

Crop demand-driven site-specific nitrogen applications in rice (*Oryza sativa*) and wheat (*Triticum aestivum*): some recent advances

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ABSTRACT

Management of fertilizer nitrogen in rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L. emend. Fiori & Paol.) in India typically consists of blanket recommendations, developed for large tracts having similar climate and land forms. It cannot help the increase N-use efficiency beyond a limit. Further improvement can be achieved only by planning strategies for fertilizer N management responsive to temporal variations in crop N demand and field-to-field variability in soil-N supply. Improvement in the synchrony between crop N demand and the N supply from soil or the applied N fertilizer is likely to be the most promising strategy to improve N-use efficiency. It can be achieved by following real-time N management based on periodic assessment of plant-N status and delayed application of fertilizer N until the N level goes below a critical level. Gadgets like chlorophyll-meter (SPAD-meter) and inexpensive leaf colour chart (LCC) have proved quick and reliable tools to decide the time when fertilizer N needs to be applied to the crop. Recently significant progress has been made in the development and on-farm evaluation of LCC-based real-time N management in rice, but there is a need to work out appropriate criteria for using need-based N-management strategy in wheat. Optical sensors offer an opportunity to take into account both plant N status (or leaf colour) as well as crop biomass for making crop-demand-driven fertilizer-N recommendations. Combination of preventive location-specific split schedule with corrective LCC or SDAD-meter or optical sensor-based N management constitutes another attractive strategy for achieving high N-use efficiency in rice and wheat. The fixed-time or adjustable-dose approach seems very promising for wheat, because unlike in rice, the fertilizer applications need to be synchronized with irrigation events. Appropriate preventive fertilizer-N management scenarios need to be worked out that can be used before using the SPAD meter, LCC or optical sensors to guide corrective fertilizer-N application at a given crop-growth stage.

Key words: Chlorophyll meter, Crop-demand driven, Fertilizer-use efficiency, Green-seeker, Nitrogen, Leaf-colour chart, Optical sensor, Rice, SPAD meter, Wheat

The current recommendations for nitrogen fertilizer typically consist of fixed rate and timing for large tracts to grow rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L. emend. Fiori & Paol.). Depending on the type of rice and wheat culture and the region, blanket recommendations in different parts of the country vary from 60 to 150 kg N/ha to be applied in two or three split doses. These blanket recommendations for fertilizer N are developed for large tracts having similar climate and land forms in the quest of achieving high yield levels and fertilizer-use efficiency. These have served the purpose very well but could not help increase the nutrient-use efficiency beyond a limit. And many a times, to ensure high yields, ignorant farmers apply fertilizer N doses even higher than the blanket recommendations. Over-application of N fertilizer in cereal crops leads to further lowering of N recovery efficiency. Its application in excess of crop requirements also leads to higher cost of production, increased attack of

pests and diseases as well as the possibility of nitrate pollution of ground water and emission of gases like nitrous oxide, which can attack the ozone layer that protects earth from harmful ultra-violet (UV) radiations.

The nitrogen-use efficiency in rice and wheat is low. A recent world-wide evaluation shows that the fertilizer N-recovery efficiency is around 30% in rice and wheat with current practices (Krupnik *et al.*, 2004). Due to large field-to-field variability of soil N supply, efficient use of N fertilizer is not possible when broad-based blanket recommendations for fertilizer N are used (Adhikari *et al.*, 1999). The recommendations based on soil tests remain ignorant about the dynamics of N release from crop residues, organic manures and irrigation water, and are not very successful in rice and wheat. Thus the farmers often apply nitrogenous fertilizers over and above the recommended doses to ensure higher yields by avoiding the risk of N deficiency. The main reason of low N-use efficiency is inefficient splitting of N applications, including the use of N in excess to the requirements. The need of the time

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is to synchronize the N application with crop demand. In addition to field-to-field variability, the strategies for fertilizer N management must be responsive to temporal variations in crop N demand and soil N supply to achieve supply-demand synchrony and to minimize N losses. When N application is not synchronized with crop demand, N losses from the soil-plant system are large, leading to low use efficiency of N fertilizer. Peng and Cassman (1998) demonstrated that recovery efficiency of top-dressed urea during panicle initiation stage could be as high as 78%. Thus it seems that improvement in the synchrony between crop-N demand and N supply from soil or the applied N fertilizer is likely to be the most promising strategy to increase N-use efficiency in rice and wheat. The crop demand-driven site-specific N applications have the potential to add to farmers' productivity and profits and are crucial for achieving high yield and N-use efficiency, because with burgeoning populations to feed countries like India can neither afford low yields nor ignore environmental concerns linked with low N-use efficiency in these crops.

