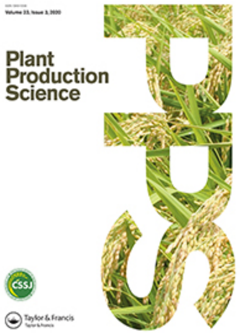

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Optimizing chlorophyll meter (SPAD) reading to allow efficient nitrogen use in rice and wheat under rice-wheat cropping system in eastern India

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ABSTRACT
Conventional agricultural practices that rely heavily on blanket fertilizer recommendation, eventually leading to deteriorated partial factor productivity and N use efficiency. We investigated the effect of SPAD-based N-management on productivity and N use efficiency of rice and wheat in eastern India. Here, in the experiment three SPAD thresholds (34, 36 and 38 in rice and 38, 40 and 42 in wheat) using three N levels (15, 25 and 35 kg N ha^{-1}) in split were incorporated as real-time N management (RTNM), one fixed-time N management (FTNM), farmers' fertilizer practice (FFP) and control (No fertilizer) were introduced in wet and dry seasons for rice and wheat, respectively, during the years 2010 to 2012. Topdressing with 25 kg N ha^{-1} at medium SPAD (S_{36} in rice and S_{40} in wheat) increased soil N availability, leaf N content and grain yield of rice (5215 kg ha^{-1}) and wheat (4483 kg ha^{-1}) over the grain yield recorded under a low rate of N topdressing at low SPAD. While saving 33.3% N in rice and 18.8% N in wheat, the agronomic N use efficiency (58.5% in both rice and wheat) and nitrogen recovery efficiency (32.2% in rice and 15.1% in wheat) can be increased when compared with conventional FTNM. The SPAD-based management strategy showed great promise in efficient management of N fertilizer, and we estimated the optimal SPAD threshold for rice and wheat as 37.5 and 41.8, respectively.

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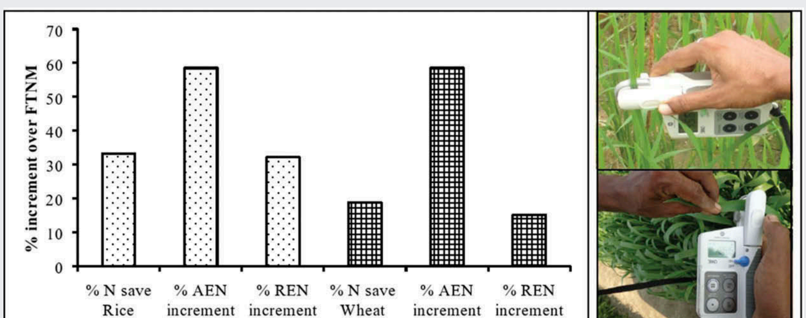
Crop productivity; N use efficiency; rice; SPAD based N management; wheat



SPAD meter can enhance the NUEs in addition saving of N fertilizer over fixed time farmers practice.

Introduction

The main staple food crops which have been cultivated and consumed worldwide in different countries are the rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.). Together, the two crops contribute 80% of the total cereal production in the south Asian countries (Timsina & Connor, 2001). The rice-wheat cropping system is the most widely adopted production system in Asian countries and worldwide. China ranks first in production and consumption for both rice and wheat (Li et al., 2012). With the introduction of dwarf wheat from CIMMYT, Mexico, the rice-wheat system was adopted in the late 1960s in India, which has witnessed a phenomenal growth since then. Nitrogen (N) remains the most widely used nutrient in rice and wheat; however, the quantity of grain produced in rice and wheat per unit of applied N has shown a continuous decline in rice–wheat system (Dobermann et al., 2002), with the N use efficiency reportedly existing as low as 30% (Krupnik et al., 2004). The recommended practice of fertilizer application in South Asia involves applying one-third and one-half of the N in rice and wheat, respectively, at transplanting/sowing time, whereas the remaining N is applied at the

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fixed stages, i.e. before flower initiation (Peng et al., 2006; Singh et al., 2010). After flowering generally fertilizer recommendation was not applicable because the crop is at the reproductive phase and excess vegetative growth due to excess fertilizer application at the reproductive phase can be delayed the maturity. A range of factors such as spatial soil N variability, agro-climatic circumstances, and varietal differences greatly hamper the efficient use of fertilizer N when broad-based general or blanket recommendations are followed. Poor N use efficiency is also due to unproductive splitting of N doses in excess of crop demand (Singh et al., 2012a). This calls for need-based N-management practices in rice-wheat systems in order to increase system productivity, improve N use efficiency, and minimize fertilizer N loss to the environment. The spectral properties of leaves are used in leaf color charts (LCC) and chlorophyll or SPAD (Soil Plant Analysis Development) meters to measure light transmittance through leaves in order to guide real-time N topdressings in rice and wheat. The chlorophyll meter offers an alternative to the nitrogen nutrition index in a non-destructive way (Ecarnot et al., 2013; Lemaire et al., 2008), enabling efficient management of N in rice and wheat under situations that face diversity in field, season and variety (Yang et al., 2014).

Requirement-based N management in real-time and fixed-time manners was developed to increase the N-use efficiency in rice and wheat (Huang et al., 2008; Singh et al., 2002). In real-time N management (RTNM), N-fertilizer is applied at a certain rate only when leaf N content is below a doorstep limit (Singh et al., 2010). On the other hand, yield response to N application in fixed-time N management (FTNM) stems from the difference between the targeted yield and grain yield achieve under zero N treatment (Buresh et al., 2005). In RTNM, excessive N application can be avoided by harmonizing the time of fertilizer N application and the amount of fertilizer according to the plant's need. Notwithstanding the greater significance of site-specific N management (SSNM) to current agriculture, studies on SSNM in rice-wheat system are limited in eastern India. In view of the above, the present investigation intends to optimize the critical SPAD reading to allow efficient N management in rice and wheat under rice-wheat cropping system in eastern India. The findings reported here help in improving the crop productivity and N-use efficiency of the rice-wheat cropping system.

Material and methods

Experimental site

A field experiment was carried out during the wet seasons (June–October) of 2010 and 2011 for rice and dry seasons (November–March) of 2010–2011 and 2011–2012 for wheat at the research farm of the Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur (22°19′ N latitude, 87°19′ E longitude and an elevation of 44.0 m a.s.l.), India. The soil of the experimental field is red lateritic and acidic in nature, sandy loam in texture, low in soil fertility status and taxonomically grouped under Haplustaff. The climate of Kharagpur is distinguished by hot in summer (April to May) and dry in winter (December to January) (Table 1). Kharagpur received about 70–75% of total annual rainfall (1400 mm) in the monsoon months (June to October). The average temperature varies from 21°C in December/January and 32°C in May/June.

Experimental design

The experiment was laid out in a completely randomized block design replicated thrice in 6m×5m plot size for each treatment. The treatments included three SPAD values (34, 36 and 38) combined with the three N levels (15, 25 and 35 kg N ha^{-1}) as RTNM, one non-SPAD recommendation as FTNM, farmers' fertilizer practice (FFP) and control (No fertilizer) for rice. The same layout and experimental design were used for wheat having the treatment combinations of three different SPAD values (38, 40 and 42), one FTNM, one FFP and control. Except FFP and the control, all the treatments

Table 1. Monthly weather parameters during the study period at Kharagpur, India.

	Tmax (ºC)		Tmin (ºC)		Rainfall (mm)		RH (%)		Sunshine hours	
Month	2010–11	2011–12	2010–11	2011–12	2010–11	2011–12	2010–11	2011–12	2010–11	2011–12
July	33.2	32.5	26.7	25.8	173.8	339.7	86.4	84.9	9	7
August	33.6	32.1	27.1	25.8	148.3	309.4	83.1	89.1	8	6
September	32.6	32.2	26.2	25.2	217.3	252.6	87.2	88.6	7	7
October	31.9	31.6	24.3	22.8	91.0	74.8	85.0	76.5	7	8
November	31.8	29.2	22.0	18.1	1.5	17.8	74.8	69.7	9	8
December	25.9	26.2	13.8	13.9	11.7	6.2	72.0	66.7	9	8
January	25.5	25.4	13.5	14.2	12.7	31.8	64.9	75.3	8	9
February	29.4	30.3	16.9	15.6	23.8	42.0	61.6	55.8	8	9
March	34.3	35.4	21.3	22.3	52.3	0.0	60.3	50.8	8	10

