RESEARCH ARTICLE

SPAD Chlorophyll Meter-Based Real-Time Nitrogen Management in Manure-Amended Lowland Rice

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ABSTRACT

Precise adjustment of nitrogen (N) application time and dose under real-time nitrogen management (RTNM) is crucial for optimal benefits. The study aimed to assess and recommend best combination of threshold SPAD-502 chlorophyll-meter reading (SCMR) and topdressing N rate for lowland flooded-rice (manure amended at 5 t ha^{-1}) to maximize yield, N use efficiency, and economic gains. Four SCMR-based N scheduling ($SCMR_{34}$, $SCMR_{36}$, $SCMR_{38}$, $SCMR_{40}$), each with three topdressing N rates (15, 20, 25 kg N ha^{-1}) as RTNM were evaluated and compared with fixed-time N management (FTNM) (100 kg N ha^{-1}, 4 splits). Topdressing of 20 kg N ha^{-1} at ≤ SCMR 38 ($SCMR_{38}N_{20}$) led to a higher yield (+8%), N use efficiency (+43%), net return (+11%) and reduced N input (-18%) compared to FTNM. The yield advantage with $SCMR_{38}N_{20}$ was attributed to higher internal N use efficiency and optimal source-sink balance (higher harvest index). The best-fit treatment $SCMR_{38}N_{20}$ along with a low-yielding treatment ($SCMR_{36}N_{20}$) was tested across seven rice cultivars for validation. Treatment $SCMR_{38}N_{20}$ led to yield advantage (+7%), but significant only for four cultivars. In lowland rice, RTNM can therefore increase yield and N use efficiency. However, cultivar-specific adjustments to the SCMR threshold and N rate are necessary.

KEYWORDS: Real–time N management, Lowland flooded–rice, Lower Indo–Gangetic plain, Agronomic N use efficiency, N recovery efficiency, Multivariate regression analysis.

Introduction

Rice (*Oryza sativa* L.) is predominantly grown in lowland soils that are mostly deficient in available nitrogen (N) (Choudhury and Kennedy 2005; Hou et al. 2019). The current practice of N management [fixed-time N management (FTNM)] in rice has several drawbacks including lower N use efficiency, groundwater and atmospheric pollutions, and suboptimal productivity. Now, there is a major concern over the decline in partial N factor productivity in flooded-rice production primarily attributed to discrepancy in crop N demand and supply and higher magnitude of losses (Fagodiya et al. 2020). This has led to an interest in crop demand-driven real-time N management options to maximize nutrient use efficiency, yield, and profitability in rice production systems (Bandaogo et al. 2015).

Crop season temporal N dynamics in anoxic-flooded rice soils depends on time and rate of fertilizer/manure, crop nutrient removal, and N losses, and thus, ensuring optimal N bioavailability throughout the crop season as per the crop demand is a potential challenge (Qin et al. 2020). According to Fageria et al. (2011), the non–synchrony between crop N demand and supply largely constrains rice production. In this context, sensor-based real-time N management (RTNM) could be a potential approach to site-specific and demand-driven N management to improve N use efficiency and reduce N losses (Huda et al. 2016). Several researchers have demonstrated strong positive associations between rice plant N status and leaf chlorophyll content (Wood et al. 1993; Lin et al., 2010). Crop N nutrition as monitored by chlorophyll-meter reading at different growth stages differs with cultivar, soil fertility, environmental conditions, and locally adopted crop management practices (Mohanty et al. 2021). The precise adjustment of chlorophyll-meter reading thresholds for fertilization scheduling with the optimal topdressing N rate is therefore necessary in order to achieve maximum benefits of RTNM. Pre-sowing application of manure in tropical soils can substantially contribute towards crop N nutrition, depending on quantity, nutrient content, and rate of mineralization (Venkatesh et al. 2017). Chlorophyll-meter based N scheduling would be a more realistic approach to N management in integrated nutrient management module(s). However, the efficacy RTNM under integrated nutrient management for yield advantage, nutrient use efficiency, and N economy module has not been adequately studied. Further, variable N rates and timing as alter with different RTNM treatments would provide valuable insights into N yield functions and relative weightage of N application at different growth stages of rice crops.

In view of this, two years of calibration and one year of validation trials were conducted to determine the best chlorophyll meter threshold for application scheduling and top-dressing N rate in lowland rice crop that is amended with farmyard manure at 5 t ha^{-1} to maximize productivity, nutrient use efficiency, and N economy and validate the best-fit RTNM treatment across predominant rice cultivars. The major hypotheses of the study were (i). RTNM with optimal combination(s) of N scheduling based on threshold chlorophyll-meter reading and top-dress N rate lead to yield advantage and higher nutrient use efficiency over FTNM in lowland flooded rice, (ii) temporal scheduling of fertilizer-N application (time of application), total applied N rate, and frequency of N topdressing as differ within the RTNM treatments would have a direct influence on rice productivity, (iii) the response scale of rice to SPAD chlorophyll-meter based RTNM would differ with cultivars having variable yield potential and crop duration, and (iv) chlorophyll-meter based RTNM can be effectively integrated with manure amended lowland rice production system for yield advantage and N economy.

Materials and Methods

Site characteristics

The experiments were conducted at the research farm of Bihar Agricultural University, Sabour, Bhagalpur (25°15' N; 87°02' E, and 37 m a.s.l.). The site is located in the lower Indo–Gangetic plain (IGP) region (subtropical humid climate). The weather conditions during the crop seasons are presented in Supplementary Figure 1. The experimental soil is a silty–clay loam and classified as *Fluvisol* (IUSS Working Group WRB, 2015). The soil (0–0.15 m) had neutral pH 7.1, electrical conductivity of 0.47 dS m^{-1}, 4.9 g kg^{-1} soil organic carbon, 12.2 mg kg^{-1} of Olsen-

P and 66.9 mg kg^{-1} of NH_4OAc–K (Jackson 1973). The soil available-N (98.2 mg kg^{-1} $KMnO_4$–N) of the field was lower than the critical soil N level (125 mg kg^{-1} $KMnO_4$–N).