In general three kinds of strategies can be followed for guiding N management in rice and wheat using the principles based on N need of plants: (i) location-specific split schedules for preventive N management, (ii) corrective or real-time N management, and (iii) a combination of both, in which corrective N management is used at certain growth stages to identify the need for fertilizer N. Possibly some innovative fertilizer N management strategies in rice and wheat can be evolved by integrating both preventive and corrective strategies to manage N efficiently, sustain the soil-resource base and increase the profitability. Location-specific split schedules for preventive N management can be worked out by defining fertilizer N requirements on the basis of crop requirement and native soil N supply. An estimate of the latter can be obtained by analysing the current farm yields and the farmer's N management strategies in combination with local knowledge of soil fertility (Dobermann *et al.*, 2004). Precision in preventive N management strategies can be increased by following techniques that can provide an in-season estimate of biomass and N requirements of rice and wheat.

Real-time N management in rice and wheat

In many field situations, substantial portions of applied N are lost due to the lack of synchrony of plant-N demand with N supply, which leads to reduced physiological use of the N by the crop. Presently, the timing of fertilizer N as a part of regional recommendations is being used to best match demand with supply for rice and wheat. However, the farmers generally apply fertilizer N in several split applications. As a result the number of splits, the amount

of N applied per split, and the time of application vary considerably even within small recommendation domains. On the positive side, flexibility of the farmers in adjusting the timing and amount of fertilizer N applied offers great potential to synchronize the N application with the demand of the crop in real time. Although generally good correlations with grain yield have been observed with methods based on soil tests and laboratory analyses of tissue samples to predict cereal N needs during vegetative growth stages (Fox *et al.*, 1989; Hong *et al.*, 1990; Magdoff *et al.*, 1990; Justes *et al.*, 1997; Lemaire and Gastal, 1997), these are time consuming, cumbersome, and expensive. And the prospects remain bleak for accurate N prescriptions developed using soil tests prior to the cropping season. Tissue tests are also less useful for the support of decisions on N supplementation than indicators that are directly related to the measurement of leaf and canopy greenness (Schröder *et al.*, 2000).

Real-time corrective N management is based on periodic assessment of plant N status, and the application of fertilizer N is delayed until N deficiency symptoms start to appear. Thus a key ingredient for real-time N management is a method for rapid assessment of leaf N content, which is closely related to photosynthesis rate and biomass production and is a sensitive indicator of changes in crop N demand during the growing season. Although estimation of soil N supply or calculation of a pre-season fertilizer rate is not required, the real-time N management revolves around quick and reliable tools to decide the time when fertilizer N needs to be applied to the crop. Spectral characteristics of the radiation reflected, transmitted or absorbed by the leaves can provide an estimate of chlorophyll content. In turn the leaf chlorophyll concentration can help diagnose the N deficiency and indirectly correct the amount of N fertilization (Shapiro, 1999). During the last 2-3 decades some non-invasive optical methods based on leaf greenness, absorbance, transmittance or reflectance of red, green or near infra-red radiation by the intact leaf have been developed. These include chlorophyll-meters, leaf-colour charts, ground-based remote sensors, and the digital, aerial and satellite imageries. Over the last decade these methods have been extensively tried to improve the N-use efficiency in cereals grown in different agro-ecosystems and regions of the world.

The chlorophyll-meter (SPAD-502, Minolta, Ramsey, NJ), also known as SPAD (soil-plant analysis development) meter, can quickly and reliably assess the N status of a crop based on leaf area. Relatively high price of the instrument was always an issue regarding the use of the chlorophyll-meter for real-time N management in rice. As the SPAD meter measures the leaf colour as a proxy for leaf N, a simplification is to use the green colour as an

indicator. The leaf-colour chart (LCC), as developed through collaboration of International Rice Research Institute with agricultural research systems of several countries in Asia (IRRI, Manila, 1996), is a visual and subjective indicator of plant N deficiency. With its six colour panels of different shades of green, LCC is used as a reference tool for evaluating the colour of the leaves. It has turned out to be an inexpensive alternative to the chlorophyll-meter, as it also works on the basic principle that rice leaf colour is a good indicator of leaf-N content. Although it has no buttons, no cords, not even a moving part and obviously not as precise or as accurate as the chlorophyll-meter (as the difference between two LCC shades is 4 to 5 SPAD units), it allows measurement of N level in rice crop simply by matching colours. Like chlorophyll meter, it gives the results instantly.