Tmax = Maximum temperature; Tmim = Minimum temperature; RH = Relative humidity received 30 kg N, 21.8 kg P and 50.0 kg K ha^{-1}as basal in rice and 60 kg N, 21.8 kg P and 50.0 kg K ha^{-1} as basal in wheat. In RTNM treatments, N was topdressed in the form of urea when the actual SPAD value went below the SPAD limit. The SPAD measurement with the SPAD 502 (Konica Minolta, Inc., Tokyo, Japan) was started from 20 days after transplanting (DAT) (Active tillering stage) in rice and 25 days after sowing (DAS) (Crown root initiation stage) in wheat and was continued up to the panicle emergence/soft dough stage at 10-day interval for all plots. Here in the study, the fully expanded and youngest leaves were used and a mean of 15 readings from 15 different hills/plants per plot were considered as representative SPAD. The readings were taken from midway between leaf base and tip of a leaf blade. The N rate as per treatment (15, 25 and 35 kg ha^{-1}) was used for topdressing at each SPAD threshold during both years (Tables 2 and 3). In the FTNM treatment, 30 kg ha^{-1} N in each split was topdressed at active tillering, panicle initiation (40 DAT) and flowering stages (60 DAT) in rice and the same amount was applied at crown root initiation (CRI) and the earhead initiation stage (45 DAS) in wheat. In FFP 30 kg N, 13.1 kg P and 12.5 kg K ha^{-1} were applied as basal and the same amount of N and K at panicle initiation stage of rice as a topdress. Whereas, in wheat treatment, FFP received 40 kg N, 26.2 kg P and 12.5 kg K ha^{-1} as basal and 20 kg N and 12.5 kg K ha^{-1} each at CRI and earhead initiation stages as topdressing. Here in the experiment fertilizer urea, single super phosphate and muriate of potash were used. The details of treatment combinations in rice and wheat are as follows:

Treatment combinations followed in rice.

$T_1 = S_{34}N_{15}$	$T_4 = S_{36}N_{15}$	$T_7 = S_{38}N_{15}$	$T_{10} =$ FTNM (120–21.8–50 kg N-P-K ha^{-1})
$T_2 = S_{34}N_{25}$	$T_5 = S_{36}N_{25}$	$T_8 = S_{38}N_{25}$	$T_{11} =$ FFP (60–13.1–25 kg N- P-K ha^{-1})
$T_3 = S_{34}N_{35}$	$T_6 = S_{36}N_{35}$	$T_9 = S_{38}N_{35}$	$T_{12} =$ Control (No application of fertilizer)

Treatment combinations followed in wheat.

$T_1 = S_{38}N_{15}$	$T_4 = S_{40}N_{15}$	$T_7 = S_{42}N_{15}$	$T_{10} =$ FTNM (120–21.8–50 kg N-P-K ha^{-1})
$T_2 = S_{38}N_{25}$	$T_5 = S_{40}N_{25}$	$T_8 = S_{42}N_{25}$	$T_{11} =$ FFP (80–26.2–37.5 kg N- P-K ha^{-1})
$T_3 = S_{38}N_{35}$	$T_6 = S_{40}N_{35}$	$T_9 = S_{42}N_{35}$	$T_{12} =$ Control (No application of fertilizer)

Crop management practices

The rice variety 'IR-36', developed at International Rice Research Institute (IRRI), was used for this investigation. 'IR-36', generally matured in 120 days, it is a prominent variety in subtropical climates and has been recommended as a non-coagulating type. Concerning wheat, 'Sonalika' variety was used, which takes about 110 days to mature under short and mild winter conditions in subtropical regions. Pre-germinated rice seeds were sown on seedbed and about 22-day-old seedlings were uprooted for transplanting on 15 July 2010 and 16 July 2011 at a spacing of 20cm×20cm. One day before transplanting the initial dose of N, P and K were incorporated in all plots except control as basal dose. The experimental field remained at full water saturation from transplanting to 20 days before maturity. Plant protection measure was taken by using insecticide Chlorpyrifos 20% EC and manually hand weeding was done at 20 and 40 DAT during both the years. Rice was harvested at 90 days after transplanting during the study. After harvesting of rice, 5.0 t ha^{-1} well-decomposed farmyard manure was added to the experimental field in both the years and mixed thoroughly with soil by crosswise ploughing the field twice with a power tiller. The basal dose of fertilizer as per the treatments was applied and incorporated in each plot at 1 day before sowing of wheat. The crop was sown on November 25 in 2010 and November 28 in 2011 at a spacing of 20 cm between rows. The plant population of about 95–100 plants m^{-2} was maintained in the experiment. Here the wheat was harvested at 110 days after sowing in both years of study.

Data collection, processing and analysis

At maturity, both the rice and wheat crops were harvested from 10-square meter area earmarked for yield estimation in each plot. After threshing the grain and straw of both the crops were dried in the sun for 3–4 days followed by oven dry for 72 h at 65°C constant temperature and their weights were recorded. The grain and straw yields of rice and wheat are corrected to 12% moisture content. Before each top dressing of N whenever it was required and at maturity, the aboveground biomass was collected for both the crops for analysis of N (Yoshida & Coronel, 1976). The N accumulation by the crop was determined by multiplying N contents with their respective biomass (grain

Table 2. SPAD-based timing of N application in rice.

	Total N applied (kg ha^{-1})						Time of N application (DAT)					
	2010			2011			2010			2011		
Treatments	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3
S_{34} N_{15}	60	60	45	60	60	45	0, 30, 50	0, 40, 50	0, 30	0, 40, 50	0, 30, 40	0, 40
S_{34} N_{25}	80	55	55	55	55	55	0, 30, 60	0, 50	0, 30	0, 40	0, 40	0, 40
S_{34} N_{35}	65	100	65	65	65	65	0, 60	0, 30, 50	0, 50	0, 40	0, 30	0, 40
S_{36} N_{15}	75	60	75	60	60	60	0, 30, 50, 60	0, 50, 60	0, 30, 50, 60	0, 30, 40	0, 30, 40	0, 30, 40
S_{36} N_{25}	80	55	105	80	80	80	0, 40, 60	0, 50	0, 30, 50, 60	0, 30, 40	0, 30, 50	0, 30, 40
S_{36} N_{35}	65	100	100	65	100	100	0, 50	0, 30, 50	0, 30, 60	0, 30	0, 30, 50	0, 30, 50
S_{38} N_{15}	90	90	75	90	75	75	0, 30, 40, 50, 60	0, 30, 40, 50, 60	0, 30, 50, 60	0, 30, 40, 50, 60	0, 30, 40, 50	0, 30, 40, 50
S_{38} N_{25}	105	105	80	105	80	105	0, 30, 50, 60	0, 30, 50, 60	0, 40, 50	0, 30, 40, 60	0, 30, 40	0, 30, 40, 60
S_{38} N_{35}	100	135	100	100	100	100	0, 30, 60	0, 30, 50, 60	0, 40, 60	0, 30, 40	0, 30, 40	0, 30, 40
FTNM	120	120	120	120	120	120	0, 20, 40, 60	0, 20, 40, 60	0, 20, 40, 60	0, 20, 40, 60	0, 20, 40, 60	0, 20, 40, 60
FFP	60	60	60	60	60	60	0, 40	0, 40	0, 40	0, 40	0, 40	0, 40
Control	0	0	0	0	0	0	–	–	–	–	–	–

S = SPAD threshold value for rice; N = nitrogen topdressing (kg N ha^{-1}); FTNM = fixed-time nitrogen management; FFP = farmers' fertilizer practice; DAT = days after transplanting (basal dose of 30 kg N ha^{-1} applied to all plots except control plots); R_1 = Replication 1; R_2 = Replication 2; R_3 = Replication 3.

and straw) during both years. The nitrogen-use efficiency of rice and wheat in terms of agronomic N use efficiency (AE_N), and partial factor productivity of applied N (PFP_N) as described by Swain et al. (2006), Huang et al. (2008) and Singh et al. (2012b) were computed as follows:

$$AEN\ (\text{kg kg}^{-1}) = \frac{\text{Grain yield in N fertilized plot (kg ha}^{-1}) - \text{Grain yield in Nzero plot (kg ha}^{-1})}{\text{Quantity of Nfertilizer applied in fertilized plot (kg ha}^{-1})}$$

$$RE^{N}(\%) = \frac{\text{Total Naccumulated in fertilized plot (kg ha}^{-1}) - \text{Total Naccumulated in Nzero plot (kg ha}^{-1})}{\text{Quantity of Nfertilizer applied in fertilized plot (kgha}^{-1})} \times 100$$

$$PFP^{N}(\text{kg kg}^{-1}) = \frac{\text{Grain yield in fertilized plot (kg ha}^{-1})}{\text{Quantity of Nfertilizer applied (kg ha}^{-1})}$$

The soil samples during the crop growth period were collected with the help of screw soil auger from 0 to 20 cm and 20–40 cm depth at five spots in each plot before N topdressing as per the N management treatments and plot-wise homogenous dry soil samples were prepared for estimation of available N (Subbaiah & Asija, 1956).

