	Exchange-able Ca Cmol$_c$ kg^{-1}	Exchange-able Mg Cmol$_c$ kg^{-1}	HCl-ext-ractable Zn mg kg^{-1}
<u>Rice-rice cropping pattern</u>									
M1	Mozammel Haque	6.7	0.55	6.54	15.0	0.28	15.8	2.85	0.16
M2	Altaf Hossain-1	7.3	0.61	6.89	26.0	0.32	16.9	3.17	0.33
M3	Bonomali Biswas	7.2	0.47	5.68	21.0	0.18	14.6	2.10	0.39
M4	Rezaul Karim	7.6	0.42	5.40	10.0	0.20	31.4	2.79	0.06
M5	Ramjan Ali-1	7.5	0.59	6.61	14.0	0.11	14.1	1.65	0.31
M6	Abdul Motaleb	7.3	0.75	7.88	16.0	0.28	16.7	2.96	0.32
M7	Abder Ali	7.5	0.38	4.76	16.0	0.11	21.8	1.55	0.10
M8	Tatul Shakh	7.3	0.59	6.32	21.0	0.21	14.2	2.35	0.58
M9	Nazirul Islam	7.4	0.49	5.11	8.6	0.23	14.5	2.34	0.32
M10	Ramjan Ali-2	7.4	0.65	7.32	17.0	0.24	14.8	2.59	0.24
Mean		**7.3**	**0.55**	**6.25**	**16.5**	**0.22**	**17.5**	**2.44**	**0.28**
K1	Ibrahim	7.6	0.33	5.11	3.5	0.18	36.5	1.94	0.05
K2	Shariffujjaman	7.6	0.29	4.48	3.1	0.06	36.3	1.36	0.05
K4	Toffajjal Hossain	7.6	0.39	5.61	4.3	0.19	30.1	1.90	0.06
K5	Nurul Islam	7.8	0.25	2.27	1.8	0.07	36.2	1.15	0.04
K6	Abdur Rashid	7.6	0.48	5.68	3.6	0.32	37.4	3.06	0.04
K7	Murad Hossain	7.5	1.03	10.9	2.4	0.44	19.5	4.31	0.07
K9	Muslem Miah	7.8	0.39	5.33	3.2	0.10	35.3	1.84	0.04
Mean		**7.6**	**0.45**	**5.63**	**3.1**	**0.19**	**33.0**	**2.22**	**0.05**
<u>Rice-wheat cropping pattern</u>									
M11	Ebadat Ali	7.8	0.34	4.40	10.0	0.11	28.7	1.28	0.09
M12	Aker Ali	7.0	0.63	6.39	22.0	0.24	21.9	2.70	0.05
M13	Bablu Miah	7.7	0.52	5.90	6.2	0.16	17.8	1.93	0.17
M14	Sirajul Islam	7.6	0.24	4.33	11.0	0.03	27.5	0.76	0.12
M15	Altaf Hossain-2	7.6	0.51	5.61	17.0	0.18	27.7	1.71	0.05
M16	Azer Ali	7.1	0.51	6.18	17.0	0.18	13.9	2.25	1.60
M17	Taluk Chand	7.5	0.57	6.11	30.0	0.14	13.0	1.84	1.40
M18	Moinul Islam	7.6	0.25	3.91	7.0	0.05	10.2	0.87	1.50
M19	Abdul Latif	7.7	0.52	6.11	14.0	0.08	27.5	1.39	0.04
M20	Sofdal Hossain	7.7	0.47	4.90	12.0	0.08	24.4	1.51	0.06
Mean		**7.5**	**0.46**	**5.38**	**14.6**	**0.13**	**21.3**	**1.62**	**0.51**
C1	Anwar Joardar	7.7	0.52	5.47	4.3	0.21	23.2	2.14	0.07
C2	Lavlu	7.2	0.63	6.11	11.0	0.28	23.9	2.45	0.06
C3	Nazrul	7.2	0.47	4.76	15.0	0.24	31.1	2.21	0.07
C4	Ileus Joardar	7.5	0.47	5.11	3.8	0.18	29.9	1.56	0.05
C5	Khairul Joardar	7.0	0.63	6.25	9.1	0.31	14.9	3.26	0.28
C6	Rezaul Joardar	7.3	0.42	4.76	7.0	0.22	30.3	1.86	0.05
C7	Azgar Joardar	7.7	0.74	6.68	6.4	0.31	18.8	2.92	0.10
C8	Dulu	7.1	0.58	5.68	6.6	0.23	13.4	2.65	1.30
C9	Sitab Ali	7.3	0.42	5.04	3.9	0.21	32.0	2.09	0.04
C10	Halim Joradar	7.2	0.47	5.33	5.8	0.29	14.6	3.00	0.43
Mean		**7.3**	**0.54**	**5.52**	**7.3**	**0.25**	**23.2**	**2.41**	**0.25**

M=Meherpur district, K= Kushtia district, C= Chuadanga district

Table 3.2. (b) Physico-chemical properties of soils (0-15 cm) used for calibration of leaf color charts during the T-Aman rice-, Boro rice- and Rabi wheat-growing seasons of 2001-02 in Bangladesh

Farmer ID	Farmer's Name	Soil pH (water)	Total N (g kg^{-1})	Organic C (g kg^{-1})	Olsen P (mg kg^{-1})	Exchangeable K ($Cmol_c$ kg^{-1})	Exchangeable Ca ($Cmol_c$ kg^{-1})	Exchangeable Mg ($Cmol_c$ kg^{-1})	HCl-extractable Zn (mg kg^{-1})
Research activity-2 (T-Aman rice, 2001)									
M21	Ramjan Ali-3 (R-R)	7.5	0.70	7.30	16.0	0.25	15.6	2.70	0.24
Research activity-3 (T-Aman rice, 2001)									
M22	Abdul Hakim (R-R)	7.6	0.63	6.54	14.0	0.14	16.7	2.15	0.09
M23	Giash Uddin Raqib (R-W)	7.4	0.58	6.32	30.0	0.08	11.7	1.36	1.30
K11	Mobarak Ullah-1 (R-R)	7.8	0.31	4:33	3.1	0.05	31.2	1.01	0:04
K12	Mobarak Ullah-2 (R-W)	7.7	0.28	4.12	3.2	0.08	32.8	1.15	0.04
Research activity-3 (Boro rice, 2001-02)									
BM21	Ramjan Ali-3 (R-R)	7.1	0.58	6.75	17.0	0.23	15.3	2.67	0.27
BM22	Abdul Hakim (R-R)	7.3	0.47	5.11	6.9	0.22	15.2	2.56	0.19
BM23	Abdur Rhaman Kanu (R-R)	7.3	0.36	4.76	5.5	0.10	15.3	1.74	0.08
Research activity-3 (Rabi wheat, 2001-02)									
BM24	Kadermaster (R-W)	7.1	0.60	6.25	34.0	0.15	20.7	1.74	0.05
BM25	Harun Rashid (R-W)	7.3	0.42	4.83	17.0	0.70	29.9	1.30	0.03

M = Meherpur district, K = Kushtia district, B = Boro and Rabi season, R-R = rice-rice system, R-W = rice-wheat system.

3.5 Crop management

Thirty-day-old rice seedlings were transplanted at a 20 x 15 cm spacing. During the growing season, irrigation was provided using both well and canal water. Plots were irrigated starting 2 weeks after transplanting and continued to maintain soil submergence until the heading stage. Water was drained two weeks before harvest. Anaerobic conditions predominated for more than 75% of the rice-growing period although the soil was well-draining. Hand-weeding was done once, and pest and disease control followed standard farmers' practices and no damage occurred. Nitrogen topdressing was applied at 25 kg N ha^{-1} in the T-Aman and at 30 kg N ha^{-1} in the Boro seasons each time when LCC or SPAD readings were below the respective critical value. In case of the recommended-N rate, application rates and timing followed the recommendations provided by BRRI (Bangladesh Rice Research Institute).

Wheat was line-seeded at a 20 cm row spacing at a seeding rate of 120 kg ha^{-1}. A small plank was dragged over the plot to cover the seeds after seeding by hand. At 20 days after sowing (DAS) (crown root initiation stage) and at 50 DAS (maximum tillering stage) irrigation was supplied. Weed, pest and disease control were done as required.

3.6 Soil sampling and analysis

Initial soil samples were collected from 4-12 spots in each farm at 0-15 cm depth, using a 5-cm-diameter augar. Subsampling was done after thorough mixing of soil cores at the Kushtia Regional Station of Bangladesh Rice Research Institute. Samples were spread, air-dried, finely ground and stored for further analysis. Samples were transported to the Crop, Soil and Water Science Division (CSWSD) of the International Rice Research Institute (IRRI), Philippines and analyzed at the Analytical Service Laboratory. Soil pH was determined using a soil:water suspension ratio of 1:1.25 (Jackson, 1973). Total N was determined by the Kjeldahl method (Page et al., 1982); available P content was determined photometrically after extraction in bicarbonate (Olsen et al., 1954); NH_4OAc exchangeable K was determined by flame photometer (Black, 1965). Exchangeable Ca, Mg and Zn were determined following the Agro-Services International Method using Atomic Absorptic Spectrometery (Hunter, 1984).

3.7 Plant sampling and analysis

Rice plant height, tiller number and panicle number per hill were recorded from 16 hills adjacent to the harvest area. Eight hills were further selected to determine the yield components and N content.

In wheat, plant samples were taken either from 0.4m^2 sampling area (N omission plot) or from two 1-meter long rows that bordered the harvest area (in other wheat experiments) to measure the total above-ground dry matter, yield components and N content.

A ten-leaves sample, used for SPAD and LCC readings, was collected from the sampling areas of each plot at 10-day intervals to determine leaf area (Leaf Area

Meter Model AAM-8, Licor, Lincoln, Nebrasca, USA), dry weight (after oven-drying at 70°C for 24 hours), and N content (Kjeldhal method).

Grain, straw, and dried leaves samples were finely ground (0.5 mm) and transported to CSWSD, IRRI, Philippines for chemical analysis. The N content in grain, straw and leaves was determined by digesting the samples in sulfuric acid (H_2SO_4), followed by distillation and titration (Yoshida *et al*., 1976). All chemical analyses were done at the Analytical Service Laboratory of IRRI.

3.8 Chlorophyll meter (SPAD) and leaf color chart (LCC) measurement

SPAD (chlorophyll) meter reading were taken with a Minolta SPAD-502 chlorophyll meter (Minolta Ltd, Tokyo, Japan), starting 15 days after transplanting (DAT) in Aman and 20 DAT/DAS in Boro (rice) and Rabi (wheat) seasons. From each hill, three SPAD readings were recorded from the uppermost fully expanded leaf of 10 randomly selected hills and continued at 10-day intervals until the flowering stage.

In addition to the SPAD, the LCC (leaf color chart) was used to measure greenness of leaves from the same hills that were used for SPAD readings. Placing the middle part of each leaf on top of the color strip of the LCC allowed matching the color of the topmost youngest fully expanded leaf with the displayed LCC shades. As with the SPAD meter, LCC readings were taken up to flowering (CREMNET, 1995 and 1999). At 10-day intervals, tiller number and plant height were recorded from the same hills that were used for LCC and SPAD readings. Three types of LCCs (origin: IRRI, China and California) were used for comparison and calibrated with SPAD. After recording SPAD and LCC values, leaves were cut and leaf area and dry weight were determined from composite samples at the Kushtia Regional Station. Samples were transported to CSWSD, IRRI, Philippines, to determine tissue N content.

Rice grain yield was determined based on one or two 5.04 m^2 harvest areas, depending on the experiment, and expressed at 14% moisture content. Straw yield was calculated from the grain:straw-ratio on an oven-dry basis. Wheat grain yield was determined from one or two spots of ten 2-m long rows (4 m^2) and expressed at 12% moisture content. Straw yield was calculated from the grain:straw-ratio on an oven-dry basis.

3.9 Treatment application

A series of three on-farm experiments was conducted to determine native soil N supply and to optimize the timing of mineral N fertilizer applications.

3.9.1 Evaluation of leaf color chart (LCC) and chlorophyll meter (SPAD) for estimating native soil N supply

The aim of the study was to quantify the native soil N supply capacity using crop N uptake in N omission plots. A single crop cycle experiment was conducted in 40 farmers' fields in three districts of Bangladesh in the wet season (T-Aman) of 2001 to determine the native soil N supplying capacity. Farmers' fields were selected in a radius of about 100 km to cover a range of soil nitrogen-supplying capacities in each district. The experimental soils are characterized in Table 3.2(a). Two cropping systems, namely, rice-rice and rice-wheat, were compared. Twenty farmers' fields were selected in the rice-rice systems at Chandbill village in Meherpur district (10 fields) and at Baria village in Kushtia district (10 fields). Another 20 fields were selected in the rice-wheat system at Chandbill village in Meherpur district (10 fields) and Hatikata village in Chuadanga district (10 fields).

The activity was continued in the Rabi (wheat) and Boro (rice) seasons of 2001-02. The farmers' fields and layout were the same as in the T-Aman season of 2001; however, only 9 farms in Meherpur and 5 farms in Kushtia were continued for Boro rice.

Land was plowed, puddled, and leveled for rice transplanting. Basal fertilizer was applied at 9 kg P ha^{-1} (as triple superphosphate), 25 kg K ha^{-1} (as murate of potash), 11 kg S ha^{-1} (as gypsum), and 5 kg Zn ha^{-1} (zinc sulphate) at final land preparation in the T-Aman season. For Boro-rice, the basal P fertilizer application was increased to 14 kg P ha^{-1}. In each farmer's field, areas of at least 7 x 6 m were delineated and separated from the main field with a small bund. These areas varied from 42 to 100 m^2 depending on the farm size. Transplanting was done during the last week of July and the first week of August in the T-Aman season of 2001 and during the second week of January 2002 in the Boro season. Fields were harvested during the second and last week of November 2001 in the T-Aman season and in the last week of April 2002 in the Boro season. For wheat cultivation, the land was plowed twice to about 20 cm depth and leveled before seeding. Basal fertilizer was applied at the rate of 36 kg P (as triple superphosphate), 25 kg K (as murate of potash), 20 kg S (as gypsum), 4 kg Zn (zinc sulphate) and 1.1 kg B (as borax) before sowing. Fields were sown during the last week of November 2001 and harvested during the last week of March 2002. The N supply was determined by LCC, SPAD, and crop N uptake and correlated to yield and yield parameters as described in Section 3.7.

3.9.2 Comparison of three types of LCC-based N managements in rice production

The aim of the study was a comparative evaluation of the three leaf color charts developed in the Philippines, China and the USA (IRRI-LCC, China-LCC and California-LCC). The evaluation was conducted in one farmer's field at Meherpur during the T-Aman season, 2001. The characteristics of the experimental soil (M21) are provided in Table 3.2(b). The LCCs were compared in 12 treatments laid out in a randomized complete block design (RCB) with three replications. Treatments consisted of 12 N-management options: control (without applied N), recommended-N, SPAD (threshold value 35), IRRI-LCC critical values 3, 4 and 5, China-LCC critical values 4, 5 and 6, and California-LCC critical values 4, 5 and 6. The plot size was 4 x 5 m. All plots received basal fertilizer at rates of 20 kg P, 50 kg K, 10 kg S and 4 kg Zn ha^{-1} as triple superphosphate, murate of potash, gypsum and zinc sulphate, respectively. Rice was transplanted on 1st August 2001 and harvested on 28th November 2001. Crop N uptake and N use efficiency at harvest were evaluated.

3.9.3 Estimation of critical leaf color chart (LCC) values for different crops and seasons

In a first set of three experiments, the critical LCC value was determined for T-Aman rice varieties in rice-rice and rice-wheat systems. Four farmers' fields, two each in Meherpur and Kushtia, were selected in this study. Characteristics of the experimental soils (M22, M23, K11 and K12) are provided in Table 3.2(b). Only the IRRI-LCC was used. Five-N management treatments and 3 rice varieties were arranged in randomized complete block design with 3 replications in each field. N management options comprised: (1) N-control, (2) recommended N, (3) critical LCC value of 3, (4) critical

LCC value of 4, and (5) critical LCC value of 5. The plot size was 4 x 5 m. All plots received basally 20 kg P, 50 kg K, 10 kg S, and 4 kg Zn ha^{-1} as triple superphosphate, murate of potash, gypsum and Zinc sulphate, respectively. Transplanting was done 6-9 August 2001. Harvest dates depended on the maturity group of the varieties. Rice yield and NUE were evaluated.

A second experiment compared the critical LCC values for rice varieties in the Boro season**.** This experiment was conducted at Chandbill village in Meherpur district during the Boro (rice) season of 2001-02. In the case of this experiment, three farmers' fields were used as replications. The characteristics of the experimental soils (BM21, BM22 and BM 23) are provided in Table 3.2(b). Six N management treatments comprised a control (without applied N), recommended N and four SPAD threshold values: 32, 35, 39 and 43. Plot size was 4 x 5 m. Each plot received the basally recommended fertilizer rates for the respective varieties (Table 3.3). Transplanting was done 6-8 January 2002. Fields were harvested on 29 April and 7 May 2002. Yield and NUE at harvest were evaluated. SPAD values were calibrated based on leaf N content, and the corresponding LCC values were determined from the relationship of SPAD and LCC readings.

Table 3.3. Recommended fertilizer rates for test rice varieties during the Boro season of 2001-02 in Bangladesh

Variety	**Rate (kg ha^{-1})**						Remark
	N	**P**	**K**	**S**	**Zn**		
BRRI dhan-28	35-35-32*	25	42	10	5	-	* 15, 30, 50 DAT
BRRI dhan-29	126*	27	60	12	5	-	* 3 equal split at 15, 45, 55 DAT
BRRI dhan-36	35-35-32*	25	42	10	5	-	* 15, 30, 50 DAT
BRRI hybrid-1	126*	27	60	12	5	-	* 4 equal split at basal, 15-20, 35-40 DAT & flowering
Alok	126*	27	48-12**	10	5	-	* 3 equal split at basal, 21 & 42 DAT **basal and PI stage
Sonar Bangla-1	126*	17	33	19	5	1.1	*3 equal split at basal, 15-20 & 40-50 DAT

The final set of three experiments aimed at comparing critical LCC values for selected wheat varieties. To estimate the critical LCC value for wheat varieties, two trials were conducted in two farmers' fields at Chandbill village in Meherpur district during the cold dry (Rabi) season of 2001-02. The characteristics of the experimental soils (BM24 and BM 25) are provided in Table 3.2(b). The experiments were laid out in a completely randomized block design with three replications. The plot size was 3 x 4 m. Each experiment compared three wheat varieties at either six N levels or ten N management treatments (Table 3.4 and 3.5). All plots received basal fertilizers at the rate of 36 kg P, 25 kg K, 21 kg S, 4 kg Zn and 1.1 kg B ha^{-1} as urea, triple superphosphate, murate of potash, zinc sulphate, and borax, respectively. Fields were seeded on 5^{th} and 6^{th} December 2001 and harvested on 26^{th} and 29^{th} March 2002. The SPAD and three types of LCCs readings were recorded only once at 50 DAS (maximum tillering stage). Yield and NUE at harvest were evaluated. SPAD values were calibrated based on leaf N content and the correspondent LCC values were determined from the relationship of SPAD and LCC readings.

Table 3.4. N-level treatments for three wheat varieties (Gaurab, Shatabdi, and Protiva) during the cold dry (Rabi) season of 2001-02 in Bangladesh

N level	**Nitrogen rate (kg ha^{-1})**				**Description**
	Basal	**CRI**	**MT**	**Total**	
1	00	00	00	-	N control
2	67	33	00	**100**	Recommended N
3	60	60	30	**150**	50% more than Rec- N
4	54	54	27	**135**	90% of N level-3
5	48	48	24	**120**	80% of N level-3
6	42	42	21	**105**	70% of N level-3

CRI = CROWN ROOT INITIATION; MT = MAXIMUM TILLERING

Table 3.5. N-management treatments for three wheat varieties (Kanchan, Gaurab, and Protiva) during the cold dry (Rabi) season of 2001-02 in Bangladesh

N management	Nitrogen rate (kg ha^{-1})				Description
	Basal	CRI	MT	Total	
1	00	00	00	**00**	N control
2	67	33	00	**100**	Recommended N
3	40	40	00	**80**	
4	40	40	20*	**100**	*when SPAD value < 40 at MT
5	40	40	20*	**100**	*when SPAD value < 44 at MT
6	40	40	20*	**100**	*when SPAD value < 48 at MT
7	50	50	00	**100**	
8	50	50	20*	**120**	*when SPAD value < 40 at MT
9	50	50	20*	**120**	*when SPAD value < 44 at MT
10	50	50	20*	**120**	*when SPAD value < 48 at MT

CRI = CROWN ROOT INITIATION; MT = MAXIMUM TILLERING

3.10 Data analysis

Regression analyses were performed following the procedures outlined by Gomez and Gomez (1984). Data were subjected to simple and multiple regression analyses with grain yield and total nitrogen uptake as dependent variables and LCC and SPAD readings as independent variables (soil N supply). Simple regression and correlation analyses were used to study the relationship of SPAD and LCC readings with leaf N, dry weight and leaf area. Analysis of variance (ANOVA) and means separating by Duncan's Multiple Range Test (DMRT) were done using IRRI-STAT and SAS version 6.12.

Internal efficiency (IE) was calculated as

$$IE = \frac{Grain\,yield\left(kg\,ha^{-1}\right)}{Total\,N\,uptake\left(kg\,ha^{-1}\right)} \qquad \text{(Witt et al., 1999)}$$

Nitrogen harvest index (NHI) was calculated as

$$NHI = \frac{N\,accumulation\,in\,grain\left(kg\,ha^{-1}\right)}{Total\,N\,uptake\left(kg\,ha^{-1}\right)} \qquad \text{(Witt et al., 1999)}$$

The N-use efficiency or partial factor productivity (PFP) was calculated as

$$PFP = \frac{Grain\,yield\left(kg\,ha^{-1}\right)}{Applied\,N\left(kg\,ha^{-1}\right)} \qquad \text{(Peng et al., 1996)}$$

The agronomic N-use efficiency (AE) was calculated as

$$AE = \frac{Grain\ yield\ in\ N\ fertilized\ plot - Grian\ yield\ in\ N\ control\ plot\left(kg\ ha^{-1}\right)}{Applied\ N\ in\ N\ fertilized\ plot\left(kg\ ha^{-1}\right)}$$

(Novoa and Loomis, 1981)

The N recovery efficiency (RE) was calculated as

$$RE\,(\%) = \frac{N\ uptake\ in\ N\ fertilized\ plot - N\ uptake\ in\ N\ control\ plot\left(kg\ ha^{-1}\right)}{Applied\ N\ in\ N\ fertilized\ plot\left(kg\ ha^{-1}\right)} x100$$

(Dilz, 1988)

The physiological N use efficiency (PE) was calculated as

$$PE = \frac{Grain\ yield\ in\ N\ fertilized\ plot - Grain\ yield\ in\ N\ control\ plot\left(kg\ ha^{-1}\right)}{N\ uptake\ in\ N\ fertilized\ plot - N\ uptake\ in\ N\ control\ plot\left(kg\ ha^{-1}\right)}$$

(Isfan, 1990)

4 RESULTS AND DISCUSSION

The following three sub-chapters summarize and discuss the findings obtained in the three experimental series conducted in the farmers' fields in the Meherpur, Kushtia and Chuadanga districts of Bangladesh during the T-Aman (wet), Boro (dry), and Rabi (cold dry) seasons of 2001-02.

4.1 Evaluation of leaf color chart (LCC) and chlorophyll meter (SPAD) for estimating native soil N supply

Since information on native soil N supply is necessary for defining the N fertilizer requirement for a target yield, the relationship of soil N supply and LCC or SPAD reading at the early growth stage of rice and wheat will be discussed under the following headings.

4.1.1 Soil N supplying capacity of rice fields

The indigenous N supply can be estimated by determining plant N uptake in plots where mineral fertilizer N has not been applied and where other nutrients do not limit yields (Janssen et al., 1990; Cassman et al., 1996b). In the present study of 40 farmers' fields in three districts of Bangladesh, total N uptake (TNU) ranged from 25.5 to 53.8 kg N ha^{-1} in both the T-Aman and Boro seasons with an average N uptake of 38.6 kg N ha^{-1}. Grain yield in N omission plots ranged from 1.70 to 3.15 t ha^{-1} with an average yield of 2.5 t ha^{-1}. Figure 4.1 illustrates the distribution histogram of grain yield.

It has been reported that N uptake by rice varied between 35 and 95 kg N ha^{-1} at maturity in the Philippines (Cassman et al., 1996b), and between 24 and 107 kg N ha^{-1} at first flowering in India (Stalin et al., 1996). Toriyama and Sekiya (1991) reported year-to-year fluctuations of 60% in N uptake by rice receiving only P and K fertilizer in a long-term experiment in Japan. A similar degree of variation was found in the humid lowland tropics of Asia and West Africa (Becker and Johnson, 2001). Soil N generally provides the largest proportion of the N absorbed by rice even when mineral N fertilizer is applied, and is often sufficient for a crop yield of 2 to 4 t ha^{-1} (Bouldin, 1986; De Datta, 1987). Evidence from field studies in temperate regions indicates that the indigenous N supply varies greatly among soils within a rice-growing domain between seasons or years. Dolmat et al. (1980) reported rice yields ranging from 2.3 to 5.7 t ha^{-1} at 31 locations in Louisiana. Cassman et al. (1996b) showed that yields ranged from 2.5 to 6.0 t ha^{-1} in N omission plots in on-farm experiments in the Philippines. Similarly, grain yield in N omission plots ranged from 1.09 to 5.71 t ha^{-1} in field experiments in India (Stalin et al., 1996) and from 1.9 to 3.7 t ha^{-1} in West Africa (Becker and Johnson, 2001).

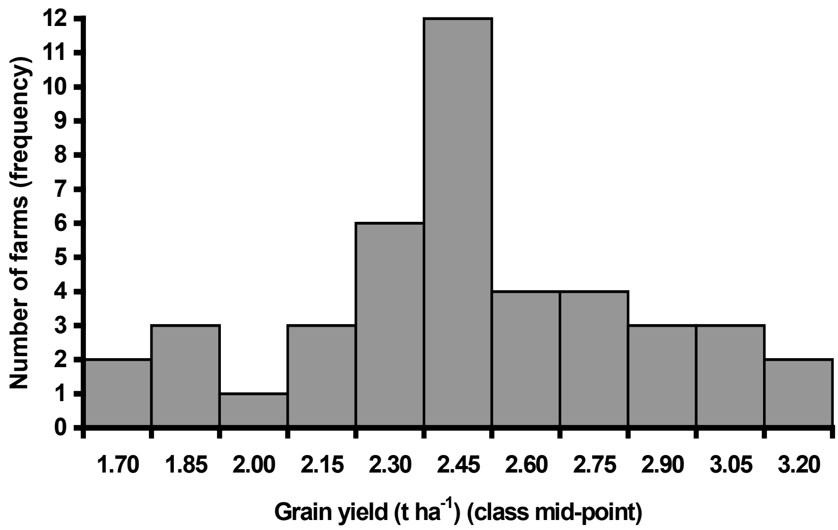

Figure 4.1. Distribution histogram of grain yield in N omission plots from 43 rice crops grown during the T-Aman and Boro seasons (Bangladesh, 2001-02)

In the present study, a significant relationship was observed between rice yield and N uptake at harvest (r^2 = 0.66; Figure 4.2). Although this correlation was significant, the r^2 value was lower than that reported by Cassman et al. (1998) or Becker and Johnson (2001). It has been documented that total N accumulation in rice was positively correlated with grain yield, with moderate variation (Adhikari et al., 1999). Total crop N accumulation in plots without applied N provides a useful index of indigenous N supply, because it is easily measured, is tightly correlated with grain yield, and provides a quantitative indicator of system productivity (Cassman et al., 1998). Thus, the correlation with grain yield may serve as a substitute for predicting native N supply by various soil tests (Stalin et al., 1996).

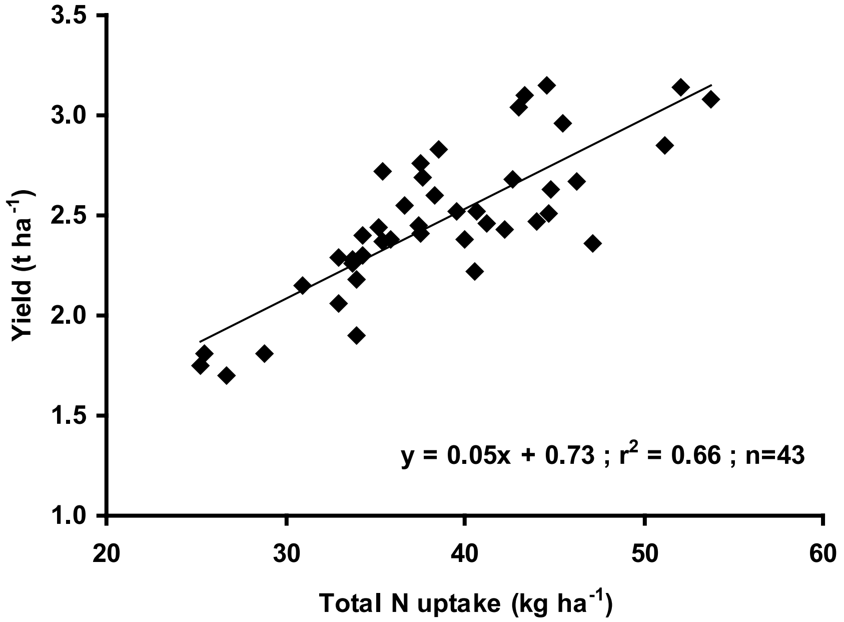

Figure 4.2. Relationships between grain yield and N uptake at harvest from 43 rice crops grown during the T-Aman and Boro seasons (Bangladesh, 2001-02)

4.1.2 Correlation of rice grain yield and LCC / SPAD values

The relationship between yield and LCC reading at 15 DAT in the T-Aman and 20 DAT in the Boro season was significant; however, yield data were not correlated with tiller number or plant height (Figure 4.3a and Table 4.1). It appears that LCC readings at the early growth stage can estimate the final yield in the absence of applied fertilizer N, but it explained only 41% of the variation in the field. Even though all three parameters (LCC, tiller number and plant height) were included in the multiple linear-relationship, the coefficient of determination was <50%.

The correlation with grain yield was higher when the plant N status was determined by SPAD explaining 69% of the variation (Figure 4.3b). A multiple regression additionally including the factors tiller number and plant height did not improve the correlation (Table 4.1). Similar to the LCC, the SPAD meter can be used to estimate the soil N supply during the early growth stage of rice, however, the estimates of the SPAD meter appear to be more reliable than those of the LCC.

Table 4.2 shows the correlation coefficients of yield with different variables in the T-Aman and the Boro seasons. The r^2 values were similar among varieties despite the fact that data were collected at 15 DAT in the T-Aman season, and at 20 DAT in the

Boro season, where recovery was slow after transplanting due to low temperature. The r^2 values were improved by a multiple regression that included tiller number and plant height but they did not differ significantly for LCC and SPAD.

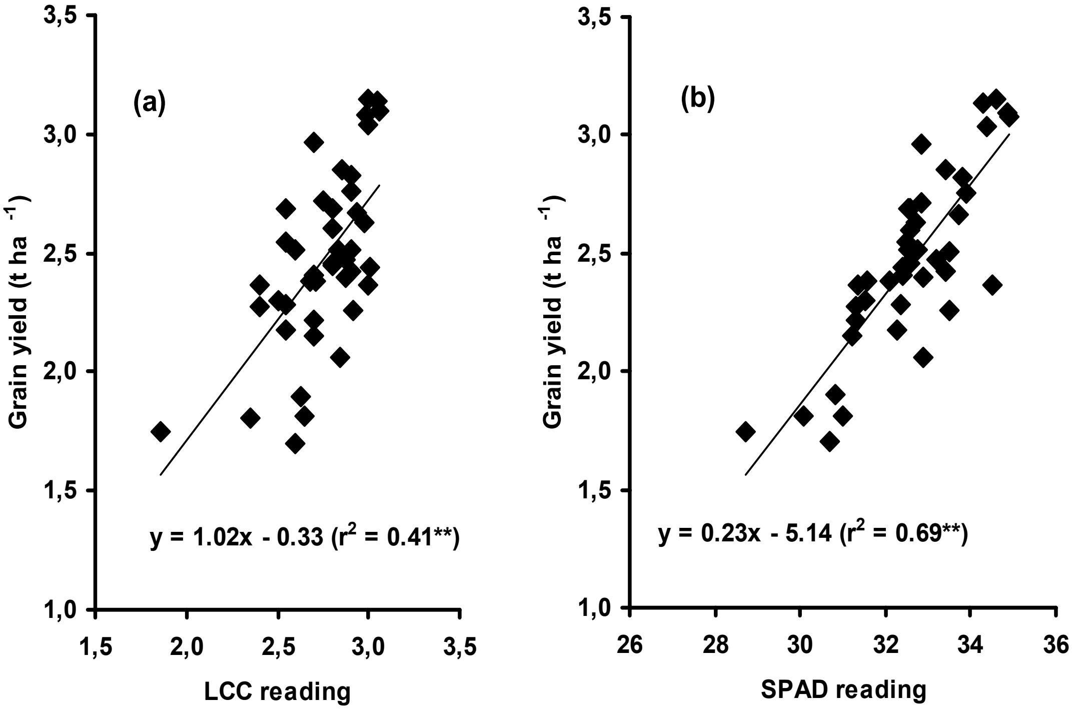

Figure 4.3. Relationship of grain yield with (a) LCC and (b) SPAD readings at the early growth stage of rice (15 DAT in the T-Aman and 20 DAT in the Boro) of BR-11, BRRI dhan-39 and BRRI dhan-28 during the T-aman and Boro seasons of 2001-02 (n = 43 rice crops)

Table 4.1. Relationship of grain yield and LCC, SPAD, tiller number per hill, and plant height (cm) at the early growth stage of rice (15 DAT in the T-Aman and 20 DAT in the Boro) for 43 rice crops during the T-Aman and Boro seasons of 2001-02

Factor	Regression equation and coefficient of determination
Yield (Y) vs. LCC (L)	Y = - 0.33 + 1.02 L; r^2 = 0.41**
Yield vs. SPAD (S)	Y = - 5.14 + 0.23 S; r^2 = 0.69**
Yield vs. Tiller number (T)	Y = 2.15 + 0.05 T; r^2 = 0.08^{ns}
Yield vs. Plant height (H)	Y = 1.94 + 0.02 H; r^2 = 0.06 ^{ns}
Yield vs. LCC + Tiller	Y = - 0.44 + 1.10 L - 0.02 T; r^2 = 0.41**
Yield vs. LCC + Height	Y = - 0.38 + 1.19 L - 0.02 H; r^2 = 0.43**
Yield vs. SPAD + Tiller	Y = - 5.13 + 0.23 S + 0.001 T; r^2 = 0.69**
Yield vs. SPAD + Height	Y = - 5.29 + 0.25 S - 0.010 H; r^2 = 0.70 **
Yield vs. LCC + Tiller + Height	Y = - 0.42 + 1.21 L - 0.007 T - 0.016 H; r^2 = 0.43**
Yield vs. SPAD + Tiller + Height	Y = - 5.20 + 0.24 S + 0.012 T - 0.012 H; r^2 = 0.70**

Table 4.2. Correlation between grain yield and LCC, SPAD, tiller number per hill, and plant height at the early growth stage of rice (15 DAT in the T-Aman and 20 DAT in the Boro) for 43 rice crops during the T-Aman and Boro seasons of 2001-02

Factor	**Coefficient of determination (r^2)**		
	T-Aman season (2001)		**Boro season (2001-02)**
	BR-11 (17 farms)	**BRRI dhan-39 (15 farms)**	**BRRI dhan-28 (11 farms)**
Yield (Y) vs. LCC (L)	0.53**	0.63**	0.63**
Yield vs. SPAD (S)	0.74**	0.69**	0.71**
Yield vs. Tiller number (T)	0.25 *	0.18 ns	0.03 ns
Yield vs. Plant height (H)	0.08 ns	0.06 ns	0.06 ns
Yield vs. LCC + Tiller	0.62**	0.66**	0.65**
Yield vs. LCC + Height	0.58**	0.63**	0.63**
Yield vs. SPAD + Tiller	0.84**	0.71**	0.71**
Yield vs. SPAD + Height	0.74**	0.70**	0.74**
Yield vs. LCC + Tiller + Height	0.66**	0.66**	0.65**
Yield vs. SPAD + Tiller + Height	0.85**	0.71**	0.74**

4.1.3 Correlation of rice N uptake and LCC / SPAD values

The relationship between TNU and LCC reading was significant and linear relationship can be accounted for 47% of the total number of farms (Figure 4.4a). However, there were no significant linear correlations between yield with tiller number (11%), and with plant height (14%). Although the correlation increased when more than one plant variable (LCC reading and tiller number or plant height) was included in the correlation analysis, there was no appreciable difference in regression coefficients (Table 4.3). The LCC can, therefore, stand when estimating the native soil N supply; however, correlation is less than 50%.

The result shows 62% accounted for the linear relationship between total N uptake and SPAD reading at the early growth stage (Figure 4.4b and Table 4.3). Results also indicate that the SPAD reading is more related with TNU than that of the LCC reading. The multiple regression (62%) did not improve appreciably compared to the simple linear relationship.

Table 4.4 shows the coefficient of determination (r^2) values of total N uptake with different variables in each variety in the Aman and Boro seasons. Similar to the relationship with yield, all the relationships were significant except those between yield and tiller number, and plant height. Better correlations were found for TNU with SPAD, tiller number and plant height as 65%, 62% and 61% in BR-11, BRRI dhan-39 and BRRI dhan-28, respectively.

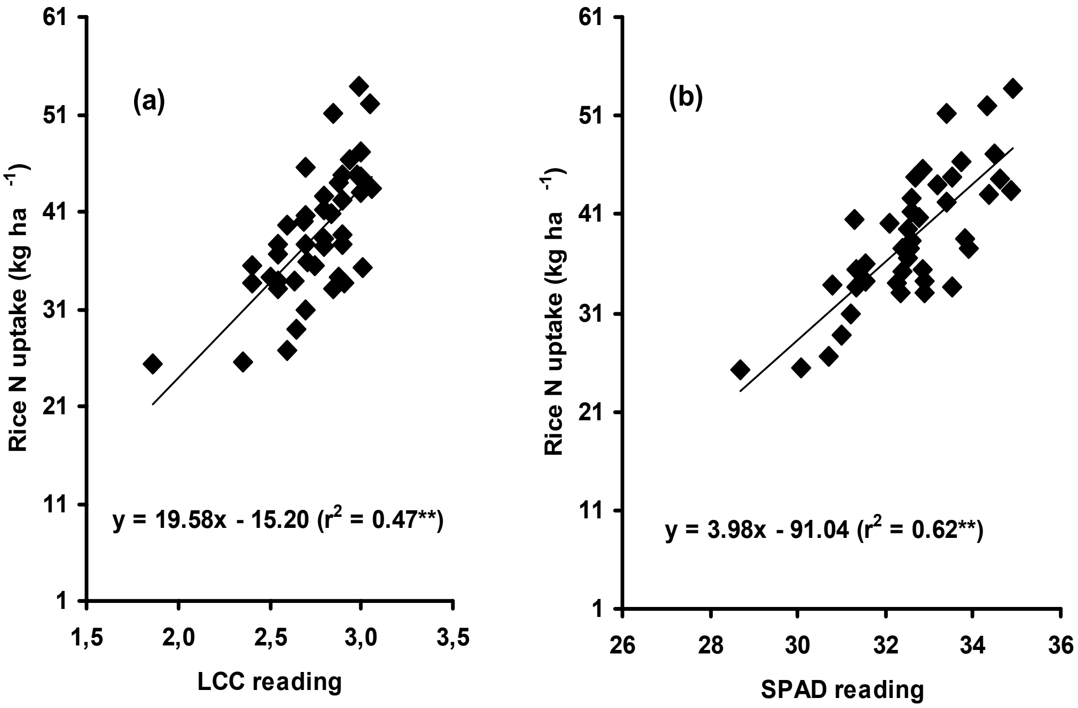

Figure 4.4. Relationship of N uptake at harvest with (a) LCC and (b) SPAD readings at the early growth stage of rice (15 DAT in the T-Aman and 20 DAT in the Boro) of BR-11, BRRI dhan-39 and BRRI dhan-28 during the T-Aman and Boro seasons of 2001-02 (n = 43 rice crops)

Table 4.3. Relationship of N uptake at harvest and LCC, SPAD, tiller number per hill, and plant height (cm) at the early growth stage of rice (15 DAT in the T-Aman and 20 DAT in the Boro) for 43 rice crops during the T-Aman and Boro seasons of 2001-02

Factor	**Regression equation and coefficient of determination**
Total N uptake (TNU) vs. LCC (L)	TNU = - 15.20 + 19.58 L; r^2 = 0.47**
TNU vs. SPAD (S)	TNU = - 91.04 + 3.98 S; r^2 = 0.62**
TNU vs. Tiller number (T)	TNU = 31.79 + 1.15 T; $r^2 = 0.11^{ns}$
TNU vs. Plant height (H)	TNU = 23.52 + 0.61 H; $r^2 = 0.14\ ^{ns}$
TNU vs. LCC + Tiller	TNU = - 16.43 + 20.42 L - 0.18 T; r^2 = 0.47**
TNU vs. LCC + Height	TNU = - 15.28 + 19.87 L - 0.03 H; r^2 = 0.47**
TNU vs. SPAD + Tiller	TNU = - 88.18 + 3.84 S + 0.27 T; r^2 = 0.62**
TNU vs. SPAD + Height	TNU = - 89.06 + 3.82 S + 0.13 H; r^2 = 0.62 **
TNU vs. LCC + Tiller + Height	TNU = - 16.42 + 20.44 L - 0.18 T – 0.003 H; r^2 = 0.47**
TNU vs. SPAD + Tiller + Height	TNU = - 87.68 + 3.77 S + 0.19 T + 0.09 H; r^2 = 0.62**

Table 4.4. Correlation between N uptake at harvest and LCC, SPAD, tiller number per hill, and plant height at the early growth stage of rice (15 DAT in the T-Aman and 20 DAT in the Boro) for 43 rice crops during the T-Aman and Boro seasons of 2001-02

Factor	Coefficient of determination (r^2)		
	T-Aman season (2001)		Boro season (2001-02)
	BR-11 (17 farms)	BRRI dhan-39 (15 farms)	BRRI dhan-28 (11 farms)
Total N uptake (TNU) vs. LCC (L)	0.45**	0.56**	0.46**
TNU vs. SPAD (S)	0.61**	0.57**	0.60**
TNU vs. Tiller number (T)	0.14 *	0.01 ^{ns}	0.01 ^{ns}
TNU vs. Plant height (H)	0.10 ^{ns}	0.05 ^{ns}	0.13 ^{ns}
TNU vs. LCC + Tiller	0.49**	0.59**	0.46**
TNU vs. LCC + Height	0.47**	0.57**	0.49**
TNU vs. SPAD + Tiller	0.65**	0.59**	0.61**
TNU vs. SPAD + Height	0.61**	0.58**	0.60**
TNU vs. LCC + Tiller + Height	0.50**	0.60**	0.49**
TNU vs. SPAD + Tiller + Height	0.65**	0.62**	0.61**

Although numerous publications exist on N availability indices in tropic lowland rice soils, comparative studies under field conditions are rare. It has been reported that strong positive correlations exist between soil N tests and N uptake or yield of rice found in greenhouse pot trials (Kai et al., 1984; Wilson et al., 1994) are often poor at other sites and under field conditions (Dolmat et al., 1980; Sahrawat, 1983; Bajaj, 1984; Zhu et al., 1984). It has also been reported that static soil tests such as soil organic carbon or total soil nitrogen have been widely used; however, recent data across different spatial and temporal scales show that these tests do not provide enough information about the indigenous N supply in tropical lowland rice (Cassman et al., 1996b). While SPAD meter readings provide objective information on the chlorophyll content of the leaf, the LCC reading is subjectively judged by visually differentiating the leaf colour. However, it has been shown that the LCC reading can be closely related to the SPAD reading (Peng et al., 1996). Given the high cost of the SPAD meter, the LCC is potentially an inexpensive alternative tool to the SPAD meter (Furuya, 1987). In this study, however, the LCC provides much less accurate estimates of the soil N supply, especially at the early growth stages.