Recently, methods based on measurement of reflectance in the red (defined by chlorophyll content) and near infrared (defined by living vegetation) regions of the electromagnetic spectrum, for estimating N requirement of crops using early-season estimates of N uptake and potential yield, have been developed. Normalized-difference vegetative index (NDVI) based on in-season sensor reading can predict the biomass, plant-N concentration and plant-N uptake. A hand-held GreenSeeker™ optical sensor unit (NTech Industries Incorporation, Ukiah, CA, the USA) is already being used for NDVI measurement of field crops. These tools have provided an excellent opportunity in terms of developing real-time N-management strategies for rice and wheat.

Chlorophyll-meter for need-based N applications in rice

A chlorophyll meter or SPAD meter can measure relative difference in crop N status and is also able to detect the onset of an N stress before it is humanly visible (Francis and Piekielek, 1999). A group of researchers has focused on evaluating the relationship between chlorophyll meter readings and the need for top-dress N (Turner and Jund, 1991, 1994; Wells *et al.*, 1993; Maiti *et al.*, 2004; Khurana *et al.*, 2007). Generally, two approaches have been followed to guide need-based fertilizer N applications using chlorophyll meter: (i) when SPAD value is less than the set critical reading ((Balasubramanian *et al.*, 1999; Bijay-Singh *et al.*, 2002; Abdulrachman *et al.*, 2004; Maiti *et al.*, 2004; Satawathananont *et al.*, 2004); and (ii) when sufficiency index (defined as SPAD value of the plot in question divided by that of a well-fertilized reference plot or strip) falls below 0.90 in rice (Hussain *et al.*, 2000). Despite greater reliability of the latter, the former approach is more popular because it does not require a well-fertilized area and is therefore easier to use.

Most of the research directly evaluating the efficacy of SPAD meter in improving the N-use efficiency has been conducted with the rice across different regions in Asia. In a majority of the 249 irrigated, transplanted or direct-seeded rice farms in Vietnam (Son *et al.*, 2004; Tan *et al.*, 2004), China (Wang *et al.*, 2001), Indonesia (Abdulrachman *et al.*, 2004), Philippines (Gines *et al.*, 2004), Thailand (Satawathananont *et al.*, 2004), and India (Bijay-Singh *et al.*, 2002; Maiti *et al.*, 2004; Nagarajan *et al.*, 2004; Khurana *et al.*, 2007), chlorophyll meter-based N management significantly increased the N-use efficiency when compared with the farmers' fertilizer practices. Critical SPAD values for rice ranged from 32 to 37.5 as determined for different regions across Asia.

Peng *et al.* (1996) were among the first who focused on determining a fixed critical SPAD value that farmers could refer to in the field. For rice cultivar 'IR 72' grown in dry season at Philippines, top-dressing of 30 kg N/ha was recommended when SPAD value falls below the critical number of 35. In field trials in the Philippines, use of the 35 critical reading was found to result in similar yields with less N fertilizer application (higher agronomic efficiency) compared with fixed split-timing schemes or recommended splits (Peng *et al.*, 1996). However, this SPAD meter threshold value of 35 is not universal and may vary in different rice-growing environments. For example, the critical value had to be reduced to 32 during the wet season due to continuous cloud cover for most of the growing season (Balasubramanian *et al.*, 1999). In another study carried out in South India (IRRI-CREMNET, 1998), a value of 37 was found to be critical for obtaining high yields and N-use efficiency of short-statured improved *indica* cultivars; and that of 37.5 for rice in north-western India (Bijay-Singh *et al.*, 2002) (Table 1). When the value of 35 was considered critical for applying 30 kg N to rice, a total of 30 or 60 kg N/ha (except for cultivar 'PR 111' grown with a basal dose of 30 kg N/ha) was found to give significantly less grain yield and N uptake than those observed in recommended fixed-time application of 120 kg N/ha. It has also been suggested that different threshold SPAD values may have to be used for different varietal groups (Balasubramanian *et al.*, 2000). For example, for rice cultivars grown in the Indo-Gangetic plain, the threshold SPAD value of 37 or 37.5 was found appropriate for optimum rice yields (Bijay-Singh *et al.*, 2002; Maiti *et al.*, 2004), but for the cultivars grown in South India it was found to be 35 (Nagarajan *et al.*, 2004). Different measures of fertilizer N-use efficiency always turned out to be significantly higher in the SPAD meter-based N management rather than in those following farmers' practice of using fertilizer N (Table 2). Experiments carried out by Balasubramanian *et al.* (1999) and Bijay-Singh *et al.*

Table 1. Rice grain yield, N uptake and total fertilizer N applied to two rice cultivars grown using need-based fertilizer N-management criteria based on threshold SPAD[†] values of 35 and 37.5 at Ludhiana