The data were analyzed statistically by applying 'Analysis of Variance' (ANOVA) method of completely randomized block design (Cochran & Cox, 1985). The significance of different sources of variations was tested by Error mean square of Fisher Snedecor's 'F' test at probability level 0.05. Standard error (SE) of mean and least significant difference (LSD) at 5% level of significance were worked out for each character and provided in the summary tables of the results to compare the difference between the treatment means. The correlations among the SPAD values, leaf N contents and soil available N contents at different stages and grain yield were tested at 5% level of significance. The desired leaf N, desired soil available N and critical SPAD levels at different stages for maximizing grain yield were evaluated through multiple regression analysis.

Table 3. SPAD-based timing of N application in wheat.

	Total N applied (kg ha^{-1})						Time of N application (DAS)					
	2010–2011			2011–2012			2010–2011			2011–2012		
Treatments	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3
S_{38} N_{15}	90	90	75	75	60	75	0, 35, 65	0, 35, 65	0, 35	0, 45	0	0, 65
S_{38} N_{25}	85	110	110	85	60	60	0, 35	0, 35, 65	0, 35, 65	0, 65	0	0
S_{38} N_{35}	95	130	95	95	95	95	0, 35	0, 35, 65	0, 35	0, 65	0, 65	0, 45
S_{40} N_{15}	90	75	90	105	75	90	0, 35, 65	0, 35	0, 25, 35	0, 25, 45, 65	0, 45	0, 25, 45
S_{40} N_{25}	85	110	85	110	85	110	0, 35	0, 35, 65	0, 35	0, 45, 65	0, 65	0, 25, 45
S_{40} N_{35}	95	130	130	130	95	130	0, 35	0, 35, 65	0, 35, 65	0, 25, 45	0, 45	0, 25, 45
S_{42} N_{15}	90	90	90	105	105	105	0, 35, 65	0, 35, 65	0, 25, 35	0, 25, 45, 65	0, 25, 45, 65	0, 25, 45, 65
$S_{42}N_{25}$	110	135	85	110	110	110	0, 35, 65	0, 35, 65	0, 35	0, 45, 65	0, 45, 65	0, 25, 45
S_{42} N_{35}	130	95	130	95	165	95	0, 35, 65	0, 35	0, 35, 65	0, 45	0, 25, 45, 65	0, 45
FTNM	120	120	120	120	120	120	0, 25, 45	0, 25, 45	0, 25, 45	0, 25, 45	0, 25, 45	0, 25, 45
FFP	80	80	80	80	80	80	0, 25, 45	0, 25, 45	0, 25, 45	0, 25, 45	0, 25, 45	0, 25, 45
Control	0	0	0	0	0	0	–	–	–	–	–	–

S = SPAD threshold value for wheat; N = nitrogen topdressing (kg N ha^{-1}); FTNM = fixed-time nitrogen management; FFP = farmers' fertilizer practice; DAS = Days after sowing (basal dose of 60 kg N ha^{-1} applied to all plots except control and FFP plots; FFP received 40 kg N ha^{-1} as basal); R_1 = Replication 1; R_2 = Replication 2; R_3 = Replication 3.

Results

SPAD-based N application

The N was applied on the basis of SPAD index and then averaged over the replications and years. Here the lower SPAD (SPAD 34/38 for rice and wheat) received the lower total dose as the actual SPAD index remained higher most of the time than the threshold value. The maximum N dose was received by the higher SPAD (SPAD 38) in rice but still lower than that of FTNM where N was applied at fixed growth stages of the crop. In both the crops all the RTNM under SPAD-based management received the lower dose of FTNM. The treatment FFP was also acted as fixed-time application but as on farmers' practice.

Rice and wheat productivity

Responding well to N management practices, both grain and straw yield of rice showed an increase in enhancing the level of SPAD and N topdressing under RTNM during both the years. The medium rate of N top dressing (25 kg ha^{-1}) at medium SPAD (S_{36}) produced grain and straw yields comparable to those of high rate of N top dressing (35 kg ha^{-1}) at high SPAD (S38) and FTNM, but significantly higher than those of low rate of N top dressing (15 kg ha^{-1}) at low SPAD level (S_{34}) during both years (Figure 1). Like rice, wheat also produced significantly greater grain and straw yields having medium rate of N top dressing

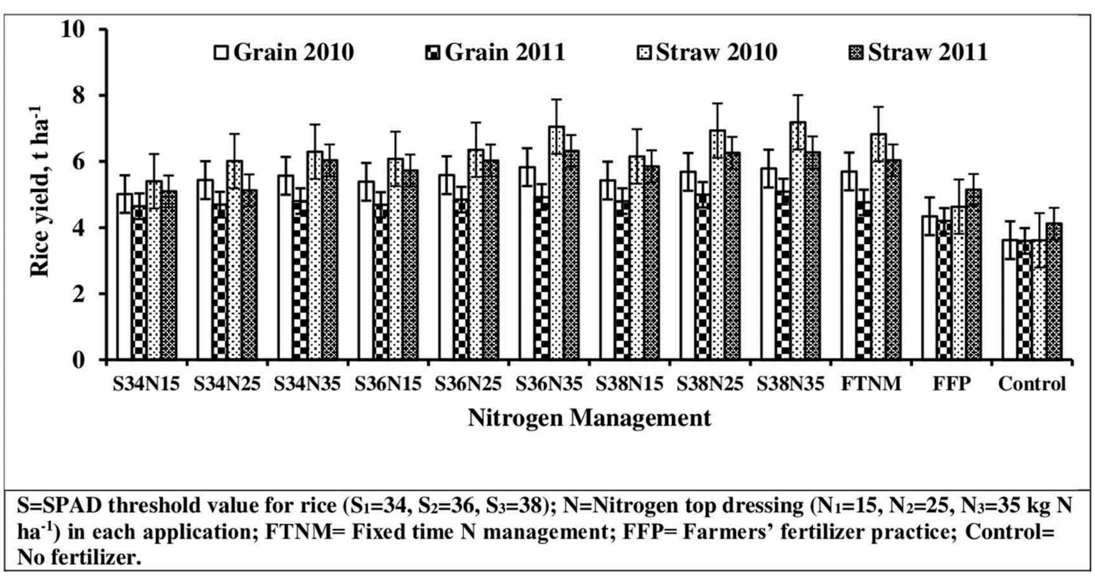


Figure 1. Rice grain and straw yield under different N management practices during 2010 and 2011 (vertical lines indicate the standard error).

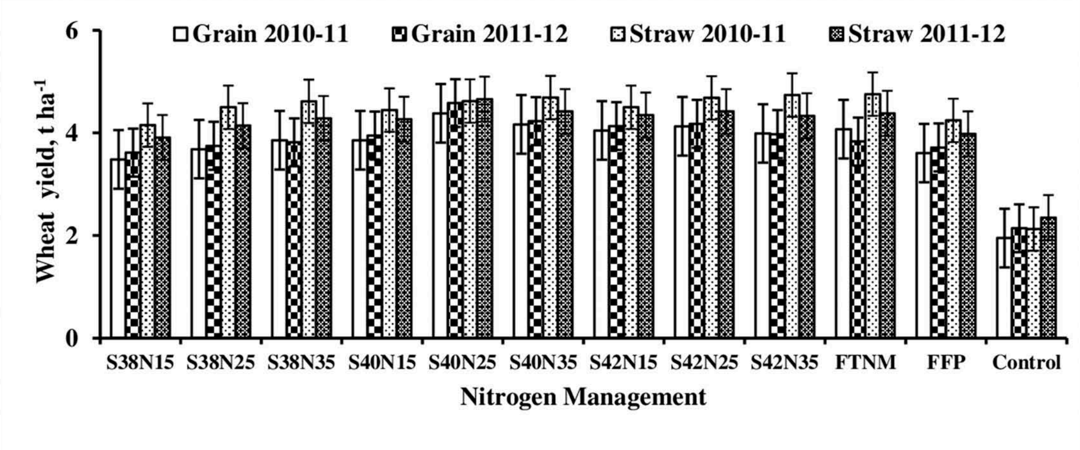
(25 kg ha^{-1}) at medium SPAD (S_{40}) than those of low rate of N top dressing (15 kg ha^{-1}) at low SPAD (S_{38}); however, the yields were comparable to those of high rate of N top dressing (35 kg ha^{-1}) at high SPAD (S_{42}) and FTNM during both years (Figure 2).

As shown in Tables 2 and 3, the number of N application splits differed across the plots under RTNM in both rice and wheat, and the application timing also played an important role in reducing the use of N fertilizer while maintaining the attainable yield. Here in the study, the application of first and second topdressing N at 30 and 50 DAT, respectively, as per the SPAD values in RTNM probably catered to the need of rice, thus leading to the desired gain in grain yield during both the years. Though SPAD 36 and 38 produced comparable grain yield, SPAD 36 had a lower N requirement. Topdressing of 25 kg N ha^{-1} recorded comparable grain yield to that of 35 kg N ha^{-1}; but topdressing of 15 kg N ha^{-1} recorded significantly lower yield than that of 25 and 35 kg N ha^{-1} in most of the cases during both the years. Thus, SPAD-based moderate rate of N (25 kg ha^{-1}) topdressing could help in reducing N requirement in rice without exerting any impact on the rice grain yield. Here in the study, a positive correlation was observed between SPAD and rice yield (Figure 3(a–c)). At active tillering most of the SPAD sprayed between 40 and 44, which indicates the high chlorophyll content rather than that of panicle initiation and flowering stages. In the later two stages, the SPAD responded up to 38, but the equations said that the cx^2 is negative ($-0.009x^2$ and $-0.004x^2$) which recommends the strong support of SPAD 36 as the optimum SPAD for maximizing the rice grain yield (Figure 3(a,b)).