Appendix 1 shows the data of grain yield, TNU, LCC and SPAD reading, tiller number and plant height at the early growth stage of rice, i.e., 15 DAT in the T-Aman season and 20 DAT in the Boro season. The average of values of LCC, SPAD reading, tiller number per hill and plant height were 2.75, 32.6, 6 and 25 cm, respectively.

Straw yields ranged from 2.1 to 3.7 t ha^{-1}, and all varieties produced total dry matter on the average of 5.0 t ha^{-1}. The average harvest index was 0.44. The observed harvest indices were lower than the anticipated harvest index of 0.50 (IRRI, 1978; Peng et al., 1994; Hay, 1995). The average values of panicle number per square meter, spikelets number per panicle, and filled-grain percent were 220, 77 and 69.6%, respectively. The yield parameters show low figures because the data were collected from N omission plots.

Nitrogen harvest indices varied in the range of 0.41 - 0.70. The minimum internal N-use efficiency was 50.1 and the maximum 76.7 kg grain per kg plant N. The average of internal use efficiency was 64.5 kg grain per kg plant N (Appendix 1). The observed average internal N-use efficiency was relatively lower than the 69 kg grain per kg of plant N in N omission plots reported before (Witt et al. 1999). The variation in internal nutrient efficiencies did not only reflect site- and season-specific differences in temperature and solar radiation but also nutritional imbalances and problems related to irrigation, and pest and weed control.

4.1.4 Soil N supplying capacity of wheat fields

The minimum total N uptake was 13.6 kg N ha^{-1} and the maximum 26.3 kg N ha^{-1}. Grain yield ranged from 0.61 to 1.11 t ha^{-1} among the all-wheat farms and the average yield was 0.79 t ha^{-1}. Figure 4.5 shows the distribution of the grain yield of wheat in N omission plots from 17 farmers' fields. It was found that the soil N-supplying capacity was greater in rice crops than in wheat crops. Ladha et al. (2000) stated that the indigenous supply of N, P, K under wheat was much smaller than that measured for rice in many on-farm trials in India, Nepal, and Bangladesh, but it was highly variable in both crops (Adhikari et al., 1999; IRRI, 1999). A greater soil N supply in the rice-growing season may be attributed to higher rates of non-symbiotic nitrogen fixation and N mineralization than during the wheat crop growing season. Broadbent (1978) mentioned that net mineralization in soil was usually greater in flooded, anaerobic conditions than in aerobic conditions, because the energy demand of microbes involved in anaerobic immobilization was lower. Shrestha and Ladha (1996) also reported that dinitrogen fixation could contribute up to 10% of the total N accumulated in flooded rice.

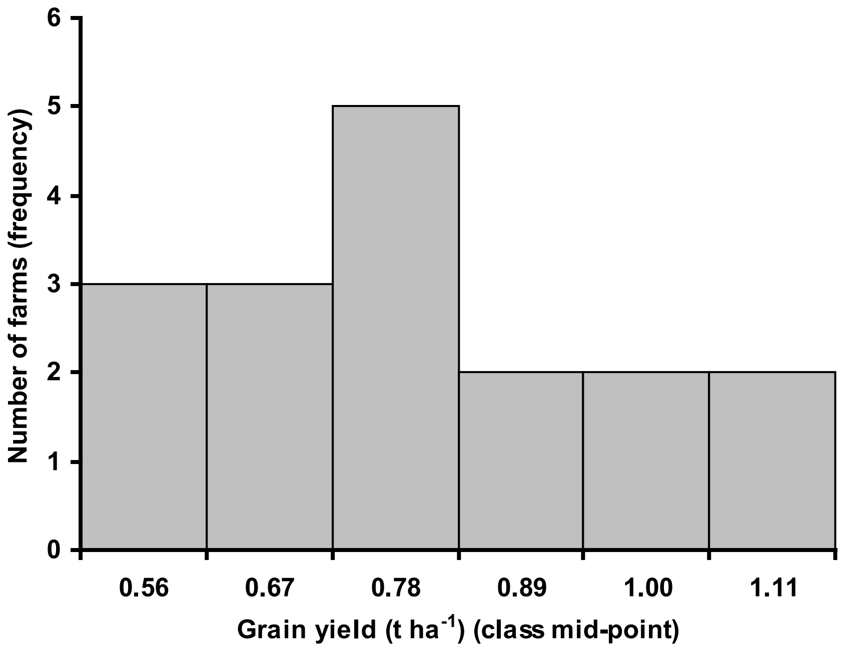

Figure 4.5. Distribution histogram of grain yield in N omission plots from 17 wheat crops during the Rabi season (Bangladesh, 2001-02)

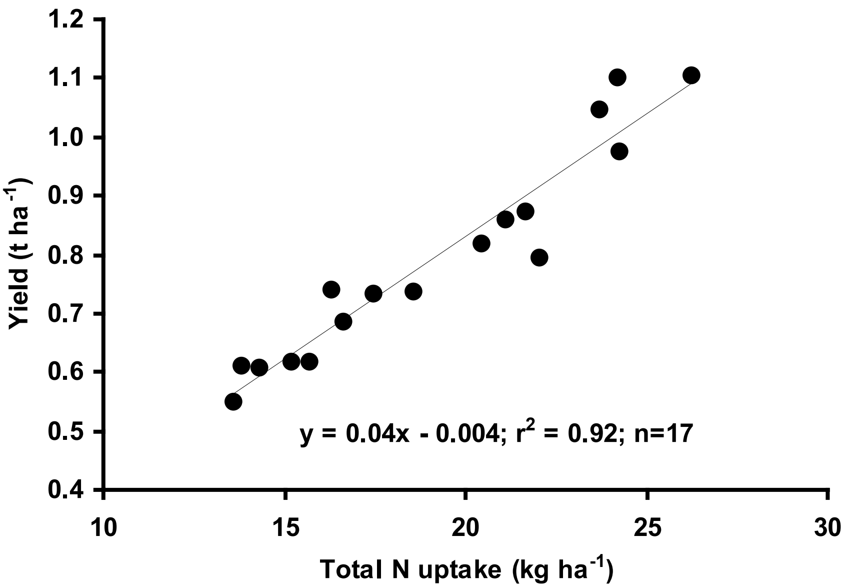

Figure 4.6. Relationships between grain yield and N uptake at harvest from 17 wheat crops during the Rabi season (Bangladesh, 2001-02)

It was observed that the total N uptake of wheat was closely related to grain yield ($r^2 = 0.92$; Figure 4.6), with less variability than in rice. A similar result has been reported by Adhikari et al. (1999). This supports their finding that mobilization of plant N to the grain in wheat was less affected by biotic and abiotic stress than in rice. Because crop N uptake (N accumulation in crop) is closely correlated with wheat grain yield, grain yield may be used as an index of the native soil N supplying capacity.

4.1.5 Correlation of wheat grain yield and LCC / SPAD values

The relationship of yield and LCC reading at the early growth stage (crown root initiation stage, 20 DAS) was significant and can account for 54% of variation by a linear relationship (Figure 4.7a). Table 4.5 shows that there is no significant relationship between yield and plant population density at the early growth stage. Although a significant correlation was found in the relationship between yield and plant height, the coefficient of determination ($r^2 = 0.23$) was low. Improved correlations resulted when yield was regressed with LCC and plant population density (57%), with LCC and plant height (59%), and with LCC, plant population density and plant height (63%). The percentages are not too much different from relation of yield with only LCC reading; however, plant population density and plant height are considerable factors for estimating soil N supply at the early growth stage of wheat.

The significant relationship between yield and SPAD reading at the early growth stage was 62%. The correlation increased to 65% with SPAD and plant population density, to 62% with SPAD and plant height, and to 65% with SPAD, plant population density and plant height (Figure 4.7b and Table 4.5). Although relationship between yield and SPAD was better than that with LCC, correlations were similar. This indicates that LCC may also be used to estimate the native soil N supply capacity.

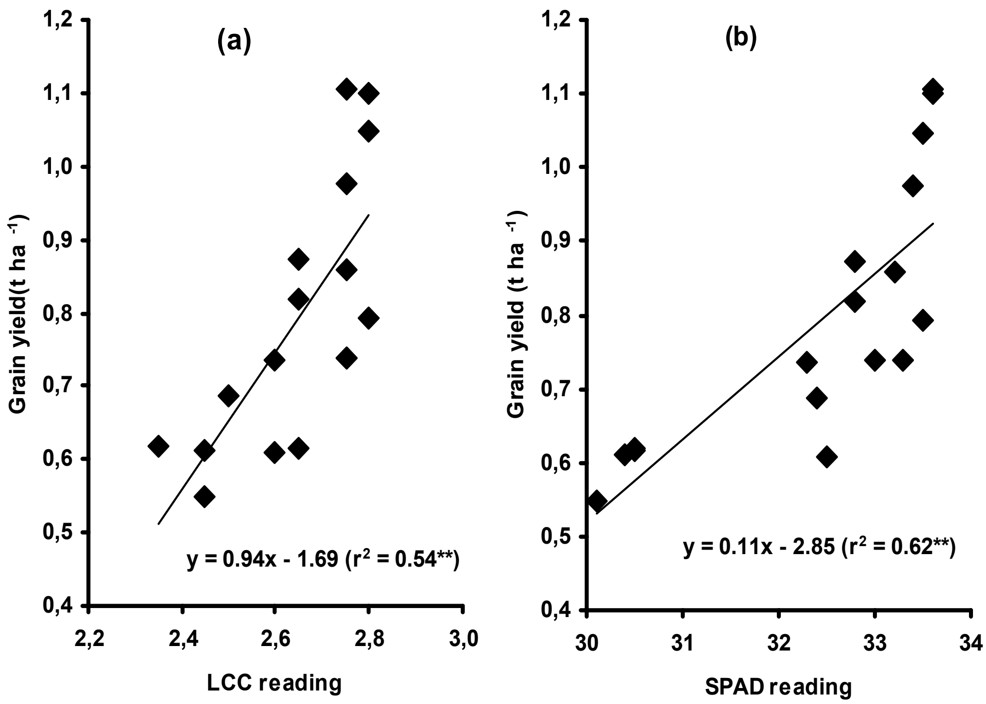

Figure 4.7. Relationship of grain yield with (a) LCC and (b) SPAD readings at the early growth stage (20 DAS) of Kanchan wheat variety during the Rabi season of 2001-02 (n = 17 wheat crops)

Table 4.5. Relationship of grain yield and LCC, SPAD, plant population density (m^{-2}) and plant height (cm) at the early growth stage of wheat (20 DAS) during the Rabi season of 2001-02 (n = 17 wheat crops)

Factor	Regression equation and coefficient of determination
Yield (Y) vs. LCC (L)	Y = - 1.69 + 0.94 L r^2 = 0.54**
Yield vs. SPAD (S)	Y = - 2.85 + 0.11 S r^2 = 0.62**
Yield vs. Plant population (T)	Y = 0.48 + 0.001 T $r^2 = 0.18^{ns}$
Yield vs. Plant height (H)	Y = - 0.18 + 0.05 H r^2 = 0.23*
Yield vs. LCC + Population	Y = -1.59 + 0.85 L + 0.001 T r^2 = 0.57 **
Yield vs. LCC + Height	Y = -1.86 + 0.82 L + 0.03 H r^2 = 0.59**
Yield vs. SPAD + Population	Y = - 2.70 + 0.10 S + 0.001 T r^2 = 0.65**
Yield vs. SPAD + Height	Y = - 2.86 + 0.11 S - 0.001 H r^2 = 0.62 **
Yield vs. LCC + Population + Height	Y = - 1.78 + 0.80 L + 0.001 T + 0.03 H r^2 = 0.63 **
Yield vs. SPAD + Population + Height	Y = - 2.65 + 0.71 S + 0.001 T + 0.01 H r^2 = 0.65 **

4.1.6 Correlation of wheat N uptake and LCC / SPAD values

The relationships of total N uptake of wheat were 55% with LCC reading, 15% with plant population density, 31% with plant height, 56% with LCC and plant population density, 66% with LCC and plant height, and 66% with LCC, plant population density and plant height (Figure 4.8a and Table 4.6). A similar relationship for LCC was observed with yield and total N uptake in both crops.

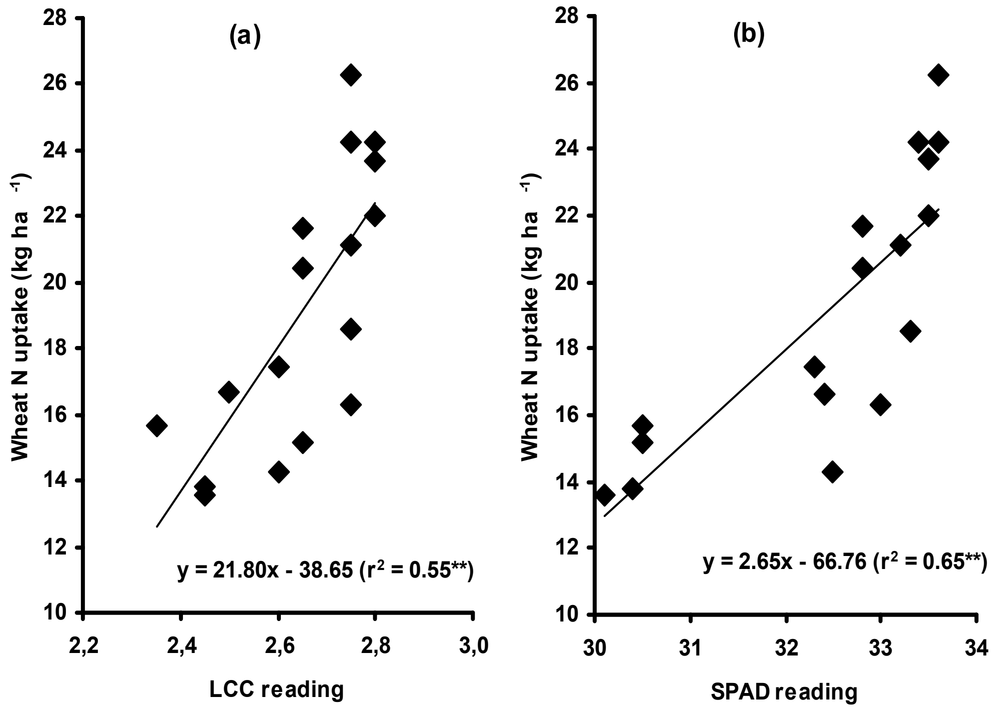

Figure 4.8. Relationship of N uptake at harvest with (a) LCC and (b) SPAD readings at the early growth stage (20 DAS) of Kanchan wheat variety during the Rabi season of 2001-02 (n = 17 wheat crops)

In the case of the SPAD reading, the relationships of total N uptake of wheat were 65% with SPAD only, 66% with SPAD and plant population density, 65% with SPAD and plant height, and 67% with SPAD, plant population density and plant height (Figure 4.8b and Table 4.6). Vidal et al. (1999) reported that SPAD readings were significantly related to nitrogen uptake at GS-45 (booting) and GS-69 (anthesis complete) but not significant at GS-30 (end tillering). They also reported that the SPAD meter seemed to accurately predict wheat grain yields and nitrogen uptake if it was used at GS-45 (booting) stage. In the present study, SPAD readings at the early growth stage (20 DAS, CRI stage) were significantly related not only to N uptake but also to wheat grain yield. The SPAD meter may, therefore, be suitable for predicting the inherent N fertility status of soil in rice-based cropping systems.

Table 4.6. Relationship of N uptake at harvest and LCC, SPAD, plant population density (m^{-2}), and plant height (cm) at the early growth stage of wheat (20 DAS) during the Rabi season of 2001-02 (n = 17 wheat crops)

Factor	Regression equation and coefficient of determination
Total N uptake (TNU) vs. LCC (L)	TNU = - 38.65 + 21.80 L r^2 = 0.55**
TNU vs. SPAD (S)	TNU = - 66.76 + 2.65 S r^2 = 0.65**
TNU vs. Plant population (T)	TNU = 12.69 + 0.02 T $r^2 = 0.15^{ns}$
TNU vs. Plant height (H)	TNU = - 6.62 + 1.41 H r^2 = 0.31*
TNU vs. LCC + Population	TNU = - 37.10 + 20.46 L + 0.01 T r^2 = 0.56**
TNU vs. LCC + Height	TNU = - 44.03 + 18.24 L + 0.81 H r^2 = 0.64**
TNU vs. SPAD + Population	TNU = - 64.24 + 2.50 S + 0.01 T r^2 = 0.66**
TNU vs. SPAD + Height	TNU = - 64.97 + 2.47 S - 0.22 H r^2 = 0.65**
TNU vs. LCC + Population + Height	TNU = - 42.27 + 16.13 L + 0.01 T +0.87 H r^2 = 0.66**
TNU vs. SPAD + Population + Height	TNU = - 60.99 + 2.19 S + 0.01 T + 0.34 H r^2 = 0.67**

The data of grain yield, TNU, LCC and SPAD readings, plant population density and plant height at 20 DAS (CRI stage) are shown in Appendix 2. The average values were 2.65, 32.4, 261 and 18.2 (cm), respectively. The test variety, Kanchan, produced on average 1.8 t ha^{-1} of total dry matter and showed 0.41 of harvest index. The mean number of spikes per square meter, and kernel (grain) number per spike were 197 and 16, respectively. Nitrogen harvest indices ranged from 0.59 to 0.70 and internal N-use efficiency from 36.1 to 45.4 (Appendix 2).

4.2 Comparison of three types of leaf color chart (LCC)-based N managements in rice production

The previous experiment showed that the early LCC estimate in N omission plots could under some conditions be used to estimate soil N supply and N uptake. The following experiment will summarize and discuss the comparison of different types of LCC in N fertilization practices during the T-Aman rice season of 2001.

4.2.1 Yield and fertilizer nitrogen application

Mean yield in N control plots of 2.0 t ha^{-1} in the present study indicate a low indigenous soil N supplying capacity (Table 4.7). This yield level was lower than the 2.9 t ha^{-1} reported by Adhikari et al. (1999). Soil-related factors have been associated with the low farm level rice yield (e.g., low organic matter content, widespread occurrence of sulphur and zinc deficiencies) (Sattar, 2000). In the present study, gypsum and zinc sulphate fertilizers were applied basally to prevent rude deficiencies, although no organic amendment was applied.

A significant yield difference was found between the recommended (Rec-N) and the SPAD-based N fertilization with a threshold value of 35 in the SPAD-based N management. The yield increase was 0.2 t ha^{-1}, but the applied-N rate with SPAD-35 was higher than that of Rec-N. In contrast to this result, Babu et al. (2000) found similar yields in both treatments in India with lower N application rates. However, their local Rec-N rate was the same as that of the SPAD-35 treatment in the present study. This may be due to different environmental factors and different varieties. Due to the large field-to-field variability of the soil N supply, the Rec-N (83 kg N ha^{-1}) was not suitable for obtaining the consistent high yield level.

The use of the IRRI-LCC with a critical value of 3 (IRRI-LCC 3) gave no different yield from that obtained with SPAD-35 and recommended-N, but N application was lower than SPAD-35 and higher than Rec-N. Yield was significantly lower than that of IRRI-LCC 4 and 5 treatments (Table 4.7). Higher panicle number may have contributed to the higher yields in IRRI-LCC 4 and 5 managements. It was found that IRRI-LCC 4 and 5 showed the same yield with the same N applications. A similar result was reported with 20 kg N ha^{-1} as basal application and 30 kg N ha^{-1} as topdressing, respectively, in India (Singh et al., 2002). It has also been reported that a basal N application has no added effect when rice yields in N control plots are greater than 3 t ha^{-1} (Balasubramanian et al., 1999; Singh et al., 2002). No basal N application was used in this study, and 25 kg N ha^{-1} was applied as topdressing each time, although the yield was less than 3 t ha^{-1} in the N-control plot. Since LCC readings at 10-day intervals were usually less than 4 in this experiment, IRRI-LCC 5 may not be appropriate to use as a critical value for N fertilization of transplanted rice in the present study area in Bangladesh during the T-Aman (wet) season.

Table 4.7. Mean comparison of yield at the different LCCs based N managements for the BR-11 variety in Bangladesh during the T-Aman season of 2001

T#	Description	N rate (kg ha^{-1})	No. of split	Yield (t ha^{-1})
1	N control	0	-	2.0 f †
2	Rec-N	83	3	3.7 d
3	SPAD (35)	125	5	3.9 c
4	IRRI LCC-3	117	4-5	3.8 cd
5	IRRI LCC-4	175	7	4.4 a
6	IRRI LCC-5	175	7	4.4 a
7	China LCC-4	108	4-5	3.7 d
8	China LCC-5	158	6-7	4.2 b
9	China LCC-6	175	7	4.4 a
10	California LCC-4	75	3	3.4 e
11	California LCC-5	150	6	4.2 ab
12	California LCC-6	175	7	4.4 a

† Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by Duncan's Multiple Range Test

Among China-LCC treatments, LCC 4 resulted in the lowest yield and LCC 6 gave the highest yield (Table 4.7). The yield of China-LCC 4 was not different from that of Rec-N and significantly lower than that of SPAD-35. There were significantly different yields between China-LCC 5 and 6, and both of them were significantly higher than those of Rec-N and SPAD-35. The higher yields were mainly the results of a higher panicles number per square meter and a higher filled grain percent. The amount of N applied and yields increased with increasing LCC values. However, the number of split applications only differs slightly between LCC-5 and -6. It was observed that rice plants needed N fertilizer application at 10-day intervals in the LCC-6 treatment, because LCC reading was usually lower than the given critical value.

In California-LCC treatments, LCC 4 showed the lowest yield with the lowest N application among all N managements except for the N-control plot (Table 4.7).

California-LCC 4 apparently does not lead to high yields, as it demands a lower N fertilizer application. Therefore, California-LCC 4 may not be appropriate as a critical value for N fertilization in rice crops in the study area. A higher yield resulted from California-LCC 6, but it was not significantly different from that of California-LCC 5 although N application rates differed slightly.

The yields of IRRI-LCC 4 and 5, China-LCC 5 and 6, and California-LCC 5 and 6 were significantly higher than those of Rec-N and SPAD-35-based N managements, where higher N rates applied (Table 4.7). California-LCC 4 resulted in a low yield (3.4 t ha^{-1}) compared to the yields of IRRI-LCC 3 and China-LCC 4. According to the greenness of the chart color, California-LCC 4 called for a lower N fertilizer application. The yield of California-LCC 5 was similar to the yield of China-LCC 5 with relatively less N applied. More or less the same yields were obtained with IRRI-LCC 4, IRRI-LCC 5, China-LCC 6, and California-LCC 6 with 175 kg N ha^{-1}. Although they gave higher yields in this experiment, N application rates were relatively high. The yield responses to the applied-N rates are plotted in Figure 4.9. It was observed that the yield increase was greater than 2 t ha^{-1} over the yield of the control plot when the applied-N was greater than or equal to 150 kg N ha^{-1}.

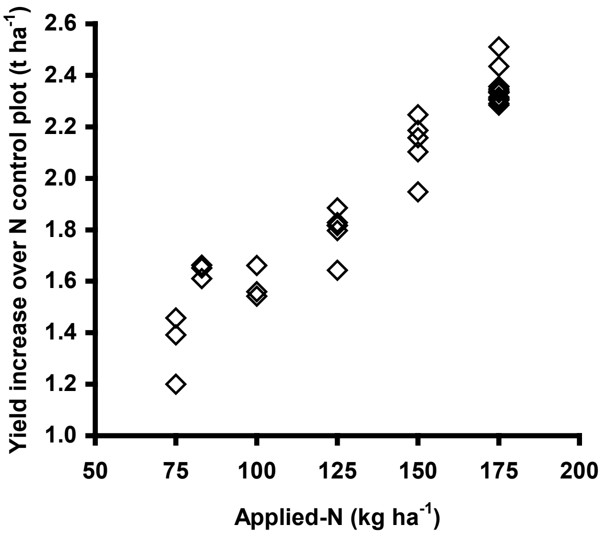

Figure 4.9. Grain yield response to the applied-N rate at different N managements for the BR-11 rice variety in Bangladesh during the T-Aman season of 2001

The mean effect of all LCCs managements on yield was highly significantly different from recommended-N and SPAD-35 N managements (Appendix 3, Analysis of Variance; ANOVA). The yields were also different between IRRI-LCC versus China-LCC or California LCC-based N managements. However, there was no difference between China-LCC and California-LCC-based N managements.

4.2.2 Yield components, straw yield, total dry matter yield, and harvest index

The panicle number per square meter increased with increasing rates of N application in each LCC management (Table 4.8). Significant differences in spikelets per panicle and percent filled grain were found between China and California-LCC managements, although these were not different from those of the IRRI-LCC management. It has been reported that panicle and spikelet numbers, as yield components, are significantly related to yield because they form the sink capacity of the rice plant (Casanova et al., 2002). However, panicle density (m^{-2}) in the present study was lower than the 400 mentioned by Balasubramanian et al. (2000a). The effect of N management among three LCC types was not significantly different with respect to panicle density, spikelet number per panicle, and percent filled grain.

Table 4.8. Comparison of yield components, straw yield, total dry matter yield (TDM), and harvest index (HI) of BR-11 variety for different LCC-based N managements in Bangladesh (T-Aman, 2001)

T#	Description	Mean comparison					
		Panicle (No. m^{-2})	Spike-lets/ panicle	Filled grain (%)	Straw yield (t ha^{-1})	TDM (t ha^{-1})	HI
1	N control	231 e †	64 e	86.7 c	2.3 e	4.1 f	0.44 a
2	Rec-N	275 abc	86 bcd	75.3 b	4.2 c	7.4 c	0.44 a
3	SPAD (35)	253 cde	95 a	73.3 b	4.3 bc	7.7 c	0.45 a
4	IRRI LCC-3	275 abc	80 d	81.1 a	4.1 c	7.5 c	0.45 a
5	IRRI LCC-4	286 ab	86 cd	80.2 a	4.5 abc	8.4 ab	0.46 a
6	IRRI LCC-5	286 ab	82 d	81.7 a	4.6 ab	8.5 a	0.46 a
7	China LCC-4	242 de	94 ab	72.3 b	3.8 d	7.0 d	0.46 a
8	China LCC-5	275 abc	81 d	82.2 a	4.4 abc	8.1 b	0.46 a
9	China LCC-6	297 a	79 d	82.3 a	4.7 a	8.5 a	0.45 a
10	California LCC-4	253 cde	79 d	75.7 b	3.5 d	6.5 e	0.46 a
11	California LCC-5	264 bcd	90 abc	79.3 a	4.5 abc	8.2 ab	0.45 a
12	California LCC-6	286 ab	81 d	83.1 a	4.6 ab	8.5 ab	0.46 a

† Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by Duncan's Multiple Range Test (DMRT)

In each LCC management, straw and total dry matter (TDM) yields increased with an increasing rate of applied N (Table 4.8). The yields of straw and TDM yields were similar among IRRI-LCC 4 and 5, China-LCC 5 and 6, and California-LCC 5 and 6, which were twice those of yields without N treatment. The difference of mean effects between IRRI and California-LCC was significant on straw yield at 5% level. The mean effect of IRRI on TDM was significantly different from that of China- and California-LCC managements.

Harvest indices (HI) of all N managements were not significantly different. They ranged from 0.44 to 0.46. The observed harvest indices were slightly lower than the anticipated HI of 0.50 or more that can be achieved with good crop management using modern high-yielding indica cultivars with growth duration between 100 and 130 days (IRRI, 1978; Peng et al., 1994; Hay, 1995). The result observed here supports the finding of Witt et al. (1999) that the HI of plants yielding between 4 and 6 t ha^{-1} was 0.47, and 19% of spikelets were unfilled, while plants with grain yields of <4 t ha^{-1} had an average HI of 0.43 and 25% unfilled spikelets.

4.2.3 Total N uptake, nitrogen harvest index, and internal N use efficiency

A significant positive response of the total N uptake to N application relative to the N control was observed in all N managements (Table 4.9). In each LCC based N management, total N uptake increased with increasing amounts of applied N fertilizer. The lowest total N uptake was found in the California-LCC 4 and the highest in the China-LCC 6 treatment.

The mean comparison of nitrogen harvest index (NHI) showed no difference among the treatments. The finding also shows that N accumulation in grain was higher than in straw (Table 4.9).

As with the NHI, internal N-use efficiencies were significantly different among LCC-based N managements except for California-LCC 4 (Table 4.9). The internal use efficiencies were lower than 68 kg grain kg^{-1}N uptake, which was predicted by QUEFTS model (Witt et al., 1999). The internal efficiency may vary greatly depending on variety, nutrient supply, crop management and climatic conditions. It has been reported that internal nutrient efficiencies decrease in a non-linear fashion at elevated yield level when actual yields approach the potential yield. A critical assumption of this approach is that the internal efficiencies of short-to-medium duration, modern high-yielding rice varieties are similar for a wide range of yield levels, which appears to contradict studies on genotypic variation in internal efficiencies (Broadbent et al., 1987; Tirol-Padre et al., 1996; Singh et al., 1998; Witt et al., 1999).

Table 4.9. Comparison of total N uptake (TNU), nitrogen harvest index (NHI) and internal N use efficiency (IE) of BR-11 variety for the different LCC-based N managements in Bangladesh (T-Aman, 2001)

T#	Description	TNU (kg ha^{-1})	NHI	IE (kg grain kg^{-1}N uptake)
1	N control	36.5 h†	0.64 a	56.0 a
2	Rec-N	80.0 fg	0.62 abc	47.0 b
3	SPAD (35)	101.5 cd	0.59 c	38.2 d
4	IRRI LCC-3	92.7 de	0.60 bc	40.6 cd
5	IRRI LCC-4	115.3 ab	0.60 abc	38.0 d
6	IRRI LCC-5	114.4 ab	0.60 abc	38.5 d
7	China LCC-4	89.8 ef	0.62 abc	40.8 cd
8	China LCC-5	111.0 abc	0.59 bc	37.6 d
9	China LCC-6	121.3 a	0.60 bc	36.2 d
10	California LCC-4	74.4 g	0.63 ab	45.6 bc
11	California LCC-5	104.2 bc	0.63 abc	41.0 cd
12	California LCC-6	114.5 ab	0.60 abc	38.2 d

† Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by DMRT

4.2.4 Partial factor productivity, agronomic efficiency, physiological efficiency, and recovery efficiency

The Rec-N and California-LCC 4 N managements had the highest partial factor productivity (PFP) (Table 4.10). The PFP of China-LCC 4 was significantly different from that of IRRI-LCC 3 and SPAD-35, although the latter were not significantly different from each other. Similar PFP values were observed in IRRI-LCC 4 and 5, China-LCC 5 and 6, and California-LCC 5 and 6 treatments. The PFP values of all LCC managements except California-LCC 4 in this experiment were lower than 44 kg grain kg^{-1} N applied, which have been obtained for irrigated rice from about 700 observations in farmers' fields in six Asian countries (Witt et al., 1999; Dobermann and Fairhurst, 2000; Buresh et al., 2001). However, one should be cautious when using PFP to compare N-use efficiency among different sites. It has been mentioned that PFP does not allow for differentiation between inadequate N fertilizer input to soils with low indigenous soil N supply or high N fertilizer input to soils with either high or low indigenous soil N supply (Olk et al., 1999). The effect of all LCC managements was different from that of Rec-N, but it was not significantly different to that of SPAD-35 (Appendix 3, ANOVA). Although IRRI versus China-LCC was not significant, California-LCC differed from the other two LCCs.

Table 4.10. Comparison of partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) of nitrogen of BR-11 variety for the different LCC- based N managements in Bangladesh (T-Aman, 2001)

T#	Description	Mean comparison			
		PFP	AE	PE	RE
		kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied (%)
1	N control	-	-	-	-
2	Rec-N	44.3 a[†]	19.8 a	40.1 a	52.4 a
3	SPAD (35)	31.0 c	14.8 cd	28.6 bc	52.0 a
4	IRRI LCC-3	29.2 cd	15.2 c	30.8 bc	48.2 a
5	IRRI LCC-4	25.0 f	13.4 d	29.8 bc	45.0 a
6	IRRI LCC-5	25.2 f	13.6 cd	30.4 bc	44.5 a
7	China LCC-4	33.9 b	15.1 c	30.5 bc	49.6 a
8	China LCC-5	26.5 ef	13.5 d	28.7 bc	47.3 a
9	China LCC-6	25.0 f	13.4 d	27.7 c	48.4 a
10	California LCC-4	45.2 a	18.0 b	35.7 ab	50.5 a
11	California LCC-5	28.2 de	14.7 cd	33.0 abc	45.1 a
12	California LCC-6	25.0 f	13.3 d	30.0 bc	44.6 a

[†] Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by DMRT

The highest agronomic efficiency (AE) was observed in Rec-N (19.8 kg additional grain kg^{-1} N applied) followed by California-LCC 4 (18.0 kg additional grain kg^{-1} N applied). Other N managements showed AE values in the range of 13.3 to 15.2 kg additional grain kg^{-1} N applied. These AE values are lower than those reported by Peng et al. (1996) in the Philippines. Yoshida (1981) reported that the typical values for agronomic fertilizer N efficiency were 15-25 kg grain kg^{-1} N applied for both rice and wheat grown with full irrigation and good agronomic management. However, Sattar (2000) reported that in most cases a very poor agronomic efficiency of N fertilizer ranging from 6 to 25 kg grain kg^{-1} N applied was achieved in the studies of BRRI (Bangladesh Rice Research Institute). The AE observed here was similar to that reported for South East Asian rice farms in the dry season (Olk et al., 1999) and in the researcher's plots in Nepal (Adhikari et al., 1999). As for PFP, a similar AE trend was observed (Appendix 3, ANOVA).

Crop-physiological N requirements are controlled by the efficiency with which N in the plant is converted to biomass and grain yield. Because cereal crops are harvested for grain, the most relevant measure of physiological N efficiency (PE) is the change in grain yield per unit change in N accumulation in aboveground biomass (Cassman et al., 2002). In each LCC management, the PE did not differ, though the value ranged from 27.7 to 35.7 kg additional grain kg^{-1} additional N uptake. The highest value in the present study was similar to the value 35 for wet season rice reported by Cassman et al. (1996c). They also reported PE values up to 55 for the dry season in the Philippines, which received much higher solar radiation than the wet seasons of the Philippines or Bangladesh. Kropff et al. (1993) noted that PE was enhanced in the high solar radiation dry season of Asia compared to the wet season. There was no differential effect of the three types of LCC on PE (Appendix 3, ANOVA).

No difference in recovery efficiency (RE) among all N managements was found. RE values ranged from 44.5 to 52.4%. These RE values were higher by 31% than those observed by Adhikari et al. (1999) in the researchers' plots in Nepal and higher by 36-39% than those reported by Cassman et al. (1996c) in farmers' fields in Central Luzon, Philippines, in the dry season. However, the RE observed in the present study were similar to values obtained in the studies of irrigated rice in north-western India (Singh et al., 2002). The relatively high RE values resulted from a significantly higher N accumulation in the plant in fertilized plots than in the control plot in the present experiment. Wopereis et al. (1999) suggested improving rice productivity and profitability by increasing nitrogen recovery (through improved crop management practices) or increasing the amount of N applied. Haefele et al. (2000 and 2001) demonstrated the profitability of improved soil fertility and weed management for small- and large-scale rice farmers in Senegal and Mauritania.

4.3 Estimation of critical LCC value for T-Aman rice varieties in rice-rice and rice-wheat systems

A total of four experiments were conducted in the Meherpur and Kushtia districts in Bangladesh during the wet season (T-Aman) of 2001 to determine the critical LCC value. Since the IRRI-LCC was found to be most suitable, this was included (Section 3.9.2).

4.3.1 Yield and fertilizer nitrogen application (rice-rice system)

In Meherpur, N-control plots produced mean yields of 2.2, 2.6 and 2.3 t ha^{-1} for BR-11, BRRI dhan-30 and BRRI dhan-31, respectively (Table 4.11). A significant positive response of rice grain yield to N application was observed in all varieties. There was no significant difference between the yields of Rec-N and LCC-3 in all varieties. However, N fertilizer application of LCC-3 was relatively higher than that of Rec-N. The highest yields were obtained in treatments with LCC-4- and LCC-5-based N managements in all three varieties. Both treatments showed the same N fertilizer rates and similar yields, which were significantly higher than those of Rec-N and LCC-3. Among the varieties, the highest yield (5.1 t ha^{-1}) was observed on BRRI dhan-30. A relatively lower N fertilizer requirement was shown in LCC-4 and -5 of BRRI dhan-31 compared to the other two varieties.

In Kushtia, N-control plots produced mean yields of 2.7, 2.8, and 2.3 t ha^{-1} for BR-11, BRRI dhan-30 and BRRI dhan-31, respectively (Table 4.11). The yields in Kushtia were generally higher than those in Meherpur. The rice yields responded to N fertilizer. The N fertilizer application in Kushtia was relatively lower than in Meherpur for all LCC managements. A lower rate of applied-N was observed in the LCC-3 management compared to Rec-N in all varieties. LCC-3 achieved similar yields to Rec-N in BRRI dhan-30 and -31, but the yield of LCC-3 was significantly lower than that of Rec-N in BR-11. Like in Meherpur, significantly higher yields resulted from the LCC-4 and LCC-5 managements, where both managements received the same N application and showed similar yields. The highest yield (5.4 t ha^{-1}) was found in BRRI dhan-30.

At both sites, BR-11 showed the lowest mean yields (3.8 t ha^{-1} in Meherpur and 3.9 t ha^{-1} in Kushita) over all N managements (Appendix 4). BRRI dhan-31 produced 4.0 t ha^{-1} in Meherpur and 4.3 t ha^{-1} in Kushtia, which was significantly higher than the yields of BR-11. The highest mean yields of 4.4 and 4.6 t ha^{-1} in Meherpur and Kushtia, respectively, were obtained from BRRI dhan-30. LCC-3 resulted in similar mean yields compared to Rec-N at both sites. The mean yields of N management in LCC-4 and LCC-5 were significantly higher than those of Rec-N and LCC-3. Although N and variety were significantly different, the interaction was not significant (Appendix 4, ANOVA).

Table 4.11. Rice grain yield and N fertilizer application for different rice varieties and different N managements in Meherpur and Kushtia during the T-Aman season of 2001 (rice-rice system)

N management	N rate	No. of splits	Grain yield	N rate	No. of splits	Grain yield	N rate	No. of splits	Grain yield
	kg ha^{-1}		t ha^{-1}	kg ha^{-1}		t ha^{-1}	kg ha^{-1}		t ha^{-1}
		BR-11			BRRI dhan-30			BRRI dhan-31	
Meherpur									
N - control	0	-	2.2 c	0	-	2.6 c	0	-	2.3 c
Rec – N	83	3	3.7 b	83	3	4.7 b	83	3	4.3 b
IRRI-LCC-3	100	3-5	4.0 b	108	3-5	4.7 b	92	3-4	4.2 b
IRRI-LCC-4	175	7	4.7 a	175	7	5.1 a	150	6	4.8 a
IRRI-LCC-5	175	7	4.6 a	175	7	5.1 a	150	6	4.7 a
Kushtia									
N - control	0	-	2.7 d	0	-	2.8 c	0	-	2.3 d
Rec – N	83	3	4.5 b	83	3	4.8 b	83	3	4.2 bc
IRRI-LCC-3	75	3	4.0 c	75	3	4.6 b	75	3	4.1 c
IRRI-LCC-4	150	6	5.1 a	150	6	5.3 a	150	6	4.5 a
IRRI-LCC-5	150	6	5.1 a	150	6	5.4 a	150	6	4.6 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

The yields of the N-control were lower than the 4.2 t ha^{-1} reported by Balasubramanian et al. (2000b) with Chinna Ponni (local improved variety) in Pondicherry, and 5.4 t ha^{-1} (Thiyagarajan et al., 2000b) with the ADT36 variety in Coimbatore, India, during the wet season of 1998. The results of the present study indicate a relatively low native soil N supply capacity in the study area in Bangladesh. This difference in lower native soil N supply may be due to that fact that in the rice-rice cropping system the soil was continuously under submerged conditions, and due to the low quality of the organic matter with slow microbial degradation of the soil humus produced in submerged soils. Even though NPK fertilizers were applied in the recommended dose, declining yield trends were observed at IRRI and at other sites in the Philippines (Flinn and De Datta, 1984; Cassman and Pingali, 1995) and Bangladesh (Pagiola, 1995) in long-term experiments with rice-rice systems. The results of the present study show that Rec-N management produced significantly lower yields compared to the yields of LCC-4 and -5 in all tested varieties in both locations. This means that the recommended N fertilizer application rate may not be adequate to attain higher grain yields. Singh et al. (2002) stated that their experimental results in northwest India suggested a need for application of N fertilizer in excess of the rates recommended for rice. The yield and applied-N were not different between LCC-4 and -5. The results show that the greenness of the rice leaf was usually lighter than the color of LCC-5 patch. The critical LCC value 5 in this study might not be appropriate to determine the N status of the rice plant with regard to N fertilization. Although LCC-3 gave the same yields with the same N fertilizer application rates as Rec-N, those yields were significantly lower than that of LCC-4. However, N fertilizer application was relatively high in the LCC-4 management.

4.3.2 Yield components, straw yield, total dry matter yield, and harvest index (rice-rice system)

All N managements produced a higher panicle number than the N-control at both sites (Table 4.12). There was no significant difference among the LCC-based N managements in all tested varieties. The LCC-based N managements produced relatively more panicles compared to the Rec-N management in Meherpur but LCC-3 produced a relatively lower number of panicles than Rec-N in Kushtia. There was no significant difference in spikelets per panicle among the N managements except for the N-control in both sites. The higher percent filled grain was generally observed in the LCC-4 and -5 N managements for all varieties at both sites. The higher panicle number and higher percent filled grain mainly contribute to the yield increase in this study. Those factors are related to the increase of applied N fertilizer. In the comparison of varieties, BRRI dhan-30 produced the higher panicle number (253 and 242) and higher filled grain percent (80.8% and 81.3%) than the other two varieties in Meherpur and Kushtia, respectively (Appendix 4). There was no significant difference in panicle number between LCC N-managements in Meherpur but it was significant at the 0.01

probability level in the contrast analysis of LCC-3 vs LCC-4 and LCC-3 vs LCC-5 in Kushtia (Appendix 4, ANOVA). Different effects on percent filled grain were observed in the comparison of LCC-3 and -5 in Meherpur, and LCC-3 and LCC-4/-5 in Kushtia.