N-management treatment	Total N applied (kg/ha)	Grain yield (t/ha)	Total N uptake (kg/ha)	Total N applied (kg/ha)	Grain yield (t/ha)	Total N uptake (kg/ha)
	Rice cultivar: 'PR 106'			Rice cultivar: 'PR 111'		
Recommended splits, N ₁₂₀	120	6.1b [†]	111c	120	6.5b	110c
N ₃₀ at SPAD [†] <35, N ₃₀ basal	60	4.9a	86b	90	5.9b	90ab
N ₃₀ at SPAD<35, no basal	30	5.1a	75a	60	5.4a	88a
N ₃₀ at SPAD<37.5, N ₃₀ basal	90	5.8b	88b	90	6.3b	96ab
N ₃₀ at SPAD<37.5, no basal	90	6.4b	93b	90	6.4b	97b

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

[†]SPAD = Chlorophyll-meter reading (soil-plant analysis development)

Courtesy: Bijay-Singh *et al.* (2002)

Table 2. Effect of SPAD meter-based fertilizer N management on fertilizer N-use efficiency in rice

Region, experimental year(s), critical SPAD value	AE _N [†] (kg grain kg/N)		RE _N [†] (kg N kg/N)		PFP _N [†] (kg grain kg/N)		Reference
	FFP‡	SPAD	FFP	SPAD	FFP	SPAD	
	Nadia, West Bengal, 2001-03, 37	24.3a§	42.4b	0.43a	0.55b	56.6a	
Aduthurai, old Cauvery delta, 1997-99, 35	13.9a	16.0b	0.39a	0.46b	32.8a	38.0b	Nagarajan <i>et al.</i> (2004)
Punjab, 2003 and 2004, 36-37.5	8.8a	16.1b	0.20a	0.30b	34.7a	44.2b	Khurana <i>et al.</i> (2007)
Ludhiana, Punjab, 1999, 37.5	20.0a	23.7b	0.44a	0.51b			Bijay-Singh <i>et al.</i> (2002) [†]
Thanjavur, new Cauvery delta, 1997-99, 35	13.6a	15.0b	0.45a	0.46a	27.9a	31.0b	Nagarajan <i>et al.</i> (2004)

[†]AE_N, Agronomic efficiency of applied N; RE_N, apparent-recovery efficiency of applied N; PFP_N, partial factor productivity of applied N.

[‡]FFP, farmers' fertilizer practice in which all nutrient management was done by the farmer without any interference by the researcher. However, in some studies conducted only on research farms and not in actual farmers' fields, it denotes fixed-schedule N application e.g., in Maiti *et al.* (2004) @100 kg N/ha and in Bijay-Singh *et al.* (2002) @120 kg N/ha.

[§]For each N-use efficiency index (AE_N, RE_N, or PFP_N) and site, values with different letters are significantly different at P=0.05.

Table 3. Grain yield and total N application to rice following sufficiency-index approach based on chlorophyll-meter and fixed-time blanket recommendation for several rice cultivars at Ludhiana

Rice cultivar	Year	SPAD-based N management		N application as per blanket recommendation	
		Grain yield (t/ha)	Total N applied (kg N/ha)	Grain yield (t/ha)	Total N applied (kg N/ha)
'PR 106'	1997‡	6.1 [†]	90	6.1	120
'PR 111'	1997	6.5	90	6.5	120
'PR 106'	1998	5.2	90	5.6	120
'PR 111'	1998	5.5	90	5.7	120
'PR 114'	1999	5.9	80	5.8	120
'PR 116'	2000	8.2	100	8.1	120
'PR 116'	2001	6.4	90	6.2	120

[†]Grain yields under SPAD-based N management and with blanket recommendation did not differ significantly by student's t-test, irrespective of year and cultivar

[‡]Data for 1997 published by Hussain *et al.* (2000)

(2002) indicate that soils producing a grain yield of 3 t/ha or more in no-N control plots do not need basal N application along with SPAD-based N management that starts 2 weeks after transplanting of rice. Rice seedlings need 7 days to recover from transplanting shock, and hence the N uptake within 2 weeks of transplanting should be very

small.

Use of chlorophyll meter led to saving in fertilizer N application compared with the blanket dose of 120 kg N/ha even when the sufficiency index approach was followed. Experiments conducted during 1997 to 2001 at Ludhiana convincingly proved the usefulness of this tech-

nique (Table 3). Though a small over-fertilized plot has to be established to follow this method of SPAD meter-based N management, it has the advantage of being self-calibrating for different soils, seasons and cultivars.