The wheat crop responded well under RTNM with a lower N requirement as compared to FTNM. In this case, the SPAD 40 produced comparable grain yield with less fertilizer N than that of SPAD 42. In light of the strong and positive relationships between SPAD values (recorded from 25 DAS to heading) and grain yield of wheat, SPAD threshold 40 could help in making a decision on the appropriate timing of N application (Figure 3(d–f)). Here in the study, the grain yield responded up to SPAD at active tillering stage but in the later two stages (earhead initiation and flowering), most of the responses were noticed up to SPAD 42. In all the three stages, it was noticed that cx^2 is negative ($-0.018x^2$, $-0.016x^2$ and $-0.021x^2$), which can indicate the SPAD value 40 could be the maximum threshold value for wheat, and based on SPAD 40, N application varied from 85 to 118 kg N ha^{-1} in 2010–2011 and 90 to 118 kg N ha^{-1} in 2011–2012 for attaining the optimum wheat grain yield in eastern India.

Trend of SPAD value, leaf and soil N content during the growth period of rice and wheat

For rice the time series SPAD index, leaf N content and soil available N status were noted higher at active tillering (20 DAT) and thereafter decrement was observed up to panicle initiation (40 DAT) in SPAD index due to high demand of N. In most of the case N was applied at panicle initiation stage and where it was not the SPAD



S=SPAD threshold value for wheat (S_1=38, S_2=40, S_3=42); N=Nitrogen top dressing (N_1=15, N_2=25, N_3=35 kg N ha^{-1}) in each application; FTNM= Fixed time N management; FFP= Farmers' fertilizer practice; Control= No fertilizer.

Figure 2. Wheat grain and straw yield under different N management practices during 2010–11 and 2011–12 (vertical lines indicate the standard error).

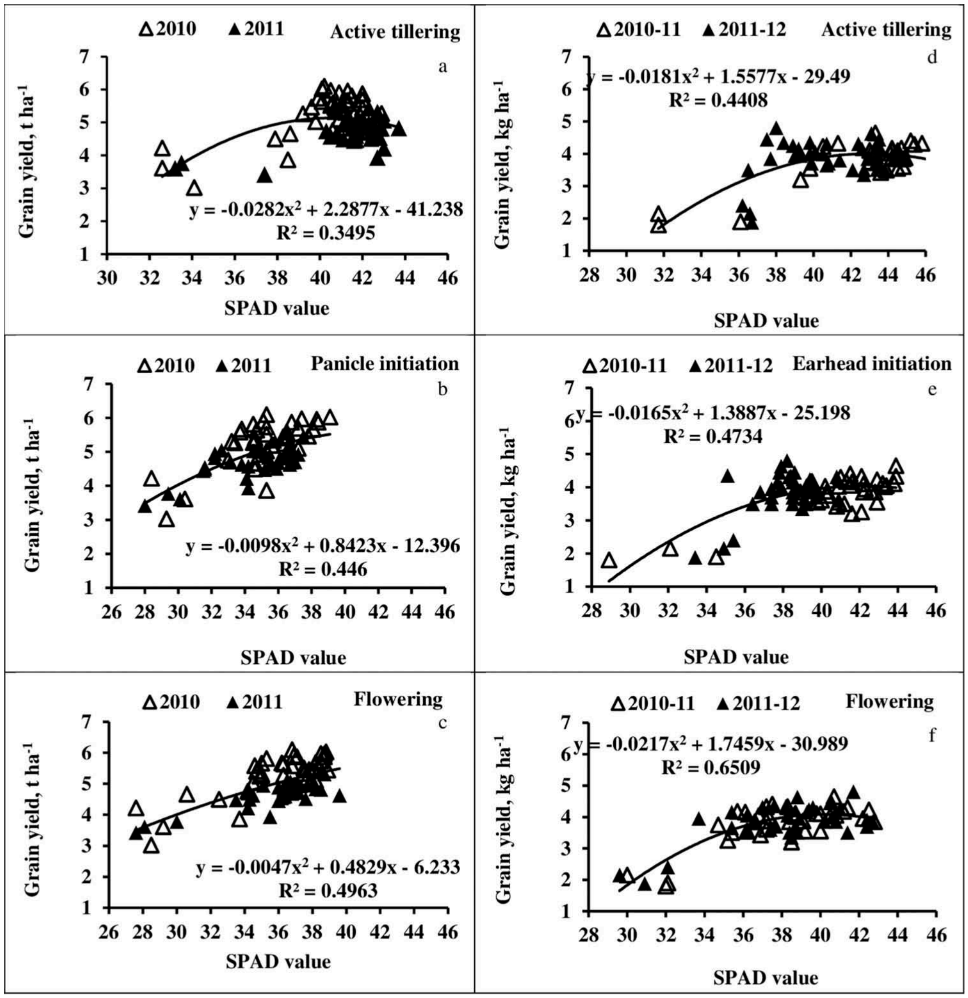


Figure 3. Relationship between grain yield and SPAD value at (a) active tillering, (b) panicle initiation and (c) flowering stages of rice; and (d) active tillering, (e) earhead initiation and (f) flowering stages of wheat (over 2 years' data).

recorded low index at 50 DAT in both the years. At 60 DAT (flowering stage) in most of the cases the SPAD showed a lower trend than that of 50 DAT, which also indicates the high N demand for rice (Figure 4). The leaf N and soil available N showed a decreasing trend as the crop matured (Figures 5 and 6). The leaf N content in some cases at 60 DAT (flowering) showed similar or a slightly higher value than that of 40 DAT (panicle initiation) in rice which may be due to the application of N at 50 DAT during the study.

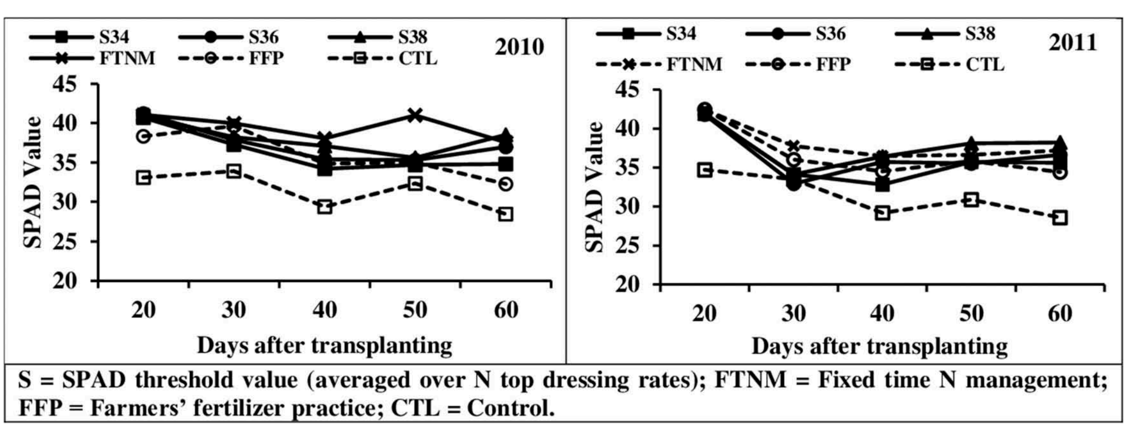


Figure 4. SPAD meter readings at different growth stages of rice under different N management practices.

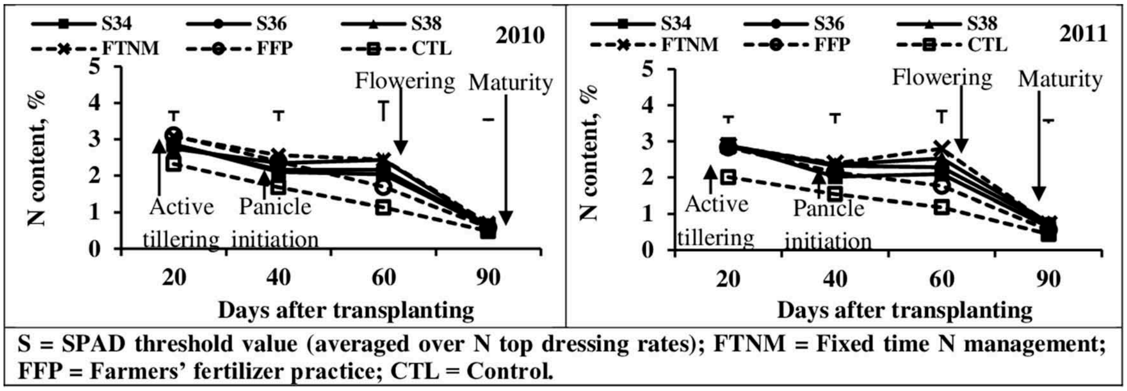


Figure 5. Leaf N content at different growth stages of rice under different N management practices (vertical lines indicate the standard error).