Experimental design and treatment details

Experiment 1 (Optimization trial)

In the optimization trial (rainy season 2013 and 2014), fourteen different N treatments were evaluated in rice [cultivar (*cv.*) Rajendra Sweta (130–135 days duration)]. The treatments comprised of one N control (no fertilizer-N application), one conventional practice of fixed–time N management (FTNM) treatment, and twelve different SPAD 502 chlorophyll-meter (SCMR) based real-time N management (RTNM) treatments using different combinations of SPAD 502 chlorophyll-meter reading (SCMR) based fertilization scheduling in which N was applied when the SCMR of the youngest fully-extended leaf was less than or equaled 34 ($SCMR_{34}$), 36 ($SCMR_{36}$), 38 ($SCMR_{38}$), and 40 ($SCMR_{40}$), each with three top-dressing N rates (15, 20, and 25 kg N ha^{-1}). SCMR were recorded (*n* =15) from each plot starting from the tiller initiation (20 DAT) to the fully heading stage (90 DAT) at a 10-day interval using SPAD-502 chlorophyll-meter (Minolta Camera Co., Osaka, Japan). The FTNM treatment represents the current recommended dose of fertilizer-N (100 kg N ha^{-1}) application in four equal splits $_{\text{i.e.}}$ basal, active tillering [40 days after transplanting (DAT)], panicle initiation (60 DAT), and heading (90 DAT) stages. The basal dose of fertilizer-N (*i.e.* 25 kg N ha^{-1}) was applied to both the FTNM and RTNM treatments and subsequent N was top-dressed as per treatments. The source of N was urea [$CO(NH_2)_2$]. Before the rice crop establishment, farmyard manure (FYM) at 5 t ha^{-1} (dry weight basis) was applied to each plot. The quantity of N added with the FYM was 25.6 ± 0. 7 kg ha^{-1} and 27.7±1.1 kg ha^{-1} (sample analyzed *n* = 3) in the year 2013 and 2014, respectively. The treatments were allocated in a randomized complete block design (RCBD) with three replications. The dimension of each plot was 6 m × 4 m. A filler space of 2.5 m was kept on all sides of each plot.

Experiment 2 (validation trial)

In the validation trial (year 2015), the best-fit RTNM treatment along with a relatively low-yielding RTNM treatment (significant lower yield compared to the best-fit RTNM treatment) were identified/selected based on the results of the optimization trial (Experiment 1). These treatments were evaluated in seven high yielding rice cultivars *viz.* 27P31 (hybrid), RAU 724, MTU 7029, Rajendra Mahsuri, Rajendra Bhagawati, Rajendra Sweta and Arize 6444 (hybrid). Similar methods and management practices were employed as in the optimization trial.

Crop management

Rice seedlings were raised on a 20 m × 5 m nursery bed (wet nursery). During the final field preparation, well-decomposed FYM (5 t ha^{-1}) was added to each plot and thoroughly mixed. Wet–tillage (puddling) was performed one day prior to transplanting. Twenty–two–day old seedlings were transplanted on July 10 in 2013, July 15 in 2014 (optimization trial), and July 13 in 2015 (validation trial) at a spacing of 10 cm × 15 cm. In both the experiments, 17.2 kg P ha^{-1} and 32.8 kg K were applied as a basal dose to all the treatments plots. From transplanting to heading stage, continuous flooding/ponding conditions were maintained with irrigation. Weeds were manually controlled by hand weeding 1-2 times. Necessary plant protection measures were taken to prevent insect pests and diseases.

Yield and yield attributes

Yield attributing parameters like panicles m^{-2}, grains $panicle^{-1}$ and 1000–grain weight were recorded from five rice hills randomly selected from each plot at the maturity stage. Grain and straw yields were estimated from a net–plot area of 5.0 m × 2.0 m. The harvested crop was threshed using a plot thresher and the produces was sun-dried. The total biomass of the crop was estimated on an oven dry weight basis, while grain yield was adjusted at 12% moisture content (w/w). Harvest index (HI) was calculated by the ratio of grain yield to total biological yield (aboveground dry matter) and expressed as a percentage.

Plant nutrient analysis and calculation of N use efficiency

At maturity, plant and grain samples were collected, oven dried, ground and analyzed for total N content was determined by micro–Kjeldahl method (Yoshida et al. 1976). Agronomic N use efficiency (AE_N), N recovery efficiency (RE_N), internal N use efficiency (IE_N), partial factor productivity of applied N (PFP_N), nitrogen harvest index (NHI) and physiological N use efficiency (PE_N) were calculated by the following equations 1-6

$$AE_N\ (kg\ kg^{-1}) = \frac{GY_T - GY_C}{FN} \qquad \text{eq. 1}$$

$$RE_N\ (kg\ kg^{-1}) = \frac{NU_T - NU_C}{FN} \qquad \text{eq. 2}$$

$$IUE_N\ (kg\ kg^{-1}) = \frac{GY}{NU} \qquad \text{eq. 3}$$

$$PFP_N\ (kg\ kg^{-1}) = \frac{GY}{FN} \qquad \text{eq. 4}$$

$$NHI\ (\%) = \frac{NU_{Grain}}{NU_{Total}} \times 100 \qquad \text{eq. 5}$$

$$PE_N\ (kg\ kg^{-1}) = \frac{AGB}{NU} \qquad \text{eq. 6}$$

where, GY_T = grain yield in fertilizer-N treated plot (kg ha^{-1}), GY_C = grain yield in N control plot (kg ha^{-1}), FN = quantity of fertilizer-N applied (kg N ha^{-1}), NU_T = total uptake of N in fertilizer-N treated plot (kg ha^{-1}), NU_C = total uptake of N in N control plot (kg ha^{-1}), GY = grain yield (kg ha^{-1}), NU = total uptake of N (kg ha^{-1}), NU_{Grain} = grain N uptake (kg ha^{-1}), NU_{Total} = Total uptake of N (kg ha^{-1}), AGB = total above ground biomass (kg ha^{-1}).