Replacement of chlorophyll meter with leaf-colour chart for crop demand-driven N management in rice

Real-time N management using LCC requires the identification of an optimal leaf colour that must be maintained throughout the season to obtain high yields. The critical colour shade on the LCC needs to be determined to guide N application to rice. It varies depending on the cultivar and crop-establishment method, but can be determined after 1-2 seasons of testing for local situations. As shade 4 on the LCC represents greenness equivalent to SPAD value somewhere between 35 and 37, it was found to be threshold value for inbred rice varieties prevalent in the Indo-Gangetic plains in India. For direct wet-seeded rice grown under north-west Indian conditions, LCC 3 proved a better threshold value (Bijay-Singh *et al.*, 2007), perhaps due to high population density. In north-eastern India, Maiti *et al.* (2004) also established LCC 4 as the critical value for transplanted rice and found that the use of LCC could save 20 to 42.5 kg N/ha, which increased the N-use efficiency quite significantly when compared with the generally recommended fixed-time split N application. In the Upper Gangetic Plains of India, Shukla *et al.* (2004) established LCC 3, 4 and 5 as the critical values for basmati, inbred and hybrid rice cultivars.

The leaf-colour chart as a tool for guiding need-based

N management in rice has been tested at on-farm and on-station locations throughout the Indo-Gangetic plains in India. Since the application of a basal dose of N is always a part of different fixed-time blanket N recommendations for rice in these plains and the farmers always derive a feeling of security against yield loss by applying a basal dose, testing of real-time N management using LCC has been carried out with and without basal N applications. Results from Punjab in the western Indo-Gangetic plains are summarized in Table 4. In most situations there was no significant advantage of applying 20 kg N/ha as basal N at transplanting on the grain yield and N use efficiency of rice compared with no basal N (Yadvinder-Singh *et al.*, 2007). Where the rice yield in no-N controls was more than 3 t/ha (as in Punjab), there was hardly any yield benefit of applying a basal dose of N to rice along with LCC-based N management (Bijay-Singh *et al.*, 2002). Under such situations the application of a basal N dose resulted in a total N application more than where no basal N was applied. At some locations LCC-based N management also helped achieve higher yield potential of rice with lower input of fertilizer N than the recommended blanket N application.

Varinderpal-Singh *et al.* (2007) studies crop demand-driven N management in on-farm experiments at 350 locations in Punjab during 2002-2005. Practice of LCC-based N management led to a saving of 9.4 to 54.2 kg N/ha or about 25% fertilizer N, without any reduction in yield compared with the farmer's practice of applying blanket N at fixed time intervals (Figure 1.). Application of fertilizer

Table 4. Evaluation of leaf-colour chart (LCC) based real-time N management in rice vis-à-vis fixed time blanket N recommendations/farmer's practice in Punjab (Source: Yadvinder Singh *et al.*, 2007)

Year, number of experiments	LCC with basal N [¶] (+B) / LCC without basal N (-B) N / blanket recommendation	LCC (threshold shade 4) based N management		AE _N (kg grain/kg N)	RE _N (kg N/kg N)	PFP _N (kg grain/kg N)
		Grain yield (t/ha)	Mean total N applied (kg N/ha) (range)			
2000, n = 8	- B, LCC	6.59±1.42 [†]	86 (75-105) [‡]	20.8a§	0.31a§	57.2a§
	+ B, LCC	6.63±1.40	95 [‡] (80-110)	27.4b	0.43b	82.7b
	Blanket/Farmer's fertilizer practice	6.53±1.29	120	28.1b	0.42b	86.3b
2001, n = 8	- B, LCC	6.89±1.59	79 (60-120)	15.4a	0.29a	59.9a
	+ B, LCC	7.20±1.89	91 [‡] (80-110)	19.8b	0.39b	97.5b
	Blanket/Farmer's fertilizer practice	6.84±1.58	120	21.6b	0.45c	90.5b
2002, n = 11	- B, LCC	6.76±1.20	71 (60-90)	11.3a	0.40a	52.1a
	+ B, LCC	7.01±0.94	91 [‡] (80-110)	19.2b	0.58b	91.7c
	Blanket/Farmer's fertilizer practice	6.69±1.07	127 [‡] (115-175) [‡]	16.4b	0.53b	73.8b

[†]Standard deviation of mean

[‡] Range of total N applied

[¶]Includes a basal application of 20 or 30 kg N/ha along with LCC-based N applications

[§]Values in column in a particular year with same letter do not differ significantly at P=0.05 probability level