Since panicle number and spikelet number form the sink capacity of a rice plant, they are generally expected to relate to the yield. Although the rice varieties produced more than 200 panicles in a square meter, those numbers were lower than the 400 observed by Balasubramanian et al. (2000a) in experiments to determine the critical SPAD values in the Philippines. However, the panicle number of the present study was relatively larger than the minimum of 160-180 that is required to stabilize spikelet number and to reduce spatial heterogeneity and weed infestation (Casanova et al., 2002). In this study, an increase in filled grain percent in LCC-4 and -5 significantly contributed to the increase grain yield compared to the other N managements. The result indicates that if an adequate amount of N accumulates in the rice plant through the growing season, this might reduce spikelet sterility. Ntamatugiro et al. (1999) stated that N absorbed by rice during the vegetative growth stage contributed to growth during the reproductive and grain-filling stage through translocation.

In Meherpur, the highest straw yield (4.8 t ha^{-1}) was found for LCC-4 in BR-11, which was not different from LCC-5 (Table 4.12). Among the LCC managements, LCC-3 in BR-11 gave a significantly lower straw yield (3.9 t ha^{-1}) than that of LCC-4 and -5; however, the straw yield was not significantly different from that of Rec-N. The same trend was observed for BRRI dhan-31, but the straw yield of BRRI- dhan-30 did not differ in any of the N managements except in the N-control. In Kushtia, straw yields responded to N application compared to the N-control treatment. There was no difference in straw yields between the Rec-N and the LCC-based managements for BR-11 and BRRI dhan-30. LCC-3 resulted in a relatively low straw yield compared to Rec-N and LCC-4. Slightly higher straw yields were observed for LCC-4 and -5 in all three varieties. The significantly highest straw yields (4.3 t ha^{-1} and 4.8 t ha^{-1}) were produced by BRRI-dhan-30 at both sites (Appendix 4). The higher straw yields affected by the N managements were observed in the LCC-4 and -5 N managements. Although N and variety factors were significant at the 0.01 probability level, there was no interaction between those two factors for either site (Appendix 4, ANOVA). A significant difference was observed between LCC-3 and LCC-4 / -5 but not between LCC-4 and -5.

Table 4.12. Comparison of yield components, straw yield (SY), total dry matter yield (TDM), and harvest index (HI) of different rice varieties and different N managements in Meherpur and Kushtia during the T-Aman season of 2001 (rice-rice system)

N management	Panicle	Spikelets	Filled grain	SY	TDM	HI
	no. m^{-2}	no. $panicle^{-1}$	%	t ha^{-1}	t ha^{-1}	
Meherpur			BR-11			
N - control	198 b	84 b	66.2 c	2.3 d	4.2 c	0.46 ab
Rec - N	242 a	92 a	69.6 bc	4.2 bc	7.5 b	0.44 b
IRRI-LCC-3	264 a	92 a	77.0 ab	3.9 c	7.5 b	0.47 a
IRRI-LCC-4	264 a	98 a	78.5 a	4.8 a	8.9 a	0.46 ab
IRRI-LCC-5	264 a	99 a	81.7 a	4.6 ab	8.7 a	0.47 a
			BRRI dhan-30			
N - control	209 c	86 c	71.3 b	2.7 b	5.0 c	0.46 a
Rec - N	242 b	103 a	83.6 a	4.6 a	8.7 b	0.48 a
IRRI-LCC-3	275 a	97 ab	81.0 a	4.6 a	8.7 ab	0.47 a
IRRI-LCC-4	275 a	96 ab	83.6 a	5.0 a	9.4 a	0.48 a
IRRI-LCC-5	264 ab	104 a	84.8 a	4.8 a	9.2 ab	0.48 a
			BRRI dhan-31			
N - control	176 b	106 b	58.7 c	2.4 c	4.4 c	0.46 a
Rec - N	220 a	124 a	73.2 b	4.1 ab	7.9 ab	0.48 a
IRRI-LCC-3	231 a	109 ab	75.5 ab	3.9 b	7.7 b	0.48 a
IRRI-LCC-4	242 a	112 ab	80.1 ab	4.6 a	8.8 a	0.48 a
IRRI-LCC-5	242 a	116 a	81.7 a	4.5 a	8.7 a	0.48 a
Kushtia			BR-11			
N - control	198 b	101 a	64.7 c	3.1 b	5.4 c	0.44 b
Rec - N	253 a	101 a	81.3 ab	4.5 a	8.5 ab	0.47 a
IRRI-LCC-3	220 b	113 a	78.6 b	4.1 a	7.7 b	0.47 a
IRRI-LCC-4	264 a	106 a	82.6 ab	4.6 a	9.1 a	0.49 a
IRRI-LCC-5	264 a	104 a	84.0 a	4.7 a	9.2 a	0.49 a
			BRRI dhan-30			
N - control	209 c	97 a	64.1 c	3.3 b	5.7 c	0.44 b
Rec - N	253 ab	102 a	83.7 b	5.1 a	9.3 ab	0.46 a
IRRI-LCC-3	231 bc	110 a	85.3 b	4.7 a	8.8 b	0.46 a
IRRI-LCC-4	253 ab	111 a	89.4 ab	5.4 a	10.2 a	0.46 a
IRRI-LCC-5	264 a	110 a	84.2 b	5.4 a	10.2 a	0.47 a
			BRRI dhan-31			
N - control	198 b	109 a	61.8 c	2.8 c	4.8 c	0.43 b
Rec - N	231 a	112 a	73.4 b	4.3 ab	7.9 ab	0.46 a
IRRI-LCC-3	220 ab	108 a	76.4 b	3.9 b	7.5 b	0.48 a
IRRI-LCC-4	231 a	113 a	81.7 a	4.4 ab	8.4 ab	0.48 a
IRRI-LCC-5	231 a	110 a	81.8 a	4.7 a	8.8 a	0.47 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

The total dry matter yields (TDM) of LCC-4 (8.9 t ha^{-1}) and LCC-5 (8.7 t ha^{-1}) were significantly higher than those of Rec-N and LCC-3 of the BR-11 variety in

Meherpur (Table 4.12). The highest TDM (9.4 t ha^{-1}) of BRRI dhan-30 was observed for LCC-4 but it was not much increased compared to TDM produced by LCC-3 (8.7 t ha^{-1}) and LCC-5 (9.2 t ha^{-1}). For BRRI dhan-31, LCC-4 and -5 produced significantly higher TDM (8.8 t and 8.7 t ha^{-1}, respectively) than LCC-3 (7.7 t ha^{-1}); however, they did not differ from Rec-N (7.9 t ha^{-1}). The TDM of LCC-3 was not significantly different from that of Rec-N in all three varieties in both locations. By each variety, more or less similar TDM was produced by LCC-4 and -5 in Kushtia. The TDM of LCC-4 and -5 was significantly higher than that of LCC-3 in all three varieties. A smaller amount of TDM was produced with LCC-3 N management in each variety (7.7 t ha^{-1} in BR-11, 8.8 t ha^{-1} in BRRI dhan-30 and 7.5 t ha^{-1} in BRRI dhan-31); however, it was not significantly different from Rec-N (8.5 t ha^{-1} in BR-11, 9.3 t ha^{-1} in BRRI dhan-30 and 7.9 t ha^{-1} in BRRI dhan-31). The maximum mean effect of variety on TDM was 8.2 and 8.8 t ha^{-1} in BRRI dhan-30 in Meherpur and Kushtia, respectively (Appendix 4). The mean effect of the LCC-4 and -5 N managements was significantly higher than those of the other N managements in both locations (Appendix 4, ANOVA). There was no interaction between N and variety factors even though those factors were significant at the probability 0.05 level. A significant difference was observed in the contrast of LCC-3 vs LCC-4 or -5, while the comparison of LCC-4 versus LCC-5 was not significant.

Straw and total dry matter yields produced in LCC-4 and -5 managements were relatively higher than those for Rec-N and LCC-3 due to the response to the higher N application. The N absorbed during the vegetative period promotes particularly the early growth of plant and increases the tiller number, which determines the potential number of panicles and also contributes to straw and total dry matter yield. Mae and Shoji (1984) proved that the number of tillers was closely correlated to the amount of N absorbed during the vegetative period.

In general, the harvest indices (HI) were not significantly different among the N managements except for the N-control treatment in each variety in both locations (Table 4.12). The mean effect of variety on HI was different in Meherpur but not in Kushtia (Appendix 4). The HI affected by N managements was not significantly different in N managements except for the N-control; however, the relatively higher HI values were observed in the treatments LCC-3, -4 and -5. The N factor was not significant but the variety factor was significant in Meherpur (Appendix 4, ANOVA). On the contrary, the N factor was significant in the analysis of variance, although the variety factor was not significant in Kushtia. There was no interaction between N and variety, and no difference among the LCC-based N managements. Mae (1997) reported that the total dry weight of a rice crop under favorable conditions is around 10-20 t ha^{-1} depending on variety, management, and environment. The harvest index is about 0.5 for improved semi-dwarf varieties. As a result, grain yield ranges between 3 and 10 t ha^{-1} (Yoshida, 1981). The harvest indices of the present study were relatively lower than those in Mae's report (1997).

4.3.3 Total N uptake, nitrogen harvest index, and N-use efficiencies (rice-rice system)

The total N uptake (TNU) of N-control treatments was 34.2 kg ha^{-1} in BR-11, 34.3 kg ha^{-1} in BRRI dhan-30 and 32.5 kg ha^{-1} in BRRI dhan-31 in Meherpur (Table 4.13). In Kushtia, the TNU values of the N-control treatments were 41.8, 46.4 and 33.3 kg ha^{-1} in BR-11, BRRI dhan-30 and BRRI dhan-31, respectively. The significantly high TNU responded to applied-N in the different N managements over the N-control. It was observed that TNU in Kushtia was relatively higher than that in Meherpur. The TNU values of LCC-4 and -5 were significantly higher than those of the other N managements for each variety and location. The significantly highest N accumulation was observed in BRRI dhan-30, i.e., 84.2 kg ha^{-1} in Meherpur and 92.2 kg ha^{-1} in Kushtia (Appendix 5). The TNU affected by LCC-4 (108.0 kg ha^{-1}) or LCC-5 (103.5 kg ha^{-1}) was significantly higher than that of the other treatments in Meherpur. The same trend was observed in Kushita. There was no interaction between N and variety factor but each factor was significant in both locations (Appendix 5, ANOVA). There was a difference between the effects of LCC-3 and LCC-4 or -5 but not between LCC-4 and -5. The TNU of the N-control treatments in this study was similar to the findings of Singh et al. (2002) with the rice cultivars PR-106 and PR-111 at Ludhiana, India. However, LCC-4 and -5 resulted in the higher N accumulation in the rice plants of this study than that in the experiments in India. This may due to the higher N application in the present study, different rice cultivars, and different environmental conditions.

Table 4.13. Comparison of total N uptake (TNU), nitrogen harvest index (NHI), internal N use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) of N applied of different rice varieties and different N managements in Meherpur and Kushtia during the T-Aman season of 2001 (rice-rice system)

N-management	TNU	NHI	IE	PFP	AE	PE	RE
	kg ha^{-1}		kg grain kg^{-1}N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied(%)
Meherpur				BR-11			
N - control	34.2 c	0.67 a	64.1 a	-	-	-	-
Rec – N	70.9 b	0.65 ab	52.7 b	44.8 a	18.6 a	41.9 a	44.3 a
IRRI-LCC-3	75.4 b	0.62 b	53.1 b	40.7 a	17.9 a	44.1 a	40.9 a
IRRI-LCC-4	102.2 a	0.62 b	46.4 bc	26.7 b	14.3 b	38.4 a	38.9 a
IRRI-LCC-5	104.9 a	0.62 b	44.5 c	26.4 b	14.0 b	35.1 a	40.0 a
				BRRI dhan-30			
N - control	34.3 d	0.67 ab	75.7 a	-	-	-	-
Rec – N	70.4 c	0.69 a	66.4 b	56.2 a	25.0 a	58.4 a	43.5 a
IRRI-LCC-3	91.2 b	0.65 ab	51.5 c	44.6 b	19.5 b	36.6 b	53.5 a
IRRI-LCC-4	117.9 a	0.61 b	42.9 d	28.9 c	14.1 c	29.6 b	47.6 a
IRRI-LCC-5	106.9 a	0.64 b	47.6 cd	29.0 c	14.1 c	34.7 b	41.5 a
				BRRI dhan-31			
N - control	32.5 c	0.66 a	71.5 a	-	-	-	-
Rec – N	66.1 b	0.67 a	64.5 b	51.4 a	23.3 a	57.7 a	40.4 a
IRRI-LCC-3	72.3 b	0.64 a	58.3 c	45.8 a	20.3 b	48.4 a	43.9 a
IRRI-LCC-4	103.9 a	0.63 a	45.6 d	31.6 b	16.1 c	33.9 b	47.6 a
IRRI-LCC-5	99.5 a	0.63 a	48.1 cd	31.4 b	15.9 c	36.8 b	44.6 a
Kushtia				BR-11			
N - control	41.8 c	0.63 a	63.8 a	-	-	-	-
Rec – N	83.4 b	0.63 a	54.1 b	54.4 a	22.3 a	44.5 a	50.1 a
IRRI-LCC-3	82.3 b	0.63 a	49.5 bc	54.2 a	18.7 ab	35.0 a	54.0 a
IRRI-LCC-4	110.1 a	0.64 a	45.8 c	33.7 b	15.9 b	34.6 a	45.6 a
IRRI-LCC-5	112.3 a	0.64 a	45.3 c	33.9 b	16.2 b	34.3 a	47.0 a
				BRRI dhan-30			
N - control	46.4 c	0.65 a	62.8 a	-	-	-	-
Rec – N	89.8 b	0.60 a	53.7 b	58.1 a	24.2 a	47.0 a	55.0 a
IRRI-LCC-3	87.1 b	0.60 a	52.8 bc	61.5 a	23.9 a	44.4 ab	57.2 a
IRRI-LCC-4	115.2 a	0.59 a	46.3 c	35.6 b	16.8 b	37.3 ab	47.3 a
IRRI-LCC-5	122.6 a	0.59 a	43.7 c	35.7 b	16.9 b	33.8 b	52.3 a
				BRRI dhan-31			
N - control	33.3 c	0.62 a	69.5 a	-	-	-	-
Rec – N	79.3 b	0.58 a	52.4 b	49.8 a	22.0 a	40.2 ab	55.5 a
IRRI-LCC-3	75.9 b	0.62 a	53.9 ab	54.3 a	23.5 a	42.0 a	56.8 a
IRRI-LCC-4	109.6 a	0.59 a	41.5 c	30.3 b	14.9 b	29.3 b	50.9 a
IRRI-LCC-5	109.7 a	0.58 a	42.1 c	30.8 b	15.8 b	30.1 b	50.9 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

The NHI was not clearly different among the varieties and the N managements (Table 4.13). Although the mean effect of variety on NHI was not different in Meherpur, the mean NHI of BR-11 (0.64) was significantly higher than that of other two varieties in Kushtia (Appendix 5). The effect of LCC-based N managements was not significant with regard to NHI (Appendix 5, ANOVA). It was observed that, in general, NHI values increased when the amount of N applied decreased. The results show that rice plants might absorb the N applied at the late growth stage and perhaps at the flowering stage, but the N might not translocate to the grain.

Internal N use efficiencies (IE) of the N-control in Meherpur were 64.1, 75.7 and 71.5 kg grain kg^{-1} N uptake in BR-11, BRRI dhan-30 and BRRI dhan-31, respectively (Table 4.13). The lowest IE (44.5 kg grain kg^{-1} N uptake) was observed in BR-11 in the LCC-5 management, which was not significantly different from that of LCC-4. There was no significant difference between Rec-N (52.7), LCC-3 (53.1) and LCC-4 (46.4 kg grain kg^{-1} N uptake). However, the IE of Rec-N (66.4 and 64.5 kg grain kg^{-1} N uptake) were significantly higher than those of LCC-based managements with BRRI dhan-30 and BRRI dhan-31, respectively. The relatively low IE of the N-control compared to in Meherpur was observed in Kushtia. Those values were 63.8, 62.8 and 69.5 kg grain kg^{-1} N uptake in BR-11, BRRI dhan-30 and BRRI dhan-31, respectively. The effect of variety on IE of BR-11 (52.1 kg grain kg^{-1} N uptake) was significantly lower than the other two varieties in Meherpur, but the varietal effect on IE was not different in Kushtia (Appendix 5). Different N managements led to different IE in both locations. The mean effect of Rec-N on IE (61.2 kg grain kg^{-1} N uptake) was significantly higher than that of all LCC-based N managements in Meherpur, but the effect (53.4 kg grain kg^{-1} N uptake) was not significantly different from that of LCC-3 in Kushtia. There was an interaction between N and the variety factor in Meherpur, but not in Kushtia (Appendix 5, ANOVA). Significant differences were observed between LCC-3 and -4, and LCC-3 and -5, but not between LCC-4 and -5.

The N-control plots in the present study showed the similar optimal IE of 68 kg grain kg^{-1} N uptake reported by Witt et al. (1999). The IE values of the other N management treatments in the presnent study were relatively lower than the optimal IE. However, those IE values were within the IE borderlines between 48 and 112 kg grain kg^{-1} N uptake (Haefele et al., 2003). The large variation of IE does not only reflect site-and season-specific differences in temperatures and solar radiation but also nutritional imbalances and problems related to irrigation, pest and weed control. The internal efficiency of N was greatly affected by nutrient management (Witt et al., 1999). Thus, N was more diluted in plants of the N-control plots than in other N management treatments because of N limitation.

In Meherpur, partial factor productivity (PFP) of Rec-N (44.8 and 51.4 kg grain kg^{-1} N applied) was not significantly different from that of LCC-3 (40.7 and 45.8 kg grain kg^{-1} N applied) in BR-11 and BRRI dhan-31, respectively (Table 4.13). In BRRI dhan-30, the PFP of Rec-N (52.6 kg grain kg^{-1} N applied) was the significantly highest value followed by LCC-3 (44.6 kg grain kg^{-1} N applied). LCC-4 and -5 N managements resulted in significantly lower PFP than those of Rec-N and LCC-3 in all three varieties. A similar trend was observed in Kushita. However, the PFP of LCC-3 did not significantly differ from that of Rec-N in all three varieties. In general, the PFP values in Kushtia were relatively higher than those in Meherpur. BR-11 showed a significantly low PFP (34.7 kg grain kg^{-1} N applied) on average across N managements in Meherpur; however, the lowest PFP value (41.3 kg grain kg^{-1} N applied) was observed in BRRI dhan-31 in Kushtia (Appendix 5). LCC-4 and -5 showed significantly lower PFP than those of Rec-N and LCC-3 in both locations. Significant differences were observed in the N and variety factors, between LCC-3 and -4 / -5, but there was no difference between LCC-4 and -5. There was no significant difference in the interaction between N and variety (Appendix 5, ANOVA).

Many measurements of productivity exist (Dawe and Dobermann, 1999); however, grain yield can be used to measure the productivity of land (Ladha et al., 2000). The PFP proves to be a useful index for diagnosis of constraints to improved N-use efficiency under field conditions, because it reflects both agronomic efficiency and the balance between the native soil N supply and N applied (Cassman et al., 1996c). The PFP of LCC-4 and -5 were relatively lower than the 38 kg grain kg^{-1} N applied reported for the ASD20 rice cultivar (110 d) with 165 kg N ha^{-1} application in Coimbatore, India during the wet season of 1998 (Thiyagarajan et al., 2000b). However, in the present study, Rec-N and LCC-3 gave higher PFP values because of a lower amount of N applied.

Like PFP, a similar trend was observed with the agronomic efficiency of N applied (AE) for all varieties in both locations (Table 4.13). In Meherpur, the maximum AE value (25.0 kg additional grain kg^{-1} N applied) was achieved in Rec-N with BRRI dhan-30. The minimum AE was 14.0 kg additional grain kg^{-1} N applied in LCC-5 for the BR-11 variety. In Kushtia, the maximum AE (24.2 kg additional grain kg^{-1} N applied) was observed at Rec-N in BRRI dhan-30, and the minimum 14.9 kg additional grain kg^{-1} N applied at LCC-4 in BRRI dhan-31. Although the mean effect of variety on AE showed no difference in Kushtia, BR-11 showed a significant low AE among the three varieties in Meherpur (Appendix 5). In both locations, the effect of LCC-4 and -5 showed significantly low AE compared to that of Rec-N and LCC-3. Although interaction between N and variety was present in Meherpur, it was not significant in Kushtia (Appendix 5, ANOVA). The minimum and maximum AE values of the present study were relatively higher than the values of 13.7 and 20.6 kg additional grain kg^{-1} N applied reported by Janaki et al. (2000) with ADS-18 rice variety under SPAD-based N topdressing management in the wet season of 1998 and 1999 in Coimbatore, India. LCC-4 and -5 of this study resulted in a lower AE compared to the findings of Singh et al. (2002) with PR-111 rice cultivar at Ludhiana, India. However, those AE values were higher than those observed in Nepal (Adhikari et al., 1999).

Physiological efficiency (PE) ranged from 29.6 to 58.4 kg additional grain kg^{-1} additional N uptake in Meherpur (Table 4.13). There was no difference in PE in the BR-11 variety, but the PE of Rec-N (58.4 kg additional grain kg^{-1} additional N uptake) was significantly higher than that for BRRI dhan-30 in LCC-based N managements. In BRRI dhan-31, the PE of Rec-N (57.7 kg additional grain kg^{-1} additional N uptake) and LCC-3 (48.4 kg additional grain kg^{-1} additional N uptake) was significantly different from LCC-4 (33.9 kg grain kg^{-1} additional N uptake) and LCC-5 (36.8 kg grain kg^{-1} additional N uptake). The maximum and minimum PE values were 29.3 and 47.0 kg additional grain kg^{-1} additional N uptake, respectively, in Kushtia. There was no difference in PE in the BR-11 variety. Although Rec-N showed the maximum PE in BRRI dhan-30, it was not significantly different from that of LCC-3 and LCC-4. In BRRI dhan-31, the maximum PE (42.0 kg additional grain kg^{-1} additional N uptake) was observed in LCC-3. There was no difference between Rec-N, LCC-4 and -5. The mean effect of variety on PE was also the same in both locations (Appendix 5). The effects of LCC-4 and -5 on PE were significantly lower than those of Rec-N and LCC-3 in both locations. The interaction between N and variety factors was present in Meherpur but not in Kushtia (Appendix 5, ANOVA). The PE values in the present study approached the PE of 35-55 kg grain kg^{-1} additional N uptake reported for rice in the Philippines (Cassman et al., 1996c). Similar findings in Nepal have been reported by Adhikari et al. (1999). The difference in PE may be due to the different solar radiation in different locations during the growing season. Kropff et al. (1993) reported that PE was enhanced in the high solar radiation dry seasons of Asia compared to wet season.

No significant difference in recovery efficiency (RE) was observed in any of three varieties in both locations (Table 4.13). RE percents ranged from 40.0 to 53.5% in Meherpur and from 45.6 to 57.2% in Kushtia. LCC-3 resulted in relatively higher RE percent compared to that of the other N managements in all three varieties in Kushtia. The RE affected by the variety and N management was not significantly different in both locations (Appendix 5). No difference was observed in the analysis of variance. The RE of the present study was greater than the 31% reported by Adhikari et al. (1999) in Nepal. The RE of LCC-4 and -5 approached the RE of 55% and 49% reported by Singh et al. (2002) in India. Becker et al. (1994) reported that N supply, rice N uptake, and extent of N loss were tightly interlinked processes, and 35% of N loss from urea represented the mean of losses from the basal and later applications. The higher N application in LCC-4 and -5 showed relatively lower RE (%) compared to the RE of LCC-3 in the present study. Thus, later N application may not be effective to increase RE. The results support the findings of Becker et al. (1994). Using ^{15}N, Craswell et al. (1985) reported that the ^{15}N recovery declined slightly between flowering and maturity possibly because of lodging, loss of grain or leaves, or losses of ^{15}N from the plant itself.

4.3.4 Yield and fertilizer nitrogen application (rice-wheat system)

The rice grain yields ranged from 1.9 to 4.5 t ha^{-1} in Meherpur and from 2.7 to 5.1 t ha^{-1} in Kushtia (Table 4.14). LCC-3 produced similar yields to Rec-N in all three varieties in both locations. The amount of applied-N in the LCC-3 management was relatively higher than that of Rec-N in Meherpur, but the amount was lower than that of Rec-N in Kushtia. The significantly higher grain yields were observed in LCC-4 and -5 N managements in all three varieties in both locations. The N fertilizer application rate (125 kg N ha^{-1}) of LCC-4 and -5 was larger than that of the other two N managements (Rec-N and LCC-3). Among the varieties, the maximum yields (4.5 and 5.1 t ha^{-1}) were observed in the BRRI dhan-39 variety in both locations.

The mean effect of variety on grain yield was significant in Meherpur but not in Kushtia (Appendix 6). BRRI dhan-39 showed the higher yield on the average across N managements with 3.8 t ha^{-1} in Meherpur and 4.4 t ha^{-1} in Kushtia. The mean effects of LCC-4 and -5 on the yield were significantly higher than those of the other two N managements in both locations. The mean effect of LCC-3 on yield was not different from that of Rec-N in Meherpur; however, it was significantly lower than that of Rec-N in Kushtia. There was no interaction between N management and variety (Appendix 6, ANOVA). Differences were observed between LCC-3 and LCC-4 or -5, but none between LCC-4 and -5.

The yields from the N-control plots under the rice-wheat system (Table 4.14) were relatively lower than those from the rice-rice system because of a relatively lower amount of total soil N (Section 3.3; Table 3.2b). The results show a lower indigenous soil N supply compared with 4.3 and 3.4 t ha^{-1} in the Cauvery Delta, Tamil Nadu, India, during the wet season (Babu et al., 2000). The amounts of N applied in LCC-4 and-5 in this system were less than those in the rice-rice system due to the short duration varieties (Section 3.4). As in the rice-rice system, results show that the critical LCC value of 5 might not be appropriate for the rice varieties in the rice-wheat system during the T-Aman season. Although LCC-3 produced a similar yield with less N applied to the yield of Rec-N, the yield was significantly lower than that of LCC-4. Both LCC-3 and Rec-N managements seem not to be able to attain the high yield level. The results of this study suggest that the rate of recommended N application should be revised to the increase grain yield. On the other hand, LCC-4 produced a significantly high yield with a higher amount of N applied. This means that the critical LCC value for T-Aman rice varieties may be between LCC-3 and LCC-4 for achieving high yields with optimum N application.

Table 4.14. Rice grain yield and N fertilizer application for different rice varieties and different N managements in Meherpur and Kushtia during the T-Aman season of 2001 (rice-wheat system)

N management	N rate	No. of splits	Grain yield	N rate	No. of splits	Grain yield	N rate	No. of splits	Grain yield
	kg ha^{-1}		t ha^{-1}	kg ha^{-1}		t ha^{-1}	kg ha^{-1}		t ha^{-1}
	BRRI dhan-32			BRRI dhan-33			BRRI dhan-39		
Meherpur									
N - control	0	-	1.9 c	0	-	2.1 c	0	-	2.1 c
Rec - N	83	3	3.9 b	83	3	4.0 b	83	3	4.1 b
IRRI-LCC-3	92	3-4	4.1 b	92	3-4	4.0 b	92	3-4	4.2 b
IRRI-LCC-4	125	5	4.4 a	125	5	4.3 a	125	5	4.5 a
IRRI-LCC-5	125	5	4.4 a	125	5	4.2 a	125	5	4.5 a
Kushtia									
N - control	0	-	2.7 c	0	-	2.7 c	0	-	2.7 c
Rec - N	83	3	4.6 b	83	3	4.7 b	83	3	4.7 b
IRRI-LCC-3	75	3	4.5 b	50	2	4.1 b	75	3	4.5 b
IRRI-LCC-4	125	5	5.0 a	125	5	5.0 a	125	5	5.0 a
IRRI-LCC-5	125	5	5.0 a	125	5	5.0 a	125	5	5.1 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

4.3.5 Yield components, straw yield, total dry matter yield, and harvest index (rice-wheat system)

A significant positive response through panicle number per square meter to N application relative to the N-control was observed in all N managements in both locations (Table 4.15). LCC-3 produced a significantly lower panicle number (253 m^{-2}) than that of LCC-4 (275 m^{-2}) and -5 (308 m^{-2}) in BRRI dhan-32 in Meherpur. In the other two varieties, it produced a relatively small number of panicle compared to the other N managements. In Kushita, a significantly small number of panicles was observed in LCC-3 N managements in all test varieties. The spikelet number per panicle did not differ much in all N managements in BRRI dhan-33 and -39 in Meherpur. There was no significant difference in spikelet number in different N managements except in the N-control in Kushtia. The mean effect of variety on spikelet number was not different in Meherpur, but BRRI dhan-33 showed a significantly lower spikelet number than the other two varieties in Kushtia (Appendix 6). The mean effect of N management on spikelet number did not differ much in both locations; however, the spikelet number per panicle in the different N managements was significantly higher than that of the N-control. There was no difference in spikelet number per panicle in the analysis of variance in Meherpur (Appendix 6, ANOVA). Significant differences were observed for N and variety factors, and in the contrast analysis of LCC-3 vs -5 and LCC-4 vs-5. The highest filled-grain percent (85.9%) was observed in the LCC-5 management of the BRRI dhan-32 variety in Meherpur (Table 4.15). The percent filled-grain was generally higher with increasing N applied in all varieties. The same trend was observed in Kushtia. The percent filled-grain affected by variety was not significant in Meherpur, but BRRI dhan-39 (81.9%) showed significantly higher values than BRRI dhan-33 (79.2%) in Kushtia. The significant differences were observed at N management and in the contrast analysis of LCC-3 vs LCC-4 or -5 (Appendix 6, ANOVA). Among the yield components, increased panicle number per unit area mainly contributed to the higher grain yield with an increased N application. An adequate N application produces a higher tiller number and maintains a healthy rice plant that reflects the decrease in grain sterility. The results of the present study support the findings of ten Berge et al. (1997).

The straw yields ranged from 1.9 t ha^{-1} to 4.5 t ha^{-1} in Meherpur (Table 4.15). LCC-4 and -5 produced similar straw yields, which were significantly larger than those of Rec-N and LCC-3 in BRRI dhan-32. In the other two varieties, straw yields were not significantly different among the N managements except the N-control. The maximum straw yield was 5.0 t ha^{-1} and the minimum 2.7 t ha^{-1} in Kushtia. There was no difference in straw yield in the different N managements except in the N-control. Straw yield was not affected by variety in Meherpur. However, in Kushtia BRRI dhan-39 produced a significantly higher straw yield (4.5 t ha^{-1}) than BRRI dhan-32 (4.2 t ha^{-1}) (Appendix 6).

Table 4.15. Comparison of yield components, straw yield (SY), total dry matter yield (TDM), and harvest index (HI) of different rice varieties and different N managements in Meherpur and Kushtia during the T-Aman season of 2001 (rice-wheat system)

N-management	Panicle	Spikelets / panicle	Filled grain	SY	TDM	HI
	no. m^{-2}	no.	%	t ha^{-1}	t ha^{-1}	
Meherpur			BRRI dhan-32			
N - control	198 c	77 b	67.5 c	1.9 c	3.7 c	0.46 a
Rec - N	264 ab	84 ab	80.4 b	3.9 b	7.5 b	0.46 a
IRRI-LCC-3	253 b	91 a	81.0 ab	4.1 b	7.6 a	0.48 a
IRRI-LCC-4	275 a	93 a	85.7 ab	4.4 a	8.1 a	0.48 a
IRRI-LCC-5	308 a	81 ab	85.9 a	4.4 a	8.3 a	0.47 a
			BRRI dhan-33			
N - control	220 b	79 a	67.4 c	2.1 b	4.1 b	0.45 b
Rec - N	275 a	84 a	78.6 b	4.0 a	7.5 a	0.47 ab
IRRI-LCC-3	253 ab	86 a	83.7 ab	4.0 a	7.5 a	0.47 ab
IRRI-LCC-4	275 a	89 a	85.4 a	4.2 a	8.0 a	0.48 a
IRRI-LCC-5	264 a	88 a	83.9 a	4.2 a	7.9 a	0.47 ab
			BRRI dhan-39			
N - control	209 b	84 a	69.7 c	2.1 b	4.0 b	0.46 b
Rec - N	297 a	81 a	79.6 ab	4.1 a	8.0 a	0.46 b
IRRI-LCC-3	264 a	90 a	78.6 ab	4.2 a	7.8 a	0.48 ab
IRRI-LCC-4	297 a	84 a	84.5 a	4.5 a	8.2 a	0.49 a
IRRI-LCC-5	275 a	92 a	83.4 ab	4.5 a	8.4 a	0.47 ab
Kushtia			BRRI dhan-32			
N - control	198 c	93 b	75.8 b	2.9 b	5.2 b	0.46 b
Rec - N	264 a	106 a	78.5 b	4.4 a	8.5 a	0.48 ab
IRRI-LCC-3	231 b	105 a	81.3 ab	4.4 a	8.4 a	0.47 ab
IRRI-LCC-4	275 a	104 a	83.5 a	4.6 a	9.0 a	0.49 a
IRRI-LCC-5	286 a	97 ab	84.0 a	4.5 a	8.9 a	0.49 a
			BRRI dhan-33			
N - control	209 c	82 b	71.2 b	2.8 b	5.1 c	0.46 a
Rec - N	275 ab	103 a	79.9 ab	4.5 a	8.7 ab	0.48 a
IRRI-LCC-3	253 b	103 a	76.8 b	4.2 a	7.9 b	0.47 a
IRRI-LCC-4	286 a	103 a	84.0 a	4.8 a	9.3 a	0.48 a
IRRI-LCC-5	276 ab	96 a	83.8 a	4.8 a	9.2 a	0.48 a
			BRRI dhan-39			
N - control	198 c	90 c	74.3 b	2.7 b	5.0 b	0.47 a
Rec - N	242 ab	105 ab	82.3 a	4.6 a	8.8 a	0.47 a
IRRI-LCC-3	231 b	106 b	84.0 a	5.2 a	9.2 a	0.43 b
IRRI-LCC-4	264 a	109 a	84.2 a	4.9 a	9.3 a	0.48 a
IRRI-LCC-5	264 a	100 a	84.7 a	5.0 a	9.5 a	0.48 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

In both locations, total dry matter yield (TDM) ranged from 3.7 to 9.5 t ha^{-1} in all tested varieties (Table 4.15). The TDM (7.5 t ha^{-1}) produced by Rec-N was significantly lower than that of the LCC-based N managements of BRRI dhan-32 in Meherpur. There was no difference in TDM in N managements except for the N-control in BRRI dhan-33 and -39. A similar trend was observed in Kushtia, particularly in BRRI dhan-32 and -39. In BRRI dhan-33, LCC-3 produced a significantly lower straw yield (7.9 t ha^{-1}) than those of LCC-4 (9.3 t ha^{-1}) and -5 (9.2 t ha^{-1}), but it did not differ to that of Rec-N (8.7 t ha^{-1}). The BRRI dhan-39 variety showed a higher TDM than those of the other two varieties in Meherpur; however, it did not differ much in Kushtia (Appendix 6). The effects of LCC-4 and -5 were significantly greater than those of Rec-N and LCC-3 in both locations. Significant differences were observed in the N factor in both locations but the variety factor showed differences in Meherpur, not in Kushtia (Appendix 6, ANOVA). In a contrast analysis, differences were observed for LCC-3 and LCC-4 or -5 although they were not significant for LCC-4 vs. -5.

The straw and total dry matter yields increased with increasing amounts of N applied. Those yield increases led to an increase in N accumulation in the rice plant and to translocation of the absorbed N to the grain at the grain-filling stage. It has been reported that the amount of N absorbed by the plant during the grain-filling period is much smaller than the amount of N accumulated in the mature grains, and that a large part of grain N is translocated from vegetative organs, especially from leaf blades (Mae, 1997).

The harvest indices (HI) generally did not differ much between the three varieties in both locations (Table 4.15). The maximum HI value (0.49) in BRRI dhan-39 was significantly higher than that of Rec-N (0.46) in Meherpur. A significantly low HI (0.43) was observed in LCC-3 of BRRI dhan-39 in Kushtia. All three varieties showed no effect on HI in both locations (Appendix 6). However, LCC-based N managements showed a great influence with respect to increasing HI. There were no differences except for the N factor in the analysis of variance in Meherpur (Appendix 6, ANOVA). In addition, significant differences were observed at LCC-3 vs -4 and LCC-3 vs. -5 in Kushtia. The harvest indices of the present study approached the HI of long duration varieties in a field experiment at IRRI during the dry seasons of 1991 and 1992 (Ladha et al., 1998a). However, the HI values were relatively low compared to the HI (0.5) for improved semi-dwarf varieties in the tropics (Yoshida, 1981).

4.3.6 Total N uptake, nitrogen harvest index, and N-use efficiencies (rice-wheat system)

The total N uptake (TNU) ranged from 35.9 to 100.0 kg ha^{-1} in Meherpur (Table 4.16). There was no significant difference among N managements except in the N-control for all three varieties in Merhepur. The TNU values increased with an increase of applied-N in both locations. In Kushtia, LCC-4 and -5 resulted in significantly higher TNU values than those of Rec-N and LCC-3 in all test varieties. BRRI dhan-33 showed a lower absorption of N than the other two varieties in both locations (Appendix 7). LCC-4 and -5 showed a significantly higher N accumulation in the rice plant than those of Rec-N and LCC-3 in both Meherpur and Kushtia. An interaction between the N and variety factors was absent in both locations, and there was also no difference between LCC-4 and -5 (Appendix 7, ANOVA). In general, a relatively low TNU was observed in the present study compared with the TNU of the varieties grown under the rice-rice systems in each N management. This may be due to different native soil N supply capacity, crop maturity days and crop productivity. The N accumulation of LCC-4 in the present study was slightly higher than the amount reported by Singh et al. (2002) with less total N applied in India.

Nitrogen harvest indices (NHI) were generally not different among the N managements of each variety in Meherpur (Table 4.16). In Kushtia, NHI of N-control was significantly higher than that of the other N managements in all varieties. BRRI dhan-33 showed a low NHI (0.54) in Meherpur, but the mean effect of variety on NHI was not significant in Kushtia (Appendix 7). No difference in NHI was observed among the N managements in Meherpur; however, the mean NHI (0.64) of the N-control was significantly higher than that of the other managements in Kushtia.

There was no difference in the contrast analysis of LCC based managements in both locations (Appendix 7, ANOVA). The NHI under this system was generally lower than that under the rice-rice system. Higher grain yields produced by the varieties in the rice-rice system may reflect the increased NHI. Since the varieties grown under the rice-rice system produced higher TDM yields than the varieties under the rice-wheat system, the TDM might contribute to increased N accumulation in the grain. Mae (1997) reported that the remobilized N from the vegetative organs accounts for 70-90% of the total panicle N. The leaf blades are the major source of remobilized N and account for about 60% of the remobilized-N, followed by the leaf sheaths and stem. Meanwhile, roots are only a minor contributing factor (Mae and Ohira, 1981).

Internal N use efficiency (IE) ranged from 44.8 to 56.7 kg grain kg^{-1} N uptake in Meherpur (Table 4.16). The relatively lower IE values were observed at LCC-4 and -5 in all varieties. A similar trend was observed in Kushtia. Hence, the maximum IE value was 72.1 kg grain kg^{-1} N uptake and the minimum was 40.8 kg grain kg^{-1} N uptake. The mean effect of variety on IE was not different in Meherpur, but a low IE value (49.6 kg grain kg^{-1} N uptake) was observed for BRRI dhan-39 in Kushtia (Appendix 7). Although there were no marked differences in the effect of N managements in Meherpur, the effects of LCC-4 (44.0 kg grain kg^{-1} N uptake) and LCC-5 (43.4 kg grain kg^{-1} N uptake) were significantly lower than those of Rec-N and LCC-3.

The IE values of the present study were generally within the ranges of maximum dilution and maximum accumulation derived by Witt et al. (1999). Similar values have been reported from the studies conducted in farmers' fields of Nepal and Bangladesh (Adhikari et al., 1999) and from the on-farm studies of irrigated rice in West Africa (Wopereis et al., 1999).

The partial factor productivity (PFP) value ranged from 33.9 to 49.7 kg grain kg^{-1} N applied in Meherpur (Table 4.16). The PFP of LCC-3 (44.8 and 46.8 kg grain kg^{-1} N applied) was not significantly different from that of Rec-N (46.8 and 49.7 kg grain kg^{-1} N applied) in BRRI dhan-32 and BRRI dhan-39, respectively. However, a significant difference was observed between LCC-3 (43.7 kg grain kg^{-1} N applied) and Rec-N (47.8 kg grain kg^{-1} N applied) in BRRI dhan-33. The PFP of LCC-4 and -5 was significantly lower than that of Rec-N and LCC-3 in all varieties. A similar trend was observed in Kushtia. The BRRI dhan-39 variety showed a greater effect on PFP (42.0 and 54.9 kg grain kg^{-1} N applied) than the other two varieties in both locations (Appendix 7). An interaction of N and variety was present in Kushtia but not in Meherpur (Appendix 7, ANOVA).

Table 4.16. Comparison of total N uptake (TNU), nitrogen harvest index (NHI), internal N use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) of applied-N of different rice varieties and different N managements in Meherpur and Kushtia during the T-Aman season of 2001 (rice-wheat system)

N-management	TNU	NHI	IE	PFP	AE	PE	RE
	kg ha^{-1}		kg grain kg^{-1}N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied (%)
Meherpur				BRRI dhan-32			
N - control	35.9 b	0.59 a	54.2 a	-	-	-	-
Rec - N	78.8 a	0.58 a	49.5 a	46.8 a	23.5 a	48.0 a	51.7 a
IRRI-LCC-3	79.4 a	0.60 a	51.3 a	44.8 a	23.4 a	51.9 a	48.3 a
IRRI-LCC-4	95.9 a	0.58 a	46.0 b	35.2 b	19.7 b	42.6 a	48.0 a
IRRI-LCC-5	96.4 a	0.60 a	46.1 b	35.3 b	19.9 b	43.6 a	48.4 a
				BRRI dhan-33			
N - control	40.7 b	0.50 b	52.2 a	-	-	-	-
Rec - N	73.0 a	0.56 a	54.6 a	47.8 a	22.5 a	57.6 a	39.0 a
IRRI-LCC-3	80.9 a	0.58 a	50.0 a	43.7 b	20.3 a	47.6 b	43.7 a
IRRI-LCC-4	85.9 a	0.56 a	50.1 a	34.2 c	17.4 b	48.0 b	36.2 a
IRRI-LCC-5	89.9 a	0.54 ab	47.6 a	33.9 c	17.1 b	43.8 b	39.4 a
				BRRI dhan-39			
N - control	36.9 b	0.60 a	56.7 a	-	-	-	-
Rec - N	85.7 a	0.58 a	48.3 b	49.7 a	24.5 a	42.2 a	58.8 a
IRRI-LCC-3	90.2 a	0.58 a	47.0 b	46.8 a	23.5 a	40.5 a	58.5 a
IRRI-LCC-4	100.0 a	0.59 a	44.8 b	35.8 b	19.1 b	37.9 a	50.4 a
IRRI-LCC-5	97.2 a	0.58 a	46.3 b	35.8 b	19.1 b	40.5 a	48.2 a
Kushtia				BRRI dhan-32			
N - control	39.4 c	0.64 a	68.6 a	-	-	-	-
Rec - N	86.4 b	0.59 b	53.3 b	55.5 a	22.8 a	40.3 a	56.6 a
IRRI-LCC-3	90.7 b	0.59 b	49.1 bc	59.3 a	23.2 a	34.0 ab	68.4 a
IRRI-LCC-4	109.1 a	0.58 b	45.4 c	39.6 b	18.0 b	32.2 b	55.7 a
IRRI-LCC-5	108.7 a	0.59 b	45.9 c	39.8 b	18.2 b	32.9 b	55.4 a
				BRRI dhan-33			
N - control	36.9 d	0.61 a	72.1 a	-	-	-	-
Rec - N	90.9 b	0.56 b	51.8 c	56.5 b	24.4 a	38.0 a	65.1 a
IRRI-LCC-3	71.8 c	0.59 b	57.9 b	82.8 a	29.6 a	42.7 a	69.7 a
IRRI-LCC-4	116.5 a	0.56 b	43.6 d	40.3 c	19.0 b	30.3 b	63.8 a
IRRI-LCC-5	115.8 a	0.57 b	43.6 d	40.3 c	19.0 b	30.2 b	63.2 a
				BRRI dhan-39			
N - control	39.0 c	0.67 a	68.2 a	-	-	-	-
Rec - N	90.3 b	0.59 b	51.8 b	56.3 a	24.3 a	39.3 a	61.7 b
IRRI-LCC-3	102.1 b	0.55 b	44.4 c	59.6 a	24.2 a	29.8 b	70.7 a
IRRI-LCC-4	116.4 a	0.57 b	43.0 c	40.1 b	18.7 b	30.3 b	62.0 b
IRRI-LCC-5	125.9 a	0.54 b	40.8 c	40.7 b	19.4 b	28.5 b	69.5 ab

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

Increased PFP values in the LCC-based N managements were observed in this system compared to the PFP under the rice-rice system. This may be mainly due to the lower N application to the varieties under the rice-wheat system. Yadav (1998) mentioned that it was important to determine PFP in intensive rice-wheat cropping systems in order to know whether benefits currently accruing from N application in intensive cropping were similar to those obtained during the early phase of the Green Revolution in India in the mid-1970s. The PFP of the present study was higher than the 33.3 kg grain kg^{-1} N applied reported by Yadav (1998) with application of 120 kg N ha^{-1} at four locations in India.