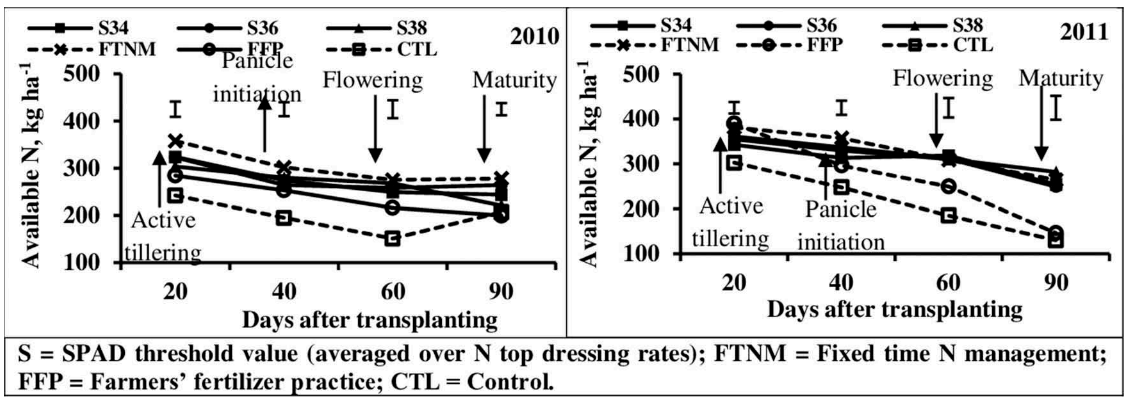


Figure 6. Soil available N status of 0–20 cm depth at different growth stages of rice under different N management practices (vertical lines indicate the standard error).

In the case of wheat, the SPAD Index showed a decreasing trend after booting stage (55 DAS) of the crop (Figure 7). The leaf N content and available soil N status decreased as the crop tends towards maturity in both the years (Figure 8). However, herein the study after flowering (65 DAS) the available soil N status slightly increased at maturity of wheat crop, and this may be due to the less vegetative growth leads to less N uptake after anthesis of wheat crop (Figure 9).

Threshold SPAD value to maintain desired soil available N and leaf N content for maximizing rice grain yield

Correlations among leaf N content, SPAD value and available N content in soil at critical crop growth stages reflected significant and positive relationships among these (Table 4). Grain yield was significantly and positively related with leaf N content and SPAD value at active tillering, panicle initiation and flowering stages of rice. Grain yield also showed a significant and positive correlation with available N content in soil at flowering (Table 4). The relationships between leaf N content and SPAD value were positive and significant ($p \le 0.01$) at active tillering (R^2 = 0.39), panicle initiation (R^2 = 0.81), and flowering (R^2 = 0.61) stages of the crop. Similarly, the relationships between grain yield and leaf N contents were also significant at active tillering (R^2 = 0.29), panicle initiation (R^2 = 0.34), and flowering (R^2 = 0.42) stages of the crop. From the above quadratic relations (Table 5), the desired leaf N content was 2.95(±0.03), 2.50(±0.03) and 2.46(±0.05)% at active tillering, panicle initiation and flowering stages of the crop, respectively, to achieve maximum rice grain yield. A similar linear and significant relationship was obtained between soil available N and leaf N content at these growth stages. The soil available N content was derived as 426(±6.2), 378(±5.0) and 324 (±5.3) kg ha^{-1} at active tillering, panicle initiation and flowering stages, respectively, for the desired leaf N content in rice. As the leaf N content and SPAD value correlated linearly, the derived SPAD values at the above

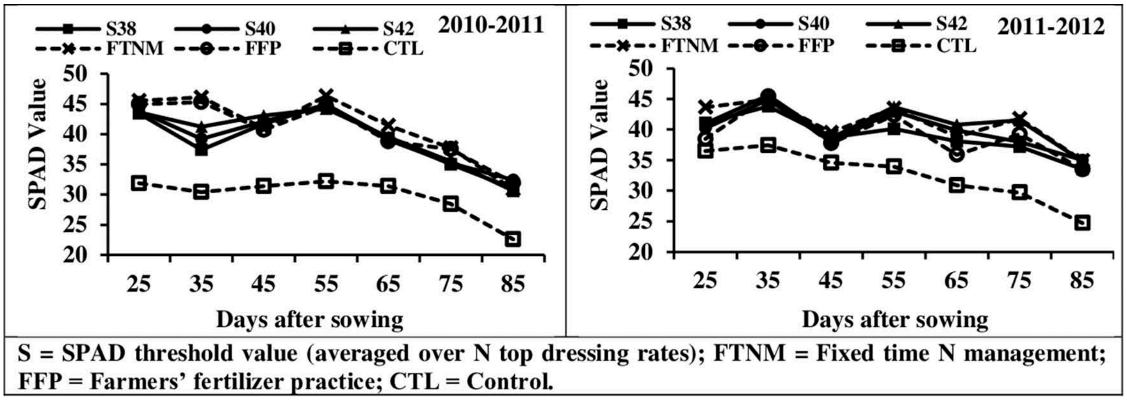


Figure 7. SPAD meter readings at different growth stages of wheat under different N management practices.

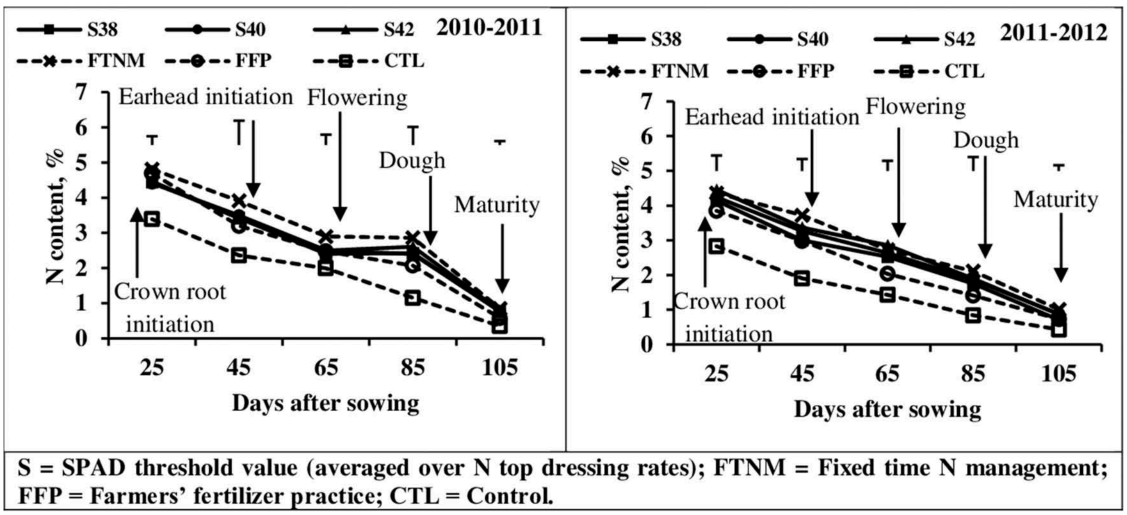


Figure 8. Leaf N content at different growth stages of wheat under different N management practices (vertical lines indicate the standard error).

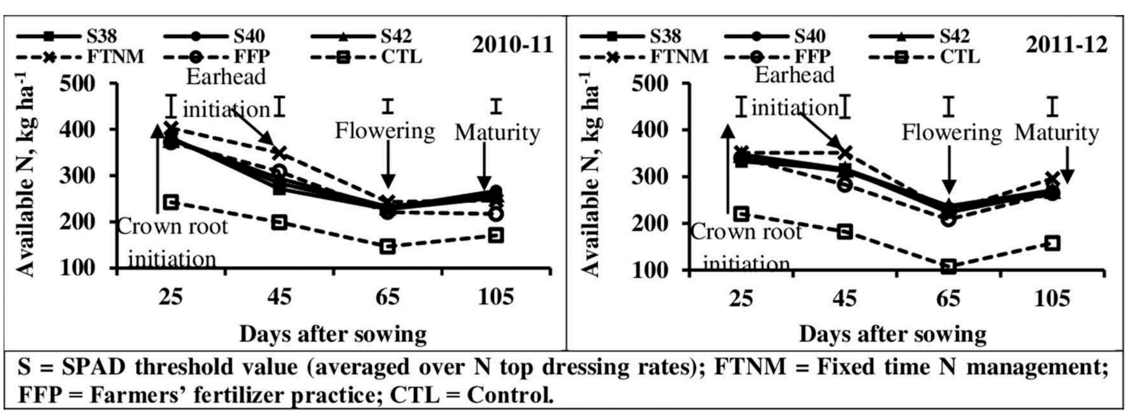


Figure 9. Soil available N status of 0–20 cm depth at different growth stages of wheat under different N management practices (vertical lines indicate the standard error).

growth stages were 41.5(±0.28), 37.5(±0.28), and 37.5 (±0.33) for the desired leaf N content to maximize grain yield. Flowering is one of the most important critical growth stages of rice that influences grain filling and hence, the grain yield. At flowering, the desired leaf N content was 2.46% for maximum grain yield of rice;

Table 4. Correlations among SPAD values, leaf N content, soil available N status and grain yield of rice (Over 2 years' data).