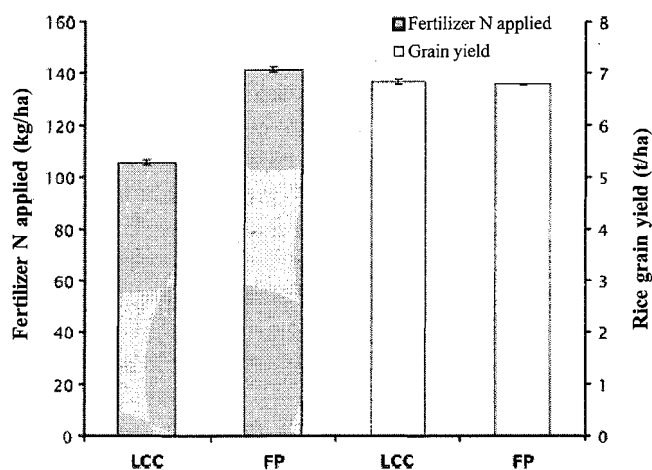


Figure 1. Average fertilizer N applied and grain yield of rice in 350 on-farm trials comparing LCC-based N management with farmers' practice in Punjab (Source: Varinderpal Singh *et al.*, 2007)

N when the colour of the first fully expanded leaf was less than LCC shade 4 increased the N-use efficiency from 48-65 kg grain/kg N. In 50 experiments conducted during 2004 by Varinderpal-Singh *et al.* (2007), the first top-dressing of N fertilizer was applied within 20 days of transplanting rice at 44% of the experimental sites, and during 21-40 days after transplanting (DAT) at 54% locations. The second dose of fertilizer N as guided by LCC was top-dressed during 21-40 and 41-55 DAT at 48 and 41% of the experimental sites. The third top-dressing was

required in 50% of the locations, and out of these at 56% of locations it was applied after 55 days of transplanting. These data emphatically point out that fertilizer N applications made even 55 days after transplanting rice can be efficiently utilized by rice if the N supply is inadequate from the soil or from previous applications.

Table 5 lists two categories of comparisons between LCC method and farmers' fertilizer practice (FFP) for managing N in rice in India. In the first category, the most commonly observed effect of following LCC-based N management is the production of rice yield similar to that with FFP but with less fertilizer N application. In the second category a reduction in N fertilizer use led to increase in grain yield by following LCC method (Table 5). The partial factor productivity in all these comparisons might also increase due to retention of increasing proportion of N inputs in the soil organic and inorganic N pools.

Adoption of LCC for managing N by farmers is not likely without the promise of adequate economic returns, because in the end the economic benefit holds the key to the success or failure of a technology. Ladha *et al.* (2005) placed the use of leaf-colour chart in the very high benefit : cost ratio category. In fact, with small to medium farm size in developing countries like India, the use of a simple and inexpensive LCC can greatly assist the farmers in applying N when the crop needs. The LCC is an ideal tool to optimize N use, irrespective of the source of N application - organic, bio- or chemical fertilizers. It is very effective in avoiding overapplication of N fertilizers (Bijay-Singh *et*

Table 5. Comparison of leaf-colour chart (LCC) method with farmer's fertilizer practice (FFP) for N management in transplanted rice

Region, year, critical LCC value, number of farms	N used (kg N/ha)		Grain yield (t/ha)		AE _N † (kg grain/kg N)		PFP _N † (kg grain/kg N)		Reference
	FFP‡	LCC	FFP	LCC	FFP	LCC	FFP	LCC	
<i>Same grain yield with reduced N fertilizer application following LCC</i>									
Haryana, 2001, LCC-4, 165	149	124	6.4a	6.4a			43	51	Balasubramanian <i>et al.</i> (2003)
Punjab, 2002, LCC-4, 107	153	113	6.0a	6.0a			39	53	Varinderpal-Singh <i>et al.</i> (2007)
Punjab, 2003, LCC-4, 48	115	91	6.5a	6.5a			57	71	
Punjab, 2004, LCC-4, 53	134	100	8.1a	8.2a			61	82	
Punjab, 2005, LCC-4, 142	145	107	7.0a	7.1a			48	66	
Punjab, 2000, LCC-4, 8	120	91	6.5a	6.6a	20.8	27.8	57	85	Yadvinder-Singh <i>et al.</i> (2007)
Punjab, 2001, LCC-4, 8	120	85	7.1a	7.0a	15.4	20.7	60	94	
Punjab, 2002, LCC-4, 11	126	78	6.9a	7.1a	11.3	17.8	52	83	
<i>Increase in grain yield with reduced N fertilizer application following LCC</i>									
Uttar Pradesh, 2002, LCC-4, 1	150	135	6.9b	7.6a	20.7b	28.1a	46	56	Shukla <i>et al.</i> (2004)

†AE_N, Agronomic efficiency of applied N; RE_N, apparent recovery efficiency of applied N; PFP_N, partial factor productivity of applied N. ‡FFP, farmers' fertilizer practice in which all nutrient management was done by the farmer without any interference by the researcher. However, in some studies conducted only on research farms and not in actual farmers' fields, it denotes fixed-schedule N application §For grain yield and N use efficiency indices of AE_N and PFP_N at different sites, values with different letters are significantly different at the P=0.05 probability level.

al., 2002), which ensures minimum pollution of the environment. It is being introduced to the farmers through field researchers, extension staff (government and non-government organizations) and private-sector agencies.