Agronomic efficiency (AE) ranged from 17.1 to 29.6 kg additional grain kg^{-1} N applied in all varieties at both locations (Table 4.16). The AE of LCC-3 was not significantly different from that of Rec-N for each variety and in each location. However, LCC-4 and -5 resulted in a significantly lower AE than those of Rec-N and LCC-3 for all varieties in both locations. The mean effect of BRRI dhan-39 on AE (19.3 kg additional grain kg^{-1} N applied) was significantly lower than that of the other two varieties in Meherpur, but it did not differ from the other two varieties in Kushtia (Appendix 7). Although N and variety factors were significant, there was no interaction between those two factors (Appendix 7, ANOVA). There was no difference between LCC-4 and -5. As with PFP, AE values were higher in this system compared to the rice-rice system.

The AE was also higher than the 12.4 kg additional grain kg^{-1} N applied with a rate of 120 kg N ha^{-1} at four locations in India (Yadav, 1998). The AE in the LCC-based managements in the present study were appreciable values for the T-Aman rice varieties according to the AE value of 15 kg additional grain kg^{-1} N applied, proposed by R.J. Buresh, IRRI, Philippines (personal communication), for a target yield of 4.5 t ha^{-1} with 2.5 t ha^{-1} supplied by native soil N in the T-Aman season.

There was no difference in physiological efficiency (PE) among the N managements of BRRI dhan-32 and -39 in Meherpur (Table 4.16). In BRRI dhan-33, PE of Rec-N (57.6 kg additional grain kg^{-1} additional N uptake) was significantly higher than that of LCC-based N managements. However, LCC-3 showed no different PE (34.0 and 42.7 kg additional grain kg^{-1} additional N uptake) compared to Rec-N (40.3 and 38.0 kg additional grain kg^{-1} additional N uptake) in BRRI dhan-32 and BRRI dhan-33 in Kushtia, respectively. LCC-4 and -5 resulted in low PE in all varieties at both locations. Although variety showed no effect on PE in Kushtia, the mean effect of BRRI dhan-39 on PE (40.3 kg additional grain kg^{-1} additional N uptake) was significantly lower than that of the other two varieties (Appendix 7). However, the variety factor was not significant in the analysis of variance in both locations (Appendix 7, ANOVA). There was no difference in PE between LCC-based managements in Meherpur, but differences were observed for LCC-3 vs. -5 and LCC-3 vs. -4 at the 0.05 probability level.

Yoshida (1981) reported that a PE of 50 kg grain kg^{-1} additional N uptake is typical of modern rice cultivars grown under favorable conditions with good crop managements in the tropics. The PE values of LCC-based managements were relatively lower than the typical PE value in the present study, but relatively higher PE was observed in LCC-3 (51.9 kg grain kg^{-1} additional N uptake) and Rec-N (57.6 kg grain kg^{-1} additional N uptake) in Meherpur. The PE of LCC-4 and -5 in Meherpur was higher than the PE of 32 kg grain kg^{-1} additional N uptake reported by Peng et al. (1996) with an application rate of 120 kg N ha^{-1} in the Philippines. However, the PE of LCC-4 and -5 in Kushtia was more or less similar to the findings of Peng et al. (1996). The low phosphorous content in the Kushtia soil may reflect the reduced N-use efficiency in this field (Section 3.3; Table 3.2b).

The recovery percent of applied N (RE) was generally not different among the N managements in both locations (Table 4.16). The maximum RE (70.7%) was observed in LCC-3 for BRRI dhan-39 in Kushtia and the minimum (36.2%) in LCC-4 for BRRI dhan-33 in Meherpur. The relatively low effects of variety on RE (39.5% and 59.0%) were observed for BRRI dhan-33 in Meherpur and for BRRI dhan-32 in Kushtia, respectively (Appendix 7). No difference was observed among the LCC-based managements in both locations except for LCC-3 vs. -4 in Kushtia (Appendix 7, ANOVA).

The RE values in Kushtia were relatively higher than those in Mehrpur. This may be due to the different total soil N content in those fields (Section 3.3; Table 3.2b). It has been demonstrated that it is possible to achieve a high RE with relatively high N fertilizer rates, but only when crop N demand is much higher than the indigenous supply (Cassman et al., 2002). However, The RE of LCC-4 and -5 was generally lower than those of the Rec-N and LCC-3 managements in both locations. The results indicate that the losses of applied-N might be large in LCC-4 and -5 managements. Stutte and da Silva (1981) stated that high temperatures exacerbate volatile losses of N during the grain filling period in rice. Using ^{15}N, Katyal et al. (1985) reported that 46 to 50% of the urea and ammonium sulfate was unaccounted for and considered lost from the system, in Punjab, India. Denitrification is considered to be one of the main pathways of nitrogen losses in the flooded rice fields (Reddy and Patrick, 1986).

4.4 Estimation of the critical LCC values for rice varieties in the Boro season

The experiment was conducted at Chandbill village in the Meherpur district during the Boro season 2001-02. Six Boro rice varieties, three inbred and three hybrid varieties, were transplanted into six N managements.

4.4.1 Yield and fertilizer nitrogen application

Grain yield ranged from 2.4 to 8.6 t ha^{-1} (Table 4.17). Yield from the N-control treatment in each variety was less than 3 t ha^{-1}, indicating that the experimental fields had a low indigenous soil N-supplying capacity.

The SPAD-32 management resulted in similar a yield (4.8 t ha^{-1}) with less applied-N (70 kg N ha^{-1}) compared to the yield (5.1 t ha^{-1}) of recommended N management (102 kg N ha^{-1}) for the BRRI dhan-28 variety. The yield (6.0 t ha^{-1}) of SPAD-35 with less N (90 kg N ha^{-1}) was significantly higher than that of Rec-N. The significantly higher yields (6.6 and 7.0 t ha^{-1}) were obtained from SPAD-39 and SPAD-43 with 150 and 180 kg N applied ha^{-1} with the BRRI dhan-28 variety. With BRRI dhan-29, the yields of Rec-N (5.5 t ha^{-1}) and SPAD-32 (5.1 t ha^{-1}) were not significantly different; however, SPAD-32 could save about 50% of N fertilizer compared to Rec-N. SPAD-35 resulted in a significantly higher yield (6.8 t ha^{-1}) than that of Rec-N, and its N application (120 kg N ha^{-1}) was relatively lower than that of Rec-N. There was no significant difference between the yields of SPAD-35, -39 and -43, but the N application rates of SPAD-39 (180 kg N ha^{-1}) and -43 (210 kg N ha^{-1}) were higher than that of the SPAD-35 management. As with BRRI dhan-29, a similar trend was observed for BRRI dhan-36. Although the differences in yield between Rec-N (5.6 t ha^{-1}) and SPAD-32 (5.5 t ha^{-1}) were not significant, the N application rate was lower in SPAD-32

(70 kg N ha^{-1}) compared to Rec-N (102 kg N ha^{-1}). The significantly high yield (6.0 t ha^{-1}) was observed in SPAD-35 with a rate of 120 kg N ha^{-1}. The yields of SPAD-39 (6.5 t ha^{-1}) and -43 (6.9 t ha^{-1}) were significantly higher than those of the other N managements.

With the BRRI hybrid-1 variety, SPAD-32 resulted in similar a yield (6.7 t ha^{-1}) with an application of 92 kg N ha^{-1} compared to the yield of Rec-N (6.7 t ha^{-1}) with 126 kg N ha^{-1}. The yield of SPAD-35 (7.2 t ha^{-1}) was significantly higher than those of Rec-N and SPAD-32; N application rate was 132 kg N ha^{-1}. The significantly high yields were observed at SPAD-39 (7.9 t ha^{-1}) and SPAD-43 (7.8 t ha^{-1}) with N fertilizer rates of 171 and 242 kg N ha^{-1}, respectively. There was no difference in yield between SPAD-39 and -43.

A similar trend was observed for the Alok variety. The yield of SPAD-32 (5.8 t ha^{-1}) with 102 kg N ha^{-1} showed a non-significant difference from the yield of Rec-N (6.0 t ha^{-1}) with 126 kg N ha^{-1} application. SPAD-35 produced a significantly higher yield (6.6 t ha^{-1}) than Rec-N and SPAD-32; its N application was 122 kg N ha^{-1}. Both SPAD-39 (7.4 t ha^{-1}) and -43 (7.3 t ha^{-1}) resulted in significantly higher yields compared to the yields of the other N managements. The applied-N amounts of those two treatments were 162 and 222 kg N ha^{-1}, respectively. With the Sonar Bangla-1 variety, SPAD-32 gave the relatively lower yield (6.8 t ha^{-1}) with 102 kg N ha^{-1} application compared to Rec-N (7.1 t ha^{-1}) with 126 kg N ha^{-1}, but those yields were not significantly different. The relatively higher yield (7.4 t ha^{-1}) was observed for SPAD-35 with a lower N application (122 kg N ha^{-1}) compared to Rec-N. Significantly higher yields were observed for SPAD-39 (8.3 t ha^{-1}) and SPAD-43 (8.6 t ha^{-1}) with N applications of 202 and 222 kg N ha^{-1}, respectively.

Among the varieties, Sonar Bangla-1 produced the highest mean yield (6.8 t ha^{-1}) and BRRI dhan-28 the lowest (5.4 t ha^{-1}) over all N managements (Appendix 8). The greatest effect of N management on yield was observed at SPAD-39 (7.3 t ha^{-1}) and SPAD-43 (7.5 t ha^{-1}). Significant differences were observed with respect to the N management factor and also to the variety factor (Appendix 8, ANOVA). There was a significant interaction between N and variety. All N managements were significantly different from each other, but there was no difference between SPAD-39 and SPAD-43.

Table 4.17. Comparison of grain yield and yield components of different rice varieties and different N managements in Meherpur during the Boro season 2001-02

N-management	N rate	No. of splits	Grain yield	Panicle	Spikelets / panicle	Filled grain
	kg ha^{-1}		t ha^{-1}	no. m^{-2}	no.	%
				BRRI dhan-28		
N - control	0	0	2.4 d	209 d	81 d	70.3 b
Rec - N	102	3	5.1 c	297 c	96 a	85.5 a
SPAD 32	70	2-3	4.8 c	330 b	85 cd	84.9 a
SPAD 35	90	3	6.0 b	330 b	86 bcd	87.5 a
SPAD 39	150	5	6.6 a	352 b	95 ab	84.4 a
SPAD 43	180	6	6.9 a	396 a	93 abc	88.1 a
				BRRI dhan-29		
N - control	0	0	2.4 c	198 c	80 c	80.3 a
Rec - N	126	3	5.5 b	352 b	91 b	83.4 a
SPAD 32	60	2	5.1 b	319 b	90 b	80.4 a
SPAD 35	120	3-5	6.8 a	330 b	106 a	86.4 a
SPAD 39	180	6	7.0 a	396 a	91 b	86.2 a
SPAD 43	210	7	7.0 a	396 a	93 b	85.4 a
				BRRI dhan-36		
N - control	0	0	2.3 d	176 c	79 b	74.1 c
Rec - N	102	3	5.6 bc	363 b	79 b	79.2 bc
SPAD 32	70	2-3	5.5 c	341 b	81 b	85.0 a
SPAD 35	120	4	6.0 b	352 ab	82 b	81.6 ab
SPAD 39	170	5-6	6.5 a	407 a	86 ab	77.5 bc
SPAD 43	180	6	6.9 a	407 a	92 a	75.4 c
				BRRI hybrid-1		
N - control	0	0	2.7 d	196 c	88 b	74.3 b
Rec - N	126	3	6.7 c	341 b	89 b	83.2 a
SPAD 32	92	3	6.7 c	341 b	90 b	84.3 a
SPAD 35	132	3-5	7.2 b	363 ab	103 a	77.1 b
SPAD 39	172	5-6	7.9 a	396 a	96 ab	85.3 a
SPAD 43	242	8	7.8 a	385 a	94 ab	84.0 a
				Alok		
N - control	0	0	2.8 d	220 c	90 b	72.4 c
Rec - N	126	3	6.0 c	352 b	104 a	77.2 bc
SPAD 32	102	3	5.8 c	341 b	100 a	81.1 ab
SPAD 35	122	3-4	6.6 b	385 a	100 a	82.9 ab
SPAD 39	162	5	7.4 a	407 a	102 a	84.2 a
SPAD 43	222	7	7.3 a	418 a	98 ab	84.8 a
				Sonar Bangla-1		
N - control	0	0	2.7 d	176 d	94 b	70.6 b
Rec - N	126	3	7.1 bc	275 c	112 a	87.1 a
SPAD 32	102	3	6.8 c	264 c	112 a	87.6 a
SPAD 35	122	3-4	7.4 b	286 c	112 a	85.7 a
SPAD 39	202	6-7	8.3 a	341 b	106 a	86.2 a
SPAD 43	222	7	8.6 a	374 a	104 a	85.8 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

Note- Numbers of split application for hybrid varieties (BRRI hybrid-1, Alok and Sonar Bangla-1) included the basal application.

In both inbred and hybrid varieties, SPAD-32 resulted in similar yields with a lower N application compared to Rec-N. The result indicates that SPAD-based management can save N fertilizer and produces the same yields as achieved with the locally recommended N applications. Thus, SPAD-based N management can benefit resource-poor, small-scale farmers, because it may save about 31-52% N-fertilizer in inbred varieties and about 19-27% in hybrid varieties due to improved synchrony between plant demand and N supply. Babu et al. (2000) reported that SPAD-based management could save fertilizer rates of 50-65 kg N ha^{-1} during the dry season and 78-95 kg N ha^{-1} in the wet season in the Cavery delta, Tamil Nadu, India. Ladha et al. (2000) stated that 20-25% of the N fertilizer input was saved without reducing rice grain yield based on a large number of SPAD experiments both at the research stations of the National Agricultural Research Systems (NARS) in Bangladesh, India and Nepal, and in farmers' fields carried out through the Crop and Resource Management Network (CREMNET). However, both SPAD-32 and Rec-N did not produce a high grain yield in the present study. This indicates that the current recommendation of fertilizer N application should be revised, and also shows the need for higher N applications. The findings of this study agree with the proposal of Wopereis et al. (1999), who stated that by increasing N recovery (through improved crop management practices) or increasing the amount of N applied, rice productivity and profitability could be improved.

SPAD-43 management resulted in non-significantly increased yield compared to the yield of SPAD-39 management with a lower N application in all test varieties. The final N application at the flowering stage apparently contributed less to the increase in grain yield. It has been reported that top dressing of N fertilizer before or after heading is one way to prevent a rapid decline of leaf N and photosynthesis, but its effect on yield was estimated to be only marginal (10% increase) (Wada et al., 1986). The increase in yields of SPAD-43 in the present study were only 8% for BRRI dhan-28, 6% for BRRI dhan-36 and 4% for Sonar Bangla-1 over the yields of SPAD-39. Thus, SPAD-43 may not be a suitable critical SPAD value for determining topdressing N fertilizer in the study area in Bangladesh during the Boro season.

Among the inbred varieties, there was no significant difference in yields between SPAD-35 and -39 for BRRI dhan-29 and -36, although SPAD-35 resulted in lower a yield than that of SPAD-39 for BRRI dhan-28. Several factors affect SPAD values: radiation differences between seasons, plant density, varietal group, nutrient status other than N in soil and plant, and biotic and abiotic stress that induce leaf discoloration (Peterson et al., 1993; Turner and Jund, 1994). In the present study, although the varieties are semi-dwarf indica, the differences in yield response to same SPAD critical value may be due to the varietal difference.

In hybrid varieties, significantly higher yields were obtained with SPAD-39 management; however, the amount of N applied was relatively high. Because basal N fertilizer was applied at the transplanting time in all SPAD-based managements following the recommended N fertilizer application, the amount of N applied was high. There is no N uptake during the week after transplanting due to the transplanting shock (Becker et al., 1994), and rice seedlings take about 7 days to recover (Meelu and Gupta, 1980). Thus, the basal applied-N may not be efficiently used by the rice plants and may be lost. The other factor may be cool temperature at the early growth stage during the Boro season (Section 3.1; Figure 3.1). Leaf growth was found to be sensitive to various environmental stresses, e.g., low air temperature (Shimono et al., 2000), drought (Boonjung and Fukai, 1996), and nitrogen deficiency (Hasegawa and Horrie, 1997). Furthermore, leaf area was largely responsible for limited growth in cool water. Shimono et al. (2002) reported a grain yield decreased by 3.4% with a 1°C decrease in water temperature in the range of 16-23°C.

4.4.2 Yield components, straw yield, total dry matter yield, and harvest index

A significant positive response of panicle number per square meter to N application relative to the N-control was observed in all N managements in this experiment (Table 4.17). The highest panicle number (396) was observed with SPAD-43 for BRRI dhan-28. There is no significant difference in panicle number between SPAD-32, -35 and -39; however, those panicle numbers were significantly higher than that of Rec-N. In BRRI dhan-29, SPAD-39 and -43 produced significantly higher panicle numbers compared to the other N managements. The panicle number produced by SPAD-35 in BRRI dhan-36 was not different from that of SPAD-39 and -43, and was also not significantly different from SPAD-32 and Rec-N. A similar trend was observed in the BRRI hybrid-1 variety. There was no significant difference in panicle number between SPAD-35, -39 and -43 for the Alok variety, which showed significantly higher numbers than SPAD-32 and

Rec-N. The highest panicle number was observed with SPAD-43 for the Sonar Bangla-1 variety. There was a significant effect of variety on panicle number (Appendix 8). The lowest panicle number (286) was observed in the Sonar Bangla-1 variety and the highest in the Alok variety (354). An effect of N management on panicle number is the increase in number with the increase in N applied. In general, an increase in panicle number was the main factor contributing to an increase in grain yield in all varieties. As with grain yield, a significant interaction was present between N and variety factors (Appendix 8, ANOVA). There was no difference effect in the contrast analysis of SPAD-39 vs. -43.

The number of spikelets per panicle ranged form 79 to 112 depending on variety (Table 4.17). Although all N managements resulted in a higher spikelet number per panicle than the N-control, there is no marked difference between the N managements. The yield component factor of spikelet number per panicle may contribute less to yield increase compared to the panicle number factor. The different varietal effect was observed on spikelet number per panicle (Appendix 8). Although effects of different N managements on spikelet number were observed in this experiment, they were not very clear. The interaction of N and variety factors was significant at 0.01 probability level (Appendix 8, ANOVA). There was no difference among the N managements except in the contrast analysis of SPAD-32 vs. SPAD-35.

There was no difference in percent filled grain among the N managements in BRRI dhan-28 except the N-control (Table 4.17). Although the filled grain percent of SPAD-35 (87.5%) was relatively higher than that of SPAD-39 (84.4%), this value was less than that of SPAD-43 (88.1%). In contrast, the percent filled grain of SPAD-35 was relatively higher than that of SPAD-39 and -43 for BRRI dhan-29 and BRRI dhan-36. SPAD-32 resulted in a higher filled grain percent (85.0%) than that of N-control (74.1%), Rec-N (79.2%), SPAD-39 (77.5%) and SPAD-43 (75.4%), but the value was not significantly different from that of SPAD-35 (81.6%). Among the hybrid varieties, the filled grain percents of SPAD-39 and -43 were generally higher than that of SPAD-35. The relatively higher mean filled grain percents over N managements were observed for BRRI dhan-29 (83.7%) and Sonar Bangla-1 (83.8%) varieties (Appendix 8). No different effect of N managements on filled grain percent over the varieties was observed. Interaction was present at the 0.01 probability level (Appendix 8, ANOVA).

Among the yield components, a yield increase was mainly result of an increase in panicle number produced per square meter. ten Berge et al. (1997b), Thakur et al. (1999), Morales et al. (2000), and Balasubramanian et al. (2000b) reported similar findings. The N supply-demand synchronization could speculate to reduce the number of unproductive tillers and increase harvest index and agronomic N-use efficiency (Morris et al., 1986; Becker et al., 1991).

The hybrid varieties had a greater number of spikelets per square meter than inbred varieties because of a relatively higher number of spikelets per panicle and panicle number per square meter. However, filled-grain percents did not differ much. It has been reported that the number of spikelets per panicle and per square meter was correlated significantly and negatively with the percentage of ripened grain among 13 rice varieties (Yamamoto et al., 1991). In contrast, Peng et al. (1999) reported that the variation in percentages of filled and partially filled spikelets was not correlated with spikelet number per panicle among 12 tropical japonica lines. Yang et al. (2002) also reported that the correlation between spikelet filling percentage and spikelet number per panicle was not singnificant among the 36 japonica / indica hybrid varieties. The results of the present study support the finding of Yang et al. (2002) that a large number of spikelets per panicle did not necessarily result in poor grain filling.

The straw yields ranged from 2.5 to 6.8 t ha^{-1} in inbred varieties and from 2.8 to 8.3 t ha^{-1} in hybrid varieties (Table 4.18). There was no significantly different straw yield between Rec-N and SPAD-32, and between SPAD-35 and -39 in the BRRI dhan-28 variety. The highest straw yield (6.8 t ha^{-1}) was obtained from SPAD-43. In BRRI dhan-29, there was no difference between SPAD-35 (6.1 t ha^{-1}), SPAD-39 (6.3 t ha^{-1}) and SPAD-43 (6.5 t ha^{-1}), but those straw yields were significantly higher than those of Rec-N (5.0 t ha^{-1}) and SPAD-32 (4.7 t ha^{-1}). The highest straw yield (6.5 t ha^{-1}) was observed for SPAD-43 in BRRI dhan-36, which was not significantly different from SPAD-39 (6.2 t ha^{-1}). Those straw yields were significantly higher than those of Rec-N (5.1 t ha^{-1}) and SPAD-32 (5.3 t ha^{-1}). In the BRRI hybrid-1 variety, there was no significant difference between SPAD-35 (7.0 t ha^{-1}), SPAD-39 (7.2 t ha^{-1}) and SPAD-43 (7.5 t ha^{-1}). The straw yields obtained from SPAD-39 and -43 were significantly higher than those of the other N managements with the Alok and Sonar Bangla-1 varieties. It was observed that the mean effect of hybrid varieties on straw yield was higher than that of inbred varieties (Appendix 8). The greatest effect of N management on straw yield was found in SPAD-43 (7.1 t ha^{-1}) followed by SPAD-39 (6.9 t ha^{-1}) over all varieties. Both N and variety factors resulted in significant differences in this experiment (Appendix 8, ANOVA). An interaction of N and variety was present at the probability 0.01 level. All contrast analyses between the N managements were significant.

Total dry matter yields (TDM) ranged from 4.6 to 14.4 t ha^{-1} in all tested varieties (Table 4.18). The TDM of SPAD-35, -39 and -43 was generally larger than those of Rec-N and SPAD-32 in all varieties. The greatest mean effect of variety on TDM (12.8t ha^{-1}) was observed in the Sonar Bangla-1 variety (Appendix 8). The highest mean effect of N management on TDM (13.7 t ha^{-1}) was found in SPAD-43 followed by SPAD-39 (13.3 t ha^{-1}) and SPAD-35 (12.2 t ha^{-1}). The significant differences were observed for all factors except replication and the contrast analysis of SPAD-39 vs. -43 (Appendix 8, ANOVA).

Harvest indices (HI) ranged from 0.45 to 0.50 in all tested varieties (Table 4.18). There was no difference in HI for N managements in inbred varieties. SPAD-35 and -39 resulted in relatively high HI in the BRRI hybrid-1 variety. SPAD-32 gave a significantly lower HI (0.46) compared to the other N managements with the Sonar Bangla-1 variety. Among the varieties, the highest HI value was observed in BRRI dhan-29; however, HI values did not differ much between the N managements (Appendix 8). An interaction effect of N and variety was absent in the HI (Appendix 8, ANOVA). The HI of the present study approached the value of 0.5 determined in the other studies (Yoshida, 1981; Witt et al., 1999). Since the increase in grain yield related to an increase in total dry matter production, the HI did not differ much between the N managements except in the N-control in the present study.

4.4.3 Total N uptake, nitrogen harvest index, and internal use efficiency

The minimum total N uptake (TNU) was 30.9 kg N ha^{-1} and the maximum 159.8 kg N ha^{-1} (Table 4.18). The significantly higher TNU values were observed in SPAD-39 and -43 in all varieties due to the higher N application during the growing season. Among the varieties, BRRI hybrid and Sonar Bangla-1 showed the highest N accumulation, i.e., 105.3 and 102.0 kg N ha^{-1}, respectively (Appendix 8).

Table 4.18. Comparison of straw yield (SY), total dry matter yield (TDM), harvest index (HI), total N uptake (TNU), nitrogen harvest index (NHI) and internal N use efficiency (IE) of different rice varieties and different N managements in Meherpur during the Boro season 2001-02

N-Management	SY t ha^{-1}	TDM t ha^{-1}	HI	TNU kg ha^{-1}	NHI	IE kg grain kg^{-1} N uptake
			BRRI dhan-28			
N - control	2.5 d	4.7 d	0.45 b	34.6 d	0.57 c	69.2 ab
Rec - N	4.6 c	9.1 c	0.49 a	67.7 c	0.69 a	75.1 a
SPAD 32	4.6 c	9.1 c	0.49 a	79.4 c	0.64 ab	63.7 ab
SPAD 35	5.7 b	11.0 b	0.48 a	81.6 c	0.66 ab	73.3 a
SPAD 39	6.1 b	11.9 b	0.49 a	110.2 b	0.66 ab	59.7 bc
SPAD 43	6.8 a	13.1 a	0.48 a	137.2 a	0.62 bc	51.1 c
			BRRI dhan-29			
N - control	2.5 c	4.6 c	0.46 b	30.9 c	0.58 ab	77.7 ab
Rec - N	5.0 b	9.9 b	0.50 a	70.6 b	0.61 a	79.0 ab
SPAD 32	4.7 b	9.2 b	0.49 a	63.6 b	0.62 a	80.2 a
SPAD 35	6.1 a	12.1 a	0.50 a	96.6 b	0.61 a	70.3 ab
SPAD 39	6.3 a	12.6 a	0.50 a	104.7 a	0.61 a	68.3 b
SPAD 43	6.5 a	12.8 a	0.49 a	139.5 a	0.55 b	50.5 c
			BRRI dhan-36			
N - control	2.5 d	4.6 c	0.46 b	31.4 c	0.60 b	74.8 a
Rec - N	5.1 c	10.1 b	0.49 a	75.1 b	0.65 ab	74.6 a
SPAD 32	5.3 c	10.1 b	0.48 a	86.1 b	0.64 ab	63.9 ab
SPAD 35	5.7 bc	11.0 b	0.49 a	91.5 b	0.66 a	65.8 ab
SPAD 39	6.2 ab	12.0 a	0.48 a	113.7 a	0.64 ab	57.7 b
SPAD 43	6.5 a	12.7 a	0.48 a	126.0 a	0.63 ab	55.4 b
			BRRI hybrid-1			
N - control	2.9 c	5.2 d	0.45 c	34.7 c	0.61 ab	77.4 a
Rec - N	6.5 b	12.4 c	0.48 b	98.0 b	0.63 ab	67.9 ab
SPAD 32	6.6 b	12.5 c	0.47 b	99.2 b	0.60 b	69.4 ab
SPAD 35	7.0 ab	13.4 bc	0.48 ab	104.0 b	0.64 ab	70.2 ab
SPAD 39	7.2 a	14.2 ab	0.49 a	135.8 a	0.66 a	60.3 b
SPAD 43	7.5 a	14.4 a	0.48 b	159.8 a	0.61 ab	48.8 c
			Alok			
N - control	2.8 d	5.3 d	0.46 b	40.1 e	0.61 a	70.3 ab
Rec - N	5.9 bc	12.4 c	0.47 ab	85.1 cd	0.64 a	70.6 ab
SPAD 32	5.6 c	12.5 c	0.48 ab	79.1 d	0.64 a	73.4 a
SPAD 35	6.3 b	13.4 bc	0.48 a	97.7 c	0.66 a	68.1 ab
SPAD 39	7.2 a	14.2 ab	0.48 ab	121.4 b	0.64 a	61.4 bc
SPAD 43	6.9 a	14.4 a	0.48 a	143.0 a	0.61 a	51.5 c
			Sonar Bangla-1			
N - control	2.9 c	5.3 c	0.45 b	34.2 c	0.62 b	72.3 a
Rec - N	6.7 b	11.2 c	0.49 a	88.5 b	0.68 a	80.3 a
SPAD 32	7.0 b	10.8 c	0.46 b	88.2 b	0.65 ab	77.8 a
SPAD 35	7.1 b	12.2 b	0.48 a	94.9 b	0.67 ab	78.0 a
SPAD 39	8.2 a	13.7 a	0.48 a	149.4 a	0.62 ab	55.9 b
SPAD 43	8.3 a	13.5 a	0.48 a	156.9 a	0.62 b	55.1 b

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

The highest mean N accumulation (143.7 kg N ha^{-1}) was observed for SPAD-43 and the lowest (80.9 kg N ha^{-1}) for Rec-N except for the N-control. There were significantly different effects in the analysis of variance, and the interaction of N and variety was absent in TNU (Appendix 8, ANOVA). Nitrogen accumulation increased with increasing dose of N fertilizer application in all varieties. The efficiency in uptake and utilization of N in the production of grain requires that those processes associated with adsorption, transloaction, assimilation and redistribution of N operate effectively (Moll et al., 1982). Nitrogen absorbed by rice during the vegetative growth stage contributes to growth during the reproductive and grain-filling growth stages through translocation (Ntamatungiro et al., 1999). Thus, crop N uptake with an adequate soil N supply is to a large extent determined by crop growth rate (Gastal and Lemaire, 2002).

The nitrogen harvest index (NHI) ranged from 0.57 to 0.69 in this experiment (Table 4.18). In general, the NHI of SPAD-43 was usually less than those of SPAD-39 and -35 in all varieties. There was no varietal effect on NHI except in BRRI dhan-29 (Appendix 8). The mean effect of SPAD-43 on NHI (0.61) was significantly lower than that of the other N managements. There was no significant interaction of N and variety factors on NHI (Appendix 8, ANOVA). Nitrogen harvest indices of SPAD-based managements in the present study were relatively lower than the 0.68 reported by Peng et al. (1996). However, the values in this study were relatively higher than the 0.59 reported by Witt et al. (1999).

Internal N use efficiency (IE) ranged from 50.5 to 80.3 kg grain kg^{-1} N uptake in all N managements and varieties (Table 4.18). The IE values of SPAD-35, -39 and -43 were generally lower than those of Rec-N and SPAD-32 in all test varieties. Among the varieties, the maximum IE values (71.0 kg grain kg^{-1} N uptake) were observed in the BRRI dhan-29 and Sonar Bangla-1 varieties (Appendix 8). There was no significantly different effect on IE between Rec-N, SPAD-32 and 35, but the values were significantly higher than those of SPAD-39 and -43. The interaction effect of N and variety factors on IE was not significant (Appendix 8, ANOVA). The IE values in the present study were within the range of the 48 and 112 kg grain kg^{-1} N uptake reported by Haefele et al. (2003) in both on-station and on-farm experiments in four West African countries. Similar findings are reported for Nepal and Bangladesh (Adhikari et al., 1999) and for West Africa (Wopereis et al., 1999). The IE in the present study decreased with increasing yield. This finding supports the statements of Cassman and Harwood (1995) and Dobermann et al. (1996b and c) that a decrease in internal nutrient efficiencies could generally be expected when target yields were close to the yield potential.

4.4.4 Partial factor productivity, agronomic efficiency, physiological efficiency, and recovery efficiency

The minimum partial factor productivity (PFP) value was 31.7 kg grain kg^{-1} N applied and the maximum 84.2 kg grain kg^{-1} N applied in all varieties (Table 4.19). SPAD-32 resulted in maximum PFP values in all varieties.

There was no difference between SPAD-32 (70.8 kg grain kg^{-1} N applied) and SPAD-35 (66.2 kg grain kg^{-1} N applied) in BRRI dhan-28. The PFP of SPAD-39 (43.6 kg grain kg^{-1} N applied) was not significantly different from Rec-N (49.9 kg grain kg^{-1} N applied) or from SPAD-43 (38.9 kg grain kg^{-1} N applied). In BRRI dhan-29, there was no difference between Rec-N (43.8 kg grain kg^{-1} N applied), SPAD-39 (39.4 kg grain kg^{-1} N applied), and SPAD-43 (33.5 kg grain kg^{-1} N applied). SPAD-35 gave a significantly higher PFP value (58.4 kg grain kg^{-1} N applied) than Rec-N, SPAD-39 and -43. In BRRI dhan-36, the PFP of SPAD-35 (50.0 kg grain kg^{-1} N applied) was not different from Rec-N (54.9 kg grain kg^{-1} N applied). The PFP values of SPAD-39 (38.7 kg grain kg^{-1} N applied) and SPAD-43 (38.5 kg grain kg^{-1} N applied) were significantly lower than those of Rec-N and SPAD-35.

In BRRI hybrid-1, the PFP values for SPAD-35 (58.0 kg grain kg^{-1} N-applied) and SPAD-39 (46.1 kg grain kg^{-1} N applied) were not significantly different from Rec-N (52.8 kg grain kg^{-1} N applied). SPAD-43 resulted in the lowest PFP values among the N managements in the BRRI hybrid-1 (32.3 kg grain kg^{-1} N applied) and Alok varieties (31.7 kg grain kg^{-1} N applied). There was no significant difference between Rec-N (47.6 kg grain kg^{-1} N applied), SPAD-35 (54.9 kg grain kg^{-1} N applied) and SPAD-39 (45.7 kg grain kg^{-1} N applied) in the Alok variety. In Sonar Bangla-1, SPAD-39 and SPAD-43 gave significantly lower PFP values, 41.4 and 38.9 kg grain kg^{-1} N applied, respectively, compared to Rec-N (56.4 kg grain kg^{-1} N applied), SPAD-32 (66.8 kg grain kg^{-1} N applied), and SPAD-35 (60.9 kg grain kg^{-1} N applied).

Table 4.19. Comparison of partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) of N applied for different rice varieties and different N managements in Meherpur during the Boro season 2001-02

N-management	PFP	AE	PE	RE
	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied (%)
			BRRI dhan-28	
Rec - N	49.9 b	26.4 b	81.2 a	32.5 b
SPAD 32	70.8 a	34.5 a	59.1 b	65.5 a
SPAD 35	66.2 a	39.6 a	77.3 ab	52.3 a
SPAD 39	43.6 bc	27.6 b	55.8 b	50.3 a
SPAD 43	38.9 c	25.6 b	44.9 b	57.0 a
			BRRI dhan-29	
Rec - N	43.8 c	24.7 c	82.4 ab	31.5 b
SPAD 32	84.2 a	44.1 a	84.4 a	54.5 a
SPAD 35	58.4 b	37.3 b	66.7 b	57.0 a
SPAD 39	39.4 c	25.7 c	64.9 b	41.0 ab
SPAD 43	33.5 c	22.0 c	42.8 c	51.7 a
			BRRI dhan-36	
Rec - N	54.9 b	31.9 b	74.7 a	42.8 b
SPAD 32	81.4 a	46.8 a	58.1 b	80.5 a
SPAD 35	50.0 b	30.5 bc	61.3 ab	50.1 b
SPAD 39	38.7 c	24.9 c	51.2 b	48.6 b
SPAD 43	38.5 c	25.5 bc	48.7 b	52.6 b
			BRRI hybrid-1	
Rec - N	52.8 bc	31.7 bc	62.9 a	50.3 b
SPAD 32	72.9 a	43.8 a	66.6 a	70.5 a
SPAD 35	58.0 b	36.4 b	66.6 a	54.1 ab
SPAD 39	46.1 c	30.5 c	55.2 a	55.7 ab
SPAD 43	32.3 d	21.2 d	40.9 b	51.8 b
			Alok	
Rec - N	47.6 ab	26.4 a	72.8 ab	34.9 a
SPAD 32	56.8 a	29.4 a	78.8 a	37.2 a
SPAD 35	54.9 ab	31.6 a	68.2 ab	46.8 a
SPAD 39	45.7 b	28.5 a	58.3 bc	49.6 a
SPAD 43	31.7 c	19.6 b	44.5 c	44.1 a
			Sonar Bangla-1	
Rec - N	56.4 b	34.9 a	81.1 a	43.1 a
SPAD 32	66.8 a	40.3 a	77.4 a	52.9 a
SPAD 35	60.9 ab	38.5 a	78.2 a	49.6 a
SPAD 39	41.4 c	28.0 b	49.1 b	57.0 a
SPAD 43	38.9 c	26.7 b	48.4 b	55.3 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

A low mean effect of variety on PFP was observed in the Alok variety, while effects of the other varieties were not significant (Appendix 8). The highest mean effect of N management on PFP was observed for SPAD-32 followed by SPAD-35 over all test varieties. Significant differences were observed in the analysis of variance except variety factor and in the contrast of Rec-N vs. SPAD-based N managements (Appendix 8, ANOVA). The interaction effect of N and variety was significant at the 0.01 probability level.

The PFP is a useful measure of nutrient-use efficiency providing an integrative index that quantifies total economic output relative to the utilization of indigenous and applied nutrient. It is possible to increase PFP by increasing the amount, uptake and utilization of indigenous nutrients, and by increasing the efficiency with which applied nutrients are taken up by the crop and utilized to produce grain (Cassman et al., 1996b). The PFP of SPAD-35 and -39 in the present study was higher than the range of 26.7 and 38.9 kg grain kg^{-1} N applied reported by Yadav et al., (2000) in with long-term field experiments in the Indo-Gangetic Plains. Similar findings are reported by Ramanathan et al. (2000) in Thanjavur, India.

In three inbred varieties, although agronomic efficiency (AE) values of SPAD-39 and -43 were low among the N managements, they did not differ from the AE value of Rec-N (Table 4.19). SPAD-35 resulted in generally higher AE values compared to Rec-N in all inbred varieties. As with PFP, a similar trend was observed in the AE values of the BRRI hybrid-1 variety. There was no difference in AE between Rec-N, SPAD-32, -35 and -39 in Alok variety, but the AE of SPAD-43 (19.6 kg additional grain kg^{-1} N applied) was significantly lower than those of the other N managements. In Sonar Bangla-1, AE values of SPAD-39 (28.0 kg additional grain kg^{-1} N applied) and SPAD-43 (26.7 kg additional grain kg^{-1} N applied) were significantly lower than those of the other N managements. There was no different mean effect of variety on AE except in the Alok variety (Appendix 8). The highest mean effect of N management was observed for SPAD-32 followed by SPAD-35. Compared to Rec-N, SPAD-39 showed a similar mean effect. All statistical analyses were significant (Appendix 8, ANOVA). The AE values of all N managements in the present study approach the values of 24-33 kg additional grain kg^{-1} N applied that can be achieved at high yield level with proper crop and fertilizer management (Peng et al., 1996). The AE values of SPAD-35 and -39 were relatively higher than the range of 6-28 kg additional grain kg^{-1} N applied reported by Sattar (2000) from the studies during the early days of the Bangladesh Rice Research Institute (BRRI). Witt et al. (1999) reported that a mean AE of only 10 kg increase in grain kg^{-1} applied N fertilizer was obtained from about 700 observations in farmers' fields in six Asian countries. However, recent research has demonstrated the considerable opportunity to improve the efficiency of N fertilizer use in farmers' fields through improved timing of N applications and a reduced quantity of N fertilizer applied per unit increase in grain yield (Dobermann and Fairhurst, 2000). Current research in long-term experiments at IRRI indicates that a 25 kg increase in grain kg^{-1} N fertilizer can be obtained under researcher-managed conditions with dynamic timing of N fertilizer to match the real-time N requirement of the rice crop (Buresh et al., 2001).

There was no difference in physiological efficiency (PE) values among the SPAD-based N managements in BRRI dhan-28 (Table 4.19). SPAD-35 resulted in similar PE (77.3 kg additional grain kg^{-1} additional N uptake) compared to the PE of Rec-N (81.2 kg additional grain kg^{-1} additional N uptake). The highest PE value (84.4 kg additional grain kg^{-1} additional N uptake) was observed for SPAD-32 and the lowest PE value (42.8 kg additional grain kg^{-1} additional N uptake) was for SPAD-43 in BRRI dhan-29. The PE values did not differ between Rec-N (82.4 kg additional grain kg^{-1} additional N uptake), SPAD-35 (66.7 kg additional grain kg^{-1} additional N uptake) and SPAD-39 (64.9 kg additional grain kg^{-1} additional N uptake). Although there was no difference in PE between the SPAD-based managements in BRRI dhan-36, SPAD-35 resulted in a similar PE (61.3 kg additional grain kg^{-1} additional N uptake) compared to Rec-N (74.7 kg additional grain kg^{-1} additional N uptake).

There was no significant difference in PE values among N managements except for SPAD-43 (40.9 kg additional grain kg^{-1} additional N uptake) in the BRRI hybrid-1 variety. In the Alok variety, the PE value of SPAD-39 (58.3 kg additional grain kg^{-1} additional N uptake) was not significantly different from that of Rec-N (72.8 kg grain kg^{-1} additional N uptake) and SPAD-35 (68.2 kg additional grain kg^{-1} additional N uptake), and also not different from that of SPAD-43 (44.5 kg additional grain kg^{-1} additional N uptake). In Sonar Bangla-1, the PE values of SPAD-39 (49.1 kg additional grain kg^{-1} additional N uptake) and SPAD-43 (48.4 kg additional grain kg^{-1} additional N uptake) were significantly lower than those of Rec-N (81.1 kg additional grain kg^{-1} additional N uptake), SPAD-32 (77.4 kg additional grain kg^{-1} additional N uptake) and SPAD-35 (78.2 kg additional grain kg^{-1} additional N uptake).