Calculation nitrous oxide emission

Total N_2O emission from each treatment plot was calculated indirectly following the mathematical model (eq. 7) suggested by Tubiello et al. (2015) with the necessary modifications at the regional scale and cropping period. A global warming potential equivalent factor 265 was multiplied with the N_2O emission value to express the total emission as kg CO_2 equivalent ha^{-1}.

$$N_2O \text{ emissions } (\text{kg ha}^{-1}\text{day}^{-1}) = N \times EF_1 \times \frac{44}{28} \qquad \text{eq. 7}$$

where N_2O emissions from the fertilizer-N, manures, and residues added to the managed soil; N = N consumption from fertilizers and crop residues (kg N input year^{-1}); EF_1 = emitting factors of 0.01 for N_2O emissions from N input (kg N_2O–N kg^{-1} N input).

Economic analysis

Costs and prices of all consumed inputs and outputs were considered in the economic analysis. All input cost components were summed up and denoted as working cost of cultivation, on which 3.5% interest, transportation and miscellaneous costs were added to calculate total variable cost of cultivation (TVCC). The total economic return from the grain and straw output was calculated as the gross return. The year-wise minimum support price of rice (paddy) (Government of India) and local market price of rice straw was used to convert the grain and straw yield to their economic value. Net return (NR) was calculated as the difference between gross return and TVCC. The ratio of net return to TVCC was denoted as the benefit-cost ratio (BCR). Marginal return (MR) from N management treatments was computed using eq. 9.

$$MR\ (\$\ ha^{-1}) = \frac{NR_T - NR_C}{TVCC_T - TVCC_C} \quad \text{eq. 10}$$

NR_T = net return with fertilizer-N treatment, NR_C = net return from N control treatment, $TVCC_T$ = total variable cost of cultivation in fertilizer-N treatment, $TVCC_C$ = total variable cost of cultivation without fertilizer-N treatment (N control).

Statistical analysis

The data of optimization trial was analyzed following analysis of variance (ANOVA) of RCBD, while validation trial data were subjected to split–plot ANOVA (Cochran and Cox 1957). Principal component analysis was performed using statistical software PAST (version 3.26). The multivariate regression analysis was performed using 'Data Analysis Toolpak' Add–In of Microsoft Excel to explain the independent variables (X_1-Xn) as yield function and their corresponding coefficient weightage (C_1-Cn) [$Y = C + C_1X_1 + C_2X_2 + \ldots\ldots\ldots + CnXn$].

Results

Optimization trial (Experiment 1)

Fertilizer-N scheduling

The total fertilizer-N rate ranged between 55 kg ($SCMR_{34}N_{15}$) to 92 kg ($SCMR_{40}N_{25}$) N ha^{-1} within the RTNM treatments (Table 1). The fertilizer-N rate was consistent over replications and cropping years, except for the treatment $SCMR_{40}N_{20}$ (Supplementary Table 1). The frequency of N splits ranged from 2 to 4 ($SCMR_{40}N_{15}$) (Table 1).

Crop response to N management treatments

The treatment $SCMR_{38}N_{20}$ had 8% (p < 0.05) higher yield than the FTNM treatment (Table 1). The RTNM treatments $SCMR_{34}N_{15}$, $SCMR_{34}N_{20}$, $SCMR_{36}N_{15}$, and $SCMR_{36}N_{20}$ resulted in a yield reduction (11-24%, p < 0.05) as compared to the FTNM, whereas the remaining RTNM treatments had a similar yield to FTNM. The treatment $SCMR_{38}N_{20}$ had a lower panicle m^{-2} but equivalent grains panlcle^{-1}, stover yield and HI to the FTNM. Under fertilizer-N deficient conditions (control), yield traits decreased (compared with FTNM) in the order of straw yield (-55%), grain yield (-45%), panicle m^{-2} (-43%), grains panicle^{-1} (-17%) and 1000-grain weight (-10%), but increased HI (+11%) (p < 0.05). The highest HI was recorded in the treatment $SCMR_{36}N_{25}$ (48.8%) followed by the N control treatment (47.1%). Grain yield showed higher positive correlation with panicle density (r = 0.86) and straw yield (r = 0.80) (p < 0.05) (data not presented). Under RTNM, a higher N rate increased yield in SCMR 34, 36, and 38, but not with SCMR 40. Similarly, increasing SCMR threshold increased yield under N rate (kg ha^{-1}) of 15 kg (r = 0.996), 20 kg (r = 0.888), but not 25 kg N (r = 0.221) (data not presented).

N uptake and N use efficiency

The highest N uptake was recorded in the FTNM treatment (113 kg N ha^{-1}), while N uptake within the RTNM treatments ranged between 69 ($SCMR_{34}N_{15}$) to 112 ($SCMR_{38}N_{20}$) (Table 2). In the N control treatment, a greater magnitude of reduction (compared to FTNM treatment) was observed in the N uptake (62%) than in the scale of grain yield loss (45%). Strong positive correlations were observed between the N rate and N uptake in both the cropping years (r = 0.911-0.938, p < 0.01) (Figure 1). Treatments $SCMR_{38}N_{20,}$ $SCMR_{38}N_{25}$ led to the highest increase in AE_N over FTNM, while, except $SCMR_{38}N_{20}$, all the RTNM treatments had either equal or higher AE_N over FTNM (Table 2). The RE_N (kg kg^{-1}) was higher in treatments $SCMR_{38}N_{25}$ (0.87), $SCMR_{36}N_{25}$ (0.86), $SCMR_{38}N_{20}$ (0.84), which were significantly higher than the FTNM (0.70). The parameters IUE_N, PFP_N, NHI, and PE_N were higher in the RTNM treatments than the FTNM treatment. The highest IUE_N, NHI, and PE_N were recorded in the N control treatment (Table 2).

Multivariate analysis, economic return, and N_2O emission

Variable N rates, particularly at 50, 70, 80, and 90 DAT had a significant and higher positive influence on yield ($p < 0.05$). Likewise, among the variables N rate, N splits and NTI (an index that defines the earliness or delay in the application of fertilizer–N), only the N rate exhibited a significant positive influence on rice yield. There are marked year-to-year variations in the regression coefficient for the NTI (Figure 1). According to the PCA, treatment-induced vitiations in N splits, AE_N, RE_N, net return, and N rate. The strong positive association between total N rate and straw yield was evident from PCA results (Supplementary Figure 2).