Crop demand-driven N management in wheat using SPAD meter and LCC

The crop demand-driven N management using SPAD-meter in wheat has mainly focused on determining (a) the most appropriate stage to take SPAD-meter readings and use this information to adjust mid-season N fertilization, and (b) critical SPAD values at different growth stages of wheat. Useful information on finding appropriate crop stage for using SPAD-meter to predict grain yield and guiding fertilizer N application has been generated for winter wheat in the USA (Reeves *et al.*, 1993; Murdock *et al.*, 1997; Girma *et al.*, 2006). Studies on these lines are underway for irrigated wheat in the Indo-Gangetic plains in India.

Unlike in rice, where N can be top-dressed two to four times during the growth period, N application in wheat is linked to irrigation. Generally N is applied in two equal splits - basal N at land preparation and N top-dressing at crown-root initiation but the farmers often apply another dose of N with the maximum-tillering irrigation. Suitable criteria are, however, lacking to determine whether N application at maximum tillering is needed. The chlorophyll meter can help in establishing the need for N application at maximum tillering, which will largely depend on the soil-N supply, date of planting and seasonal temperature. Bijay-Singh *et al.* (2002) used SPAD meter to determine whether top-dressing was needed at maximum tillering stage and, if so, how much. Experiments conducted at Ludhiana indicated that wheat yield is likely to respond

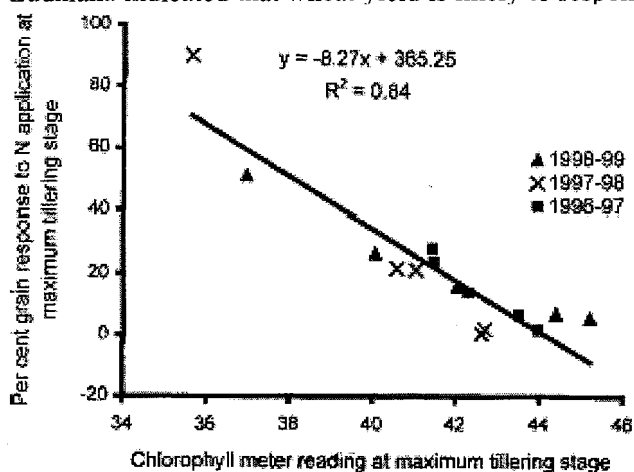


Figure 2. Relationship between percent grain-yield response (%) of wheat to 30 kg N/ha applied at maximum tillering and SPAD values recorded at maximum tillering before N application for three seasons (1996–1999) at Ludhiana, (Source: Bijay-Singh *et al.*, 2002)

with top-dressing of 30 kg N/ha when the SPAD reading at maximum tillering is less than 44. Wheat yield increased by 20% when 30 kg N/ha was applied at SPAD value of 42 at maximum tillering (Figure 2). Using critical SPAD value of 42, Khurana *et al.* (2008) showed significant increases in agronomic (63%) and apparent recovery (59%) in the N efficiency compared with the farmers' fertilizer (fixed-time N application) practices. Compared with the current farmers' fertilizer practice, average grain yield increased from 4.2 to 4.8 t/ha, whereas the N, P and K accumulations in the plant increased by 12–20% with site-specific nutrient management.

At Modipuram, Shukla *et al.* (2004) conducted experiments on wheat using LCC the way it is used in rice. In wheat the maintenance of leaf colour equivalent to LCC shade 4 required 120 kg N/ha, which produced higher grain yield, N uptake and N-use efficiency than that observed with applying blanket recommended dose of fertilizer N in splits at fixed times. Work on crop demand-driven N management in wheat using LCC and SPAD meter is in progress in the Indo-Gangetic plains. Criteria are being developed to find critical values of SPAD and LCC to apply fertilizer as per need of the crop at growth stages coinciding with irrigation events. An appropriate combination of preventive and corrective N management is also being worked out. Management of fertilizer N using SPAD-meter following sufficiency index approach also appears promising.