The mean effect of variety on PE did not differ much among the varieties (Appendix 8). The mean effects of Rec-N, SPAD-32 and SPAD-35 were significantly higher than those of SPAD-39 and -43. There was no interaction between N and variety factor (Appendix 8, ANOVA). Crop-physiological N requirements are controlled by the efficiency with which N in the plant is converted to biomass and grain yield. Since cereal crops are harvested for grain, the most relevant measure of physiological N efficiency is the change in grain yield per unit in N accumulation in aboveground biomass (Cassman et al., 2000). The PE values of the present study were higher than the typical PE of 50 kg grain kg^{-1} additional N uptake for modern rice cultivars grown under favorable conditions with good crop management in the tropics (Yoshida, 1981). A similar result was reported by Peng et al. (1996) at the IRRI farm in the Philippines, by Cassman et al. (1996 b) in Nueva Ecija Province, Central Luzon, Philippines, and by Adhikari et al. (1999) in Nepal and Bangladesh.

Recovery efficiency (RE) of SPAD-based managements was generally higher than those of Rec-N in all varieties (Table 4.19). There was no difference in RE percents between the SPAD-based managements in BRRI dhan-28. A similar trend was observed in the BRRI dhan-29 variety. However, SPAD-32 resulted in the highest RE percent in BRRI dhan-36. In the BRRI hybrid-1 variety, although SPAD-32 gave a high RE percent among the N managements, the values were not significantly different from those in SPAD-35 and -39. There was no significant difference among the N managements in the Alok and Sonar Bangla-1 varieties. A low RE was observed in the BRRI dhan-29 and Alok varieties (Appendix 8). The mean effect of Rec-N on RE was significantly lower than that of SPAD-based N managements over all varieties. There was no difference between SPAD-35, -39 and -43. There was no interaction of N and variety (Appendix 8, ANOVA). Since RE percentages of SPAD-based managements were higher than those of recommended N management in the present study, SPAD-based N management could reduce applied-N losses and improve N-use efficiency. The result indicates that SPAD-based N management can match timing of N fertilizer application with the time N requirement of the rice plant. The RE percentages of SPAD-35 and -39 in this study were relatively lower than the 61% reported by Peng et al.

(1996) and Hussain et al. (2000) in the Philippines. However, RE values of the present study were similar to the finding of Singh et al. (2002) in Northwestern India and relatively higher than those reported by Adhikari et al. (1999) in Nepal and Bangladesh.

4.4.5 Relationship of leaf N on a weight or area basis with SPAD reading

Table 4.20 shows the correlation coefficients (r) between leaf N concentration on a leaf dry weight (N_{dw}) and area (N_a) basis and SPAD values, and minimum, maximum and mean specific leaf weight (SLW) of leaves measured at different days after transplanting (DAT) in six rice varieties grown in the Boro season 2001-02. The minimum SLW was 31.1 gm^{-2} and the maximum 54.6 $g\ m^{-2}$. Mean SLW values ranged from 38.6 to 50.5 $g\ m^{-2}$. The relationship of SPAD reading and leaf N concentration was highly significant on both dry weight (N_{dw}) and area basis (N_a) at each sampling date and for each variety. It was observed that the relationship between SPAD reading and leaf N concentration expressed on a leaf area basis was higher than that on a leaf dry weight basis. When the data on all sampling dates and all varieties were pooled, the linear relationship became poor. However, a better correlation was observed for the relationship between SPAD reading and leaf N on an area basis ($r = 0.59$) compared to that on a leaf dry weight basis ($r = 0.42$) for the pooled data of the four sampling dates and six rice varieties (Figures 4.10a and b).

Past experiments with maize indicated a strong positive correlation between leaf N concentration and leaf chlorophyll content (Zelitch, 1982; Girardin et al., 1985). Leaf greenness quantified by the SPAD meter represents a unitless measurement of relative leaf chlorophyll content, because the mass of the sample is not determined. Traditional wet chemical procedures used to determine leaf chlorophyll content are usually based on the mass of tissue, and the relationship between SPAD meter reading and chlorophyll content has been established in maize (Dwyer et al., 1991). Schepers et al. (1992) reported that the calibration of the SPAD meter against leaf N concentration in a general sense is possible because of the close relationship between leaf N concentration and leaf greenness. It has been documented that the SPAD meter can estimate N concentration in rice leaves on a dry weight basis (N_{dw}) for predicting the need for fertilizer-N topdressing (Chubachi et al., 1986; Miyashita et al., 1986; Takebe and Yoneyama, 1989; Takebe et al., 1990; Turner and Jund, 1991). In the present study, the correlation coefficients of N_{dw} with SPAD readings at each sampling date and for each variety were similar to a range of degree of correlation (r = 0.82 to 0.98 for rice) determined in other studies (Chubachi et al., 1986; Miyashita et al., 1986; Takebe and Yoneyama, 1989; Takebe et al., 1990). However, the poor correlation between SPAD reading and N_{dw} in the present study is based on pooled data of four different sampling dates and six varieties. The correlation coefficient (r = 0.42) was similar to the finding (r=0.43) of Peng et al. (1995a) with ten different sampling dates and two rice varieties. It has been reported that the regression equations for leaf chlorophyll content or N_{dw} based on the SPAD reading differed markedly depending on growth stage, genotype, and environment (Takebe and Yoneyama, 1989: Campbell et al., 1990).

Table 4.20. Correlation coefficients (r) between leaf N concentration on a leaf dry weight (N_{dw}) and area (N_a) basis and SPAD values, and minimum, maximum, and mean specific leaf weight (SLW) of leaves measured at different days after transplanting (DAT) for different rice varieties in Meherpur during the Boro season 2001-02

DAT	Variety	Number of samples	r		SLW (g m^{-2})		
			N_{dw}	N_a	Min.	Max.	Mean
40	BRRI dhan-28	18	0.83$^{\pm}$	0.86	35.2	45.0	38.6
70	BRRI dhan-28	18	0.84	0.94	42.0	49.8	45.6
50	BRRI dhan-29	18	0.95	0.96	37.5	48.7	42.8
80	BRRI dhan-29	18	0.90	0.93	46.8	54.6	50.5
40	BRRI dhan-36	18	0.77	0.94	31.1	44.1	39.7
70	BRRI dhan-36	18	0.95	0.96	44.8	50.5	48.0
50	BRRI hybrid-1	18	0.89	0.91	42.0	47.9	45.0
80	BRRI hybrid-1	18	0.94	0.96	45.8	53.6	49.5
50	Alok	18	0.53	0.82	38.3	47.9	44.0
80	Alok	18	0.76	0.91	39.5	54.1	50.5
40	Sonar Bangla-1	18	0.80	0.91	35.6	50.6	44.3
70	Sonar Bangla-1	18	0.65	0.87	31.4	53.4	46.0
	Pooled	216	0.42	0.59	31.4	54.6	45.4

$^{\pm}$ All correlations are significant at the 0.01 probability level.

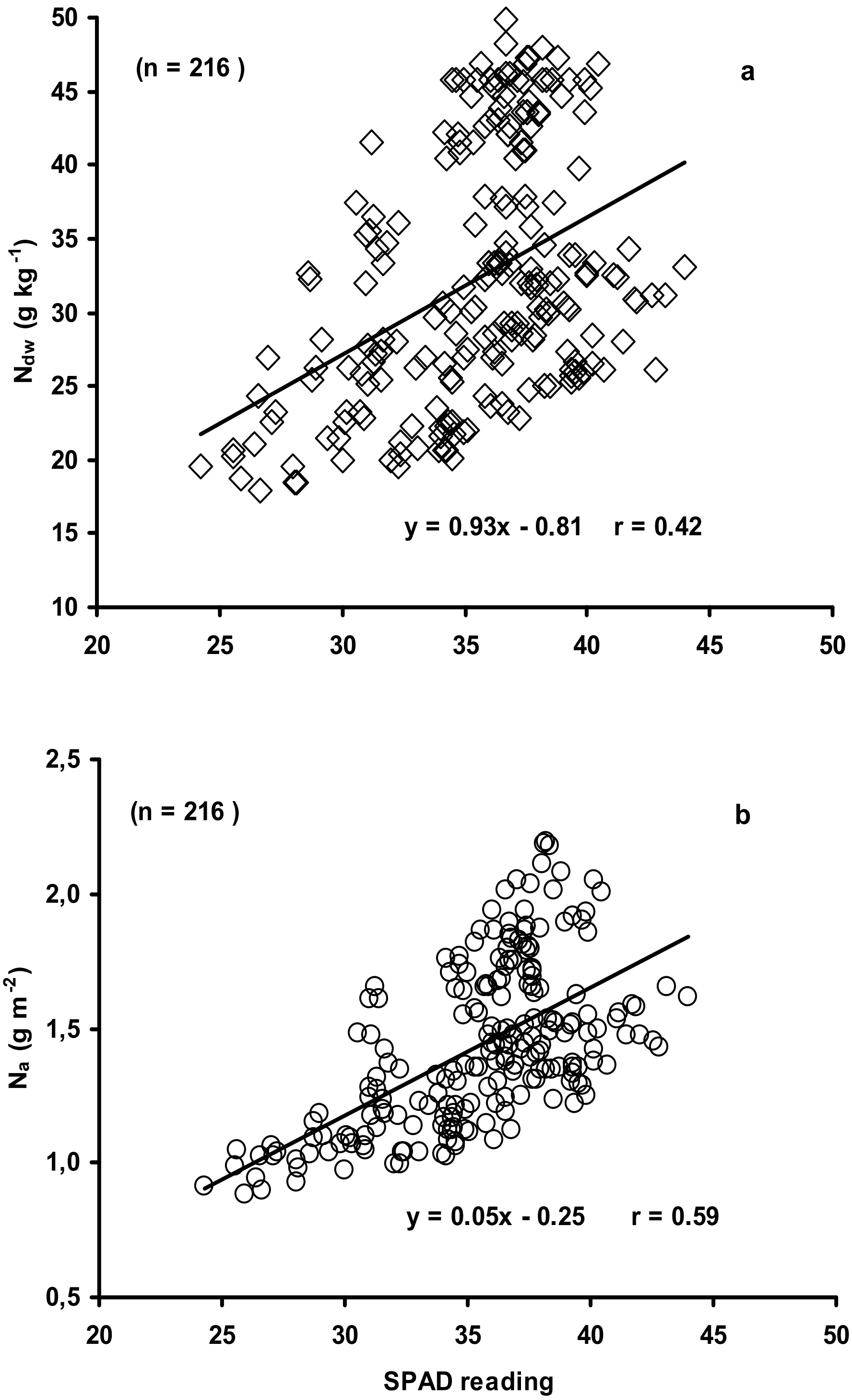

Figure 4.10. Linear regression of (a) dry weight-based (N_{dw}) and (b) area-based (N_a) leaf N concentration in SPAD readings of six rice varieties using pooled data of four different sampling dates in Meherpur during the Boro season of 2001-02 (see Table 4.20)

The relationship between chlorophyll content on a leaf area basis and SPAD reading has been demonstrated in rice, cotton, soybean, sorghum, maize, and apple (Jiang and Vergara, 1986; Yadanava, 1986; Marquard and Tipton, 1987; Takebe and Yoneyama, 1989; Tenga et al., 1989; Campbell et al., 1990; Dwyer et al., 1991; Fanizza et al., 1991). The correlation coefficients of N content based on leaf area (N_a) with SPAD readings at each sampling date and in each variety of this study were very similar to those values reported by Peng et al. (1995a). However, the r-value (0.59) based on the pooled data of the present study was relatively lower than the r-value 0.81 with two varieties at ten different sampling dates and the value 0.88 with 80 genotypes on a single sampling date (Peng et al., 1995a). This difference may be due to the number of different varieties and the number of sampling times. A SPAD critical value of 35 in the present study is equal to 1.5 g N m^{-2} leaf area, which is within the range of 1.4 to 1.5 g N m^{-2} leaf area in semi-dwarf indica varieties as reported by Peng et al. (1995b).

Although SLW widely ranged from 31.1 to 54.6 g m^{-2} in the present study, the relationship between SPAD reading and N content based on leaf area (N_a) showed a good correlation for the pooled data. This finding supports results of studies that show that SLW has little effect on the relationship between N_a and SPAD reading (Peng et al., 1995a). Peng et al. (1993) proposed that an adjustment of SPAD values for SLW was required to accurately predict N_{dw} of different genotypes at different growth stages. It may not be applicable for determining the SLW because of the required destructive sampling. In later research, Peng et al. (1995a) reported that the SPAD meter can be used directly to diagnose the N status of the rice plant by estimating N_a and to determine the timing of N topdressing, because the maximum leaf photosynthetic rate per unit leaf area was closely related to N_a in rice (Yoshida and Coronel, 1976; Uchida et al., 1982; Makino et al., 1988; Peng et al., 1995b).

4.4.6 Relationship of SPAD and three types of LCC readings

The regression coefficients of SPAD reading with each LCC reading in each variety were very similar. Therefore the data of all six varieties for each LCC during the crop-growing season have been pooled in Table 4.21 and Figure 4.11. For each variety, IRRI-LCC was more related to the SPAD reading than the other two LCC types. A similar trend was also observed with the pooled data of six varieties during the rice-growing period of the Boro season 2001-02.

Table 4.21. Relationship of SPAD and three types of LCC readings for six rice varieties grown in Meherpur during the Boro season of 2001-02

Variety	IRRI-LCC			China-LCC			California-LCC		
	a	b	r	a	b	R	A	b	r
BRRI dhan-28[§]	- 0.81	0.11	0.98[±]	0.13	0.13	0.78	0.80	0.14	0.82
BRRI dhan-29	- 0.84	0.10	0.92	- 1.18	0.17	0.81	1.02	0.13	0.79
BRRI dhan-36	- 0.79	0.10	0.94	- 0.66	0.15	0.84	0.68	0.15	0.85
BRRI hybrid-1	- 1.14	0.11	0.93	- 0.73	0.16	0.83	0.70	0.14	0.75
Alok	- 1.16	0.12	0.95	- 0.30	0.14	0.84	0.83	0.14	0.86
Sonar Bangla-1	- 1.24	0.12	0.97	- 0.63	0.16	0.85	0.39	0.16	0.83
Pooled (n= 648)	- 0.98	0.11	0.94	- 0.53	0.15	0.82	0.79	0.14	0.81

[±]All correlations are significant at the 0.01 probability level.
[§] Number of observations was 108 on six sampling dates for each variety.

Since the different types of LCC readings were closely related to the SPAD reading in different varieties during the whole growing period, the LCC could be an alternative tool for determining the time of N fertilizer application in rice production. Among the LCC types, IRRI-LCC (r=0.94) was more related to the SPAD reading than China-LCC (r=0.82) and California-LCC (r=0.81). This difference may be due to the different varieties and crop-growth stage, different color differentiation of the leaf color chart and visual assessment of leaf greenness.

Turner and Jund (1994) reported that visual assessment of leaf greenness was influenced by sunlight variability (sun's intensity and angle). Although LCCs were developed from a Japanese prototype (Furuya, 1987) standardized with the chlorophyll meter to assess the relative accuracy of the LCC in measuring the greenness of rice leaves, they could not determine smaller differences in leaf greenness as was possible with the chlorophyll meter (Balasubramanian, et al., 1999). Based on the field observations, the findings of the latter study show that the LCC can still be used to determine the time of N topdressing to rice crops, and once the critical color shades are established for different cultivar groups and crop conditions with the help of the chlorophyll meter. According to the regression equations of the SPAD and LCC readings in the present study, the LCC values corresponding to the SPAD critical value as treatments in this experiment are shown in Table 4.22.

Table 4.22. Three types of LCC values corresponding to the SPAD value based on the regression analyses using pooled data of six sampling dates and six rice varieties in Meherpur during the Boro season of 2001-02

SPAD critical value in the experiment	Correspondent LCC value		
	IRRI-LCC	China-LCC	California-LCC
32	2.6	4.3	5.3
35	2.9	4.7	5.8
39	3.3	5.3	6.3
43	3.8	5.9	6.9

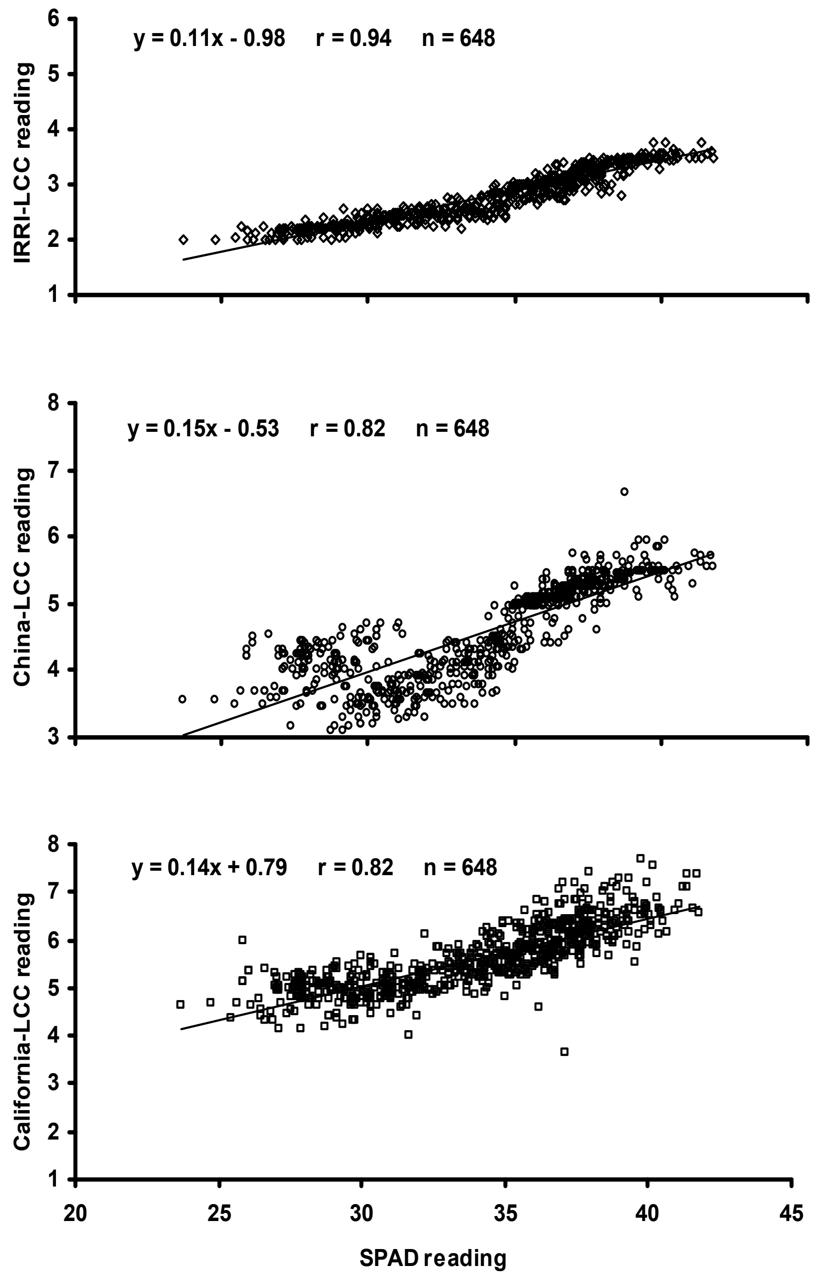

Figure 4.11. Relationship of SPAD reading and three types of LCC readings in six rice varieties in Meherpur during the Boro season of 2001-02

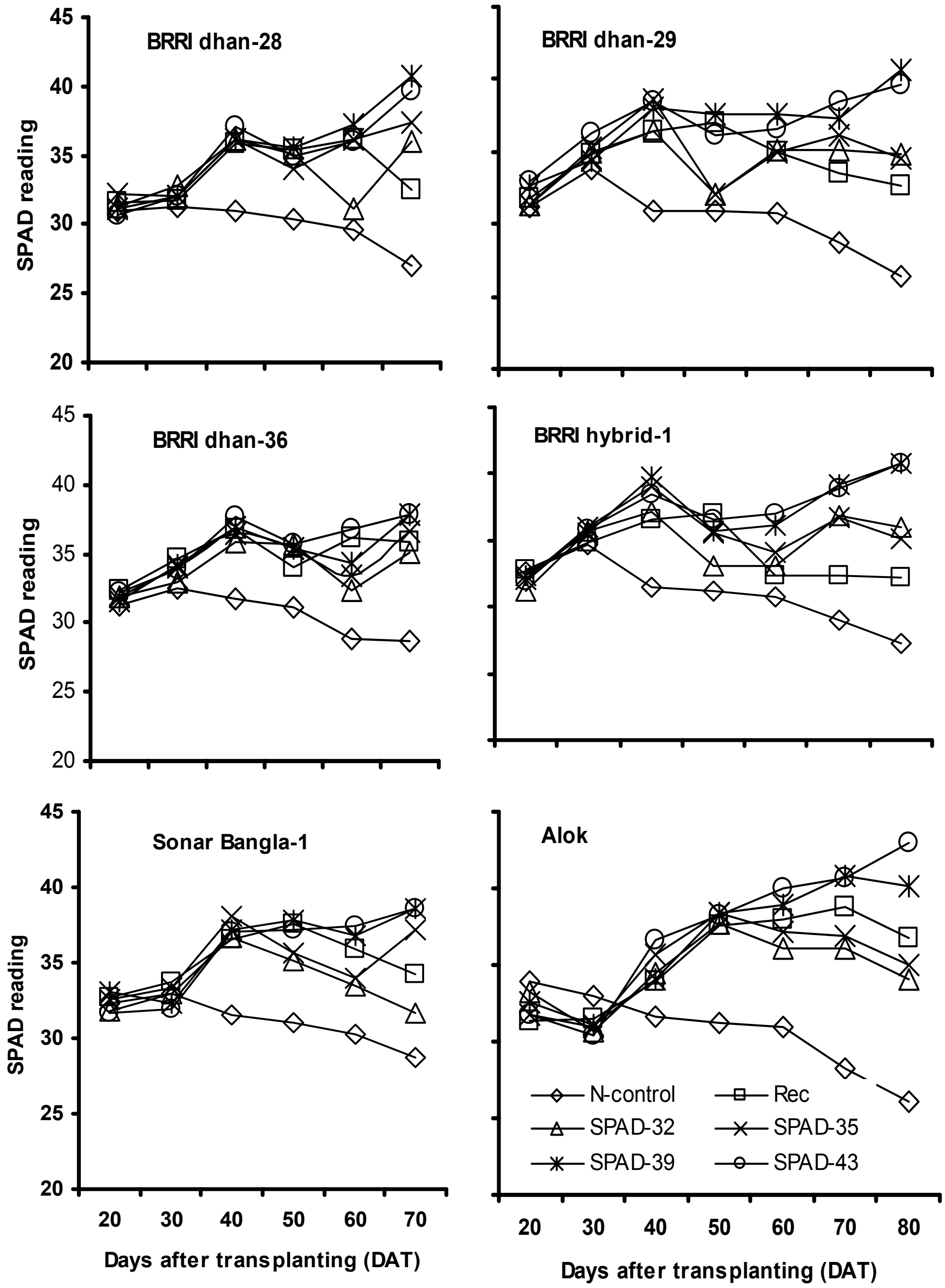

Figure 4.12. SPAD reading as affected by N managements in six rice varieties in Meherpur during the Boro season of 2001-02

The SPAD readings of different N managements in different varieties were usually lower than the value 43 during the whole season (Figure 4.12). The results indicate that the critical SPAD value of 43 might not be appreciable for determining the time of N fertilization in the present study area during the Boro rice-growing season.

In the inbred varieties, Rec-N and SPAD-32 managements showed lower SPAD readings than those of the other treatments. The low N status of rice plants at a later growth stage may lead to a decrease in grain yield. Although basal N fertilizer was applied to hybrid varieties, there was no great difference in the SPAD readings among the treatments. Due to the transplanting shock and cool temperatures at the early growth stage, the rice plants could not efficiently use the basal N fertilizer. The results suggest that the need for basal N fertilizer application should be considered for the hybrid varieties grown in the Boro season. Like inbred varieties, the SPAD readings of Rec-N, SPAD-32 and SPAD-35 were lower than those of the other two SPAD-based N managements in all three hybrids. The results of the present study indicate that an excessive N supply at an early growth stage should be avoided, and adequate N accumulation in the rice plants during the later growth stages should be provided.

4.5 Estimation of critical LCC values for selected wheat varieties in the Rabi (wheat) season of 2001-02

The results of the previous experiments show that wheat grain yield is closely related to the total N uptake measured at harvest and that SPAD can predict the N status in wheat plants (Section 4.1). Two experiments were conducted in two farmers' fields at Chandbill village in the Meherpur district during the Rabi (wheat) season of 2001-02 to estimate the critical LCC values for wheat varieties.

4.5.1 Evaluation of yield response to different N fertilizer levels and managements for selected wheat varieties

In order to compare the yields attained with recommended N fertilizer management to those attained with different N managements, six N levels with three wheat varieties were used in a randomized complete block design with three replications (Table 4.23).

Grain yield and fertilizer nitrogen application

Grain yields ranged from 1.3 to 3.8 t ha^{-1} in all N levels of three varieties (Table 4.23). In the Gaurab variety, the maximum yield (3.7 t ha^{-1}) was observed at N level of 120 kg N ha^{-1}, and was significantly higher than that of recommended-N (3.1 t ha^{-1}) with 100 kg N ha^{-1}. Although the yields were not significantly different among the N levels in the Shatabdi variety, the yield (3.8 t ha^{-1}) of 120 kg N ha^{-1} was relatively higher than those of the other N levels. The significantly higher yield (3.6 t ha^{-1}) was also observed for 120 kg N ha^{-1} in the Protiva variety compared to the yields of recommended 100 kg N ha^{-1} (2.7 t ha^{-1}), 150 kg N ha^{-1} (3.0 t ha^{-1}) and 135 kg N ha^{-1} (3.0 t ha^{-1}); however, it was not significantly different from the yield (3.6 t ha^{-1}) of 105 kg N ha^{-1}. The largest mean effect of variety on yield (3.3 t ha^{-1}) was observed in the Shatabdi variety and 120 kg N ha^{-1} resulted in the largest mean effect of N level on yield (3.7 t ha^{-1}) among the N levels (Appendix 9). There was no interaction between N level and variety factor (Appendix 9, ANOVA). The significant differences were observed in the contrast of 120 kg N ha^{-1} with 150, 135, and 105 kg N ha^{-1}. In all three varieties, recommended N management gave generally lower yields compared to the yields of the other N managements except the N management 54-54-27 (135 kg N ha^{-1}) in the Shatabdi variety (Figure 4.13). There was no difference in yields between recommended N and 60-60-30 (150 kg N ha^{-1}) in the Shatabdi or in the 42-42-21 (105 kg N ha^{-1}) treatment with the Gaurab variety. In all three varieties, 48-48-24 (120 kg N ha^{-1}) gave the maximum increase in yield 600, 200 and 900 kg ha^{-1} over the recommended N 67-33-00 (100 kg N ha^{-1}) in Gaurab, Shatabdi and Protiva, respectively. These results indicate that grain yield responded to an additional N applied at the maximum tillering (MT) growth stage of wheat. Singh et al. (2002) reported that the yield increased up to 0.80 t ha^{-1} with an additional N application of 30 kg ha^{-1} at MT in northwestern India. Singh and Singh (1997) reported that response of wheat grain yield to applied N at MT ranged from -0.12 to 0.95 t ha^{-1} on plots that received 120 and 60 kg N ha^{-1} of basal plus CRI-N, respectively, with the wheat cultivar PBW 343 in Ludhiana, Pubjab, India, during the Rabi season of 1996-97. In addition, an equal split amount of N applied at the basal and crown root initiation (CRI) growth stage is more preferable to prevent N losses and increase grain yield than high basal applications such as in the recommended N management (67-33-00) in the present study. The results of the present study provide evidence that current fertilizer N recommendation is inadequate for maintaining current yields of wheat. It has been reported that yield growth declined at constant input levels in long-term experiments in the Indo-Gangetic Plains of Pakistan, India, Nepal and Bangladesh, because of an unbalanced use of fertilizers (Hobbs et al., 2000). They also pointed out that profitability had dropped, as more inputs were needed to obtain the same yield.

Table 4.23. Comparison of grain yield of three varieties with six nitrogen levels in Meherpur during the Rabi (wheat) season of 2001-02

N level	N rate kg ha^{-1}	Grain yield t ha^{-1}		
		Gaurab	**Shatabdi**	**Protiva**
1. N - control	0	1.4 c[±]	1.3 b	1.3 d
2. Recommended (67-33-00)[§]	100	3.1 b	3.6 a	2.7 c
3. 50% more than T_2 (60-60-30)	150	3.6 ab	3.6 a	3.0 bc
4. 90% of T_3 (54-54-27)	135	3.5 ab	3.5 a	3.0 bc
5. 80% of T_3 (48-48-24)	120	3.7 a	3.8 a	3.6 a
6. 70% of T_3 (42-42-21)	105	3.1 b	3.7 a	3.5 ab

[±] In a column, means followed by a common letter are not significantly different at the 5% level by DMRT.
[§] Nitrogen fertilizer was applied at seeding, crown root initiation (CRI) and maximum tillering (MT)

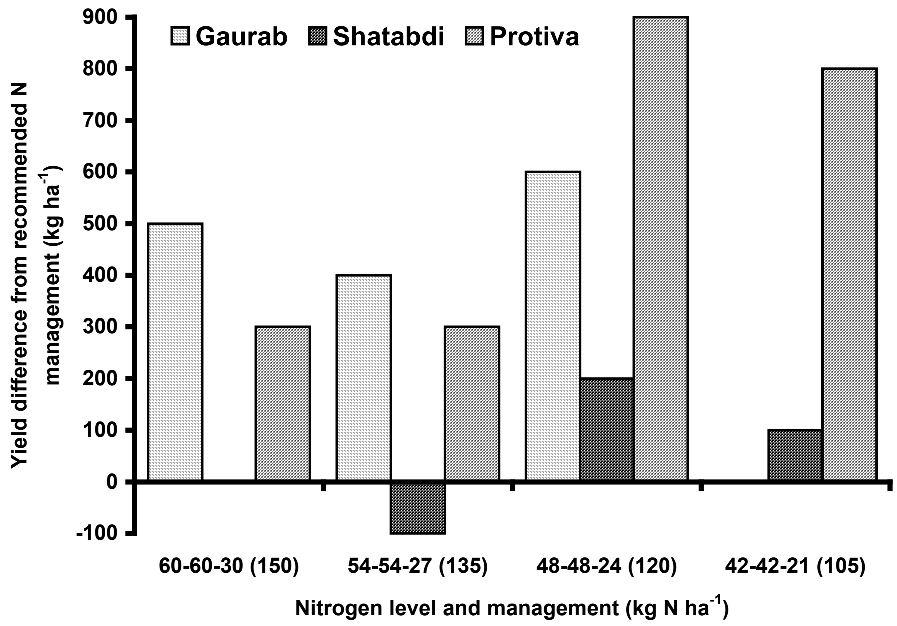

Figure 4.13. Yield differences of different nitrogen levels from the recommended N management (67-33-00) for Gaurab, Shatabdi and Protiva wheat varieties in Meherpur during the Rabi season of 2001-02

Yield components, straw yield, total dry matter yield, and harvest index

The number of spikes per square meter ranged from 254 to 397 in all varieties (Table 4.24). The kernel number produced on a spike was only differed lightly among the N managements except for the N-control. However, 120 kg N ha^{-1} (48-48-24) produced a relatively larger number of kernels per spike compared to the recommended N level (67-33-00) in all varieties. Kernel weight ranged from 32.0 to 42.1 mg among the different N levels and different varieties. Although kernel weight hardly differed in the different N levels, 150 kg N ha^{-1} (60-60-30) showed a lower kernel weight 35.1 and 32.0 mg in the Shatabdi and Protiva variety, respectively. The N level of 135 (54-54-27) also resulted in significantly low kernel weight (32.4 mg) in the Protiva variety. There was no significant difference in straw yield between the Gaurab and Shatabdi varieties, but the maximum straw yield (4.7 t ha^{-1}) was observed at the level of 105 kg N ha^{-1} (42-42-21) in the Protiva variety.

Total dry matter yields (TDM) were not significantly different in the Gaurab and Shatabdi varieties; however, the TDM with 120 kg N ha^{-1} (7.5 t ha^{-1}) and 105 kg N ha^{-1} (7.9 t ha^{-1}) was significantly higher than that in the recommended N management (6.2 t ha^{-1}) in the Protiva variety. The maximum HI value (0.47) was observed with 120 kg N ha^{-1} (48-48-24) in the Shatabdi variety and the minimum was 0.36 at the N-control in the Protiva variety. It was observed that the HI of the recommended N management were generally lower than those of the other N level managements. The level of 120 kg N ha^{-1} (48-48-24) resulted in a relatively higher harvest index compared to the level of 150, 135 and 105 kg N ha^{-1}. The interaction of N level and variety was observed for kernel number per spike, kernel weight and total dry matter (Appendix 9, ANOVA).

The results of the present study show that the larger number of spikes per square meter and kernel number per spike contributed to an increased grain yield, thereby increasing the harvest index. Similar findings were reported by Sankaran et al. (2000) in northen India, and by Ladha et al. (2003) who reviewed long-term experiments in the Indo-Gangetic Plain. The equal split application of N fertilizer as a basal fertilizer and at the crown root initiation stage (CRI) resulted in a generally larger number of spikes than that of the recommended N management in the present study. The result indicates that wheat plants may not efficiently use the high amount of basal N applied at an early growth stage.

Table 4.24. Comparison of yield components, straw yield, total dry matter yield (TDM), and harvest index (HI) of three varieties with six nitrogen levels in Meherpur during the Rabi (wheat) season of 2001-02

N level	Spike number	Kernel number	Kernel weight	Straw yield	TDM	HI
	no. m^{-2}	no. $spike^{-1}$	mg	t ha^{-1}	t ha^{-1}	
			Gaurab			
1. N - control	254 b	16 c	36.8 b	2.1 b	3.4 b	0.39 b
2. Recommended (67-33-00)	309 ab	28 ab	41.5 a	3.6 a	6.4 a	0.44 a
3. 50% more than T_2 (60-60-30)	328 a	28 ab	42.1 a	3.8 a	7.1 a	0.46 a
4. 90% of T_3 (54-54-27)	334 a	28 ab	41.9 a	3.6 a	6.8 a	0.46 a
5. 80% of T_3 (48-48-24)	334 a	31 a	41.0 a	3.9 a	7.3 a	0.46 a
6. 70% of T_3 (42-42-21)	289 ab	26 b	41.9 a	3.6 a	6.4 a	0.44 a
			Shatabdi			
1. N - control	226 c	20 c	38.0 a	1.6 b	2.9 b	0.42 b
2. Recommended (67-33-00)	300 b	32 ab	38.9 a	4.6 a	7.9 a	0.41 b
3. 50% more than T_2 (60-60-30)	397 a	30 b	36.6 ab	4.4 a	7.7 a	0.42 b
4. 90% of T_3 (54-54-27)	350 ab	34 a	35.1 b	4.2 a	7.3 a	0.43 b
5. 80% of T_3 (48-48-24)	377 a	31 ab	36.8 ab	3.9 a	7.3 a	0.47 a
6. 70% of T_3 (42-42-21)	313 ab	32 ab	38.7 a	4.4 a	7.8 a	0.43 b
			Protiva			
1. N - control	299 b	20 b	34.2 bc	2.1 c	3.2 d	0.36 c
2. Recommended (67-33-00)	318 b	25 a	36.3 ab	3.8 b	6.2 c	0.39 bc
3. 50% more than T_2 (60-60-30)	423 a	26 a	32.0 c	3.7 b	6.5 bc	0.42 ab
4. 90% of T_3 (54-54-27)	421 a	25 a	32.4 c	3.6 b	6.4 bc	0.43 a
5. 80% of T_3 (48-48-24)	390 a	27 a	35.8 ab	4.2 ab	7.5 ab	0.44 a
6. 70% of T_3 (42-42-21)	328 b	27 a	37.7 a	4.7 a	7.9 a	0.40 ab

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

Total nitrogen uptake, nitrogen harvest index, and nitrogen-use efficiency

The total N uptake (TNU) of wheat plants ranged from 29.3 to 104.1 kg N ha^{-1} (Table 4.25). Nitrogen accumulation in the plant was lower in the recommended N management compared to the other N level managements. The nitrogen harvest indices (NHI) did not differ greatly in the Gaurab variety, but the NHI of 120 and 105 kg N ha^{-1} were significantly higher than that of the recommended N in the Shatabdi variety. In Protiva, relatively low NHI values were observed at 150 or 135 kg N ha^{-1} level. Internal use efficiency (IE) at the 150 kg N ha^{-1} level was much lower than those of the other N levels in all three varieties. The IE of 120 kg N ha^{-1} was not significantly different from the IE of the recommended N among the varieties. The partial factor productivity (PFP) values ranged from 19.7 to 35.7 kg grain kg^{-1} N applied. A low PFP was observed at 150 and 135 kg N ha^{-1} due to the high N application. The PFP of 120 kg N ha^{-1} was not significantly different from that of the recommended N and 105 kg N ha^{-1} in each variety.

There was no difference in agronomic efficiency (AE) among the N levels in the Gaurab variety. Higher AE values were observed at 120 and 105 kg N ha^{-1} in the Shatabdi and Protiva varieties. Application of 120 kg N ha^{-1} resulted in relatively higher AE values compared to those of the recommended N in the Gaurab and Protiva varieties. The lowest physiological efficiency (PE) values were observed with 150 kg N ha^{-1} due to the high N accumulation in the plant. The PE of 120 kg N ha^{-1} was not significantly different from that of the recommended N and 105 kg N ha^{-1} in each variety. Recovery efficiency (RE) of applied nitrogen ranged from 29.6 to 57.1% in this study. There was no significant difference in RE in the Gaurab and Shatabdi varieties. However, the RE of 120 (55.9%) and 105 kg N ha^{-1} (53.1%) was significantly higher than that of the recommended N (35.7%) in the Protiva variety. No interaction effects of N level and variety were observed for TNU, IE, AE, PE and RE except for NHI and PFP (Appendix 9, ANOVA).

Lower values of TNU by wheat plants were observed in this experiment compared to the TNU values of rice plants (Section 4.3 and 4.4). Since the soil was warmer and wetter during the rice-growing seasons, higher rates of N mineralization were achieved than during the cool and dry wheat season. Therefore, the accumulation or uptake of N from fertilizer was relatively more important than from the native soil N supply in wheat (Adhikari et al., 1999). Higher N uptake by the plant in 150, 135 and 120 kg N ha^{-1} may be due to the higher N application. The effect of the higher doses of N on TNU may be due to the differences in grain yield of wheat (Nair and Gupta, 1999). However, the result of the present study indicates an effect of N applied at the maximum tillering stage through the larger N accumulation in the 105 kg N ha^{-1} level than in the recommended N 100 kg N ha^{-1}. The NHI values of the present study were within the range of 0.51 to 0.91 as reported by van Sanford and Mackown (1987). The remobilization of vegetative N during the grain-filling stage of wheat may contribute to grain N content. Although the IE of 120 (48-48-24) kg N ha^{-1} was not significantly different from that of the recommended N, the IE values in Gaurab and Protiva were relatively lower than those of recommended N due to the larger N accumulation in the plant.

The PFP values in the present study were within the range of 12.5 to 42.1 kg grain kg^{-1} applied N reported by Yadav (1998) and Yadav et al. (2000) with an N application of 120 kg N ha^{-1} in the Indo-Gangetic Plains, where rice-wheat is a predominant cropping system. The AE values were in a range of 11.2 to 22.9 kg additional grain kg^{-1} N applied. This range of values observed here was similar to that reported for the Indo-Gangetic Plains, where the values ranged from 15.3 to 20.9 kg additional grain kg^{-1} N applied with a rate of 120 kg N ha^{-1} and 11.3 to 26.1 kg additional grain kg^{-1} N applied with a rate of 100 kg N ha^{-1} (Yadav, 1998; Yadav et al., 2000). The PE values of the present study were lower than the 50 kg additional grain kg^{-1} additional N uptake reported by Adhikari et al. (1999) with an application of 100 kg N ha^{-1} in Nepal. The difference may be due to the different environmental conditions in the two countries. In the present study, the RE of wheat was generally higher than that of T-Aman rice with a similar rate of N application under the rice-wheat cropping system. A similar result was reported by Bronson et al. (1997) in north India. They pointed out that nitrification-denitrification and leaching losses of fertilizer N were greater in rice than in wheat. However, ammonia volatilization may be a significant loss pathway in wheat in the present study, because N fertilizer (urea) was topdressed on wet soil (i.e., after irrigation) in wheat.

Table 4.25. Comparison of total nitrogen uptake (TNU), nitrogen harvest index (NHI), internal use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) of applied-N of three varieties with six nitrogen levels in Meherpur during the Rabi (wheat) season of 2001-02

N level	TNU	NHI	IE	PFP	AE	PE	RE (%)
	kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
			Gaurab				
1. N - control	33.7 d	0.77 b	42.8 a	-	-	-	-
2. Recommended (67-33-00)	73.8 c	0 .81 ab	41.8 a	30.8 a	16.4 a	41.3 a	40.1 a
3. 50% more than T_2 (60-60-30)	104.1 a	0. 80 ab	34.4 b	23.9 c	14.3 a	30.5 b	47.0 a
4. 90% of T_3 (54-54-27)	90.2 ab	0. 83 a	38.5 ab	25.7 bc	15.0 a	35.9 ab	41.8 a
5. 80% of T_3 (48-48-24)	97.0 a	0.83 a	38.5 ab	31.2 a	19.2 a	36.2ab	52.7 a
6. 70% of T_3 (42-42-21)	78.1 bc	0.80 ab	39.0 ab	29.0 ab	15.3 a	36.3 ab	42.2 a
			Shatabdi				
1. N - control	29.3 b	0.81 a	46.1 a	-	-	-	-
2. Recommended (67-33-00)	86.4 a	0.74 c	41.9 ab	35.7 a	22.3 a	41.4 ab	57.1 a
3. 50% more than T_2 (60-60-30)	97.3 a	0.72 c	36.9 c	23.9 b	15.0 b	33.2 c	45.3 a
4. 90% of T_3 (54-54-27)	89.7 a	0.75 bc	39.0 bc	25.8 b	15.9 b	35.6 bc	44.7 a
5. 80% of T_3 (48-48-24)	90.7 a	0.79 ab	41.9 ab	31.6 a	20.5 a	40.2 abc	51.1 a
6. 70% of T_3 (42-42-21)	84.3 a	0.79 ab	44.6 a	35.6 a	22.9 a	44.3 a	52.4 a
			Protiva				
1. N - control	29.8 c	0.75 ab	43.5 a	-	-	-	-
2. Recommended (67-33-00)	65.4 b	0.75 ab	41.0 ab	26.7 bc	13.9 b	40.2 a	35.7 b
3. 50% more than T_2 (60-60-30)	86.7 a	0.73 b	34.3 c	19.7 d	11.2 b	29.6 b	38.0 b
4. 90% of T_3 (54-54-27)	87.6 a	0.73 b	34.7 c	22.5 cd	13.0 b	30.3 b	42.8 ab
5. 80% of T_3 (48-48-24)	96.9 a	0.75 ab	37.3 bc	29.9 ab	19.2 a	34.6 ab	55.9 a
6. 70% of T_3 (42-42-21)	85.5 a	0.78 a	40.5 ab	33.1 a	20.9 a	39.5 a	53.1 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

Relationship of leaf N on a weight or area basis with SPAD reading at maximum tillering stage

Significant correlations were observed between SPAD reading at maximum tillering (MT) and leaf N concentration based on both leaf dry weight (N_{dw}) and area (N_a) (Table 4.26). Since the regression coefficients did not differ, the data were pooled. Leaf N concentrations on a dry weight (r = 0.85) and area basis (r = 0.91) were also closely related to the SPAD reading at MT in the linear regression analysis (Figures 15a and b). It was observed that the N concentration on a leaf area base (N_a) was more related to the SPAD reading than that on a leaf dry weight base (N_{dw}) in both individual variety and pooled data (Table 31 and Figures 15a and b). The specific leaf weight (SLW) ranged from 28.5 to 45.2 g m^{-2} in all varieties and the mean value was 35.8 g m^{-2}.