The RTNM treatment $SCMR_{38}N_{20}$ led to the highest net return and benefit–cost ratio, which were +11% and +4% higher than the FTNM treatment ($p < 0.01$) (Table 3). With an increase in N top-dress rate, the marginal return was increased in $SCMR_{34}$ (up to 25 kg N ha^{-1}) $SCMR_{38}$ only (up to 20 kg N ha^{-1}). A reduction in seasonal N_2O emission (simulated) was estimated in all the RTNM treatments (2.4-12.9 kg CO_2 equivalent ha^{-1}) ($p < 0.001$) as compared to the FTNM treatment (N_2O GWP = 37.8 kg CO_2 equivalent ha^{-1}) (Figure 2)

Experiment 2 (Validation trial)

Treatment $SCMR_{38}N_{20}$ exhibited higher precision for N rate within replications over the treatment $SCMR_{36}N_{20}$ (Supplementary Table 2). Notably, the yield difference between treatments ($SCMR_{36}N_{20}$, $SCMR_{38}N_{20}$) for *cv.* Rajendra Sweta was 15.6% ($p < 0.05$) that was almost similar to the optimization trial (13.9-28.7%, $p < 0.05$) (Table 4, Table 1). The yield increment with the treatment $SCMR_{38}N_{20}$ over $SCMR_{36}N_{20}$ was recorded as > +10% for the *cvs.* RAU724, Rajendra Sweta, and Rajendra Mahsuri, but remained comparable for *cvs.* MTU 7029, Rajendra Bhagawati, and Arize 6444. The treatment $SCMR_{38}N_{20}$ had a higher straw yield and N uptake than the treatment $SCMR_{36}N_{20}$ (Table 4, Table 5).

Discussion

Experiment 1 (Optimization trial)

The results show that SPAD-meter-based RTNM could be an efficient N management approach to lowland flooded-rice production. Meanwhile, our results show that precise adjustment of SCMR threshold for N scheduling along with optimal N top-dress rate are essential for yield advantage and higher N use efficiency over conventional FTNM. As, FYM (5 t ha^{-1}) was applied to each treatment plot prior to crop establishment, therefore the organically bound N in manure could have complemented the crop N requirement. In tropical climates, the faster mineralization of organically bound N is readily accessible to the immediate crop; however, this may be partially limited under flooded–rice soils due to anoxic soil conditions (Borase et al. 2020). The release kinetics of organically bound nitrogen can differ with crop stage, which is hard to monitor. Therefore, RTNM could be a realistic approach to synchronize the demand and supply of N based on relative chlorophyll meter readings and thereafter optimum scheduling of N fertilization.

According to the results, not all RTNM treatments are effective in producing higher yield but fertilizer savings is common in all treatments. Results indicate that RTNM following a lower SCMR threshold ($SCMR_{34}$, $SCMR_{36}$) in combination with a low or medium top–dressed N rate (15 and 20 kg N ha^{-1}) could lead to a yield loss (compared to the FTNM treatment), while, with a higher top–dress N rate (25 kg N ha^{-1}) had attained a similar yield to conventional FTNM treatment with a saving of 25 kg N ha^{-1} (Table 1). This result suggests that a higher N topdressing rate is essential to have an extended effect of top-dress N in RTNM following a SCMR threshold below 38. A topdressing N rate of 20 kg N ha^{-1} in combination with fertilizer-N scheduling with $SCMR_{38}$ could produce higher yields, fertilizer-N use efficiency, and higher economic return compared to FTNM (Tables 1, 2, and 3), and was therefore recommended as a best-fit RTNM treatment for the medium duration rice *cv.* Rajendra Sweta. The positive impact of the treatment $SCMR_{38}N_{20}$ was possibly attributed to synchronous and balance N application as per crop demand. The N fertilization schedules in the $SCMR_{38}N_{20}$ treatment are basal, 50, 70, 90 DAT, while in the FTNM treatment they are basal, 40, 60, 90 DAT (Supplementary Table 1, Supplementary Figure 3), and thus, the delayed application of topdressing fertilization may have been the cause for balanced growth, whereas the higher N rates applied in the FTNM treatment resulted in higher vegetative growth, but no apparent increase in yield attributing traits. The multivariate regression analysis results indicate that the variable N application at 50, 70, 80, and 90 DAT had a direct positive influence on yield, which closely matched with the best-fit RTNM treatment $SCMR_{38}N_{20}$ (Figure 1). The consistency in the results within the cropping year also validates the regression model. The treatment $SCMR_{38}N_{20}$ had a lower panicle density than the FTNM treatment, whereas the number of grains $panicle^{-1}$ and seed weight was higher in the treatment $SCMR_{38}N_{20}$ over the FTNM treatment (Table 1), and this finding specifically hints a higher intra-plant competition in the FTNM treatment possibly attributed to increased tiller production that might have reduced number of grains panicle^{-1} and their weights. The reduction in yield determining traits like grains panicle^{-1} and seed weight are mostly genetically configured, but an imbalance in growth (higher biomass growth, (Supplementary Figure 4) may lead to affect source-sink balancing, which is further confirmed with the results of HI. Wei et al. (2018) also reasoned that the source-sink relationship during grain filling is not merely a matter of carbon supply versus demand, but highly coupled with grain N demand.

Results indicate that the RTNM following a higher threshold SCMR (> 38) could increase topdressing frequency but not necessarily increase yield over the FTNM. This is especially true when N splits are not uniformly distributed (temporal) during the crop season. Additionally, faster growth may result in the dilution of chlorophyll in leaf tissue, misleading the SCMR-based RTNM.

Besides, a faster growth may cause dilution of chlorophyll in leaf tissue and thereby mislead the SCMR-based RTNM. Concerning the increased yield benefits from N application at the later growth stages (50-90 DAT) a dynamic approach of N management (lower N topdressing rate at the initial growth stages and higher rate at the later growth stages) would result in further up-scaling of N use efficiency. Peng et al. (2006) also suggested that a quantum leap in AE_N is possible in the intensive rice-growing areas in China by simply reducing the current N rate and by allocating less N at the early vegetative stage. PCA reveals that the frequency of N split application is not significantly correlated with higher N use efficiency (especially AE_N) as a right-angle relationship between variables (or traits) represents a non-significant correlation (Supplementary Figure 2). A trait vector length represents the sensitivity scale of a variable to N management treatments, and the results suggest that the benefits of RTNM are much more prominent on N use efficiency parameters (AE_N and RE_N) than yield and its attributes. The prominent year-wise deviations in the regression coefficient of NTI could be attributed to the seasonal variation in weather conditions (particularly rainfall) and mineralization rate (Figure 1).