Characters	Leaf N at AT	Leaf N at PI	Leaf N at FL	SPAD at AT	SPAD at PI	SPAD at FL	Soil N at AT	Soil N at PI	Soil N at FL	Yield
Leaf N at AT	1.00									
Leaf N at PI	0.55**	1.00								
Leaf N at FL	0.46**	0.60**	1.00							
SPAD at AT	0.62**	0.53**	0.67**	1.00						
SPAD at PI	0.53**	0.90**	0.68**	0.61**	1.00					
SPAD at FL	0.51**	0.69**	0.78**	0.77**	0.82**	1.00				
Soil N at AT	0.35**	0.28*	0.34**	0.53**	0.27*	0.29*	1.00			
Soil N at PI	0.37**	0.55**	0.52**	0.66**	0.51**	0.53**	0.59**	1.00		
Soil N at FL	0.50**	0.50**	0.70**	0.80**	0.50**	0.73**	0.50**	0.81**	1.00	
Yield	0.46**	0.52**	0.58**	0.49**	0.66**	0.70**	0.10	0.14	0.34**	1.00

Table values of correlation coefficient at 70 error df at 5% and 1% P level are 0.229 and 0.298 respectively; AT = Active tillering; PI = Panicle initiation; FL = Flowering; * indicates significance at $p < 0.05$; ** indicates significance at $p < 0.01$.

Table 5. Relationships between leaf N content and grain yield, leaf N content and SPAD value and leaf N content and soil available N at different growth stages of rice and desired leaf N, SPAD value and soil available N for maximum grain yield.

Growth stages	(i) Relationship (leaf N and grain yield)	R^2 value	Desired Leaf N content†
Active tillering	$Y = -1771X^2 + 10466X - 10329$ ($1.88 \le X \le 3.24$, n = 72)	0.29**	2.95 ± 0.03
Panicle initiation	$Y = -1545X^2 + 7735X - 4443$ ($1.28 \le X \le 2.70$, n = 72)	0.34**	2.50 ± 0.03
Flowering	$Y = -873X^2 + 4295X - 48.74$ ($1.04 \le X \le 2.90$, n = 72)	0.42**	2.46 ± 0.05
Maturity	$Y = -34576X^2 + 45994X - 10010$ ($0.42 \le X \le 0.80$, n = 72)	0.41**	0.67 ± 0.01
Growth stages	**(ii) Relationship (leaf N and SPAD value)**	**R^2 value**	**Desired SPAD value**
Active tillering	$Y = 5.706X + 24.67$ ($1.88 \le X \le 3.24$, n = 72)	0.39**	41.5 ± 0.28
Panicle initiation	$Y = 8.217X + 16.89$ ($1.28 \le X \le 2.70$, n = 72)	0.81**	37.5 ± 0.28
Flowering	$Y = 5.073X + 25.07$ ($1.04 \le X \le 2.90$, n = 72)	0.61**	37.5 ± 0.33
Growth stages	**(iii) Relationship (leaf N and Soil avail. N)**	**R^2 value**	**Desired soil availability N (kg ha^{-1})**
Active tillering	$Y = 0.0017X + 2.226$ ($226 \le X \le 512$, n = 72)	0.12**	426 ± 6.2
Panicle initiation	$Y = 0.0035X + 1.175$ ($181 \le X \le 388$, n = 72)	0.31**	378 ± 5.0
Flowering	$Y = 0.0067X + 0.288$ ($146 \le X \le 331$, n = 72)	0.49**	324 ± 5.3

(i) Y = grain yield; X = leaf N content; (ii) Y = SPAD value; X = leaf N content; (iii) Y = leaf N content; X = soil available N status; ** indicates significance at $p < 0.01$; †values are as mean±SE.

but the leaf N content recorded in FTNM (2.62%) was higher and that in FFP (1.73%) and control treatments (1.15%) was lower than the desired value at flowering (Figure 5).

Threshold SPAD value to maintain desired soil available N and leaf N content for maximizing wheat grain yield

The leaf N content, SPAD value and soil available N contents at the critical growth stages of wheat showed very strong and positive correlations among themselves. The grain yield also significantly and positively related with leaf N content, SPAD value and soil available N content at active tillering (35 DAS), earhead initiation (45 DAS) and flowering stages (65 DAS) of the crop (Table 6). The positive and significant correlations ($p \le 0.01$) between leaf N content and SPAD value were obtained at active tillering (R^2 = 0.40), earhead initiation (R^2 = 0.28) and flowering (R^2 = 0.43) stages of the crop (Table 7). The quadratic relationships between leaf N contents and grain yield of wheat were found highly significant ($p \le 0.01$) at active tillering (R^2 = 0.59), earhead initiation (R^2 = 0.58) and flowering (R^2 = 0.53) stages of the crop. From the quadratic relations, the derived leaf N content was 4.84(±0.06), 3.76(±0.06) and 3.19 (±0.04)% at active tillering, earhead initiation and flowering stages, respectively, for maximum grain yield (Table 7). The leaf N contents and SPAD values were linearly correlated and the derived SPAD values were 44.3(±0.38) at active tillering, 40.9(±0.33) at earhead initiation and 41.8(±0.35) at flowering stages for desired leaf N contents at the respective stages in achieving maximum grain yield. Soil available N contents also linearly and significantly ($p \le 0.01$) correlated with leaf N contents and the derived soil available N contents were 436(±6.0), 357(±5.1) and 300(±3.8) kg ha^{-1} at active tillering, earhead initiation and flowering stages, respectively, for the desired leaf N content to maximize wheat grain yield. The SPAD value, leaf N content and soil available N content responded well to N management practices in wheat. The SPAD, leaf N and soil available

Table 6. Correlation among SPAD values, leaf N content, soil available N status and grain yield of wheat (over 2 years' data).

Charaters	Leaf N at AT	Leaf N at EI	Leaf N at FL	SPAD at AT	SPAD at EI	SPAD at FL	Soil N at AT	Soil N at EI	Soil N at FL	Yield
Leaf N at AT	1.00									
Leaf N at EI	0.76**	1.00								
Leaf N at FL	0.77**	0.72**	1.00							
SPAD at AT	0.63**	0.54**	0.39**	1.00						
SPAD at EI	0.60**	0.53**	0.34**	0.71**	1.00					
SPAD at FL	0.57**	0.44**	0.66**	0.42**	0.48**	1.00				
Soil N at AT	0.68**	0.63**	0.47**	0.78**	0.70**	0.47**	1.00			
Soil N at EI	0.64**	0.64**	0.78**	0.42**	0.41**	0.57**	0.46**	1.00		
Soil N at FL	0.77**	0.74**	0.76**	0.59**	0.59**	0.77**	0.64**	0.71**	1.00	
Yield	0.72**	0.64**	0.69**	0.53**	0.59**	0.69**	0.67**	0.71**	0.78**	1.00

Table values of correlation coefficient at 70 error df at 5% level and 1% level are 0.229 and 0.298, respectively; AT = Active tillering; EI = Earhead initiation; FL = Flowering; ** indicates significance at $p < 0.01$.

Table 7. Relationships between leaf N content and grain yield, leaf N content and SPAD value and leaf N content and soil available N at different growth stages of wheat and desired leaf N, SPAD value and soil available N for maximum grain yield.