Table 4.26. Correlation coefficients (r) between leaf N concentration on a leaf dry weight (N_{dw}) and area (N_a) basis and SPAD values, and minimum, maximum, and mean specific leaf weight (SLW) of leaves measured at maximum tillering for different wheat varieties with six different nitrogen levels in Meherpur during the Rabi season of 2001-02

Variety	Number	r		SLW (g m^{-2})		
	of samples	N_{dw}	N_a	Min.	Max.	Mean
Gaurab	18	0.84$^{\pm}$	0.85	32.3	45.2	38.6
Shatabdi	18	0.92	0.94	3.12	40.0	34.6
Protiva	18	0.89	0.92	28.5	41.1	34.2
Pooled data	54	0.85	0.91	28.5	45.2	35.8

$^{\pm}$ All correlations are significant at the 0.01 probability level.

It has been demonstrated that the chlorophyll content on leaf area basis can be predicted by the SPAD meter reading in rice (*Oryza sativa* L), cotton (*Gossypium hirstum* L), soybean (*Glycine max* (L) Merr.), sorghum (*Sorghum bicolar* (L) Moench), maize (*Zea mays* L), grape (*Vitis vinifera* L), tomato (*Lycopersicon esculantum* Mill), and apple (*Malus deomostica* Borhk) (Jiang and Vergara, 1986; Yadava, 1986; Marquard and Tipton, 1987; Campbell et al., 1990; Dwyer et al., 1991; Fanizza et al., 1991). Although the significant relation of leaf N concentration and SPAD meter reading has been also reported for rice (Peng et al., 1993; Peng et al., 1995a) and for maize (Schepers et al., 1992; Smeal and Zhang, 1994), a very little is known for wheat.

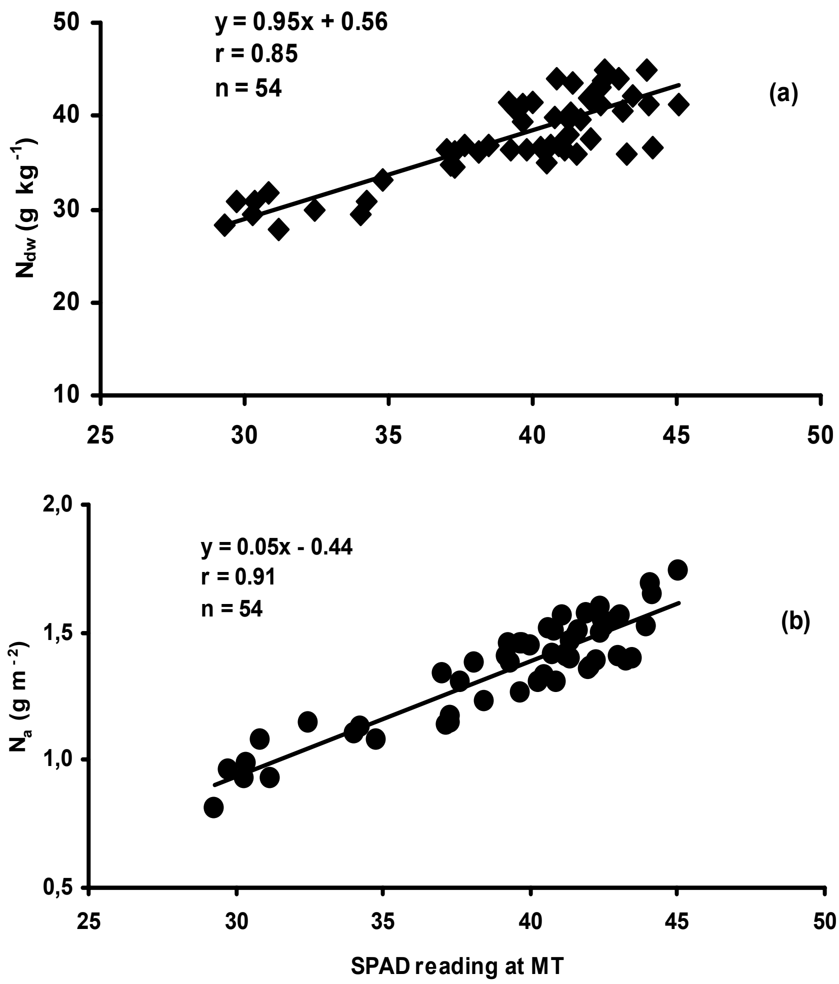

Figure 4.14. Linear regression of (a) leaf dry weight-based (N_{dw}) and (b) area-based (N_a) N concentration on SPAD reading of six nitrogen levels at maximum tillering using pooled data of three wheat varieties in Meherpur during the Rabi season of 2001-02 (see Table 31)

SPAD reading at maximum tillering stage and relationship of SPAD and three types of LCC readings

Figure 4.15 illustrates the mean SPAD reading of each N application level in each variety at the MT stage. The higher SPAD values can be attributed to the larger amount of N fertilizer, which had been already applied before the MT stage. Among the varieties, Gaurab showed the higher SPAD readings in all nitrogen level treatments, followed by Shatabdi. The low SPAD values of Protiva indicate lighter leaf-greenness compared to the other two varieties. It was noticed that all SPAD readings were less than 45.

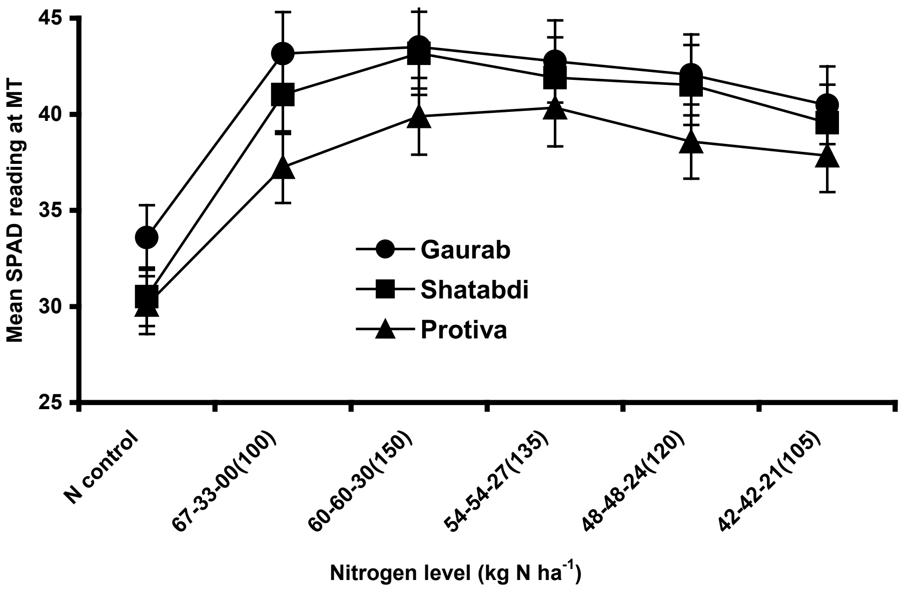

Figure 4.15. Mean SPAD reading at maximum tillering (MT) with different nitrogen levels and wheat varieties in Meherpur during the Rabi season of 2001-02

Table 4.27. Relationship of SPAD value at maximum tillering stage and three types of LCC readings of three wheat varieties with six nitrogen levels in Meherpur during the Rabi season of 2001-02

Variety	IRRI-LCC			China-LCC			California-LCC		
	a	b	r	a	b	r	a	b	r
Gaurab[§]	-2.77	0.17	0.98[±]	2.50	0.11	0.88	3.45	0.10	0.87
Shatabdi	-1.37	0.14	0.98	0.45	0.15	0.97	1.23	0.15	0.95
Protiva	-0.91	0.12	0.96	-0.04	0.16	0.96	0.57	0.16	0.96
Pooled (n= 54)	-1.67	0.14	0.97	0.10	0.16	0.94	1.07	0.15	0.94

[±]All correlations are significant at the 0.01 probability level.
[§] Number of observations was 18 in each variety.

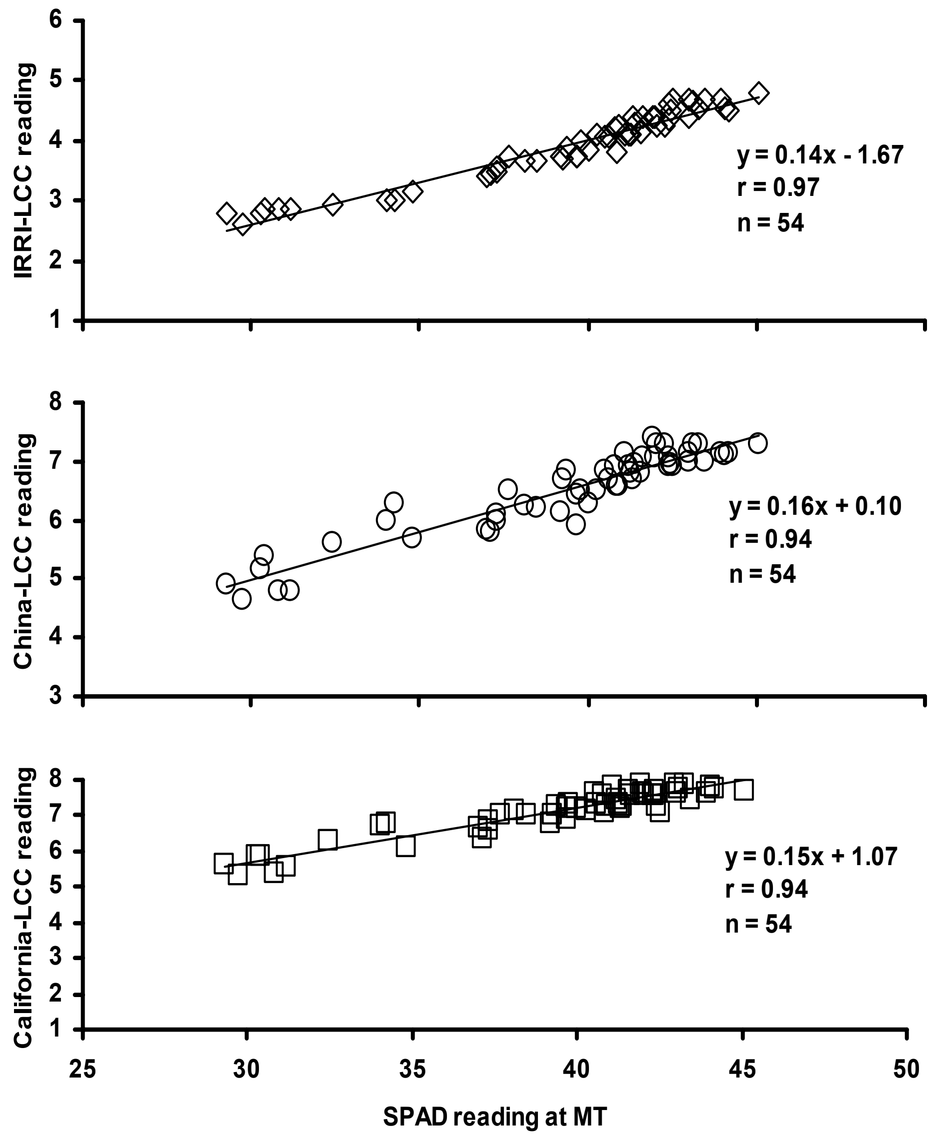

Figure 4.16. Relationship of SPAD and three types of LCC readings at maximum tillering stage (MT) of three wheat varieties, Gaurab, Shatabdi and Protiva, in Meherpur during the Rabi season of 2001-02

Table 4.27 shows the relationship of SPAD and three types of LCC readings at the MT stage of each variety. All correlation coefficients (r) were significant at 0.01 probability level. Since the regression coefficients (b) between varieties were similar for each LCC type, the data were pooled for the three varieties. The different types of LCC readings were closely related to the SPAD reading (Figure 4.16). Among them, IRRI-LCC (r = 0.97) showed a higher correlation with the SPAD reading than China-LCC (r = 0.94) and California-LCC (r = 0.94).

4.5.2 Estimation of critical LCC value for N fertilization at maximum tillering stage in different wheat varieties

An experiment was conducted with three wheat varieties in the Rabi season of 2001-02 to estimate the appropriate critical LCC value for N fertilization at the maximum tillering (MT). There were ten N managements including three SPAD threshold values for N application at MT with two different N applications at seeding and crown root initiation (CRI) (Table 4.28).

Grain yield and fertilizer nitrogen application

Grain yield ranged from 1.1 to 3.9 t ha^{-1} in all treatments and varieties (Table 4.28). The management 40-40-00 resulted in similar yields with a lower amount of N applied compared to the yields of the recommended N management 67-33-00 in all three varieties. The management 50-50-00 produced relatively higher yields than those of the recommended N management in the Kanchan and Protiva varieties. Although there was no significant difference in yield between the recommended N management and the 40-40-20 SPAD-based management at MT, the yields of SPAD-44 and -48 were relatively higher than those of recommended N with the same amount of N applied. In each variety, maximum yield (3.5 t ha^{-1}) was observed at 50-50-00 (SPAD-44 and -48) in Kanchan, 3.9 t ha^{-1} at 50-50-00 (SPAD-48) in Gaurab, and 3.8 t ha^{-1} at 50-50-00 (SPAD-44) in Protiva. The greater mean effect of N management on yield (3.7 t ha^{-1}) was observed for the 50-50-20 (SPAD-44) treatments in three varieties (Appendix 10). Interaction between N management and variety had no effect on yield; however, significant differences were observed in the contrast of recommended N and SPAD-44 and -48 N managements (Appendix 10, ANOVA). The management 40-40-00 showed relatively lower yields in the three varieties than those of the recommended N management because of the low N application rate (Figure 4.17). A similar result was observed at 40-40-20 (SPAD-40) in the Gaurab variety as no N was applied at MT, but increased yields were observed in the other two varieties. In the basal 50 kg N ha^{-1} management, yield increased over the recommended N management except for the 50-50-00 and 50-50-20 (SPAD-40) in the Gaurab variety because no N was applied at MT. The maximum yield increase (800 kg ha^{-1}) over recommended N was achieved with 50-50-20 (SPAD-44) in the Protiva variety.

Table 4.28. Comparison of grain yield of three varieties with ten nitrogen managements in Meherpur during the Rabi (wheat) season of 2001-02

N management	N rate	Grain yield	N rate	Grain yield	N rate	Grain yield
	kg ha^{-1}	t ha^{-1}	kg ha^{-1}	t ha^{-1}	kg ha^{-1}	t ha^{-1}
		Kanchan		**Gaurab**		**Protiva**
N - control	0	1.2 c$^{\pm}$	0	1.6 f	0	1.1 c
Rec – N (67-33-00)§	100	3.2 ab	100	3.4 bcd	100	2.9 b
40-40-00	80	3.0 b	80	2.9 de	80	3.0 b
40-40-20 (SPAD 40)	93	3.3 ab	80	2.9 e	100	3.2 ab
40-40-20 (SPAD 44)	100	3.4 ab	100	3.5 abc	100	3.3 ab
40-40-20 (SPAD 48)	100	3.4 ab	100	3.6 abc	100	3.3 ab
50-50-00	100	3.3 ab	100	3.3 cde	100	3.3 ab
50-50-20(SPAD 40)	107	3.2 ab	100	3.3 cde	107	3.3 ab
50-50-20(SPAD 44)	120	3.5 a	120	3.8 ab	120	3.7 a
50-50-20(SPAD 48)	120	3.5 ab	120	3.9 a	120	3.5 a

$^{\pm}$ In a column, means followed by a common letter are not significantly different at the 5% level by DMRT.

§ Nitrogen fertilizer was applied at seeding, crown root initiation (CRI) and maximum tillering (MT). Nitrogen fertilization was used at MT when the SPAD value fell below the critical value.

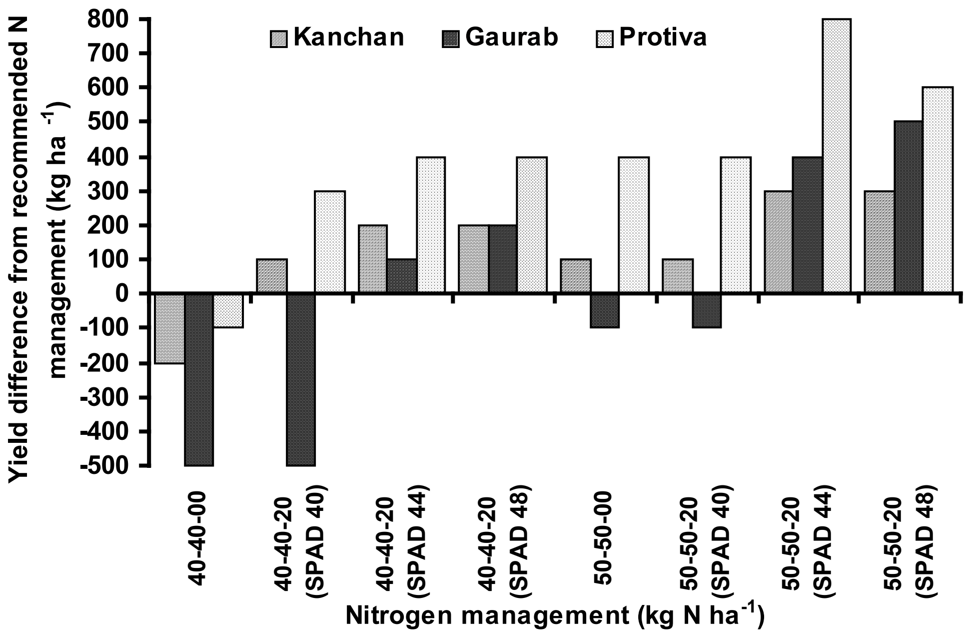

Figure 4.17. Yield differences of different N managements from recommended N (67-33-00) in Kanchan, Gaurab and Protiva varieties in Meherpur during the Rabi season of 2001-02

Since the yields of recommended N did not differ much from the yields of 40-40-00 N management and were relatively lower than those of the 50-50-00 N management, the large amount of N applied as a basal fertilizer might not be appreciable. Heavy N fertilizer applications at or prior to planting is a characteristic of wheat production systems in the Yaqui Valley, Sonora, Mexico (Meisner et al., 1992), and results in poor N uptake and low N-use efficiency due to excessive N losses (Sowers et al., 1994). In the present study, the yields of plots that received 20 kg N ha^{-1} at MT were usually higher than those of plots that did not receive N applied at MT. The result indicates that N application at MT contributes to increased grain yield. Among the varieties, Gaurab showed more a sensitive response to N application at MT. A similar increased yield response to N applied at MT was reported by Singh and Singh (1997) and Singh et al. (2002). Limited nitrogen can result in a poor grain yield due to inadequate N for kernel filling (Asseng et al., 2002).

Yield components, straw yield, total dry matter yield, and harvest index

The number of spikes per square meter ranged from 234 to 545; this was main reason for the increase in yield (Table 4.29). The maximum number of spikes was observed at the management 50-50-20 (SPAD-44 and -48) in all varieties. There was no significant difference in kernel number per spike in the Kanchan and Protiva varieties; however, a difference was observed in the Gaurab variety, but this difference was not marked. Although the kernel weight was not significant in the Protiva variety, relatively significant differences were observed in the Kanchan and Gaurab varieties. The straw yields ranged from 2.0 to 5.1 t ha^{-1}. There was no difference in total dry matter yield among the N managements in the Kanchan and Protiva variety. In Gaurab, the relatively low TDM yields resulted from the 40-40-00 (6.8 t ha^{-1}) and 40-40-20 (SPAD-40) (6.2 t ha^{-1}) N managements because of low applied N and low yields. The minimum HI was 0.32 in the N-control of the Kanchan variety and the maximum (0.45) in the 50-50-20 (SPAD-44 and -48) N management of the Protiva variety. Within each group of the 40-40-00 and 50-50-00 managements, higher HI values were observed in the SPAD-based N management at MT. An interaction of N management and variety was absent in the ANOVA for yield components and total dry matter yield, but it was present at probability 0.05 and 0.01 levels for straw yield and harvest index, respectively (Appendix 10, ANOVA).

Table 4.29. Comparison of yield components, straw yield, total dry matter (TDM) and harvest index (HI) of three varieties with ten nitrogen managements in Meherpur during the Rabi (wheat) season of 2001-02

N management	Spike number	Kernel number	Kernel weight	Straw yield	TDM	HI
	no. m^{-2}	no. $spike^{-1}$	mg	t ha^{-1}	t ha^{-1}	
			Kanchan			
N – control	249 c	16 a	35.3 b	2.2 c	3.2 b	0.32 d
Rec – N (67-33-00)	442 a	23 a	35.9 b	4.0 b	6.9 a	0.42 a
40-40-00	371 b	22 a	36.9 ab	4.7 ab	7.5 a	0.37 c
40-40-20 (SPAD 40)	347 b	26 a	36.4 ab	4.4 ab	7.4 a	0.40 abc
40-40-20 (SPAD 44)	371 b	28 a	34.1 b	4.4 ab	7.4 a	0.41 ab
40-40-20 (SPAD 48)	379 b	24 a	35.6 b	4.5 ab	7.6 a	0.41 ab
50-50-00	379 b	26 a	34.5 b	4.9 a	7.9 a	0.38 bc
50-50-20(SPAD 40)	376 b	27 a	40.2 a	4.4 ab	7.4 a	0.40 abc
50-50-20(SPAD 44)	452 a	24 a	35.0 b	4.3 ab	7.5 a	0.43 a
50-50-20(SPAD 48)	450 a	26 a	33.5 b	4.4 ab	7.6 a	0.42 a
			Gaurab			
N – control	234 d	19 c	38.2 c	2.4 c	3.8 d	0.37 e
Rec – N (67-33-00)	339 abc	28 ab	38.9 c	4.2 ab	7.2 abc	0.43 abc
40-40-00	280 cd	28 ab	41.9 abc	4.2 ab	6.8 bc	0.39 de
40-40-20 (SPAD 40)	331 bc	24 bc	40.6 bc	3.5 b	6.2 c	0.42 a-d
40-40-20 (SPAD 44)	343 ab	31 a	39.1 bc	4.0 ab	7.1 abc	0.44 a
40-40-20 (SPAD 48)	355 ab	30 ab	39.8 bc	4.8 a	8.1 a	0.41 a-e
50-50-00	380 ab	28 ab	39.7 bc	4.6 a	7.6 ab	0.40 b-e
50-50-20(SPAD 40)	349 ab	25 b	40.8 abc	4.7 a	7.7 ab	0.39 cde
50-50-20(SPAD 44)	389 ab	25 b	43.3 ab	4.5 a	8.0 a	0.43 ab
50-50-20(SPAD 48)	404 a	25 b	44.8 a	4.4 a	7.9 ab	0.44 a
			Protiva			
N – control	265 c	14 a	34.4 a	2.0 c	3.0 b	0.33 d
Rec – N (67-33-00)	412 ab	23 a	34.4 a	4.7 ab	7.4 a	0.36 cd
40-40-00	396 ab	22 a	37.2 a	4.5 ab	7.3 a	0.37 c
40-40-20 (SPAD 40)	417 ab	25 a	34.8 a	4.1 b	7.0 a	0.42 ab
40-40-20 (SPAD 44)	384 b	26 a	35.4 a	5.1 a	8.1 a	0.37 c
40-40-20 (SPAD 48)	382 b	26 a	35.4 a	4.4 ab	7.4 a	0.40 bc
50-50-00	389 ab	24 a	36.7 a	4.7 ab	7.8 a	0.39 bc
50-50-20(SPAD 40)	403 ab	24 a	37.1 a	4.2 b	7.2 a	0.43 ab
50-50-20(SPAD 44)	454 a	24 a	35.1 a	4.1 b	7.4 a	0.45 a
50-50-20(SPAD 48)	447 ab	25 a	33.0 a	4.0 b	7.2 a	0.45 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

Among the yield components, spike number per square meter was the main reason for the increase in yield. This supports the finding of Norwood (2000) indicating that fewer heads per square meter caused yield reduction in wheat, but fewer kernels per head and a lower kernel weight occasionally contributed to yield decrease in winter wheat rotation with corn or sunflower or soybean in the US Great Plain. The HI values of the present study were much lower than the theoretical maximum HI of 0.62 in high-yielding environments (Austin, 1994). However, in low-yielding environments, water and nitrogen stress can limit either the source or the sink or both, depending on the distribution of rainfall and the timing of stress (Asseng et al., 2002). The HI values observed here were higher than the 0.27 with 105 kg N ha^{-1} and similar to the 0.44 with 140 kg N ha^{-1} observed in Iran during the winter wheat seasons of 1994 to 1995 (Bahrani et al., 2002).

Total nitrogen uptake, nitrogen harvest index and nitrogen-use efficiency

Total nitrogen uptake (TNU) ranged from 25.2 to 101.0 kg N ha^{-1} (Table 4.30). Among the N managements, the critical SPAD value of 44 and 48 for N application at maximum tillering stage showed a higher N accumulation in the wheat plant compared to the recommended N management in all three varieties. Between those two groups, SPAD-44 and -48 of the 50-50-20 managements gave higher TNU values than those of the 40-40-20 managements. All N managements resulted in similar nitrogen harvest indices (NHI). However, the lowest value 0.67 was observed in the recommended N management in the Protiva variety and the highest value 0.81 in the 40-40-20 (SPAD-44) N management of the Gaurab variety. Internal N-use efficiency (IE) ranged from 36.0 to 43.7 kg grain kg^{-1} N uptake. The relatively low values of partial factor productivity of N applied (PFP) 29.5 and 29.0 kg gain kg^{-1} N applied were observed in 50-50-20 (SPAD-44 and -48, respectively); however, this is not significantly different from the recommended N and 40-40-20 (SPAD-44 and -48) managements in the Kanchan variety. A similar trend was observed in the Protiva variety, but there was no difference in PFP values in the Gaurab variety. Agronomic nitrogen use efficiency (AE) was not significantly different among the N managements in the Kanchan and Gaurab varieties. The minimum AE values 18.2 and 18.6 kg additional grain kg^{-1} N applied resulted from the recommended N management in the Gaurab and Protiva varieties, respectively. Physiological efficiency (PE) ranged from 30.4 to 42.3 kg grain kg^{-1} additional N uptake. The percents of recovery efficiency (RE) were not significantly different and ranged from 38.4 to 64.6%. Mean effects of SPAD-based N management at MT on parameters of N-use efficiency were usually higher than those of recommended N (Appendix 10). An interaction of N management and variety was not significant for the variables of nitrogen use efficiency (Appendix 10, ANOVA).

The TNU values of the present study were similar to the uptake of wheat of 94.5 kg N ha^{-1} in a rice-wheat cropping system in India (Hegde and Dwivedi, 1992). The TNU values of applied-N 120 kg ha^{-1} in the present study were greater than the 84.2 kg N ha^{-1} with the same N applied as reported by Nair and Gupta (1999) in India.

An increase in total N uptake leads to an increase in total dry matter production. Olesen et al. (2002) reported that the N uptake was found to be proportional to the green area index, and to have an additional curvilinear response to dry matter, implying decreasing N concentration with increasing dry matter. However, the minimum N uptake is associated with dry matter only, because the plant may reduce its metabolic activities until the point of senescence (Grindlay, 1997). The NHI values of the present study were relatively lower than a target NHI of 0.80 proposed by Jamieson and Semenov (2000) in their model. They assumed that there would be no further N uptake once grain filling began, and showed that grain nitrogen was determined mostly in response to the N supply in the plant at the beginning of grain filling. The minimum grain N concentration of 1.5% indicates that grain growth can be limited directly by lack of N (Sinclair and Amir, 1992).

The PFP values of the 40-40-20 SPAD-based N managements were higher than those of recommended N managements with the same amount of N fertilizer application because of the relatively higher grain yield. The results indicate that N application at MT is needed to meet crop N demand and to improve N-use efficiency. Although PFP of 50-50-20 SPAD-based N managements were relatively lower than that of the recommended N management, AE values were higher in the Gaurab and Protiva varieties due to a greater increase in grain yield. Those AE values were higher than the 17.3 kg additional grain kg^{-1} N applied reported by Bhuiyan et al. (1993) with 120 kg applied N ha^{-1} in Nashipur, Bangladesh. Although the PE values of the SPAD-based N managements were not significantly different from those of the recommended N, mean effects on PE were larger than with recommended N. This means that higher N accumulation in the plant contributes to an incremental grain yield.

Table 4.30. Comparison of total nitrogen uptake (TNU), nitrogen harvest index (NHI), internal use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) of applied N of three varieties with ten nitrogen managements in Meherpur during the Rabi (wheat) season of 2001-02

N management	TNU	NHI	IE	PFP	AE	PE	RE (%)
	kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
			Kanchan				
N – control	26.3 c	0.70 b	43.7 a	-	-	-	-
Rec – N (67-33-00)	86.4 ab	0.74 ab	36.8 bcd	31.7 bc	20.3 a	33.8 a	60.1 a
40-40-00	74.1 b	0.72 b	40.6 ab	37.5 a	23.2 a	39.0 a	59.8 a
40-40-20(SPAD 40)	82.5 ab	0.75 ab	40.2 abc	35.3 ab	22.8 a	39.0 a	59.4 a
40-40-20(SPAD 44)	88.3 ab	0.74 ab	37.9 bcd	33.5 abc	22.0 a	35.5 a	62.0 a
40-40-20(SPAD 48)	90.8 ab	0.74 ab	37.8 bcd	33.9 abc	22.4 a	35.5 a	64.5 a
50-50-00	90.0 ab	0.70 b	36.5 bcd	30.6 bc	21.1 a	33.7 a	63.7 a
50-50-20(SPAD 40)	91.3 a	0.71 ab	36.0 d	30.5 bc	19.7 a	32.9 a	60.5 a
50-50-20(SPAD 44)	97.8 a	0.73 ab	36.2 cd	29.5 c	19.9 a	33.3 a	59.6 a
50-50-20(SPAD 48)	92.4 a	0.75 a	37.8 bcd	29.0 c	19.4 a	35.5 a	55.1 a
			Gaurab				
N – control	36.5 f	0.75 b	42.7 a	-	-	-	-
Rec – N (67-33-00)	80.8 cde	0.79 ab	41.7 abc	33.7 a	18.2 a	41.0 ab	44.3 a
40-40-00	72.2 de	0.77 ab	40.5 abc	36.5 a	17.1 a	38.8 ab	44.7 a
40-40-20(SPAD 40)	67.3 e	0.78 ab	42.5 ab	35.8 a	16.3 a	42.3 a	38.4 a
40-40-20(SPAD 44)	87.7 a-d	0.81 a	39.5 abc	34.6 a	19.1 a	37.7 ab	51.2 a
40-40-20(SPAD 48)	91.3 abc	0.78 ab	39.8 abc	36.2 a	20.7 a	38.4 ab	54.8 a
50-50-00	83.4 bcd	0.76 ab	39.8 abc	33.2 a	17.7 a	37.9 ab	46.9 a
50-50-20(SPAD 40)	84.7 a-d	0.76 ab	38.4 bc	32.6 a	17.1 a	35.7 b	48.2 a
50-50-20(SPAD 44)	98.3 ab	0.77 ab	38.9 abc	31.8 a	18.9 a	36.8 ab	51.5 a
50-50-20(SPAD 48)	101.0 a	0.79 ab	38.2 c	32.2 a	19.3 a	36.0 ab	53.8 a
			Protiva				
N – control	25.2 c	0.70 bc	42.2 a	-	-	-	-
Rec – N (67-33-00)	86.3 ab	0.67 c	33.7 c	29.2 b	18.6 b	30.4 b	61.1 a
40-40-00	73.9 b	0.71 abc	40.6 ab	37.5 a	24.3 a	39.9 a	60.9 a
40-40-20(SPAD 40)	85.6 ab	0.74 ab	37.6 bc	32.2 b	21.6 ab	35.5 ab	60.4 a
40-40-20(SPAD 44)	87.3 ab	0.73 ab	38.3 b	32.7 ab	22.8 ab	36.7 a	62.1 a
40-40-20(SPAD 48)	89.8 ab	0.72 ab	36.4 bc	32.8 ab	22.2 ab	34.3 ab	64.6 a
50-50-00	87.7 ab	0.73 ab	38.0 b	33.4 ab	22.7 ab	36.4 ab	62.5 a
50-50-20(SPAD 40)	92.6 a	0.74 ab	36.6 bc	31.4 b	21.3 ab	34.5 ab	63.4 a
50-50-20(SPAD 44)	96.8 a	0.75 ab	37.9 b	30.6 b	21.8 ab	36.4 ab	59.7 a
50-50-20(SPAD 48)	95.6 a	0.76 a	37.1 bc	29.5 b	20.6 ab	35.3 ab	58.7 a

In a column and in each variety, means followed by a common letter are not significantly different at the 5% level by DMRT.

However, PE in the present study was relatively lower than the 50 kg additional grain kg^{-1} additional N uptake reported by Adhikari et al. (1999) with 100 kg N applied ha^{-1} in Nepal. The mean effects of SPAD-based N management on RE were higher than those of the recommended N in the present study. The result shows that a higher N loss occurred in the recommended N management due to the high N application at sowing. Limon-Ortega et al. (2000) reported that N fertilizer banded at the first node stage increased the N use efficiency by 3% and total N uptake by 10%, compared with basal application in northwest Mexico. Thus, for improving N-use efficiency, proper timing of N application and adequate N rates are critical to meet plant needs. Because topdressed N fertilizer (urea) might be easily moved below the soil surface by irrigation in the present study, the urea was applied after irrigation. Consequently, ammonium volatilization was the major N loss mechanism (Katyal et al., 1987). Placing the fertilizer below the ground surface or incorporating it in the soil can reduce ammonium volatilization; however, this is possible before sowing, but inconvenient with a growing crop.

Relationship of leaf N on a weight and area basis with SPAD reading at maximum tillering stage

The coefficients of correlation between SPAD reading at maximum tillering (MT) and leaf N concentration based on both dry weight (N_{dw}) and area (N_a) basis were significant at probability 0.01 level (Table 4.31). Using pooled data, leaf N concentrations on a dry weight (r = 0.72) and area basis (r = 0.84) were closely related to the SPAD reading at MT in the linear regression analysis (Figures 19a and b). Nitrogen concentration on a leaf area base (N_a) was more related to the SPAD reading than that on a leaf dry weight base (N_{dw}) in both individual variety and pooled data (Table 4.31; Figures 4.18a and b). Specific leaf weight (SLW) ranged from 28.6 to 49.1 g m^{-2} in all varieties and the mean value was 38.0 g m^{-2}.

Table 4.31. Correlation coefficients (r) between leaf N concentration on a leaf dry weight (N_{dw}) and area (N_a) basis and SPAD values, and minimum, maximum, and mean specific leaf weight (SLW) of leaves measured at maximum tillering stage for different wheat varieties with ten different nitrogen managements in Meherpur during the Rabi season of 2001-02

Variety	Number of samples	r		SLW (g m^{-2})		
		N_{dw}	N_a	Min.	Max.	Mean
Kanchan	30	0.75$^{\pm}$	0.80	33.4	49.1	37.5
Gaurab	30	0.73	0.82	33.7	45.1	40.0
Protiva	30	0.74	0.82	28.6	44.0	36.3
Pooled data	90	0.72	0.84	28.6	49.1	38.0

$^{\pm}$ All correlations are significant at the 0.01 probability level

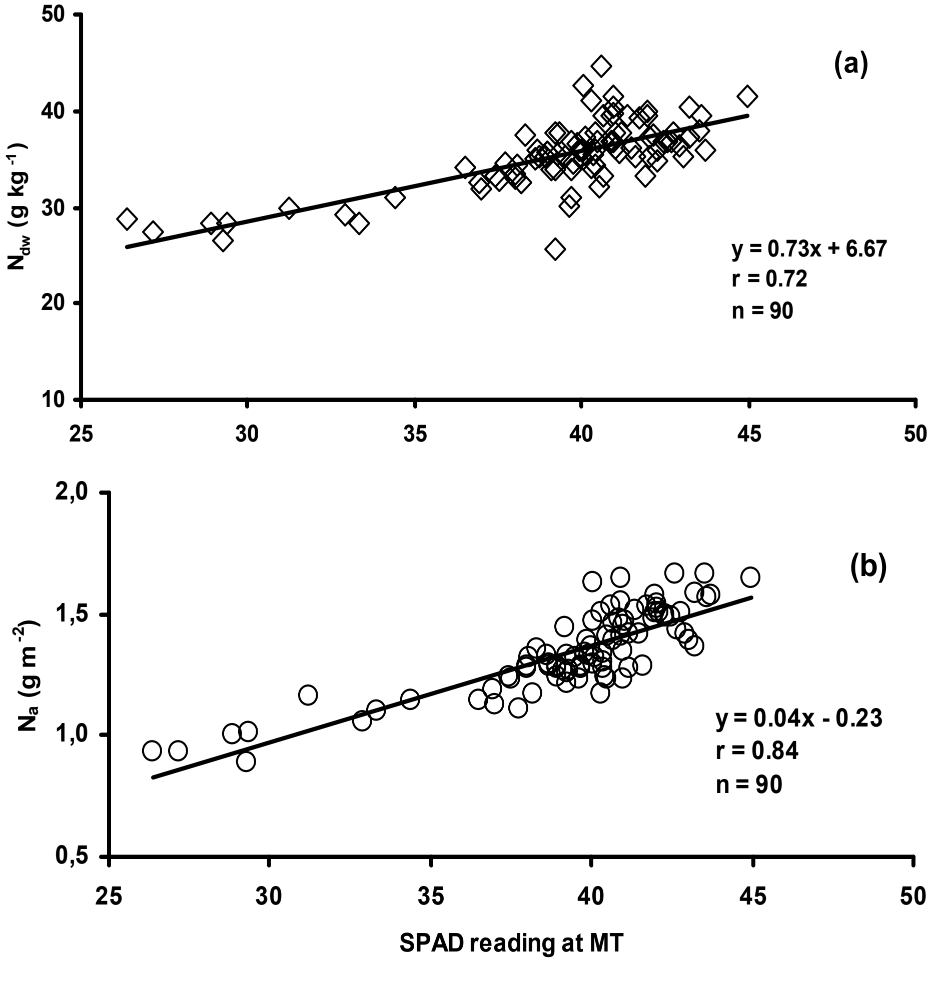

Figure 4.18. Linear regression of (a) dry weight-based (N_{dw}) and (b) area-based (N_a) leaf concentration on SPAD reading of ten N managements at maximum tillering stage using pooled data of three wheat varieties in Meherpur during the Rabi season of 2001-02 (see Table 4.31)

SPAD reading at maximum tillering stage and relationship of SPAD and three types of LCC readings

Figure 4.19 illustrates the mean SPAD reading of each N management in each variety at the MT stage. Among the varieties, Gaurab showed the higher SPAD reading in all N management treatments. The low SPAD values of Kanchan and Protiva indicate lighter leaf-greenness compared to the Gaurab variety. Since the mean SPAD reading values were lower than the value of 45, the critical SPAD value 48 might not be appreciable to use as a critical value for N topdressing at MT of wheat growth. Since the regression coefficients (b) between varieties in each LCC type were similar, the data were pooled for the three varieties (Table 4.32). The different types of LCC readings were closely related to the SPAD reading in the pooled data for three varieties (Figure 4.20). The coefficients of correlation (r) values were 0.93, 0.92 and 0.92 for IRRI-, China- and California-LCC, respectively.

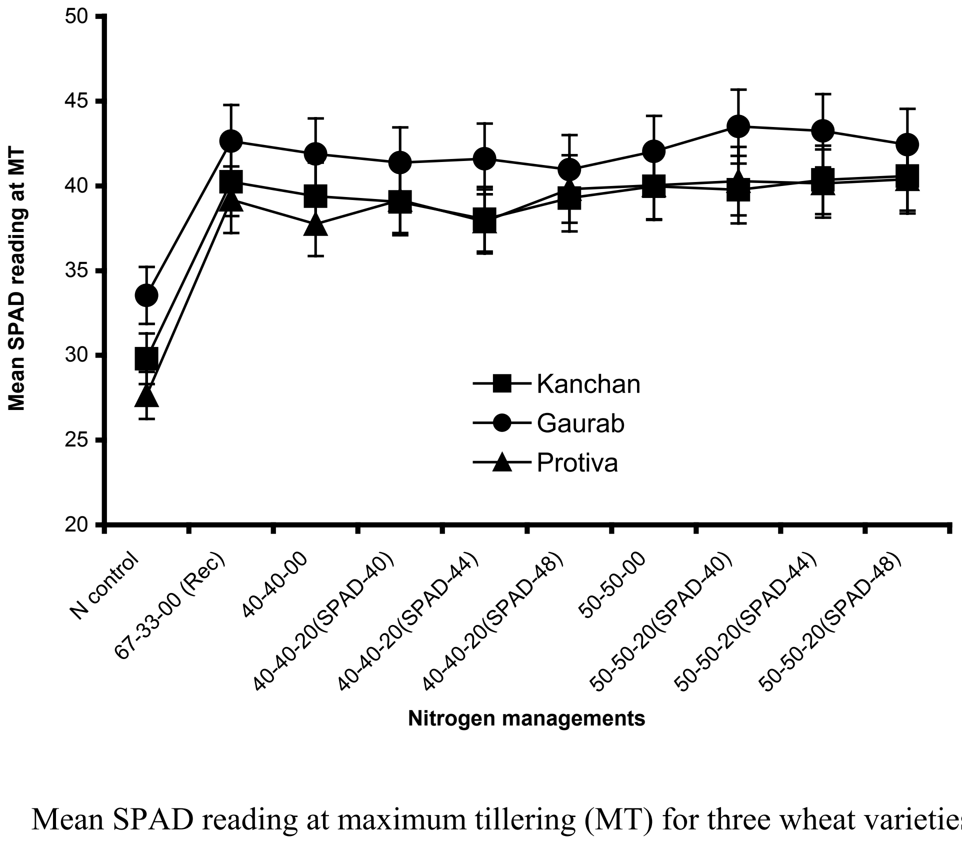

Figure 4.19. Mean SPAD reading at maximum tillering (MT) for three wheat varieties with ten nitrogen managements in Meherpur during the Rabi season of 2001-02

Table 4.32. The relationship of SPAD value at maximum tillering stage and three types of LCC readings for three wheat varieties with ten nitrogen managements in Meherpur during the Rabi season of 2001-02

Variety	IRRI-LCC			China-LCC			California-LCC		
	a	b	r	a	b	r	a	b	r
Kanchan§	-0.31	0.10	0.95±	-0.05	0.16	0.90	1.07	0.15	0.93
Gaurab	-2.31	0.16	0.97	1.66	0.13	0.92	2.08	0.13	0.96
Protiva	-0.42	0.10	0.98	-1.14	0.20	0.95	0.64	0.16	0.94
Pooled (n= 90)	-1.41	0.13	0.93	-0.65	0.18	0.92	0.76	0.16	0.92

±All correlations are significant at the 0.01 probability level.

§ Number of observations was 30 in each variety.

