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