Growth stages	(i) Relationship (leaf N and grain yield)	R^2 value	Desired Leaf N content†
Active tillering	$Y = -525.3X^2 + 5082X - 8204$ ($2.70 \le X \le 5.00$, n = 72)	0.59**	4.84 ± 0.06
Earhead initiation	$Y = -606.3X^2 + 4558X - 4441$ ($1.76 \le X \le 4.47$, n = 72)	0.58**	3.76 ± 0.06
Flowering	$Y = -684.1X^2 + 4365X - 2739$ ($1.31 \le X \le 3.24$, n = 72)	0.53**	3.19 ± 0.04
Maturity	$Y = -5730X^2 + 10697X - 759.8$ ($0.34 \le X \le 1.23$, n = 72)	0.62**	0.93 ± 0.02
Growth stages	**(ii) Relationship (leaf N and SPAD value)**	**R^2 value**	**Desired SPAD value**
Active tillering	$Y = 4.213X + 23.88$ ($2.70 \le X \le 5.00$, n = 72)	0.40**	44.3 ± 0.38
Earhead initiation	$Y = 2.787X + 30.43$ ($1.76 \le X \le 4.47$, n = 72)	0.28**	40.9 ± 0.33
Flowering	$Y = 5.293X + 24.90$ ($1.31 \le X \le 3.24$, n = 72)	0.43**	41.8 ± 0.35
Growth stages	**(iii) Relationship (leaf N and Soil avail. N)**	**R^2 value**	**Desired soil availability N (kg ha^{-1})**
Active tillering	$Y = 0.0065X + 2.0061$ ($213 \le X \le 435$, n = 72)	0.2**	436 ± 6.0
Earhead initiation	$Y = 0.0080X + 0.9018$ ($171 \le X \le 382$, n = 72)	0.42**	357 ± 5.1
Flowering	$Y = 0.0088X + 0.5480$ ($98 \le X \le 256$, n = 72)	0.57**	300 ± 3.8

(i) Y = Grain yield; X = leaf N content; (ii) Y = SPAD value; X = leaf N content; (iii) Y = leaf N content; X = soil available N status; ** indicates significance at $p < 0.01$; †values are as mean±SE.

N contents were recorded higher at active tillering and decreased gradually towards flowering of the crop (Figure 7–9).

N use efficiency of rice and wheat

Of the various parameters estimated here, agronomic N use efficiency (AE_N), nitrogen recovery efficiency (RE_N), and partial factor productivity of applied N (PFP_N) responded well to N management practices in rice (Table 8). The AE_N showed an inverse relationship with the SPAD value, while RE_N registered a positive change with increasing SPAD value. Considerably reduced values for both AE_N and RE_N were obtained for rice in FTNM than that of N management under RTNM. FFP also significantly decreased the AE_N and RE_N values when compared with N management under RTNM. The values of PFP_N showed a steady decline in increasing the rate of N top dressing with increasing SPAD value. Accordingly, a low rate of N (15 kg N ha^{-1}) top dressing at low SPAD (S_{34}) recorded markedly higher PFP_N in rice than those obtained with a higher rate of N (25–35 kg ha^{-1}) top dressing at higher SPAD (S_{36} and S_{38}). The values of PFP_N were also found to be less in the case of the FTNM than obtained with low-to-moderate rate of N top dressing at low SPAD (S_{34}) under RTNM (Table 8). In the current investigation, N management practices exerted a significant effect on AE_N, RE_N and PFP_N of wheat. Application of medium rates of N (25 kg N ha^{-1}) at medium SPAD (S_{40}) recorded the highest AE_N and RE_N of wheat, which was

Table 8. Agronomic N use efficiency (AE_N), nitrogen recovery efficiency (RE_N) and partial factor productivity of applied N (PFP_N) of rice grown under different N management practices (average data over 2 years).

Treatment	N rate (kg ha^{-1})	AE_N (kg kg^{-1})	RE_N (kg kg^{-1})	PFP_N (kg kg^{-1})
S† $_{34}$ N_{15}	55.0	21.8*	0.53*	89.3*
S_{34} N_{25}	59.2	22.8*	0.64*	87.0*
S_{34} N_{35}	70.9	22.3*	0.67*	75.0
S_{36} N_{15}	65.0	22.3*	0.59*	78.1
S_{36} N_{25}	80.0	21.4*	0.60*	67.3
S_{36} N_{35}	88.3	20.3*	0.64*	63.5
S_{38} N_{15}	82.5	18.0*	0.52*	62.3
S_{38} N_{25}	96.7	18.1*	0.55*	56.3
S_{38} N_{35}	105.9	17.2*	0.55*	52.0
FTNM	120.0	13.5	0.45	43.6
FFP	60.0	11.1	0.39	71.3
Control	0.0	–	–	–
SE		2.0	0.04	3.7
LSD (0.05)		5.8	0.13	10.8

†S = SPAD threshold value; N = nitrogen top dressing in kg N ha^{-1} in each application; FTNM = fixed-time nitrogen management; FFP = farmers' fertilizer practice; SE = standard error of mean; LSD = least significant difference; * = values statistically differed over FFP.

greater than those of high (35 kg ha^{-1}) and low (15 kg ha^{-1}) rate of N topdressing at high (S_{42}) and low SPAD (S_{38}) under RTNM and FTNM.S_{40} with N_{25} increased AE_N and RE_N by 29.2% and 50.9% over low rate of N topdressing at low SPAD, by 50% and 8.8% over high rate of N topdressing at high SPAD and by 58.5% and 15.1% over FTNM. The PFP_N decreased steadily by increasing the rate of N topdressing in wheat from 15 to 35 kg N ha^{-1} irrespective of SPAD levels. Accordingly, high rate (35 kg N ha^{-1}) of N topdressing at high SPAD (S_{42}) registered significantly lower values of IE_N, PE_N and PFP_N than those of medium (25 kg ha^{-1}) and low rate (15 kg ha^{-1}) of N topdressing at medium (S_{40}) and low SPAD (S_{38}). The FTNM also considerably reduced the PFP_N values from those of low-to-medium rate of N (15–25 kg ha^{-1}) topdressing at low-to-medium SPAD (S_{38}-S_{40}) under RTNM (Table 9).

Discussion

Rice and wheat yield

Enhancing SPAD level and N topdressing under RTMN in both the crops exerted a significant effect on the productivity. In case of the rice, the medium rate (25 kg ha^{-1}) of N topdressing at medium SPAD demonstrated grain and straw yields comparable to FTNM and saved 33.3% fertilizer N. Whereas, in case of wheat, the medium rate produced 13.4% higher grain yield with18.8% less N fertilizer as compared to FTNM. In SPAD-based N management treatments, higher or comparable grain yield with less fertilizer N to that of the FTNM implies a better translation of fertilizer N into grain yield when applied on the basis of the need of the crop (Ghosh et al., 2013; Li et al., 2009; Sen et al., 2011). Similar yield advantages with 20–30% less N fertilizer use were demonstrated previously in rice (Wang et al., 2001; Singh et al., 2010) as compared to wheat where the yield advantages were achieved with 10–12% less N fertilizer use (Diacono et al., 2013; Jia et al., 2007; Peng et al., 2012) due to SPAD-based N management in RTNM over that of FTNM. The application time ensures an important role in adequacy of N fertilizer while maintaining the productivity. Topdressing N at 30 and 50 DAT, possibly the need of rice crop, accordingly provides an increment in grain yield during the study. We could infer from the relation between SPAD values (recorded from 20 DAT to heading) and grain yield for each treatment that the SPAD threshold 36 should be used in determining the timing of N application in rice (Figure 3(a–c)). Notably, no increase in the grain yield was witnessed on increasing total N rates and number of N applications using a higher SPAD threshold (S_{38}). The maximum grain yield of 6098 kg ha^{-1} was estimated from the SPAD value of 37, which indicated that the SPAD threshold should be maintained a minimum of 36 through topdressing of N for higher grain yield in rice. Based on SPAD 36, the total amount of N to be applied varied from 70 to 88 kg N ha^{-1} in 2010 and 60 to 88 kg N ha^{-1} in 2011 and covered well the range of rice grain yield of eastern India.

In wheat crop, the SPAD 40 maintained superiority with reduced N than that of SPAD 42 and our finding contrasts with that of Hussain et al. (2003) and Win (2003) who also determined the critical SPAD value of 42 and 44 for guiding need-based N topdressing in wheat in Pakistan and Bangladesh, respectively. The maximum grain yield of 4805 kg ha^{-1} was estimated from the SPAD value of 40.7, which also supported the SPAD threshold of 40–41 to be maintained through topdressing of N for higher grain yield. Previously, SPAD threshold values of 37 and 38 were also found to be critical for guiding N fertilizer applications to wheat in the eastern Indo Gangetic Plain (IGP) and middle IGP of Indian subtropics (Maiti & Das, 2006; Singh et al., 2010). Our study clearly showed that SPAD 40 based N application in RTNM could increase grain yield by 13.4% with an 18.8% decline in N requirement from the existing N fertilizer recommendation in wheat in FTNM. Our study implies that use of N input in excess of its requirement under FTNM has reduced its yield advantage over RTNM (Khurana et al., 2008; Mueller et al., 2012; Shukla et al., 2004).

Table 9. Agronomic N use efficiency (AE_N), nitrogen recovery efficiency (RE_N) and partial factor productivity of applied N (PFP_N) of wheat grown under different N management practices (average data over 2 years).