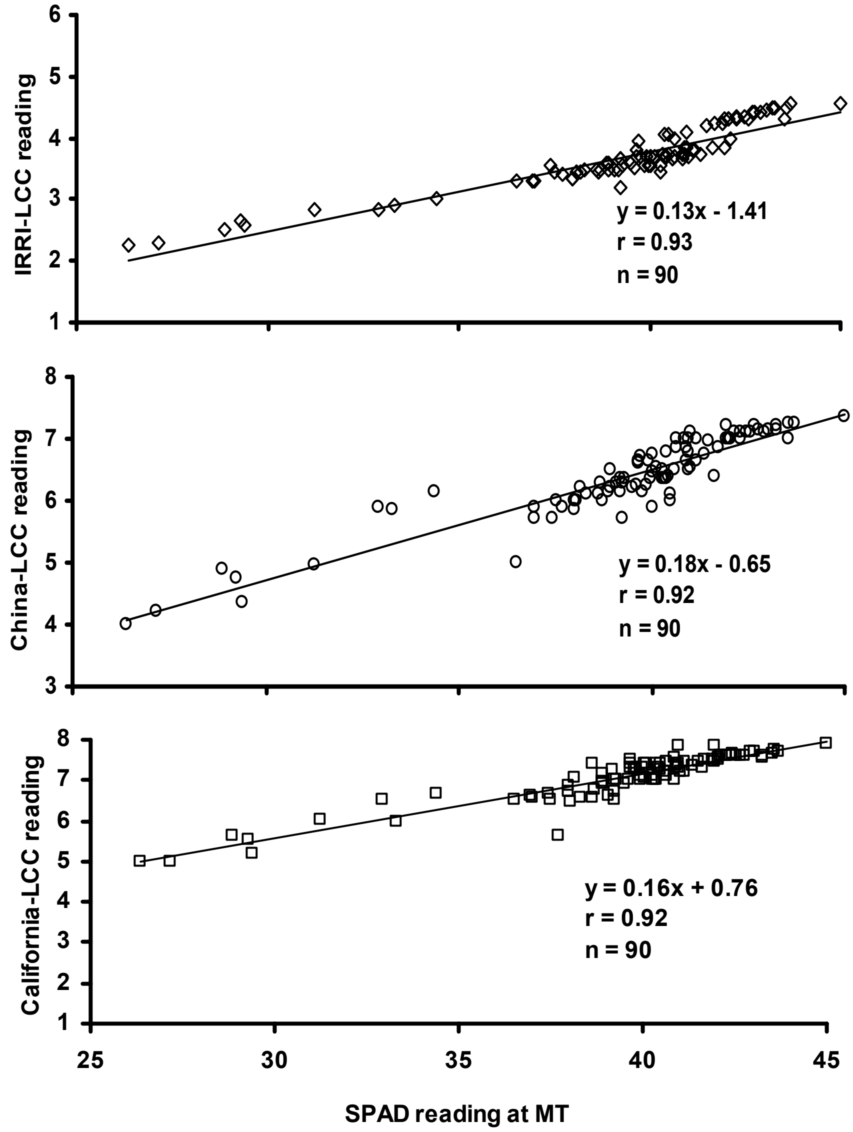

Figure 4.20. Relationship of SPAD and three types of LCC reading at maximum tillering stage (MT) in three wheat varieties (Kanchan, Gaurab and Protiva) with ten N managements in Meherpur during the Rabi season of 2001-02

In addition, the SPAD and LCC data of two experiments were pooled because of the similar regression coefficient for each LCC (Figures 4.16 and 4.20). Each type of LCC showed a very similar correlation (r = 0.93) with the SPAD reading at MT for pooled data of different varieties and different N managements (Figure 4.21).

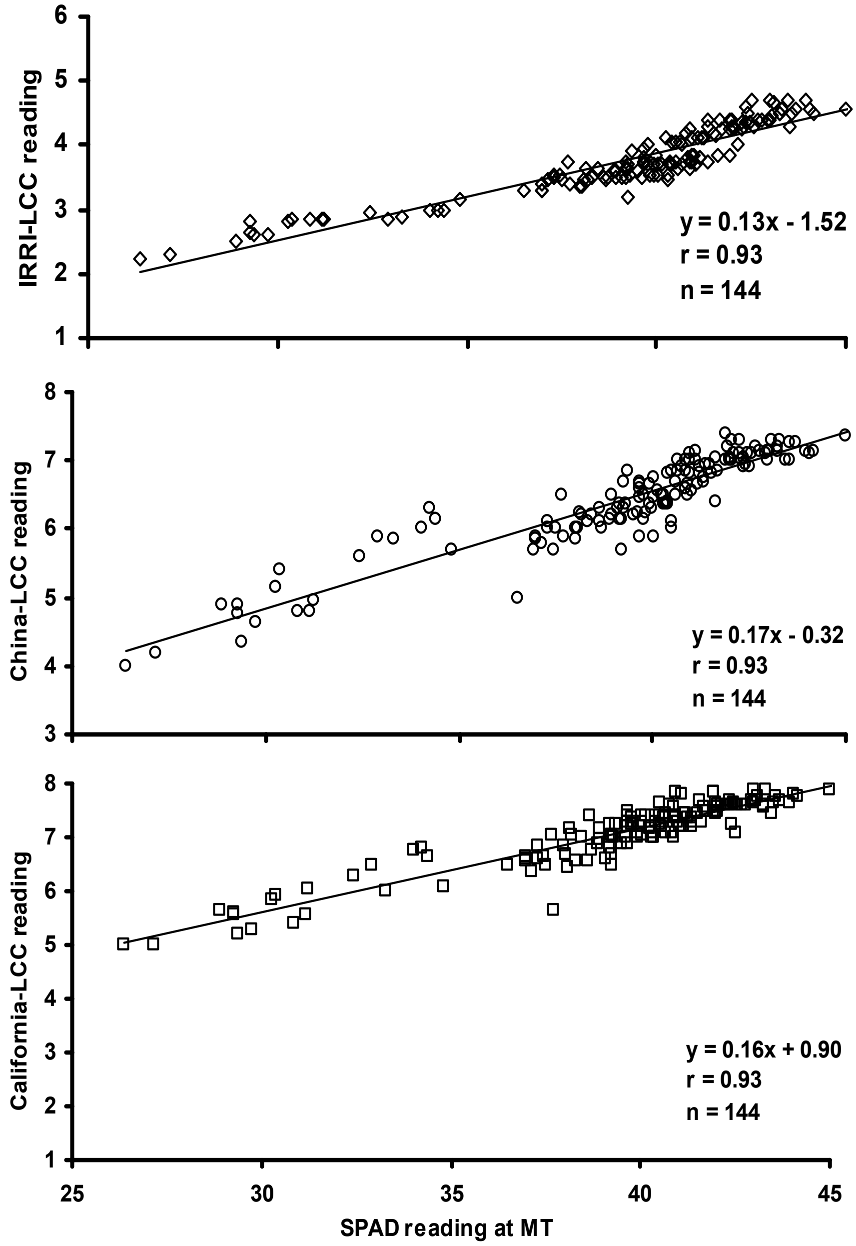

Figure 4.21. Relationship of SPAD and three types of LCC reading at maximum tillering stage (MT) for pooled data of four wheat varieties (Kanchan, Gaurab, Shatabdi and Protiva) in 16 nitrogen treatments of two experiments in Meherpur during the Rabi season of 2001-02

Based on those regression equations, Table 4.33 shows that the LCC value corresponds to the SPAD reading at the MT of wheat. The estimate IRRI-LCC values for SPAD 40, 44 and 48 were 4, 4.5 and 5, respectively. According to the equations, the LCC values were 6.5, 7 and 8 for China-LCC, and 7.5, 8 and 8.5 for California-LCC.

Table 4.33. Three types of LCC values corresponding to the SPAD value at the maximum tillering stage based on the regression analyses using pooled data of 144 observations in Meherpur during the Rabi season of 2001-02

SPAD critical value in the experiment	Correspondent LCC value		
	IRRI-LCC	China-LCC	California-LCC
40	4.1	6.5	7.3
44	4.5	7.2	7.9
48	5.2	7.8	8.6

Because the darkest greenness patch of both China and California LCC is number 8, the result indicates that the value of 8.5 is impracticable for California LCC, and the value 8 is inconvenient to use as a critical value with China- and/or California-LCC for N topdressing in wheat crop. Due to the better color differentiation of the LCC, the IRRI-LCC type is more preferable to estimate the need for N fertilization at MT of wheat than the China- and California-LCC.

5 GENERAL DISCUSSION AND CONCLUSIONS

Nitrogen fertilizer is an essential input in most crop production systems for improving crop productivity and increasing the farmers' economic return. Precise recommendations concerning the rate and the timing of mineral N fertilizer applications are required to ensure high and more profitable crop yields. The large plot-plot and farm-farm variability in soil nutrient status and the resulting variation in native soil N supply in rice fields of Asia require different amounts of fertilizer N in different fields. Thus, fertilizer N management strategies must respond to site- and system-specific variations in crop N demands and soil N supply. The present study evaluated the use of SPAD meter and LCC as alternative tools in fertilizer management strategies, and estimated native soil N supply in farmers' fields, studied the relationship of LCC and SPAD with yield and yield parameters of rice and wheat, compared three types of LCC for improving yield and N-use efficiency of rice and wheat, determined the critical LCC values for N fertilization in predominantly grown rice and wheat varieties in Bangladesh, and compared the plot-specific N fertilizer management based on LCC, SPAD and recommended N managements regarding yield and N-use efficiency in rice-rice and rice-wheat rotations.

5.1 Native soil N supply

The native soil N-supplying capacity is a key factor for estimating the N fertilizer requirement for a target yield. The present study estimated the native soil N supply by using indirect measurements such as SPAD meter and LCC readings at an early growth stage in rice and wheat in farmers' fields of Bangladesh during the T-Aman (rice), the Boro (rice) and the Rabi (wheat) seasons of 2001-02 (Section 4.1). The concept is based on results that show a close link between leaf chlorophyll content and leaf N content. Thus, the objective is to determine whether the chlorophyll meter can be used to quickly and reliably assesses the crop N status at an early growth stage.

Although total crop N uptake in N omission plots at harvest is the best way to estimate the soil N-supplying capacity, grain yield due to its high correlation with crop N uptake can also be used as a proxy of the N-supplying capacity. The present study shows this relationship in both rice (r^2= 0.66) and wheat (r^2=0.92). However, for the measurements of crop N or grain yield, the farmer has to wait till harvest. Also, farmers may be reluctant to keep N omission plots due to the loss of yield in these plots. Therefore, an indirect approach to determine whether rough estimates of the soil N supply can be made at an early stage of crop growth was investigated.

Soil N mineralization is greatest during the crop establishment phase and decreases, as soil becomes reduced 14-21 days after flooding. Thus, N fertilization is usually begun with two weeks after transplanting of rice. The results of the present study show that rice N uptake at harvest was related to the SPAD readings (r^2=0.62) and LCC readings (r^2=0.47) at an early growth stage (15 DAT in the T-Aman and 20 DAT in the Boro season) in the N omission plots. Those SPAD readings were closely related to the rice grain yield (r^2=0.69); however, the relationship of LCC readings and rice grain yield was weak (r^2=0.41). Although basal N fertilizer is usually applied in wheat, no basal N fertilizer may be needed during crop establishment when the residual effects of the previous crop and organic matter application are considered. The present study reveals that SPAD (r^2=0.64) and LCC (r^2=0.55) readings at the 20 DAS were closely related to the wheat N uptake at harvest during the Rabi season. The linear relationship of wheat grain yield with the SPAD readings could explain 62% of the variation and that with the LCC readings could explain 54% of the variation. Therefore, results of the present study suggest another promising strategy, i.e., the use of SPAD meter and/or LCC for estimating soil N-supplying capacity at early growth stages and determining the mineral N demand for an improved plot-specific N fertilizer management.

The use of indirect measurement tools such as SPAD meter and LCC at an early growth stage is desirable to improve N application during the crop season. Although LCC developed from a Japanese prototype has been standardized with the SPAD meter, visual assessment of leaf greenness is also influenced by sunlight variability (sun's intensity and angle) and other factors. Thus, the LCC cannot indicate smaller differences in leaf greenness as well as the SPAD meter. Since SPAD readings at an early growth stage are more closely related to yield and accumulative N uptake than those of the LCC in the present study, the SPAD meter is the preferable tool to predict the inherent N fertility status of soil in rice-based cropping systems. The LCC could only provide rough estimations of the native soil N supply during early crop growth. Due to the high cost of the SPAD meter, LCC might become an applicable tool to estimate the inherent soil N-supplying capacity in wheat, however not in rice.

5.2 Grain yield

Due to the large field-to-field and plot-to-plot variability of the soil N supply, plot-specific N fertilizer management may improve the productivity of rice and wheat. The present study compared the grain yields of LCC- or SPAD-based N managements with those of recommended N management in each experiment.

Among the different LCC-based N managements in the T-Aman season (Section 4.2), California-LCC with a critical value 4 resulted in the lowest yield (3.4 t ha^{-1}), which is a 70% yield increase over the N-control plot; however, the yield was significantly lower than that of the recommended N management (3.7 t ha^{-1}). Meanwhile, IRRI-LCC-3 and China-LCC-4 produced a 90% and 85% yield increase over the N-control plot, respectively, but with a relatively higher N application rate. China-LCC-5 showed a similar yield (4.2 t ha^{-1}) with slightly higher N rate compared to the California-LCC-5. The yield increase of 120% over the N-control was observed with the IRRI-LCC-4 and -5, China-LCC-6, and California-LCC-6 with the same rate of N application. The leaf greenness of the BR-11 rice variety was usually lower than that of those critical values, thus it became necessary to apply N fertilizer at 10 day-intervals during the growing season.

The use of IRRI-LCC with a critical value 3 generally resulted in similar yields compared to the yields of the recommended N management in six T-Aman rice varieties under rice-rice and rice-wheat systems at two different locations (Section 4.3). The N fertilizer application rates of IRRI-LCC-3 were higher than those of the recommended-N in Meherpur, but the rate was lower than that in Kushtia. In Meherpur, the times of application were different in the IRRI-LCC-3 treatment plots. This means that the soil N-supplying capacity can vary between locations and/or plots and N fertilizer strategies should be responsive to plot-specific differences. The significantly higher yields, which were more than or equal to double the yield of the N-control plots, resulted from the IRRI-LCC-4 and -5 N managements with relatively high N application compared to the recommended N management in both locations. Likewise, in the three types of LCC experiment (Section 4.2), all six rice varieties showed a lighter greenness color than that of IRRI-LCC-4 and -5. The data indicate that although LCC readings might be slightly influenced by variety, the N supply is the key factor. Since IRRI-LCC-3 seemed not to attain the high yield level, IRRI-LCC-4 should be taken as a critical value for N fertilization in rice production, although the N application rate was relatively high. The present data reveal that the critical IRRI-LCC value for T-Aman rice varieties might be between 3 and 4 with respect to high yield with optimum N application. However, this needs to be confirmed by another year of experiments.

In the Boro (dry) season experiment, the recommended N management resulted in a higher yield (5.1-7.1 t ha^{-1}) than that of the T-Aman season (3.7-4.7 t ha^{-1}), but yields were lower than those in the SPAD-based N managements (4.8-8.6 t ha^{-1}) (Section 4.4). In this experiments, SPAD-based N management with a critical value 32 showed a similar yield (4.8-6.8 t ha^{-1}) with a lower N applied rate (60-102 kg N ha^{-1}) compared to the recommended N management (102-126 kg N ha^{-1}) in three inbred and three hybrid varieties. The data reveals that SPAD-32 management could save about 31-52% of the recommended N rate in inbred varieties and 19-27% in hybrid varieties without sacrificing grain yield. This profit may be due to the synchrony of plant-demand and N supply in plot-specific N fertilizer application. SPAD-35 resulted in a significantly higher yield (6.0-7.4 t ha^{-1}) than that of the recommended N in all six varieties. In some cases, SPAD-35 could save 3-12% of the recommended N rate in the BRRI dhan-28, BRRI dhan-29, Alok, and Sonar Bangla-1 varieties. The data indicates that plot-specific N fertilizer management could increase grain yield and reduce production costs. However, the yields of SPAD-35 were significantly lower than those of SPAD-39 (6.5-8.3 t ha^{-1}) in all test varieties except for BRRI dhan-29. The N application rates of SPAD-39 were 50-60 and 40-80 kg N ha^{-1} higher than those of SPAD-35 for inbred varieties and hybrid varieties, respectively. With the increase of applied-N, yield increases in SPAD-39 were 200-600 and 700-800 kg grain ha^{-1} over the yields of SPAD-35 in inbred varieties and hybrid varieties, respectively. The data on the effect of a higher N application on the increase in grain yield should be useful for a cost / benefit analysis; however, an economic analysis is beyond the scope of the present study. For example, a yield increase of 0.6 t ha^{-1} in BRRI dhan-28 was obtained from SPAD 35 to 39 with an additional dose of 60 kg N ha^{-1}. The cost of 60 kg N would be about Taka 600 whereas the income from 600 kg rice would be about Taka 7200, which would be highly profitable for the farmers. The yields of SPAD-43 were not significantly different from those of SPAD-39 but the N application levels were higher than those of SPAD-39. Thus, SPAD-43 may not be useful as a critical value for N fertilization in Boro rice.

In the Rabi (winter) season experiments, both wheat experiments suggest that the current fertilizer N recommendation is not adequate for maintaining current yields of wheat (Section 4.5). Among the six N levels of the first experiment, 120 kg N ha^{-1} (48-48-24) resulted in the highest yield increases of 600, 200 and 900 kg grain ha^{-1} over the yield of the recommended N rate, 100 kg N ha^{-1} (67-33-00), in the Gaurab, Shatabdi, and Protiva varieties, respectively. The N application of 42-42-21 (100 kg N ha^{-1}) produced an increased yield of 100 and 800 kg grain ha^{-1} over the recommended N with the same amount of N fertilizer applied in the Shatabdi and Protiva varieties, respectively. In the second experiment, the results show yield increased by 100-800 kg ha^{-1} over the yield of the recommended N when N was applied at the MT stage. This confirms that additional N fertilizer should be applied at MT to increase yield. The maximum yield increases were obtained from the 50-50-20 (SPAD-44) N management in this experiment.

5.3 Nitrogen-use efficiency

The low N-use efficiency is a typical character in rice and wheat production in Asian countries. An increase in the N recovery of N applied could improve crop productivity and thus profitability. The present study evaluated the N-use efficiency between LCC- and SPAD-based N managements.

In the T-Aman season experiments, the values of agronomic efficiency (AE) of applied-N fertilizer were generally low (Sections 4.2 and 4.3). The low native soil N supplying capacity may demand the application of higher amounts of N fertilizer, which may result in a low AE. Among the different LCC types (Section 4.2), IRRI-LCC-3 resulted in the maximum AE value of 15.2 kg additional grain kg^{-1} N applied in the BR-11 variety, and its recovery efficiency (RE) was 48.2%. In the other four experiments (Section 4.3), the AE values of IRRI-LCC-3 ranged from 17.9 to 29.6 kg additional grain kg^{-1} N applied in six varieties under the rice-rice and rice-wheat systems in two locations. A range of 14.0-19.9 kg additional grain kg kg^{-1} N applied was found with the

IRRI-LCC-4 treatment. The RE values across six rice varieties and two locations were 40.9-70.7% and 36.2-63.8% in IRRI-LCC-3 and -4, respectively. The split N application using LCC may lead to an increase in RE and reduce N losses, and also increase yield.

In the Boro rice season experiment, AE values were substantially higher with higher yields than in the T-Aman season. This difference may be due to the different environmental factors (e.g., temperature, solar radiation, etc.) and different varieties (inbred and hybrid, days maturity, etc.). The AE values were 30.5-39.6 and 24.9-30.5 kg additional grain kg^{-1} N applied in SPAD-35 and -39, respectively. The AE of SPAD-35 was greater than that of SPAD-39 due to the lower N application. Although the physiological efficiency (PE) of SPAD-35 was higher than that of SPAD-39, the values were not significantly different. This means grain yield increases with an increased N accumulation in the plant. Recovery efficiency ranged from 46.8-57.0 and 41.0-57.0 kg additional N uptake kg^{-1} N applied in SPAD-35 and 39, respectively. In inbred varieties, RE values of SPAD-35 were higher than those of SPAD-39. However, the values were reversed in hybrid varieties due to the large amount of N accumulation in hybrid rice plants. As N absorption by the plant depends on the sink size, the amount of N accumulation under the same conditions may be due to the genotypic difference between the inbred and hybrid varieties.

In the Rabi (wheat) experiments, AE values ranged from 11.2 to 24.3 kg additional grain kg^{-1} N applied in both experiments (Section 4.5). The AE values of wheat were higher than those of T-Aman rice receiving a similar N rate under the rice-wheat system. Since the native soil N-supplying capacity was greater in T-Aman rice than in wheat, this might result in a smaller contribution of AE to grain yield. Higher AE values (15.3-22.9 kg additional grain kg^{-1} N applied) were found at 120 kg N ha^{-1} (48-48-24) and/or 100 kg N ha^{-1} (42-42-21) levels compared to the recommended N management (13.9-22.3 kg additional grain kg^{-1} N applied) in the first experiment (Section 4.5.1). The data suggest that equal N application at basal and CRI, and additional N application at MT may have contributed to higher grain yield and higher N-use efficiency. The data of the second experiment (Section 4.5.2) support the finding of the first experiment, because 40-40-20 SPAD-based N managements resulted in higher AE values (18.3-22.8 kg additional grain kg^{-1} N applied) than the recommended

N management (18.2-20.3 kg additional grain kg^{-1} N applied). Wheat experiments provided some responses to various N treatments (i.e., amount and timing), but they were not very conclusive. Thus, the experiments need to be repeated in further seasons to arrive at definitive conclusions.

5.4 Leaf nitrogen and SPAD meter

A large part of N in the plant is allocated to the leaves throughout the life of the plant, and photosynthetic capacity per unit leaf area is considered to be an important factor related to crop productivity. Since leaf N concentration is closely related to the leaf chlorophyll content, the measure of chlorophyll content can estimate the crop N status and thereby determine the need for additional N fertilizer. The chlorophyll (SPAD) meter provides an instantaneous, non-destructive indication of leaf chlorophyll or N concentration in the field.

The present study reveals that the correlation between SPAD readings and leaf N on an area basis (r=0.59) is better than that on a leaf dry weight basis (r=0.42) in the pooled data analysis of rice (Section 4.4.5). The data of the wheat experiments also show the better correlation of SPAD reading with leaf N area basis (r=0.91 and 0.84) than with leaf N dry weight basis (r=0.85 and 0.72) in both experiments (Sections 4.5.1 and 4.5.2). The rate of photosynthesis of a single leaf or a canopy depends on leaf area as well as on leaf N content, and thus indirect measure of the SPAD meter to estimate leaf N on an area basis would be useful to predict the crop N status and to determine the timing of N topdressing. The relation of SPAD reading and leaf N on an area basis is very close in spite of a wide range of specific leaf weights (SLW) in the present study of rice and wheat. This may indicate that a SPAD value could be used directly as a critical value without any correction factor (i.e., adjusted by using SLW) for timing of N topdressing for a given variety at a specific crop growth stage or during the entire growing period.

5.5 SPAD meter and LCC values

The chlorophyll (SPAD) meter provides a simple, quick and non-destructive method for estimating leaf chlorophyll content or leaf N concentration. Thus, the SPAD meter with proper calibration could provide growers with the ability to precisely manage N fertilization during the crop seasons to fulfill crop N requirements while minimizing N losses. The data of the present study show that LCC values are closely related to the SPAD readings in rice and wheat (Sections 4.4.6, 4.5.1 and 4.5.2), and that the LCC could be used instead of the SPAD meter for estimating leaf N or crop N status and for determining the timing of N topdressing. However, the regression analyses of the present study reveal that the differences between adjacent shades of green colour in the IRRI-, China- and California-LCC are equal to 9, 4-9 and 5-9 SPAD units in rice and 7-8, 5-7 and 5-8 SPAD units in wheat, respectively. The data indicate that the LCC could not provide an estimate of leaf N as accurately as the SPAD meter. However, the LCC has an obvious cost advantage and could be a simple, applicable tool for the farmers. In addition, the data show that the IRRI-LCC type has a more consistent difference in SPAD units compared to the other two types of LCC. Based on the regression equation for the wheat experiments (Section 4.5), the China- and California-LCC could not provide an estimate of leaf N due to the darker greenness color of the wheat leaves. Thus, the IRRI-LCC type is more applicable to estimate the need for N fertilization in both rice and wheat. The present rice and wheat data suggest that the critical LCC values of the IRRI-LCC type might be 3.5 for N topdressing in the rice-growing season and 4.5 for N fertilization at the maximum tillering stage of wheat.

5.6 Conclusions

The present study attempted to achieve synchrony of N supply and crop N demand, and to minimize the N losses by using the SPAD meter and the LCC in plot-specific N fertilizer management under the rice-based systems of Bangladesh. According to the data of this study, the following conclusions can be drawn:

- The indirect measurement of leaf N using the SPAD meter at an early growth stage of rice (69%) and wheat (62%) can reliably estimate the native soil N-supplying capacity.
- The LCC provides rough estimations (41% in rice and 54% in wheat) of the native soil N-supplying capacity at an early crop growth stage. While the cost of the SPAD meter restricts its widespread use, the LCC might become an applicable or alternative tool to estimate the native soil N supply in wheat, however not in rice.

- There is no doubt that the SPAD meter can be directly used to predict the timing of N topdressing in rice and wheat, because the relationship between SPAD reading and N content based on leaf area showed a better correlation than N content based on leaf dry weight for the pooled data of different varieties and sampling dates. Thus, no correction factor is needed to adjust the SPAD read ing.
- The data of T-Aman (wet) rice experiments show that the critical IRRI-LCC value for N topdressing might be between 3 and 4. The higher yields resulted from SPAD-39 N management with an appreciable agronomic efficiency value (24.9-30.5 kg additional grain kg^{-1} N applied) and N recovery percent (41.0-57.0%) in the Boro (dry) season. Thus, the threshold or critical value of the SPAD would be 39 for N topdressing in rice and an IRRI-LCC critical value of 3.5 is suggested in the present study area of Bangladesh.
- The data of the present experiments suggest that to avoid N losses, an equal split N application at sowing time and CRI (crown root initiation) stage is more effective than the high basal application. The data also suggest that an N application at MT (maximum tillering) stage is needed to increase yield, because this N applied may avoid the N limitation in the kernel filling stage. The critical SPAD values 44 and 48 resulted in higher AE values in both 40-40-20 and 50-50-20 SPAD-based N managements. However, SPAD readings did not reach the value of 48 in the present study. Thus, SPAD value 44 is appropriate as a critical value for N fertilization at the MT stage in wheat; the corresponding critical IRRI-LCC value is 4.5.
- Due to clearer greenness color differentiation, the IRRI-LCC provides more reliable estimates of crop N status in both rice and wheat than the China-LCC and California-LCC. The latter can be used in rice; however not in wheat. Since the highest greenness patch of both China and California LCC is number 8, the data of the wheat experiments indicate that the value of 8.5, based on the relationship of SPAD and LCC reading, is off-scale for the California-LCC, and

the value 8 is inconvenient to use as a critical value with the China- and/or California-LCC for N topdressing in wheat crops.

- The large farm-to-farm and plot-to-plot variability of soil N supply does not allow for a general recommendation for N fertilizer application. The data of the present study confirm that the recommended N application should be revised for both rice and wheat. Meanwhile, plot-specific N-fertilizer management using the SPAD and LCC at field level could improve crop productivity and N-use efficiency.

The present study was conducted in Bangladesh for only a single year cropping cycle and the work needs further confirmation if it is to be applied in various environments and crop growth stages.

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7 APPENDICES

Appendix 1. LCC, SPAD, tiller number and plant height at an early growth stage, grain yield, total nitrogen uptake, straw yield, total dry matter yield, harvest index, yield components, nitrogen uptake, nitrogen harvest index and internal use efficiency at harvest among rice farms in Bangladesh during the T-Aman and Boro seasons of 2001-02

Farmer ID	Farmer's name	Season	LCC reading	SPAD reading	Tiller	Plant height	Grain yield	TNU	Straw yield	TDM	HI	Panicle	SPP	Filled grain	N grain	N straw	Grain N	Straw N	NHI	IE
					no. hill^{-1}	cm	t ha^{-1}	kg ha^{-1}	t ha^{-1}	T ha^{-1}		no. m^{-2}	no	%	%	%	kg ha^{-1}	kg ha^{-1}		
M1	Mozammel Haque	Aman	3.05	34.30	9	28	3.14	52.1	3.7	6.5	0.43	231	92	75.64	1.22	0.49	33.9	18.2	0.65	60.2
M2	Altaf Hossain-1	Aman	2.95	32.70	6	27	2.63	44.8	3.4	5.8	0.41	264	68	70.16	1.25	0.46	29.1	15.6	0.65	58.7
M3	Bonomali Biswas	Aman	3.05	34.85	6	26	3.10	43.3	3.3	6.1	0.45	198	99	73.34	1.06	0.43	29.1	14.2	0.67	71.5
M4	Rezaul Karim	Aman	3.00	32.40	9	30	2.44	35.2	2.5	4.7	0.46	198	96	66.63	1.13	0.43	24.5	10.7	0.69	69.4
M5	Ramjan Ali-1	Aman	2.85	32.90	7	27	2.40	34.3	2.6	4.7	0.45	198	82	71.13	1.13	0.39	24.0	10.3	0.70	70.0
M6	Abdul Motaleb	Aman	1.85	28.70	6	21	1.75	25.3	2.2	3.7	0.42	231	55	62.95	1.03	0.43	16.0	9.3	0.63	69.1
M7	Abder Ali	Aman	2.85	32.76	7	28	2.52	40.7	2.9	5.2	0.43	264	64	67.70	1.22	0.46	27.2	13.5	0.67	61.8
M8	Tatul Shakh	Aman	2.70	31.56	6	30	2.38	35.9	2.8	4.9	0.43	231	66	74.49	1.09	0.46	23.0	12.9	0.64	66.3
M9	Nazirul Islam	Aman	3.00	34.38	7	30	3.04	43.0	3.2	5.9	0.46	264	71	73.17	1.09	0.43	29.4	13.7	0.68	70.6
M10	Ramjan Ali-2	Aman	2.65	30.81	8	29	1.90	33.9	3.0	4.7	0.36	264	53	64.59	1.19	0.45	20.1	13.7	0.59	56.2
K1	Ibrahim	Aman	2.70	32.10	6	30	2.38	40.0	2.4	4.5	0.47	198	69	73.34	1.18	0.62	25.0	15.0	0.63	59.6
K2	Sharifujjaman	Aman	2.90	33.40	6	27	2.43	42.2	3.0	5.2	0.41	198	88	68.66	1.22	0.52	26.2	16.0	0.62	57.5
K4	Toffajjal Hossain	Aman	2.95	33.74	5	30	2.67	46.3	3.4	5.7	0.41	231	82	66.52	1.22	0.52	28.8	17.4	0.62	57.6
K5	Nurul Islam	Aman	2.90	33.50	5	28	2.26	33.7	2.3	4.3	0.47	198	82	66.53	1.16	0.46	23.2	10.5	0.69	66.9
K6	Abdur Rashid	Aman	3.00	34.90	6	27	3.08	53.8	3.6	6.3	0.43	231	86	68.74	1.16	0.62	31.7	22.1	0.59	57.3
K7	Murad Hossain	Aman	2.90	33.20	5	30	2.47	44.0	3.6	5.8	0.38	198	86	66.39	1.19	0.49	26.1	17.9	0.59	56.3
K9	Muslem Miah	Aman	2.85	32.90	5	28	2.06	33.0	2.1	3.9	0.46	198	82	72.28	1.16	0.56	21.2	11.8	0.64	62.4
BM1	Mozammel Haque	Boro	2.70	32.85	3	25	2.96	45.5	3.2	5.9	0.45	231	81	70.88	0.95	0.63	24.9	20.5	0.55	65.2
BM3	Bonomali Biswas	Boro	2.55	32.35	4	25	2.29	33.0	2.5	4.5	0.45	231	71	67.86	0.91	0.59	18.4	14.6	0.56	69.3
BM5	Ramjan Ali-1	Boro	2.55	32.54	4	23	2.69	37.6	3.1	5.5	0.44	231	82	69.74	0.91	0.52	21.6	16.0	0.58	71.4
BM7	Abder Ali	Boro	2.40	31.33	3	19	2.37	35.4	2.6	4.7	0.45	198	87	67.32	0.69	0.81	14.5	20.9	0.41	66.8
BM8	Tatul Shakh	Boro	2.40	31.32	4	19	2.28	33.7	2.4	4.4	0.46	198	81	65.05	0.91	0.65	18.4	15.4	0.54	67.5
BM10	Ramjan Ali-2	Boro	2.55	32.26	3	28	2.18	34.0	2.4	4.3	0.45	198	85	66.90	1.00	0.62	19.2	14.7	0.57	64.1
BK2	Sharifujjaman	Boro	2.35	30.09	3	15	1.81	25.5	2.1	3.7	0.43	198	83	64.73	0.90	0.53	14.4	11.1	0.56	70.8

Appendix 1 (continued):

Farmer ID	Farmer's name	Sea-son	LCC reading	SPAD reading	Tiller	Plant heig-ht	Grain yield	TNU	Straw yield	TDM	HI	Pani-cle	SPP	Filled grain	N grain	N str-aw	Grain N	Str-aw N	NHI	IE
					no. $hill^{-1}$	cm	t ha^{-1}	kg ha^{-1}	t ha^{-1}	t ha^{-1}		no. m^{-2}	no	%	%	%	kg ha^{-1}	kg ha^{-1}		
BK4	Toffajjal Hossain	Boro	2.55	32.50	3	20	2.55	36.6	2.7	5.0	0.45	198	85	71.35	0.90	0.60	20.3	16.4	0.55	69.6
BK5	Nurul Islam	Boro	2.75	32.86	3	17	2.72	35.4	2.7	5.1	0.47	198	89	71.66	0.93	0.49	22.4	13.0	0.63	76.7
BK6	Abdur Rashid	Boro	2.60	32.52	3	17	2.52	39.5	2.7	4.9	0.46	198	88	68.09	0.97	0.68	21.6	18.0	0.55	63.6
BK7	Murad Hossain	Boro	2.50	31.53	3	18	2.30	34.3	2.5	4.5	0.45	231	79	69.79	0.90	0.64	18.4	15.9	0.54	67.1
M11	Ebadat Ali	Aman	3.00	34.46	8	27	2.36	47.2	3.2	5.3	0.39	264	58	72.28	1.13	0.73	23.7	23.5	0.50	50.1
M13	Bablu Miah	Aman	2.60	30.70	8	24	1.70	26.7	1.8	3.3	0.45	231	59	66.19	1.21	0.46	18.1	8.5	0.68	63.6
M14	Sirajul Islam	Aman	2.90	33.80	9	29	2.83	38.6	3.0	5.5	0.46	231	80	70.22	1.03	0.43	25.8	12.8	0.67	73.3
M15	Altaf Hossain-2	Aman	2.85	33.40	5	22	2.85	51.2	2.9	5.5	0.46	231	78	68.17	1.22	0.69	30.9	20.3	0.60	55.8
M16	Azer Ali	Aman	2.80	32.50	8	27	2.45	37.4	2.6	4.7	0.46	198	80	65.33	1.13	0.50	24.5	12.9	0.66	65.5
M17	Taluk Chand	Aman	2.80	32.60	5	23	2.68	42.7	2.7	5.1	0.47	198	81	68.61	1.12	0.59	26.7	16.0	0.62	62.9
M18	Moinul Islam	Aman	2.70	31.30	10	23	2.22	40.6	2.8	4.8	0.41	264	62	72.21	1.17	0.63	23.0	17.6	0.57	54.6
M19	Abdul Latif	Aman	2.70	32.40	8	31	2.41	37.6	2.8	4.9	0.44	198	84	74.76	1.12	0.50	23.9	13.7	0.64	64.0
M20	Sofdal Hossain	Aman	2.80	32.60	8	19	2.46	41.2	2.6	4.7	0.46	264	79	67.95	1.16	0.62	25.3	16.0	0.61	59.5
C1	Anwar Joardar	Aman	2.90	33.90	8	23	2.76	37.5	2.8	5.2	0.47	198	86	70.38	1.05	0.43	25.7	11.9	0.68	73.5
C4	Ileus Joardar	Aman	3.00	34.60	9	27	3.15	44.5	3.3	6.1	0.46	198	94	72.09	1.05	0.46	29.3	15.2	0.66	70.7
C5	Khairul Joardar	Aman	2.80	32.60	8	26	2.60	38.3	2.9	5.2	0.44	231	65	75.03	1.09	0.46	25.1	13.2	0.66	67.9
C7	Azgar Joardar	Aman	2.65	31.00	8	22	1.81	28.8	2.0	3.6	0.45	231	52	69.17	1.19	0.49	19.1	9.7	0.66	62.9
C8	Dulu	Aman	2.70	31.20	8	25	2.15	30.9	2.2	4.1	0.46	198	62	74.97	1.07	0.47	20.4	10.5	0.66	69.6
C10	Halim Joradar	Aman	2.90	33.50	5	23	2.51	44.7	2.7	4.9	0.46	231	71	70.98	1.08	0.78	24.0	20.7	0.54	56.2
		Mean	**2.75**	**32.6**	**6**	**25**	**2.47**	**38.6**	**2.8**	**5.0**	**0.44**	**220**	**77**	**69.63**	**1.08**	**0.54**	**23.7**	**14.9**	**0.61**	**64.5**

Note: M= Meherpur; K= Kushtia; C= Chuadanga; B= boro season; TNU= Total nitrogen uptake; TDM= Total dry matter yield; HI= harvest index; SPP = Number of spikelets per panicle; NHI= Nitrogen harvest index; IE= Internal nitrogen-use efficiency (kg grain kg^{-1}N uptake)

Appendix 2. LCC, SPAD, plant population density and plant height at an early growth stage, grain yield, total nitrogen uptake, straw yield, total dry matter, harvest index, yield components, nitrogen uptake, nitrogen harvest index and internal use efficiency at harvest among wheat farms in Bangladesh during the Rabi season of 2001-02

Far-mer ID	Farmer's name	Sea-son	LCC read-ing	SPAD read-ing	POP	Plant heig-ht	Grain yield	TNU	Straw yield	TDM	HI	SPK	Ker-nel / spike	Ker-nel wt	N grain	N str-aw	Grain N	Str-aw N	NHI	IE
					(m^{-2})	(cm)	t ha^{-1}	kg ha^{-1}	t ha^{-1}	t ha^{-1}		no m^{-2}	no	mg	%	%	kg ha^{-1}	kg ha^{-1}		
BM11	Ebadat Ali	Rabi	2.75	33.60	342	20	1.11	26.3	1.28	2.3	0.44	253	14	32.53	2.02	0.47	20.3	6.0	0.65	42.1
BM12	Aker Ali	Rabi	2.65	32.80	236	18	0.87	21.7	1.26	2.1	0.39	192	14	33.29	2.12	0.39	16.8	4.9	0.65	40.3
BM13	Bablu Miah	Rabi	2.35	30.50	248	18	0.62	15.7	1.02	1.6	0.35	231	14	29.57	2.09	0.39	11.7	4.0	0.67	39.4
BM14	Sirajul Islam	Rabi	2.65	32.80	252	20	0.82	20.4	0.93	1.7	0.44	175	15	35.48	2.26	0.39	16.8	3.6	0.69	40.2
BM16	Azer Ali	Rabi	2.50	32.40	254	19	0.69	16.7	0.93	1.5	0.40	192	12	34.07	2.05	0.42	12.8	3.9	0.70	41.2
BM17	Taluk Chand	Rabi	2.75	33.40	133	20	0.98	24.2	0.92	1.8	0.49	209	17	32.61	2.36	0.36	20.9	3.4	0.63	40.2
BM19	Abdul Latif	Rabi	2.75	33.30	220	21	0.74	18.6	1.21	1.9	0.36	201	14	31.65	2.12	0.36	14.2	4.4	0.67	39.8
BM20	Sofdal Hossain	Rabi	2.60	32.30	256	20	0.73	17.5	1.00	1.7	0.40	222	11	32.73	1.95	0.45	13.0	4.5	0.64	42.1
BC1	Anwar Joardar	Rabi	2.80	33.50	356	18	0.79	22.0	1.07	1.8	0.40	234	17	32.43	2.25	0.54	16.2	5.8	0.68	36.1
BC2	Lavlu	Rabi	2.45	30.10	159	15	0.55	13.6	0.75	1.3	0.40	80	20	36.13	2.05	0.45	10.2	3.4	0.59	40.4
BC3	Nazrul Islam	Rabi	2.45	30.40	258	16	0.61	13.8	0.83	1.4	0.40	150	18	36.16	1.91	0.39	10.6	3.2	0.63	44.3
BC4	Ileus Joardar	Rabi	2.60	32.50	257	17	0.61	14.3	0.80	1.4	0.41	225	15	34.01	1.98	0.42	10.9	3.4	0.62	42.6
BC6	Rezaul Joardar	Rabi	2.75	33.00	236	17	0.74	16.3	1.01	1.7	0.40	216	16	33.00	1.85	0.39	12.4	3.9	0.62	45.4
BC7	Azgar Joardar	Rabi	2.80	33.60	330	18	1.10	24.2	1.48	2.5	0.40	230	16	32.88	1.95	0.32	19.5	4.8	0.69	45.4
BC8	Dulu	Rabi	2.75	33.20	233	18	0.86	21.1	1.19	2.0	0.40	201	16	33.29	2.17	0.36	16.9	4.2	0.59	40.7
BC9	Sitab Ali	Rabi	2.80	33.50	381	18	1.05	23.7	1.39	2.3	0.41	190	18	34.47	1.64	0.58	15.6	8.1	0.59	44.2
BC10	Halim Joradar	Rabi	2.65	30.50	286	17	0.62	15.2	0.82	1.4	0.41	152	19	33.89	2.01	0.48	11.2	3.9	0.64	40.6
		Mean	**2.65**	**32.4**	**261**	**18**	**0.79**	**19.1**	**1.05**	**1.8**	**0.41**	**197**	**16**	**33.42**	**2.05**	**0.42**	**14.7**	**4.4**	**0.64**	**41.5**

Note: M= Meherpur; C= Chuadanga; B= boro (rabi) season; POP= population density; TNU= Total nitrogen uptake; TDM= Total dry matter yield; SPK = Number of spikes per square meter; NHI= Nitrogen harvest index; IE= Internal nitrogen-use efficiency (kg grain kg^{-1}N uptake)

Appendix 3. Grain yield (GY), panicle number (PAN), spikelet number (SPK), filled grain (FG), straw yield (SY), total dry matter yield (TDM), harvest index (HI), total N uptake (TNU), N harvest index (NHI), internal use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) as affected N managements on the BR-11 rice variety in Bangladesh during the T-Aman season of 2001