The RTNM treatment $SCMR_{38}N_{20}$ exhibited higher AE_N and RE_N over the FTNM treatment, which is due to the yield gain over the FTNM treatment as well as reduced use of fertilizer-N. This study corroborates the findings of Khurana et al. (2008) and Singh et al. (2002) in western parts of India with a SPAD critical value of 37.5. The increased IUE_N and PE_N with higher yield certainly indicate improved intra-plant nutrient use efficiency and N remobilization from source to sink in the treatment $SCMR_{38}N_{20}$ over the FTNM. The study also indicates the advantage of RTNM in reducing the NO_2 emission from a lowland flooded rice soil primarily by reducing the fertilizer-N input. Lowland flooded rice ecosystems contribute largely toward total agricultural greenhouse gas emissions. Fertilizer-N applied to flooded rice crops is much prone to several losses such as N leaching, denitrification etc., which ultimately downscale the N use efficiency. The imbalance in N fertilization scheduling and a higher rate of N topdressing might have resulted in higher N losses for FTNM treatment, whereas higher N application at early stages might have led to higher N losses.

A higher topdressing frequency with a low top-dress N rate is considered an ideal approach to upscale yield and N use efficiency; however, the economic feasibility must be taken into consideration to determine the optimum N splits. For instance, chlorophyll-meter-based RTNM following a higher SCMR as a threshold could increase the frequency of N topdressing particularly when the N topdressing rate is low as observed for the treatment $SCMR_{40}N_{15}$ (Table 1). The treatment $SCMR_{40}N_{15}$ recorded a comparable grain yield (5204 kg ha^{-1}) to the treatment

$SCMR_{38}N_{20,}$ however, the net return was higher in the $SCMR_{38}N_{20}$ treatment over the treatment $SCMR_{40}N_{15}$ (Table 5) and therefore $SCMR_{38}N_{20}$ was selected as the best treatment.

The savings of fertilizer-N and a higher yield in best-fit RTNM treatment ($SCMR_{38}N_{20}$) led to favourable production economics. The researchers noted the exorbitant cost of rice cultivation was due to the overuse of fertilizer–N (Koch et al. 2004). The economics were calculated based on the government-subsidised price of urea (Government of India). Therefore, in reality, the cost involved in N management would be higher than the estimated cost of fertilizer N in the study. Thus, the margin of economic return between the best-fit RTNM treatment and FTNM with unsubsidised fertilizer-N (urea) price would be more significant.

Experiment 2 (validation trial)

The results demonstrate a need for cultivar–specific calibration of optimal SCMR for fertilization scheduling in lowland flooded rice. According to the validation trial result, the test *cv.* Rajendra Sweta showed a similar response to that of the optimization trial, and thus, the result verifies the field scale efficacy/precision of RTNM treatments for a particular rice cultivar in lowland ecologies. Nevertheless, the yield advantage with best-fit RTNM treatment varied greatly across cultivars. Differences in yield potential, N demand, and crop duration might explain the differential response of cultivars to RTNM. Given the differential response of rice cultivars to the selected RTNM treatments, a cultivar-specific RTNM recommendation would be essential to have the best results. Additionally, the results indicate that the precision of RTNM treatment for the applied N rate and timing within replicates may be equally considered for precise adjustment and validation of cultivar and location-specific N management in rice. Shukla et al. (2004) also reasoned that site-specific nutrient management must consider the wider variability in leaf colour traits within the cultivars.

Conclusions

The study concluded that SCMR-based RTNM could be a sustainable approach of N management in lowland flooded-rice systems over the conventional FTNM. However, precise adjustment of the SCMR threshold in combination with optimal N rate is vital to realize the optimal benefits of RTNM. The results suggested that SCMR based RTNM in lowland flooded rice could be effectively applicable under integrated nutrient management module(s). The optimization trail results revealed that basal application of 25 kg N ha^{-1} followed by top-dressing of fertilizer-N at 20 kg N ha^{-1} when the SCMR ≤ 38 could improve yield, N use efficiency, net return and reduced fertilizer–N rate over FTNM. The yield gain in the treatment $SCMR_{38}N_{20}$ over the FTNM was primarily attributed to improved source-sink balance with a timely (delayed) supply of N during crop season. The regression analysis results explained that N application at later growth stages (panicle initiation to full heading stage) had a higher scale of impact on rice yield over the early applications. Therefore, a variable N top–dress rate [a lower dose at early growth stage(s) and a higher in the later growth stages] would further improve the N economy in RTNM in lowland rice, which is to be ascertained with systematic studies. The study suggests that there is a need for cultivar–specific calibration of SCMR threshold limit in combination with optimal top-dress N rate for maximum benefits.

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References

Bandaogo A, Bidjokazo F, Youl S, Safo E, Abaidoo R, Andrews O. 2015. Effect of fertilizer deep placement with urea supergranule on nitrogen use efficiency in Sourou Valley (Burkina Faso). Nutr Cycl Agroecosyst. 102:79–89. https://doi.org/10.1007/s10705–014–9653–6

Borase DN, Nath CP, Hazra KK, Senthilkumar M, Singh SS, Praharaj CS, Singh U, Kumar N. 2020. Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. Ecol Indic. 114:106322. https://doi.org/10.1016/j.ecolind.2020.106322

Choudhury AT, Kennedy IR. 2005. Nitrogen fertilizer losses from rice soils and control of environmental pollution problems. Commun Soil Sci Plant Anal. 36(11-12), 1625-39. https://doi.org/10.1081/CSS-200059104

Cochran WG, Cox GM. 1957. Experimental Designs. John Wiley & Sons, INC.N.Y, USA.