Treatment	N rate (kg ha^{-1})	AE_N (kg kg^{-1})	RE_N (kg kg^{-1})	PFP_N (kg kg^{-1})
S† $_{38}$ N_{15}	77.5	19.5	0.53	46.5
S $_{38}$ N_{25}	85.0	20.3	0.70	46.5
S $_{38}$ N_{35}	100.9	17.7	0.69	38.5*
S $_{40}$ N_{15}	87.5	21.4	0.59	45.1
S $_{40}$ N_{25}	97.5	25.2	0.80	46.6
S $_{40}$ N_{35}	118.3	18.3	0.70	36.1*
S $_{42}$ N_{15}	97.5	21.1	0.60	42.2
S $_{42}$ N_{25}	110.0	19.4	0.71	38.3*
S $_{42}$ N_{35}	118.3	16.8	0.74	34.9*
FTNM	120.0	15.9	0.70	32.9*
FFP	80.0	20.2	0.69	45.8
Control	0.0	–	–	–
SE		1.7	0.06	2.2
LSD (0.05)		5.1	0.17	6.3

†S = SPAD threshold value; N = nitrogen top dressing in kg N ha^{-1} in each application; FTNM = fixed-time nitrogen management; FFP = farmers' fertilizer practice; SE = standard error of mean; LSD = least significant difference; * = values statistically differed over FFP.

The efficiency of N in rice and wheat

The PFP_N was noted less in FTNM due to large amount of N applied at tillering in FTNM led a decrease in the earbearing tillers and grain yield of rice, and thus, resulting in poor N use efficiency (Dobermann et al., 2004; Esfahani et al., 2008; Peng et al., 1996). Moderate rate of N (25 kg ha^{-1}) topdressing at medium SPAD (S_{36}) was found conducive in recording higher AE_N, RE_N and PFP_N over FTNM of transplanted rice. It increased AE_N by 58.5% and RE_N by 32.2% and PFP_N by 54.2% over those of FTNM. The higher values AE_N, RE_N and PFP_N in rice under SPAD-based N management could be credited to supply of N in accordance with crop need, particularly late-season N supply sufficient for achieving high grain yield (Gupta & Khosla, 2012; Liu et al., 2013; Singh et al., 2013; Zhao et al., 2013). Thus, we found SPAD-based N topdressing promising for N management in transplanted rice for increasing grain yield and N use efficiency.

In case of wheat, the increase in AE_N and RE_N with medium rate of N top dressing at medium SPAD was associated with increase in grain yield with less fertilizer N use over that of high rate of N top dressing at high SPAD and FTNM (Singh et al., 2002; Tubana et al., 2008; Zebarth et al., 2007). Medium rate of N (25 kg ha^{-1}) topdressing at medium SPAD (S_{40}) recorded significantly higher values of PFP_N than those of FTNM. $S_{40}N_{25}$ increased the PFP_N by 41.5% over those of FTNM in wheat under the study. Low-to-medium rate N application at low-to-medium SPAD under RTNM promoted larger earheads, increased test weight and ultimately improved grain yield efficiency indices (Peng et al., 2012; Shukla et al., 2004; Singh et al., 2010). The SPAD-based real-time N management in wheat, thus, appears to be a better option for increasing wheat yield and N use efficiency.

Correlation for rice grain yield

Positive correlations were recorded among leaf N content, SPAD value and available soil N status at critical crop growth stages. The derived soil N status at critical growth stages (426, 378 and 324 kg ha^{-1} at active tillering, panicle initiation and flowering stages, respectively) and the leaf N content at those stages clearly indicated that soil available N and leaf N status could well be estimated using SPAD value. Thus, optimizing SPAD value at active tillering, panicle initiation and flowering could help in maintaining the desired soil available N status and leaf N content for maximizing grain yield of transplanted rice (Ghosh et al., 2013; Lin et al., 2010; Singh et al., 2007). As could be inferred from Figures 4–6, the SPAD values, leaf N contents and soil available N remained higher at active tillering stage accompanied by a gradual decrease towards flowering and maturity of rice. Variation in SPAD threshold values across different growth stages and crop varieties were also reported earlier (Balasubramanian et al., 2000; Huang et al., 2008; Swain & Sandip, 2010). The critical SPAD values at active tillering, panicle initiation and flowering stages were estimated as 41.5, 37.5 and 37.5, respectively, for attaining rice grain yield equivalent to that of 120 kg N ha^{-1} in three fixed-time splits. Thus, optimizing SPAD values at these stages could help in maximizing grain yield of transplanted rice (Gholizadeh et al., 2011; Ghosh et al., 2013; Swain & Sandip, 2010). The leaf N content in FTNM (2.62%) was quite higher than the desired value (2.46%) at flowering (Figure 5). Excess leaf N content in FTNM leads to more vegetative growth, delays flowering and reduces N use efficiency (Cabangon et al., 2011). On the other hand, deficit leaf N content in FFP and control treatments reduces the photosynthetic rate resulting in poor growth and low grain productivity (Makino, 2011; Yang et al., 2014). Thus, an SPAD threshold value of 37.5 to maintain 2.46% leaf N content at flowering may be considered as a guiding principle for N management in transplanted rice.

Correlation for wheat grain yield

As the wheat showed positive correlations among leaf N, soil N and SPAD at critical growth stages, the optimizing SPAD values at those stages (active tillering, earhead initiation and flowering) could help in achieving desired leaf N content and soil available N status for maximizing the grain yield (Ecarnot et al., 2013; Meyer-Auricha et al., 2010; Naud et al., 2009). The derived soil N status (436, 357 and 300 kg ha^{-1} at active tillering, earhead initiation and flowering stages, respectively) suggested that the SPAD threshold value developed from our study could maintain well the desired soil available N and leaf N status at the critical growth stages of wheat responsible for maximizing its grain yield. The results are in conformity with the findings of Maiti and Das (2006), Naud et al. (2009) and Singh et al. (2012b). The derived SPAD value at respective growth stages (active tillering, earhead initiation and flowering stages) were 44.3 (±0.38), 40.9(±0.33) and 41.8(±0.35) to maximize grain yield. The results suggested that grain yield of wheat could be determined between active tillering and earhead initiation by maintaining greenness of leaves through N topdressing guided by SPAD meter reading (Alam et al., 2006; Singh et al., 2013). Singh et al. (2010) and Singh et al. (2013) opined that the flowering stage was most critical from a fertility point of view, and the desired soil available N and leaf N contents (300 kg ha^{-1} and 3.19%) at flowering could be maintained by split application of N through SPAD threshold values. In our study, medium rate of N (25 kg ha^{-1}) top dressing at medium SPAD (S_{40}) significantly increased soil N availability, leaf N content and grain yield over those of low rate of N (15 kg ha^{-1}) top dressing at low SPAD (S_{40}) in RTNM, FFP and control plots. The $S_{40}N_{25}$ maintained soil N availability, leaf N content and SPAD values at desired levels at the critical growth stages and produced high grain yield comparable to those of high rate of N (35 kg ha^{-1}) top dressing at high SPAD (S_{42}) and FTNM with less amount of fertilizer N use. A similar beneficial effect of SPAD-based N management in wheat was also noticed by Zebarth et al. (2007), Khurana et al. (2008) and Singh et al. (2012b). Thus, an SPAD threshold value of 41–42 at flowering could be considered as a guiding principle for N management in wheat in eastern India.

Conclusions

The blanket, FTNM often fails to meet the N-requirement of the stressed crops. The SPAD-based RTNM in rice and wheat can effectively satisfy the spatial and temporal variable need of N fertilizer for the crops. It is very effective in maintaining high grain yield with saving of considerable amount N fertilizer in both rice and wheat over conventional FTNM in this cropping system. Our study showed that topdressing of 25 kg N ha^{-1} at medium SPAD (S_{36} in rice and S_{40} in wheat) under RTNM could produce comparable grain yield in rice and 13.4% higher grain yield in wheat along with saving of 33.3% and 18.8% N fertilizer in rice and wheat, respectively, over the conventional FTNM in rice-wheat cropping system. It increased the AE_N by 58.5% and RE_N by 32.2% in rice and those of 58.5% and 15.1%, respectively, in wheat over FTNM. The study further confirmed the significant and positive relationships of SPAD value with soil available N and leaf N status; however, the variation was subjected to crop varieties and growth stages. The SPAD threshold value based on the current study could help maintain well the desired soil available N and leaf N status at the critical growth stages of rice and wheat. Based on the results obtained here, we strongly advocate topdressing of 25 kg N ha^{-1} at SPAD threshold values 37.5 in rice and 41.8 in wheat for increasing grain yield and N use efficiency of rice and wheat in the lateritic acid belt of eastern India.

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Author contributions statement

M.G. and D.S. were designed the experiment engaged in field research. M.G., D.S. and M.J. performed the field experiment, collected the data from the field and analyzed in the laboratory. M.G. and D.S. wrote the main manuscript. V.T and A.B reviewed, commented and improved the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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