		GY	**PAN**	**SPK**	**FG**	**SY**	**TDM**	**HI**	**TNU**	**NHI**	**IE**	**PFP**	**AE**	**PE**	**RE** (%)
		t ha^{-1}	no. m^{-2}	no. pan^{-1}	%	t ha^{-1}	t ha^{-1}		kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
							Analysis of variance								
Source of variation	df	F value	F value	F value	F value	F value	F value	F Value	F value	F value	F value	F value	F value	F value	F value
Replication	2	11.16**	0.28^{ns}	0.34^{ns}	0.88^{ns}	1.60^{ns}	5.68**	0.41^{ns}	2.38^{ns}	2.03^{ns}	6.94**	2.80^{ns}	0.90^{ns}	1.62^{ns}	2.32^{ns}
N management	11	145.56**	3.80**	10.62**	14.98**	34.41**	107.46**	1.48^{ns}	43.98**	1.89^{ns}	9.68**	58.10**	18.22**	2.38^{ns}	0.67^{ns}
Rec vs. LCCs (T2 vs. T4-12)	1	47.71**	<0.01	1.18^{ns}	12.15**	1.08^{ns}	13.92**	7.82*	40.27**	0.93^{ns}	15.30**	201.87**	106.27**	14.08**	2.00^{ns}
SPAD vs. LCCs (T3 vs. T4-12)	1	11.48**	4.05^{ns}	18.16**	24.98**	0.05^{ns}	2.77^{ns}	2.03^{ns}	0.49^{ns}	2.52^{ns}	0.53^{ns}	1.89^{ns}	0.43^{ns}	0.75^{ns}	1.76^{ns}
IRRI vs. China (T4-6 vs. T10-12)	1	5.97*	1.73^{ns}	0.86^{ns}	4.23^{ns}	2.37^{ns}	5.98*	0.04^{ns}	<0.01^{ns}	0.11^{ns}	0.31^{ns}	1.33^{ns}	0.04^{ns}	0.53^{ns}	0.75^{ns}
IRRI vs. California (T4-6 vs. T10-12)	1	16.05**	1.69^{ns}	0.19^{ns}	2.74^{ns}	5.06*	14.28**	<0.01^{ns}	10.99**	3.49^{ns}	3.10^{ns}	42.20**	12.42**	1.79^{ns}	0.08^{ns}
China vs. California (T7-9 vs. T10-12)	1	2.44^{ns}	<0.01	0.24^{ns}	0.16^{ns}	0.50^{ns}	1.78^{ns}	0.23^{ns}	10.69**	2.37^{ns}	5.38*	28.57**	10.97**	4.26^{ns}	0.34^{ns}
Residual†	22	/ 20													
CV (%)		2.50	6.66	5.19	2.71	4.84	2.81	2.64	6.50	3.52	7.52	5.47	5.74	13.03	12.95

^{ns} Not significant
* Significant at the 0.05 probability level
** Significant at the 0.01 probability level
†Residual value 20 for PFP, AE, PE, and RE, and value 22 for other variables

Appendix 4. Grain yield, yield components, straw yield, total dry matter and harvest index as affected by variety (average across N management) and by N management (average across variety) in Meherpur and Kushtia during the T-Aman season of 2001 (rice-rice system)

		Grain yield	Panicle	Spikelets / panicle	Filled grain	Straw yield	Total dry matter	Harvest index	Grain yield	Panicle	Spikelets panicle	/Filled grain	Straw yield	Total dry matter	Harvest index
		t ha^{-1}	no. m^{-2}	no.	%	t ha^{-1}	t ha^{-1}		t ha^{-1}	no. m^{-2}	no.	%	t ha^{-1}	t ha^{-1}	
			Meherpur							**Kushtia**					
Variety															
BR-11		3.8 c	246 a	93 b	74.6 b	4.0 b	7.3 b	0.46 b	3.9 c	240 a	105 a	78.2 b	4.2 b	8.0 b	0.47 a
BRRI dhan-30		4.4 a	253 a	97 b	80.8 a	4.3 a	8.2 a	0.47 a	4.6 a	242 a	106 a	81.3 a	4.8 a	8.8 a	0.46 a
BRRI dhan-31		4.0 b	222 b	111 a	73.8 b	3.9 b	7.5 b	0.48 a	4.3 b	222 b	110 a	75.0 c	4.0 b	7.5 c	0.47 a
§LSD $_{(0.05)}$		0.16	13.05	6.67	2.97	0.22	0.31	0.01	0.20	10.03	5.75	1.84	0.31	0.42	0.02
N management															
N-control		2.4 c	194 c	92 b	65.4 d	2.5 c	4.5 c	0.46 b	2.6 c	202 c	102 b	63.5 c	3.0 c	5.3 d	0.44 b
Rec-N		4.2 b	235 b	106 a	75.4 c	4.3 b	8.0 b	0.46 ab	4.2 b	246 a	105 ab	79.4 b	4.6 ab	8.6 b	0.46 a
IRRI-LCC-3		4.3 b	257 a	99 ab	77.8 bc	4.1 b	8.0 b	0.48 a	4.5 b	224 b	110 a	80.1 b	4.2 b	8.0 c	0.47 a
IRRI-LCC-4		4.8 a	257 a	101 a	80.8 ab	4.8 a	9.0 a	0.47 ab	4.9 a	249 a	110 a	84.6 a	4.8 a	9.2 a	0.48 a
IRRI-LCC-5		4.8 a	260 a	103 a	82.7 a	4.6 a	8.9 a	0.48 a	5.0 a	253 a	108 ab	83.3 a	4.9 a	9.4 a	0.47 a
§LSD $_{(0.05)}$		0.21	16.84	8.61	3.84	0.29	0.40	0.01	0.26	12.95	7.43	2.38	0.40	0.55	0.02
							Analysis of variance								
Source of variation	df	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value
Replication	2	18.91**	3.90*	1.22^{ns}	1.03^{ns}	4.40**	12.68**	0.79^{ns}	9.95**	4.17*	0.94^{ns}	0.04^{ns}	5.25*	8.19**	0.11^{ns}
N	4	191.58**	22.79**	3.22^{ns}	25.99**	88.18**	169.93**	2.32^{ns}	121.34**	23.56**	1.87^{ns}	106.41**	30.67**	75.50**	4.88**
Var	2	26.42**	12.97**	18.33**	14.24**	8.34**	18.48**	4.82*	21.02**	9.83**	2.00^{ns}	24.71**	14.94**	22.19**	1.36^{ns}
N x Var	8	1.08^{ns}	0.24^{ns}	1.11^{ns}	1.76^{ns}	0.42^{ns}	0.54^{ns}	1.01^{ns}	0.59^{ns}	1.25^{ns}	0.81^{ns}	2.79*	0.33^{ns}	0.43^{ns}	0.36^{ns}
LCC-3 vs. -4	1	27.84**	0.20^{ns}	0.34^{ns}	2.45^{ns}	20.67**	30.06**	0.21^{ns}	35.15**	16.49**	<0.01^{ns}	14.70**	7.76*	20.22**	0.37^{ns}
LCC-3 vs. -5	1	25.84**	<0.01^{ns}	0.76^{ns}	6.83*	12.32**	21.48**	<0.01^{ns}	37.25**	21.54**	0.45^{ns}	7.74**	12.43**	25.81**	0.01^{ns}
LCC-4 vs. -5	1	0.04^{ns}	0.20^{ns}	0.08^{ns}	1.10^{ns}	1.08^{ns}	0.72^{ns}	0.21^{ns}	0.03^{ns}	0.34^{ns}	0.45^{ns}	1.11^{ns}	0.55^{ns}	0.34^{ns}	0.25^{ns}
Residual	28														
CV (%)		5.34	7.25	8.86	5.20	7.28	5.42	3.27	6.34	5.71	7.17	3.15	9.59	6.98	5.03

§ LSD was determined based on analysis of variance; ^{ns} Not significant; * Significant at the 0.05 probability level; **Significant at the 0.01 probability level

Appendix 5. Total N uptake (TNU), N harvest index (NHI), internal use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) as affected by variety (average across N management) and by N managements (average across variety) in Meherpur and Kushtia during the T-Aman season of 2001 (rice-rice system)

	TNU	NHI	IE	PFP	AE	PE	RE (%)	TNU	NHI	IE	PFP	AE	PE	RE (%)
	kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied	kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
		Meherpur							**Kushtia**					
Variety														
BR-11	77.4 b	0.63a	52.1 b	34.7 b	16.2 b	39.9 a	41.0 a	86.0 b	0.64a	51.7 a	44.0 b	18.3 a	37.1 a	49.2 a
BRRI dhan-30	84.2 a	0.65 a	56.8 a	39.7 a	18.2 a	39.8 a	46.6 a	92.2 a	0.60b	51.9 a	47.7 a	20.5 a	40.6 a	52.9 a
BRRI dhan-31	74.9 b	0.64 a	57.6 a	40.1 a	18.9 a	44.2 a	44.1 a	81.6 b	0.60b	51.9 a	41.3 c	19.1 a	35.4 a	53.5 a
§LSD $_{(0.05)}$	6.28	0.02	3.22	2.93	1.26	5.73	5.85	5.34	0.02	2.94	2.49	2.31	5.49	8.53
N management														
N-control	33.7d	0.67 a	70.4 a	-	-	-	-	40.5 c	0.63a	65.4 a	-	-	-	-
Rec-N	69.1c	0.67 a	61.2 b	50.8 a	22.3 a	52.7 a	42.7 a	84.2 b	0.61a	53.4 b	54.1 a	22.8 a	43.9 a	53.5 a
IRRI-LCC-3	79.7b	0.64 a	54.3 c	43.7 b	19.2 b	43.0 b	46.1 a	81.8 b	0.62a	52.1 b	56.6 a	22.0 a	40.5 a	56.0 a
IRRI-LCC-4	108.0a	0.62 a	45.0 d	29.1 c	14.8 c	34.0 c	44.7 a	111.7 a	0.61a	44.5 c	33.2 b	15.9 b	33.7 b	47.9 a
IRRI-LCC-5	103.5a	0.63 a	46.7 d	28.9 c	14.7 c	35.6 c	42.0 a	114.9 a	0.60a	43.7 c	33.4 b	16.3 b	32.8 b	50.1 a
§LSD $_{(0.05)}$	8.10	0.03	4.15	3.39	1.46	6.62	6.76	6.89	0.03	3.79	2.88	2.67	6.34	9.85

Appendix 5 (continued):

		TNU	NHI	IE	PFP	AE	PE	RE (%)	TNU	NHI	IE	PFP	AE	PE	RE (%)
		kg ha^{-1}		kg grain kg^{-1}N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied	kg ha^{-1}		kg grain kg^{-1}N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
			Meherpur							**Kushtia**					
						Analysis of variance									
Source of variation	df	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value
Replication	2	4.58^{*}	1.08^{ns}	0.04^{ns}	1.38^{ns}	4.62^{*}	0.05^{ns}	1.16^{ns}	0.83^{ns}	0.34^{ns}	4.17^{*}	7.85^{**}	7.49^{**}	3.10^{ns}	0.57^{ns}
N	4	114.87^{**}	5.55^{**}	54.02^{**}	89.45^{**}	54.98^{**}	14.33^{**}	0.64^{ns}	158.43^{**}	1.22^{ns}	44.42^{**}	169.29^{**}	16.37^{**}	6.16^{**}	1.15^{ns}
Var	2	4.39^{*}	1.25^{ns}	7.10^{**}	9.02^{**}	10.68^{**}	1.66^{ns}	1.94^{ns}	8.44^{**}	6.12^{**}	0.01^{ns}	14.30^{**}	2.00^{ns}	2.04^{ns}	0.65^{ns}
N x Var	8	0.89^{ns}	0.53^{ns}	2.68^{*}	1.31^{ns}	3.13^{*}	2.56^{*}	1.00^{ns}	0.24^{ns}	0.70^{ns}	1.38^{ns}	0.75^{ns}	0.82^{ns}	0.70^{ns}	0.04^{ns}
LCC-3 vs. -4	1	51.33^{**}	1.39^{ns}	21.00^{**}	80.40^{**}	39.32^{**}	8.05^{**}	0.17^{ns}	78.91^{**}	0.25^{ns}	16.63^{**}	285.57^{**}	22.85^{**}	4.85^{*}	2.91^{ns}
LCC-3 vs. -5	1	36.42^{**}	0.35^{ns}	13.85^{**}	81.75^{**}	41.94^{**}	5.47^{*}	1.52^{ns}	96.91^{**}	1.01^{ns}	20.56^{**}	278.84^{**}	19.90^{**}	6.34^{*}	1.57^{ns}
LCC-4 vs. -5	1	1.28^{ns}	0.35^{ns}	0.74^{ns}	0.01^{ns}	0.04^{ns}	0.25^{ns}	0.68^{ns}	0.92^{ns}	0.25^{ns}	0.21^{ns}	0.04^{ns}	0.10^{ns}	0.10^{ns}	0.21^{ns}
Residual†	28 / 22														
CV (%)		10.65	4.35	7.75	9.09	8.40	16.39	15.75	8.24	5.35	7.58	6.63	14.18	17.20	19.41

§ LSD was determined based on analysis of variance; ^{ns} Not significant; * Significant at the 0.05 probability level; **Significant at the 0.01 probability level; †Residual value 28 for TNU, NHI and IE; 22 for PFP, AE, PE, and RE

Appendix 6. Grain yield, yield components, straw yield, total dry matter and harvest index as affected by variety (average across N management) and by N management (average across variety) in Meherpur and Kushtia during the T-Aman season of 2001 (rice-wheat system)

		Grain yield	Panicle	Spikelets / panicle	Filled grain	Straw yield	Total dry matter	Harvest index	Grain yield	Panicle	Spikelets / panicle	Filled grain	Straw yield	Total dry matter	Harvest index
		t ha^{-1}	no. m^{-2}	no.	%	t ha^{-1}	t ha^{-1}		t ha^{-1}	no. m^{-2}	no.	%	t ha^{-1}	t ha^{-1}	
					Meherpur							Kushtia			
Variety															
BRRI dhan-32		3.7 b	259 a	85 a	80.1 a	3.7 a	7.0 b	0.47 a	4.3 a	250 b	101 a	80.6 ab	4.2 b	8.0 a	0.48 a
BRRI dhan-33		3.7 b	257 a	85 a	79.8 a	3.7 a	7.0 b	0.47 a	4.3 a	261 a	97 b	79.2 b	4.2 ab	8.0 a	0.47 a
BRRI dhan-39		3.8 a	268 a	86 a	79.1 a	3.8 a	7.2 a	0.47 a	4.4 a	239 c	102 a	81.9 a	4.5 a	8.4 a	0.47 a
§LSD $_{(0.05)}$		0.10	16.86	5.79	2.40	0.15	0.18	0.01	0.13	10.36	3.17	2.18	0.28	0.35	0.01
N management															
N-control		2.0 c	209 c	80 b	68.2 c	2.1 d	3.9 c	0.46 c	2.7 d	201 d	90 c	73.8 c	2.8 b	5.1 c	0.46 bc
Rec-N		4.0 b	278 a	83 ab	79.5 b	4.1 bc	7.6 b	0.46 bc	4.7 b	260 b	105 a	80.2 b	4.5 a	8.7 b	0.48 ab
IRRI-LCC-3		4.0 b	256 b	89 a	81.1 b	4.0 c	7.6 b	0.47 ab	4.3 c	238 c	104 a	80.7 b	4.6 a	8.5 b	0.46 c
IRRI-LCC-4		4.4 a	282 a	88 a	85.1 a	4.2 ab	8.0 a	0.47 ab	5.0 a	275 a	105 a	83.9 a	4.8 a	9.2 a	0.48 a
IRRI-LCC-5		4.4 a	282 a	87 ab	84.4 a	4.3 a	8.2 a	0.48 a	5.0 a	278 a	98 b	84.2 a	4.8 a	9.2 a	0.48 a
§LSD $_{(0.05)}$		0.13	21.77	7.48	3.10	0.19	0.23	0.01	0.16	13.38	4.09	2.81	0.37	0.46	0.02
								Analysis of variance							
Source of variation	df	F value	F value	F value	F value	F value	F value	F Value	F value	F value	F value	F value	F value	F value	F value
Replication	2	7.35**	1.00^{ns}	0.56^{ns}	0.53^{ns}	2.85^{ns}	8.70**	0.65^{ns}	0.41^{ns}	1.14^{ns}	2.72^{ns}	0.89^{ns}	0.74^{ns}	0.75^{ns}	0.05^{ns}
N	4	476.09**	17.45**	2.15^{ns}	40.78**	191.94**	492.75**	4.74**	305.96**	47.17**	22.82**	18.60**	44.76**	117.98**	4.32**
Var	2	7.16**	1.00^{ns}	0.10^{ns}	0.34^{ns}	1.96^{ns}	6.52**	0.16^{ns}	0.53^{ns}	9.46**	5.49**	3.28^{ns}	2.99^{ns}	2.60^{ns}	1.54^{ns}
N x Var	8	1.16^{ns}	1.42^{ns}	0.94^{ns}	0.74^{ns}	1.03^{ns}	1.41^{ns}	0.48^{ns}	1.01^{ns}	0.63^{ns}	1.41^{ns}	1.16^{ns}	1.22^{ns}	1.32^{ns}	0.98^{ns}
LCC-3 vs. -4	1	20.56**	5.38*	0.01^{ns}	7.22*	4.20*	16.10**	1.53^{ns}	70.87**	31.53**	0.25^{ns}	5.40*	0.75^{ns}	10.49**	8.59**
LCC-3 vs. -5	1	20.56**	5.38*	0.37^{ns}	4.72*	10.60**	23.95**	0.03^{ns}	75.67**	38.15**	11.54**	6.46*	0.55^{ns}	10.49**	11.09**
LCC-4 vs. -5	1	$<$0.01	$<$0.01	0.24^{ns}	0.26^{ns}	1.45^{ns}	0.78^{ns}	2.00^{ns}	0.08^{ns}	0.32^{ns}	15.19**	0.05^{ns}	0.02^{ns}	$<$0.01	0.16^{ns}
Residual	28														
CV (%)		3.58	8.61	9.07	4.03	5.22	3.39	2.83	3.87	5.52	4.22	3.61	8.91	5.81	3.75

§ LSD was determined based on analysis of variance; ^{ns} Not significant; * Significant at the 0.05 probability level; ** Significant at the 0.01 probability level

Appendix 7. Total N uptake (TNU), N harvest index (NHI), internal use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) as affected by variety (average across N management) and by N management (average across variety) in Meherpur and Kushtia during the T-Aman season of 2001 (rice-wheat system)

		TNU	**NHI**	**IE**	**PFP**	**AE**	**PE**	**RE** (%)	**TNU**	**NHI**	**IE**	**PFP**	**AE**	**PE**	**RE** (%)
		kg ha^{-1}		kg grain kg^{-1}N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied	kg ha^{-1}		kg grain kg^{-1}N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
				Meherpur								**Kushtia**			
Variety															
BRRI dhan-32		77.3 ab	0.59 a	49.4 a	40.5 ab	21.6 a	46.5 a	49.1 a	86.9 b	0.60 a	52.4 a	48.5 b	20.5 b	34.9 a	59.0 b
BRRI dhan-33		74.1 b	0.54 b	50.9 a	39.9 b	21.5 a	49.2 a	39.5 b	86.4 b	0.58 a	53.8 a	49.2 b	23.0 a	35.3 a	65.5 ab
BRRI dhan-39		82.0 a	0.58 a	48.6 a	42.0 a	19.3 b	40.3 b	54.0 a	94.7 a	0.58 a	49.6 b	54.9 a	21.7 ab	32.0 a	66.0 a
§LSD $_{(0.05)}$		4.98	0.02	3.10	2.07	1.31	4.66	5.39	5.64	0.02	2.46	2.28	1.69	3.61	6.59
N management															
N-control		37.8 c	0.57 a	54.4 a	-	-	-	-	38.4 c	0.64 a	69.6 a	-	-	-	-
Rec-N		79.2 b	0.57 a	50.8 ab	48.1 a	23.5 a	49.3 a	49.8 a	89.2 b	0.58 b	52.3 b	56.1 b	23.8 a	39.2 a	61.2 b
IRRI-LCC-3		83.5 b	0.57 a	49.4 bc	45.1 b	22.4 a	46.7 a	50.2 a	88.2 b	0.58 b	50.4 b	67.2 a	25.7 a	35.5 a	69.6 a
IRRI-LCC-4		93.9 a	0.57 a	46.9 bc	35.0 c	18.7 b	42.8 b	44.9 a	114.0 a	0.57 b	44.0 c	40.0 c	18.9 b	31.0 b	60.5 b
IRRI-LCC-5		94.5 a	0.59 a	46.7 c	35.0 c	18.7 b	42.6 b	45.3 a	116.8 a	0.57 b	43.4 c	40.3 c	18.6 b	30.5 b	62.7 ab
§LSD $_{(0.05)}$		6.43	0.03	4.00	2.38	1.51	5.38	6.23	7.28	0.03	3.18	2.63	1.96	4.17	7.61
								Analysis of variance							
Source of variation	df	F value	F value	F value	F value	F value	F value	F Value	F value	F value	F value	F value	F value	F value	F value
Replication	2	9.26**	2.27^{ns}	3.68*	1.16^{ns}	0.39^{ns}	2.24^{ns}	2.89^{ns}	0.76^{ns}	0.36^{ns}	1.64^{ns}	0.28^{ns}	1.99^{ns}	0.70^{ns}	0.67^{ns}
N	4/3†	110.20**	0.62^{ns}	5.23**	69.74**	23.55**	3.06*	1.77^{ns}	156.61**	10.87**	93.50**	217.46**	28.44**	8.39**	2.60^{ns}
Var	2	5.43*	12.10**	1.20^{ns}	2.38^{ns}	8.59**	8.42**	15.97**	5.80**	1.93^{ns}	6.17**	20.46**	4.50*	2.14^{ns}	2.96^{ns}
N x Var	8/6†	1.19^{ns}	1.81^{ns}	0.99^{ns}	0.25^{ns}	0.42^{ns}	1.25^{ns}	0.67^{ns}	2.97^{ns}	2.01^{ns}	2.62^{ns}	18.21**	1.78^{ns}	2.07^{ns}	0.45^{ns}
LCC-3 vs. -4	1	11.10**	0.98^{ns}	1.64^{ns}	76.47**	25.71**	2.18^{ns}	3.09^{ns}	52.8**	0.26^{ns}	17.17**	460.73**	56.26**	5.12*	6.17*
LCC-3 vs. -5	1	12.29**	0.81^{ns}	2.03^{ns}	76.64**	26.17**	2.43^{ns}	2.59^{ns}	64.8**	0.73^{ns}	20.53**	451.01**	51.93**	6.11*	3.52^{ns}
LCC-4 vs. -5	1	0.03^{ns}	0.01^{ns}	0.02^{ns}	<0.01	<0.01	0.01^{ns}	0.02^{ns}	0.61^{ns}	0.12^{ns}	0.15^{ns}	0.05^{ns}	0.09^{ns}	0.04^{ns}	0.37^{ns}
Residual	28 / 22†														
CV (%)		8.56	4.57	8.34	5.98	7.43	12.13	13.40	8.44	4.70	6.34	5.29	9.21	12.52	12.26

§ LSD was determined based on analysis of variance; ^{ns} Not significant; * Significant at the 0.05 probability level; **Significant at the 0.01 probability level; †Degree of freedom for PFP, AE, PE, and RE

Appendix 8. Grain yield (GY), panicle number (PAN), spikelet number (SPK), filled grain (FG), straw yield (SY), total dry matter yield (TDM), harvest index (HI), total N uptake (TNU), N harvest index (NHI), internal use efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) as affected by variety (average across N management) and by N managements (average across variety) in Meherpur during the Boro season of 2001-02

	GY	**PAN**	**SPK**	**FG**	**SY**	**TDM**	**HI**	**TNU**	**NHI**	**IE**	**PFP**	**AE**	**PE**	**RE** (%)
	t ha^{-1}	no. m^{-2}	no. pan^{-1}	%	t ha^{-1}	t ha^{-1}		kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
Variety														
BRRI dhan-28	5.4 e	319 c	89 d	83.5 ab	5.1 d	9.8 e	0.48 b	85.1 c	0.64 a	65.4 b	54.6 a	31.4 a	63.7 ab	51.5 ab
BRRI dhan-29	5.6 d	332 bc	92 cd	83.7 a	5.2 d	10.2 d	0.49 a	84.3 c	0.60 b	71.0 a	51.8 ab	30.7 a	65.6 ab	47.1 bc
BRRI dhan-36	5.5 de	341 ab	83 e	78.8 d	5.2 d	10.1 de	0.48 b	87.3 bc	0.64 a	65.4 b	52.7 a	32.0 a	58.8 b	54.9 a
BRRI hybrid-1	6.5 b	337 b	93 c	81.3 bc	6.3 b	12.0 b	0.48 bc	105.3 a	0.63 a	65.7 b	51.9 a	32.3 a	58.4 b	56.5 a
Alok	6.0 c	354 a	99 b	80.4 cd	5.8 c	11.1 c	0.48 bc	94.4 b	0.63 a	65.9 b	47.4 b	26.9 b	64.5 ab	42.5 c
Sonar Bangla-1	6.8 a	286 d	107 a	83.8 a	6.7 a	12.8 a	0.47 c	102.0a	0.64 a	71.0 a	52.9 a	33.7 a	66.8 a	51.6 ab
§LSD $_{(0.05)}$	0.20	13.01	3.53	2.22	0.22	0.38	0.01	7.19	0.02	4.24	4.47	2.95	7.30	7.78
N management														
N-control	2.6 d	196 d	85 c	73.7 b	2.7 e	5.0 e	0.46 c	34.3 e	0.60 b	74.7 a	-	-	-	-
Rec-N	6.0 c	330 bc	95 ab	82.6 a	5.6 d	11.0 d	0.49 a	80.9 d	0.65 a	74.6 a	50.9 c	29.2 c	73.6 a	39.2 c
SPAD-32	5.8 c	323 c	93 b	83.9 a	5.7 d	10.8 d	0.48 b	82.6 d	0.64 a	71.4 a	72.7 a	40.4 a	70.7 a	60.2 a
SPAD-35	6.7 b	341 b	98a	83.6 a	6.3 c	12.2 c	0.49 a	94.4 c	0.65 a	71.0 a	58.1 b	35.6 b	69.7 a	51.6 b
SPAD-39	7.3 a	383 a	96 ab	84.0 a	6.9 b	13.3 b	0.49 a	122.5 b	0.64 a	60.5 b	42.0 d	27.2 c	55.7 b	50.4 b
SPAD-43	7.5 a	396 a	96 ab	83.9 a	7.1 a	13.7 a	0.48 ab	143.7 a	0.61 b	52.0 c	35.6 e	23.4 d	45.0 c	52.1 b
§LSD $_{(0.05)}$	0.20	13.01	3.52	2.22	0.22	0.38	0.01	7.19	0.02	4.24	4.08	2.70	6.67	7.10

Appendix 8 (continued):

		GY	**PAN**	**SPK**	**FG**	**SY**	**TDM**	**HI**	**TNU**	**NHI**	**IE**	**PFP**	**AE**	**PE**	**RE** (%)
		t ha^{-1}	no. m^{-2}	no. pan^{-1}	%	t ha^{-1}	t ha^{-1}		kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
						Analysis of variance									
Source of variation	df	F value	F value	F value	F value	F value	F value	F Value	F value	F value	F value	F value	F value	F value	F value
Replication	2	0.92^{ns}	1.06^{ns}	1.09^{ns}	1.35^{ns}	0.75^{ns}	0.76^{ns}	0.59^{ns}	0.92^{ns}	0.11^{ns}	2.35^{ns}	4.62^{*}	5.24^{**}	0.57^{ns}	0.98^{ns}
N	$5/4^{†}$	620.08^{**}	238.05^{**}	12.88^{**}	26.99^{**}	408.16^{**}	567.13^{**}	27.28^{**}	220.14^{**}	8.53^{**}	36.80^{**}	100.46^{**}	50.81^{**}	26.77^{**}	8.96^{**}
Var	5	67.00^{**}	26.14^{**}	41.97^{**}	6.98^{**}	73.36^{**}	79.39^{**}	6.44^{**}	12.41^{**}	5.37^{**}	3.49^{**}	2.35^{ns}	4.89^{**}	1.87^{ns}	3.50^{**}
N x Var	$25/20^{†}$	2.79^{**}	2.17^{**}	2.47^{**}	2.89^{**}	2.97^{**}	3.13^{**}	1.23^{ns}	1.59^{ns}	0.97^{ns}	1.23^{ns}	2.85^{**}	2.49^{**}	1.46^{ns}	1.46^{ns}
Rec vs SPAD	1	101.84^{**}	35.48^{**}	0.26^{ns}	2.09^{ns}	91.31^{**}	106.74^{**}	2.63^{ns}	110.64^{**}	3.87^{ns}	41.62^{**}	0.57^{ns}	5.57^{*}	25.59^{**}	26.34^{**}
SPAD 32 vs 35	1	70.57^{**}	7.90^{**}	8.34^{**}	0.10^{ns}	35.45^{**}	55.93^{**}	4.50^{*}	10.76^{**}	2.99^{ns}	0.04^{ns}	51.72^{**}	12.47^{**}	0.09^{ns}	5.79^{*}
SPAD 32 vs 39	1	216.93^{**}	86.08^{**}	2.77^{ns}	0.01^{ns}	117.00^{**}	178.06^{**}	6.12^{*}	122.73^{**}	0.66^{ns}	25.99^{**}	227.02^{**}	95.16^{**}	20.28^{**}	7.65^{**}
SPAD 32 vs 43	1	262.49^{**}	126.47^{**}	2.09^{ns}	$<0.01^{ns}$	170.30^{**}	239.78^{**}	0.78^{ns}	287.91^{**}	5.16^{ns}	82.66^{**}	330.99^{**}	158.68^{**}	59.60^{**}	5.21^{*}
SPAD 35 vs 39	1	40.04^{**}	41.81^{**}	1.05^{ns}	0.16^{ns}	23.65^{**}	34.40^{**}	0.12^{ns}	60.82^{**}	0.84^{ns}	23.93^{**}	62.03^{**}	38.74^{**}	17.64^{**}	0.13^{ns}
SPAD 35 vs 43	1	60.85^{**}	71.14^{**}	2.09^{ns}	0.11^{ns}	50.35^{**}	64.10^{**}	1.53^{ns}	187.37^{**}	16.01^{**}	78.96^{**}	121.03^{**}	82.19^{**}	55.00^{**}	0.02^{ns}
SPAD 39 vs 43	1	2.17^{ns}	3.87^{ns}	0.05^{ns}	0.01^{ns}	4.99^{*}	4.58^{ns}	2.53^{ns}	34.69^{**}	9.50^{**}	15.95^{**}	9.77^{**}	8.08^{**}	10.35^{**}	0.23^{ns}
Residual	$70 / 58^{†}$														
CV (%)		5.13	5.96	5.66	4.08	5.89	5.17	1.97	11.61	4.90	9.48	11.80	12.97	15.86	20.99

§ LSD was determined based on analysis of variance; ^{ns} Not significant; * Significant at the 0.05 probability level; **Significant at the 0.01 probability level; †df for PFP, AE, PE, and RE

Appendix 9. Grain yield (GY), spike number (SPK), kernel number (KER), kernel weight (KW), straw yield (SY), total dry matter yield (TDM), harvest index (HI), total N uptake (TNU), N harvest index (NHI), internal efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) as affected by variety (average across six N levels) and by N levels (average across variety) in Meherpur during the Rabi (wheat) season of 2001-02

	GY	SPK	KER	KW	SY	TDM	HI	TNU	NHI	IE	PFP	AE	PE	RE (%)
	t ha^{-1}	no. m^{-2}	no. spike^{-1}	mg	t ha^{-1}	t ha^{-1}		kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
Variety														
Gaurab	3.1	308	26	40.9	3.8	6.2	0.44	79.5	0.81	39.2	28.1	16.0	36.0	44.8
Shatabdi	3.3	327	30	37.4	4.3	6.8	0.43	79.6	0.76	41.8	30.5	19.3	38.9	50.1
Protiva	2.8	363	24	34.7	4.1	6.3	0.41	75.3	0.75	38.6	26.4	15.7	34.8	45.1
§$LSD_{(0.05)}$	0.20	22.02	1.25	0.92	0.33	0.44	0.01	6.24	0.02	1.79	1.90	2.05	3.08	6.37
N level														
1. N - control	1.4	260	19	36.3	2.1	3.2	0.39	30.9	0.78	44.1	-	-	-	-
2. Recommended (67-33-00)	3.1	309	28	38.9	4.4	6.9	0.41	75.2	0.76	41.6	31.1	17.5	40.9	44.3
3. 50% more than T_2 (60-60-30)	3.4	382	28	36.9	4.4	7.1	0.43	96.0	0.75	35.2	22.5	13.5	31.1	43.4
4. 90% of T_3 (54-54-27)	3.3	368	29	36.5	4.4	6.9	0.44	89.1	0.77	37.4	24.7	14.6	33.9	43.1
5. 80% of T_3 (48-48-24)	3.7	367	30	37.9	4.4	7.4	0.46	94.8	0.79	39.2	30.9	19.6	37.0	53.2
6. 70% of T_3 (42-42-21)	3.4	310	28	39.4	4.7	7.3	0.42	82.6	0.79	41.4	32.6	19.7	40.0	49.2
§$LSD_{(0.05)}$	0.28	31.15	1.77	1.30	0.46	0.62	0.02	8.82	0.03	2.54	2.45	2.65	3.98	8.22

Appendix 9 (continued):

		GY	**SPK**	**KER**	**KW**	**SY**	**TDM**	**HI**	**TNU**	**NHI**	**IE**	**PFP**	**AE**	**PE**	**RE** (%)
		t ha^{-1}	no. m^{-2}	no. $spike^{-1}$	mg	t ha^{-1}	t ha^{-1}		kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
								Analysis of variance							
Source of variation	df	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value
Replicate	2	0.98^{ns}	3.87^{*}	1.25^{ns}	1.98^{ns}	0.17^{ns}	0.44^{ns}	1.11^{ns}	0.31^{ns}	0.44^{ns}	0.41^{ns}	0.41^{ns}	1.57^{ns}	3.96^{*}	3.71^{*}
variety	2	9.08^{**}	13.34^{**}	35.39^{**}	93.28^{**}	4.54^{*}	4.80^{*}	14.45^{**}	1.72^{ns}	20.83^{**}	7.38^{**}	10.01^{**}	7.93^{**}	3.89^{*}	1.87^{ns}
N level	5/4†	76.56^{**}	19.35^{**}	41.49^{**}	8.25^{**}	35.25^{**}	56.54^{**}	11.99^{**}	63.24^{**}	2.63^{*}	13.25^{**}	27.79^{**}	9.58^{**}	9.06^{**}	2.44^{ns}
variety x N level	10/8†	1.93^{ns}	1.43^{ns}	3.05^{**}	5.15^{**}	2.11^{ns}	2.21^{*}	1.49^{ns}	1.34^{ns}	2.47^{*}	0.66^{ns}	2.30^{*}	2.05^{ns}	0.71^{ns}	1.56^{ns}
N level (150) vs (135)	1	0.10^{ns}	0.85^{ns}	1.64^{ns}	0.49^{ns}	0.77^{ns}	0.53^{ns}	0.22^{ns}	2.53^{ns}	2.26^{ns}	3.08^{ns}	3.32^{ns}	0.79^{ns}	2.16^{ns}	0.01^{ns}
N level (150) vs (120)	1	5.85^{*}	0.99^{ns}	3.68^{ns}	2.31^{ns}	0.01^{ns}	0.89^{ns}	$5.3.9^{*}$	0.08^{ns}	8.54^{**}	10.44^{**}	49.22^{**}	22.31^{**}	9.21^{**}	5.99^{*}
N level (150) vs (105)	1	0.11^{ns}	22.55^{**}	0.15^{ns}	15.50^{**}	1.21^{ns}	0.76^{ns}	1.09^{ns}	9.57^{**}	9.03^{**}	24.41^{**}	70.99^{**}	22.83^{**}	21.27^{**}	2.09^{ns}
N level (135) vs (120)	1	7.47^{**}	0.01^{ns}	1.41^{ns}	4.93^{ns}	0.64^{ns}	2.79^{ns}	3.45^{ns}	1.72^{ns}	2.01^{ns}	2.18^{ns}	26.99^{**}	14.68^{**}	2.45^{ns}	6.36^{*}
N level (135) vs (105)	1	0.42^{ns}	14.56^{**}	0.80^{ns}	21.51^{**}	3.90^{ns}	2.56^{ns}	2.28^{ns}	2.26^{ns}	2.26^{ns}	10.16^{**}	43.62^{**}	15.11^{**}	9.88^{**}	2.31^{ns}
N level (120) vs (105)	1	4.36^{*}	14.10^{**}	2.35^{ns}	5.84^{*}	1.39^{ns}	<0.01	11.33^{**}	7.92^{**}	0.01^{ns}	2.92^{ns}	1.99^{ns}	0.00^{ns}	2.49^{ns}	1.00^{ns}
Residual	34 / 28†														
CV (%)		10.1	9.7	7.1	3.8	12.5	10.5	5.0	11.9	3.4	6.3	9.1	17.5	10.5	18.0

§ LSD was determined based on analysis of variance; ^{ns} Not significant; * Significant at the 0.05 probability level; **Significant at the 0.01 probability level; †df for PFP, AE, PE, and RE

Appendix 10. Grain yield (GY), spike number (SPK), kernel number (KER), kernel weight (KW), straw yield (SY), total dry matter yield (TDM), harvest index (HI), total N uptake (TNU), N harvest index (NHI), internal efficiency (IE), partial factor productivity (PFP), agronomic efficiency (AE), physiological efficiency (PE) and recovery efficiency (RE) as affected by variety (average across ten N managements) and by N managements (average across variety) in Meherpur during the Rabi (wheat) season of 2001-02

	GY	**SPK**	**KER**	**KW**	**SY**	**TDM**	**HI**	**TNU**	**NHI**	**IE**	**PFP**	**AE**	**PE**	**RE** (%)
	t ha^{-1}	no. m^{-2}	no. $spike^{-1}$	mg	t ha^{-1}	t ha^{-1}		kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additiona l N uptake kg^{-1} N applied
Variety														
Kanchan	3.1	382	24	35.8	4.7	7.0	0.39	82.0	0.73	38.3	32.3	21.1	35.4	60.5
Gaurab	3.2	341	23	40.7	4.5	7.0	0.41	83.3	0.78	40.2	34.0	18.3	38.3	48.2
Protiva	3.1	395	26	35.4	4.6	7.0	0.40	82.1	0.72	37.8	32.1	21.8	35.5	61.5
§$LSD_{(0.05)}$	0.14	17.86	1.18	0.01	0.25	0.31	0.01	4.66	0.01	1.15	1.52	1.52	3.13	4.78
N management														
N - control	1.3	250	16	36.0	2.4	3.3	0.34	29.3	0.71	42.9	-	-	-	-
Rec – N (67-33-00)	3.2	398	25	36.4	4.7	7.2	0.40	84.5	0.73	37.4	31.5	19.0	35.0	55.2
40-40-00	3.0	366	28	36.2	4.9	7.5	0.38	73.4	0.73	40.5	37.2	21.5	39.2	55.1
40-40-20 (SPAD 40)	3.1	379	25	39.4	4.9	7.4	0.41	78.5	0.76	40.1	34.4	20.3	38.9	52.7
40-40-20 (SPAD 44)	3.4	432	24	37.8	4.8	7.6	0.41	87.8	0.76	38.6	33.6	21.3	36.6	58.4
40-40-20 (SPAD 48)	3.4	349	24	38.7	4.9	7.2	0.40	90.6	0.75	38.0	34.3	21.8	36.1	61.3
50-50-00	3.3	433	25	37.1	4.7	7.6	0.39	87.1	0.73	38.1	32.4	20.3	36.0	57.7
50-50-20(SPAD 40)	3.3	365	25	37.3	4.4	6.9	0.40	89.5	0.74	37.0	31.5	19.4	34.4	57.4
50-50-20(SPAD 44)	3.7	382	26	37.0	5.2	7.8	0.44	97.7	0.75	37.6	30.6	20.2	35.5	56.9
50-50-20(SPAD 48)	3.6	372	27	36.9	5.0	7.7	0.44	97.3	0.77	37.7	30.0	19.8	35.6	55.8
§$LSD_{(0.05)}$	0.25	32.60	2.15	2.17	0.45	0.57	0.02	8.51	0.03	2.10	2.63	2.63	3.13	8.27

Appendix 10 (continued):

		GY	SPK	KER	KW	SY	TDM	HI	TNU	NHI	IE	PFP	AE	PE	RE (%)
		t ha^{-1}	no. m^{-2}	no. spike^{-1}	mg	t ha^{-1}	t ha^{-1}		kg ha^{-1}		kg grain kg^{-1} N uptake	kg grain kg^{-1} N applied	kg additional grain kg^{-1} N applied	kg additional grain kg^{-1} additional N uptake	kg additional N uptake kg^{-1} N applied
								Analysis of variance							
Source of variation	df	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value	F value
Replicate	2	3.14*	3.10^{ns}	0.21^{ns}	0.52^{ns}	1.27^{ns}	2.37^{ns}	0.38^{ns}	4.20*	0.37^{ns}	2.67^{ns}	4.54*	2.35^{ns}	4.24*	5.88**
variety	2	2.29^{ns}	22.74**	15.26**	46.50**	0.48^{ns}	0.11^{ns}	5.94**	0.36^{ns}	31.03**	9.50**	3.49*	12.11**	6.69**	19.42**
N management	9/8†	61.74**	20.54**	18.96**	1.72^{ns}	25.61**	43.21**	16.92**	43.04**	2.90**	6.09**	5.98**	0.94^{ns}	2.25*	0.69^{ns}
variety x N management	18/16†	1.14^{ns}	1.34^{ns}	1.73^{ns}	1.64^{ns}	1.82*	1.33^{ns}	2.68**	0.76^{ns}	1.15^{ns}	1.19^{ns}	0.56^{ns}	0.75^{ns}	1.13^{ns}	0.41^{ns}
Rec-N vs SPAD 40	1	0.28^{ns}	2.43^{ns}	0.25^{ns}	4.14*	0.11^{ns}	<0.01^{ns}	0.96^{ns}	0.02^{ns}	1.38^{ns}	1.61^{ns}	1.86^{ns}	0.61^{ns}	1.44^{ns}	<0.01^{ns}
Rec-N vs SPAD 44	1	12.18**	0.01^{ns}	2.40^{ns}	0.39^{ns}	0.30^{ns}	3.15^{ns}	6.17*	4.96*	3.47^{ns}	0.58^{ns}	0.38^{ns}	2.27^{ns}	0.57^{ns}	0.50^{ns}
Rec-N vs SPAD 48	1	11.54**	0.13^{ns}	3.01^{ns}	0.46^{ns}	0.50^{ns}	3.40^{ns}	4.65*	5.93*	4.03*	0.23^{ns}	0.31^{ns}	2.11^{ns}	0.36^{ns}	0.91^{ns}
SPAD 40 vs SPAD 44	1	13.12**	4.05*	1.66^{ns}	3.00^{ns}	1.19^{ns}	4.93*	3.39^{ns}	8.38**	0.17^{ns}	0.39^{ns}	0.84^{ns}	0.79^{ns}	0.29^{ns}	0.79^{ns}
SPAD 40 vs SPAD 48	1	12.31**	5.52*	2.30^{ns}	2.76^{ns}	1.64^{ns}	5.32*	2.08^{ns}	9.92**	1.04^{ns}	0.94^{ns}	0.97^{ns}	0.67^{ns}	0.55^{ns}	1.43^{ns}
SPAD 44 vs SPAD 48	1	0.01^{ns}	0.11^{ns}	0.05^{ns}	<0.01^{ns}	0.04^{ns}	0.01^{ns}	0.16^{ns}	0.06^{ns}	0.03^{ns}	0.12^{ns}	0.01^{ns}	<0.01^{ns}	0.04^{ns}	0.09^{ns}
Residual	58 / 52†														
CV%		8.5	9.1	8.9	6.5	10.3	8.6	5.2	11.1	3.7	5.7	8.2	13.8	9.1	15.4

§ LSD was determined based on analysis of variance; ^{ns} Not significant; * Significant at the 0.05 probability level; **Significant at the 0.01 probability level; †df for PFP, AE, PE, and RE

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