Fageria NK, Carvalho GD, Santos AB, Ferreira EP, Knupp AM. 2011. Chemistry of lowland rice soils and nutrient availability. Comm Soil Sci Plant Anal. 42(16):1913–1933. https://doi.org/10.1080/00103624.2011.591467

Fagodiya RK, Pathak H, Bhatia A, Jain N, Kumar A, Malyan SK. 2020. Global warming impacts of nitrogen use in agriculture: an assessment for India since 1960. Carbon Manag 11(3):291–301. https://doi.org/10.1080/17583004.2020.1752061

Hou W, Xue X, Li X, Khan MR, Yan J, Ren T, Cong R, Lu J. 2019. Interactive effects of nitrogen and potassium on: grain yield, nitrogen uptake and nitrogen use efficiency of rice in low potassium fertility soil in China. Field Crops Res. 236, 14-23. https://doi.org/10.1016/j.fcr.2019.03.006

Huda A, Gaihre YK, Islam MR, Singh U, Islam MR, Sanabria J, Satter MA, Afroz H, Halder A, Jahiruddin M. 2016. Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. Nutr Cycl Agroecosyst. 104:53–66. https://doi.org/10.1007/s10705–015–9758–6

IUSS Working Group WRB (2015) World Reference Base for Soil Resources 2014, update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps (World Soil Resources Reports No. 106). Rome, Italy: FAO.

Jackson ML. 1973. Soil chemical analysis. Prentice Hall of India Pvt. Ltd. New Delhi.

Khurana HS, Phillips SB, Singh B, Alley MM, Dobermann A, Sidhu AS, Singh Y, Peng S. (2008. Agronomic and economic evaluation of site–specific nutrient management for irrigated wheat in northwest India. Nutr Cycl Agroecosyst. 82:15–31. https://doi.org/10.1007/s10705–008–9166–2

Koch B, Khosla R, Frasier WM, Westfall DG, Inman D. 2004. Economic feasibility of variable–rate nitrogen application utilizing site–specific management zones. Agron J. 96: 1572–1580. https://doi.org/10.2134/agronj2004.1572

Lin FF, Deng JS, Shi YY, Chen LS, Wang K. 2010. Investigation of SPAD meter-based indices for estimating rice nitrogen status. Comput Electron Agric. 71, S60-S65. https://doi.org/10.1016/j.compag.2009.09.006

Mohanty S, Nayak AK, Bhaduri D, Swain CK, Kumar A, Tripathi R, Shahid M, Behera KK, Pathak H. 2021. Real-time application of neem-coated urea for enhancing N-use efficiency and minimizing the yield gap between aerobic direct-seeded and puddled transplanted rice. Field Crops Res. 264:108072. https://doi.org/10.1016/j.fcr.2021.108072

Peng S, Buresh RJ, Huang J, Yang J, Zou Y, Zhong X, Wang G, Zhang F. 2006. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. Field Crops Res. 96(1):37–47. https://doi.org/10.1016/j.fcr.2005.05.004

Qin H, Xing X, Tang Y, Zhu B, Wei X, Chen X. Liu Y. 2020. Soil moisture and activity of nitrite-and nitrous oxide-reducing microbes enhanced nitrous oxide emissions in fallow paddy soils. Biol Fert Soils 56(1):53-67. https://doi.org/10.1007/s00374-019-01403-5.

Shukla AK, Ladha JK, Singh, VK, Dwivedi BS, Balasubramanian V, Gupta RK, Sharma SK, Singh Y, Pathak H, Pandey PS, Padre AT. 2004. Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a systems perspective. Agron J. 96(6):1606–1621. https://doi.org/10.2134/agronj2004.1606

Singh B, Singh Y, Ladha JK, Bronson KF, Balasubramanian V, Singh J, Khind CS. 2002. Chlorophyll meter and leaf color chart based nitrogen management for rice and wheat in northwestern India. Agron J. 94:821–829. https://doi.org/10.2134/agronj2002.8210

Tubiello FN, Cóndor–Golec RD, Salvatore M, Piersante A, Federici S, Ferrara A, Rossi S, Flammini A, Cardenas P, Biancalani R, Jacobs H. 2015. Estimating greenhouse gas emissions in agriculture: a manual to address data requirements for developing countries. Estimating greenhouse gas emissions in agriculture: a manual to address data requirements for developing countries.

Venkatesh MS, Hazra KK, Ghosh PK, Khuswah BL, Ganeshamurthy AN, Ali M, Singh J, Mathur RS. 2017. Long–term effect of crop rotation and nutrient management on soil–plant nutrient cycling and nutrient budgeting in Indo–Gangetic plains of India. Arch Agron. Soil Sci. 63(14):2007-2022. https://doi.org/10.1080/03650340.2017.1320392

Wei H, Meng T, Li X, Dai Q, Zhang H, Yin X. 2018. Sink-source relationship during rice grain filling is associated with grain nitrogen concentration. Field Crops Res. 215:23-38. https://doi.org/10.1016/j.fcr.2017.09.029

Wood CW, Reeves DW, Himelrick DG. 1993. Relationships between chlorophyll meter readings and leaf chlorophyll concentration, N status, and crop yield: a review. In Proceedings of the agronomy society of New Zealand, Vol. 23, pp. 1-9.

Yoshida S, Forno DA, Cock JH, Gomez KA. 1976. Laboratory manual for physiological studies of rice. Laboratory manual for physiological studies of rice. The International Rice Research Institute 1976, Los Baños, Laguna, Manila, Philippines

Table 1. Effect of different N management practices on yield attributes of rice (pooled data of 2013 and 2014) [Experiment 1].