Optical sensors for need-based N management in rice and wheat

Chlorophyll meter and LCC have been successfully used in developing real-time N management strategies for rice (Ladha *et al.*, 2005) but these do not take into account the photosynthetic rates or biomass production and the expected yields for working out fertilizer N requirements. Application of optical sensors in agriculture is increasingly rapidly through measurement of visible and near-infrared (NIR) spectral response from plant canopies to detect the N stress (Peñuelas *et al.*, 1994; Ma *et al.*, 1996; Raun *et al.*, 2001). Chlorophyll contained in the palisade layer of the leaf controls much of the visible light (400–720nm) reflectance as it absorbs 60% of all the incident light in the red wavelength bands (Campbell, 2002). Reflectance of the NIR electromagnetic spectrum (720–1300 nm) depends upon structure of the mesophyll tissues which reflects as much as 60% of all incident NIR radiation (Campbell, 2002). Spectral vegetation indices such as the normalized-difference vegetation index (NDVI) have proved useful for indirectly obtaining information such as photosynthetic efficiency, productivity potential and potential yield (Peñuelas *et al.*, 1994; Thenkabail *et al.*,

2000; Ma *et al.*, 2001; Raun *et al.*, 2001; Báez-González *et al.*, 2002) and have been found sensitive to leaf-area index, green biomass (Peñuelas *et al.*, 1994), and photosynthetic efficiency (Aparicio *et al.*, 2002). Raun *et al.* (2001) found the expected yield as determined from NDVI to show a strong relationship with actual grain yield in winter wheat. Using NDVI measurements of wheat at different times during the crop-growth period, Raun *et al.* (2001, 2002) developed concepts of response index and potential yield and these were used to define a fertilizer N algorithm for working out the fertilizer N requirement in winter wheat-based on expected yields as well as achievable greenness of the leaves. Raun *et al.* (2002) showed that prediction of wheat response to N applications guided by optical sensor was positively correlated with the measured

N response and increased N-use efficiency

Data collected from north-western India (Karnal, Ludhiana and Modipuram) have convincingly proved that reliable estimates of potential yield of both rice and wheat can be obtained by in-season measurements with GreenSeeker optical sensor. Following a N fertilizer optimization algorithm developed on the lines of Raun (2001, 2002), response index (RI) was calculated as a ratio of NDVI in a N-rich strip and the test plot. Grain yield that can be achieved by applying fertilizer N was calculated by multiplying GY with RI. Difference in the N uptake between predicted yields from the plots with and without N fertilizer application allow calculation of the quantity of fertilizer N to be applied. Results from experiments conducted at Ludhiana, Karnal and Modipuram indicated that 10-20% N can be saved without yield reduction in wheat yield if blanket fertilizer N recommendation is replaced with GreenSeeker-based N application at Feekes 7/8 stage. GreenSeeker optical sensor can be used only in combination with appropriate preventive N management, as it cannot work properly when the crop is too young. In puddled transplanted rice the optical sensor cannot work properly up to 5-6 weeks after transplanting due to interference of standing water in the field. Thus it can be used as in wheat around 6 weeks after transplanting in combination with preventive N management at transplanting and 3 weeks after transplanting.

Research needs

The crop demand-driven N management can be better implemented in both rice and wheat by combining preventive and corrective fertilizer N applications. Systematic studies need to be carried out to work out appropriate fertilizer N management scenarios that can be used before using SPAD-meter, LCC or optical sensors to guide cor-

rective fertilizer N application at a given crop-growth stage. It seems that during 30-40 days after planting, 2-3 doses of fertilizer N can be applied as preventive N management; a corrective fertilizer N application using LCC, SPAD-meter or optical sensor can follow it.

Threshold LCC and SPAD values are needed to be worked out more rationally for different varietal groups and for different types of rice and wheat. It seems that the amount of solar radiation received in a region also influences the threshold SPAD or LCC values. The issue of applying a basal dose of N before starting N applications guided by LCC, SPAD meter or optical sensor needed to be resolved for different situations. More data need to be collected on soil properties and N-supplying capacities in no-N plots at locations where LCC or SPAD meter or the optical sensor-based N management is being evaluated. Also, the amount of basal N, if required, needs to be defined more rationally for different types of rice such as fine grain, aromatic and hybrid, and in fields amended with organic manures and crop residues.

The crop demand-driven N management avoids the application of excessive N to both rice and wheat. It should thus lead to crops that are healthier and less susceptible to lodging and diseases such as blast and bacterial leaf blights and hence to minimum loss of applied N to the environment. Research needs to be carried out to establish these advantages of need-based N-management practices. Well-planned studies to assess the effect of real-time N management on weed ecology in rice-wheat system need to be carried out.

Nitrogen management in wheat can be substantially improved using LCC, SPAD-meter or optical sensor, but the methodology needs to be perfected before it can be given to farmers. More research is needed to define the conditions under which LCC, SPAD meter or optical sensor can be used to guide N applications at a given growth stage of wheat. Chlorophyll-meter may be effectively used to guide N applications at a given growth stage by creating an over-fertilized plot, but experiments need to be initiated to standardize this technique using LCC.

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