Treatment	Fertilizer-N applied (kg ha^{-1})	N split (nos.)	Panicles m^{-2} (nos.)	Grains panlcle^{-1} (nos.)	Test weight (g)	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
$SCMR_{34}N_{15}$	55	2	235^{e}	73.3^{cd}	22.9^{cd}	3753^{e}	4403^{h}	45.9^{bcd}
$SCMR_{34}N_{20}$	65	2	260^{d}	83.1^{a}	23.7^{abc}	4164^{d}	4992^{fg}	45.5^{cde}
$SCMR_{34}N_{25}$	75	2	281^{bcd}	79.7^{abc}	24.1^{ab}	4893^{bc}	5365^{ef}	47.7^{ab}
$SCMR_{36}N_{15}$	63	3	256^{d}	74.5^{bcd}	22.9^{cd}	4132^{d}	4867^{gh}	46.1^{bc}
$SCMR_{36}N_{20}$	65	2	263^{d}	78.7^{abc}	24.1^{ab}	4412^{c}	4983^{fg}	46.9^{abc}
$SCMR_{36}N_{25}$	71	2	271^{cd}	80.8^{ab}	24.5^{a}	4767^{c}	5008^{fg}	48.8^{a}
$SCMR_{38}N_{15}$	70	3	280^{bcd}	75.8^{bc}	23.3^{bc}	4764^{c}	5496^{def}	46.4^{bc}
$SCMR_{38}N_{20}$	82	3	280^{bcd}	84.9^{a}	24.6^{a}	5323^{a}	6277^{bc}	46.0^{bc}
$SCMR_{38}N_{25}$	75	2	284^{bc}	75.9^{bc}	24.6^{a}	5106^{abc}	5745^{cde}	46.9^{abc}
$SCMR_{40}N_{15}$	85	4	282^{bc}	82.8^{ab}	24.5^{a}	5204^{ab}	5927^{bcd}	46.8^{abc}
$SCMR_{40}N_{20}$	85	3	286^{abc}	79.3^{abc}	23.7^{abc}	5005^{abc}	6545^{a}	43.2^{e}
$SCMR_{40}N_{25}$	92	3	290^{ab}	79.6^{abc}	24.0^{abc}	4862^{c}	6340^{ab}	43.6^{de}
FTNM	100	3	303^{a}	81.2^{ab}	24.2^{ab}	4952^{bc}	6800^{a}	42.3^{e}
Control	-	-	173^{f}	67.5^{d}	21.7^{d}	2700^{f}	3045^{i}	47.1^{abc}
LSD (p = 0.05)	7.4	-	17.5	7.2	1.2	346	563	2.4
Pooled ANOVA	(p value)							
Year	1.00		0.065	0.052	0.147	0.013	0.056	0.004
Treatment	< 0.001		< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001
Year × Treatment	0.124		0.150	0.564	0.309	0.002	0.027	< 0.001

SCMR, SPAD 502 chlorophyll meter reading; *N*, fertilizer-N topdressing rate (kg N ha^{-1}); *FTNM*, Fixed-time N management. *a-i*, treatments with different lowercase superscript letters are significantly different at $p \leq 0.05$.

Table 2. Effect of different N management practices on agronomic N use efficiency (AE_N), nitrogen recovery efficiency (RE_N), internal N use efficiency (IE_N), partial factor productivity of applied N (PFP_N), nitrogen harvest index (NHI) and physiological N use efficiency (PE_N) of rice (pooled data of years 2013 and 2014) [Experiment 1].

Treatment	Total N	AE_N	RE_N	IUE_N	PFP_N	NHI	PE_N

	uptake (kg ha^{1})	(kg kg^{-1})	(kg kg^{-1})	(kg kg^{-1})	(kg kg^{-1})	(%)	(kg kg^{-1})
$SCMR_{38}N_{20}$	69.0^{f}	19.1^{d}	0.47^{h}	54.3^{b}	68.2^{a}	0.64^{ab}	125^{b}
$SCMR_{38}N_{25}$	80.7^{e}	22.5^{cd}	0.57^{g}	51.6^{bc}	64.1^{abc}	0.62^{bc}	120^{bc}
$SCMR_{34}N_{25}$	103.7^{bc}	29.2^{ab}	0.80^{bc}	47.2^{efg}	65.2^{ab}	0.59^{de}	115^{cdef}
$SCMR_{36}N_{15}$	81.4^{e}	22.5^{cd}	0.61^{g}	50.7^{cd}	66.6^{a}	0.62^{bc}	121^{bc}
$SCMR_{36}N_{20}$	89.9^{d}	26.3^{bc}	0.72^{ed}	49.0^{cde}	67.9^{a}	0.61^{cd}	115^{cdef}
$SCMR_{36}N_{25}$	104.0^{bc}	28.9^{ab}	0.86^{ab}	45.8^{fgh}	67.6^{a}	0.58^{ef}	112^{def}
$SCMR_{38}N_{15}$	97.6^{c}	29.5^{ab}	0.78^{cde}	48.8^{cdefg}	68.1^{a}	0.61^{cd}	119^{bc}
$SCMR_{38}N_{20}$	111.6^{a}	32.2^{a}	0.84^{abc}	47.8^{defg}	65.6^{ab}	0.60^{cde}	112^{def}
$SCMR_{38}N_{25}$	108.7^{ab}	32.1^{a}	0.87^{a}	46.8^{efg}	68.1^{a}	0.60^{cde}	110^{f}
$SCMR_{40}N_{15}$	110.0^{ab}	29.4^{ab}	0.78^{cde}	47.4^{efg}	61.2^{bc}	0.59^{de}	118^{cd}
$SCMR_{40}N_{20}$	107.0^{ab}	26.7^{bc}	0.74^{def}	47.0^{efg}	59.2^{cd}	0.59^{de}	119^{bc}
$SCMR_{40}N_{25}$	107.5^{ab}	23.6^{c}	0.70^{f}	45.5^{gh}	54.0^{de}	0.56^{fg}	117^{cde}
FTNM	113.3^{a}	22.5^{cd}	0.70^{f}	43.7^{h}	49.5^{e}	0.55^{g}	111^{ef}
Control	43.4^{g}	-	-	62.2^{a}	-	0.67^{a}	142^{a}
LSD (p = 0.05)	7.08	4.4	0.07	3.1	5.3	0.03	6.8
Pooled ANOVA	(p value)						
Year	1.00	0.019	0.034	0.054	0.006	0.119	< 0.001
Treatment	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Year × Treatment	0.124	0.039	0.003	0.309	0.563	0.659	0.320

SCMR, SPAD 502 chlorophyll-meter reading; *N*, topdressing N rate (kg N ha^{-1}); *FTNM*, fixed-time N management; *DAT*, days after transplanting. *a-h*, treatments with different lowercase superscript letters are significantly different at $p \le 0.05$.

Table 3. Effect of different N management practices on economics of rice production (pooled data of years 2013 and 2014) [Experiment 1].

Treatment	Total variable cost of cultivation ($ ha^{-1})	Gross return ($ ha^{-1})	Net return ($ ha^{-1})	Benefit cost ratio	Marginal return ($$^{-1}$ ha^{-1})
$SCMR_{34}N_{15}$	454^{d}	697^{f}	243^{f}	1.53^{e}	2.19^{d}
$SCMR_{34}N_{20}$	465^{c}	774^{e}	309^{e}	1.66^{d}	2.77^{c}
$SCMR_{34}N_{25}$	483^{b}	903^{bcd}	420^{cd}	1.87^{bc}	3.44^{ab}
$SCMR_{36}N_{15}$	465^{c}	767^{e}	302^{e}	1.65^{d}	2.67^{c}
$SCMR_{36}N_{20}$	470^{c}	816^{e}	346^{e}	1.73^{d}	3.06^{bc}
$SCMR_{36}N_{25}$	480^{b}	876de	397^{d}	1.82^{c}	3.30^{bc}

SCMR$_{38}$N$_{15}$	481^{b}	883^{bcd}	402^{d}	1.83^{bc}	3.31^{bc}
SCMR$_{38}$N$_{20}$	495^{a}	989^{a}	494^{a}	2.00^{a}	3.76^{a}
SCMR$_{38}$N$_{25}$	487^{b}	944^{abc}	457^{abc}	1.93^{ab}	3.68^{ab}
SCMR$_{40}$N$_{15}$	496^{a}	964^{ab}	468^{ab}	1.94^{ab}	3.47^{ab}
SCMR$_{40}$N$_{20}$	484^{b}	938^{abcd}	455^{abc}	1.93^{ab}	3.78^{a}
SCMR$_{40}$N$_{25}$	482^{b}	911^{bcd}	430^{bcd}	1.89^{bc}	3.59^{ab}
FTNM	486^{b}	933^{abcd}	447^{bc}	1.92^{b}	3.62^{ab}
Control	392^{e}	499^{g}	107^{g}	1.27^{f}	-
LSD ($p = 0.05$)	7.7	62.2	44.8	0.08	0.45
Pooled ANOVA	(p value)				
Year	0.015	0.018	0.018	0.020	0.147
Treatment	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Year × Treatment	< 0.001	0.003	0.005	0.013	0.029

SCMR, SPAD 502 chlorophyll-meter reading; *N*, topdressing N rate (kg N ha^{-1}); *FTNM*, fixed-time N management. *a-g*, treatments with different lowercase superscript letters are significantly different at $p \leq 0.05$.

Table 4. Crop yields, N uptake, and partial factor productivity of applied N (PFP_N) of different rice cultivars to RTNM treatments [Experiment 2].

Cultivar	Crop duration	Grain yield (kg ha^{-1})			Straw yield (
	(days)	RTNM$_1$	RTNM$_2$	Mean	RTNM$_1$
27P31	128-132	5920$^{B\#}$	6467^{A}	6194^{d}	13854^{B}
RAU724	~150	5630^{B}	6480^{A}	6055^{d}	13595^{B}
MTU7029	~150	6487^{A}	6770^{A}	6629^{c}	14297^{B}
Rajendra Sweta	130-135	4127^{B}	4753^{A}	4440^{e}	10418^{A}
Rajendra Bhagawati	120-125	4416^{A}	4260^{A}	4338^{e}	10246^{A}
Rajendra Mahsuri	~150	6612^{B}	7330^{A}	6971^{a}	14647^{B}
Arize 6444	135-140	6727^{A}	6683^{A}	6705^{b}	14231^{A}
Mean		5702^{B}	6106^{A}		12755^{B}
LSD ($p = 0.05$)					
Cultivar (C)	-	194			319
N treatment (N)	-	351			796
C × N interaction (p value)	-	< 0.001			0.001

A-B, different uppercase superscript letters indicates significant difference within the RTNM treatments at $p \leq 0.05$. RTNM$_1$ = SCMR$_{36}$N$_{20}$, RTNM$_2$ = SCMR$_{38}$N$_{20}$. *a-e*, treatments (cultivars) with different lowercase superscript letters indicates significant difference at $p \leq 0.05$ based on the LSD value of split plot ANOVA. # two-sample *t*-test at $p \leq 0.05$ was employed to compare the significant difference within the N management treatments for individual cultivar.

Table 5. Crop yields, N uptake, and partial factor productivity of applied N (PFP_N) of different rice cultivars to RTNM treatments [Experiment 2].

Cultivar	Fertilizer N applied (kg ha^{-1})			N uptake (kg ha^{-1})			PFP
	$RTNM_1$	$RTNM_2$	Mean	$RTNM_1$	$RTNM_2$	Mean	RTN
27P31	78.3^A	85.0^A	81.7^b	117.5^A	124.8^A	121.2^c	75.6
RAU724	71.7^A	85.0^A	78.4^b	98.1^B	128.7^A	113.4^d	78.5
MTU7029	78.3^A	85.0^A	81.7^b	128.2^A	131.2^A	129.7^b	82.8
Rajendra Sweta	71.7^A	85.0^A	78.4^b	89.3^A	95.3^A	92.3^e	57.6
Rajendra Bhagawati	78.3^A	85.0^A	81.7^b	88.9^A	86.3^A	87.6^e	56.4
Rajendra Mahsuri	105.0^A	91.7^A	98.4^a	127.0^B	142.6^A	139.8^a	63.0
Arize 6444	85.0^A	78.3^A	81.7^b	128.2^A	123.0^A	125.6^{bc}	79.1
Mean	81.2^A	85.0^A		111.0^B	118.9^A		70.2
LSD (p = 0.05)							
Cultivar (C)	9.9			6.08			9.1
N treatment (N)	*ns*			11.4			*ns*
C × N interaction (p value)	*ns*			*ns*			*ns*

A-*B*, different uppercase superscript letters indicates significant difference within the RTNM treatments at $p \leq 0.05$. $RTNM_1 = SCMR_{36}N_{20}$, $RTNM_2 = SCMR_{38}N_{20}$. *a*-*e*, different lowercase superscript letters indicates significant difference within the cultivars at $p \leq 0.05$ based on the LSD value of split plot ANOVA. # two-sample *t*-test at $p \leq 0.05$ was employed to compare the significant difference within the N management treatments for individual cultivar.

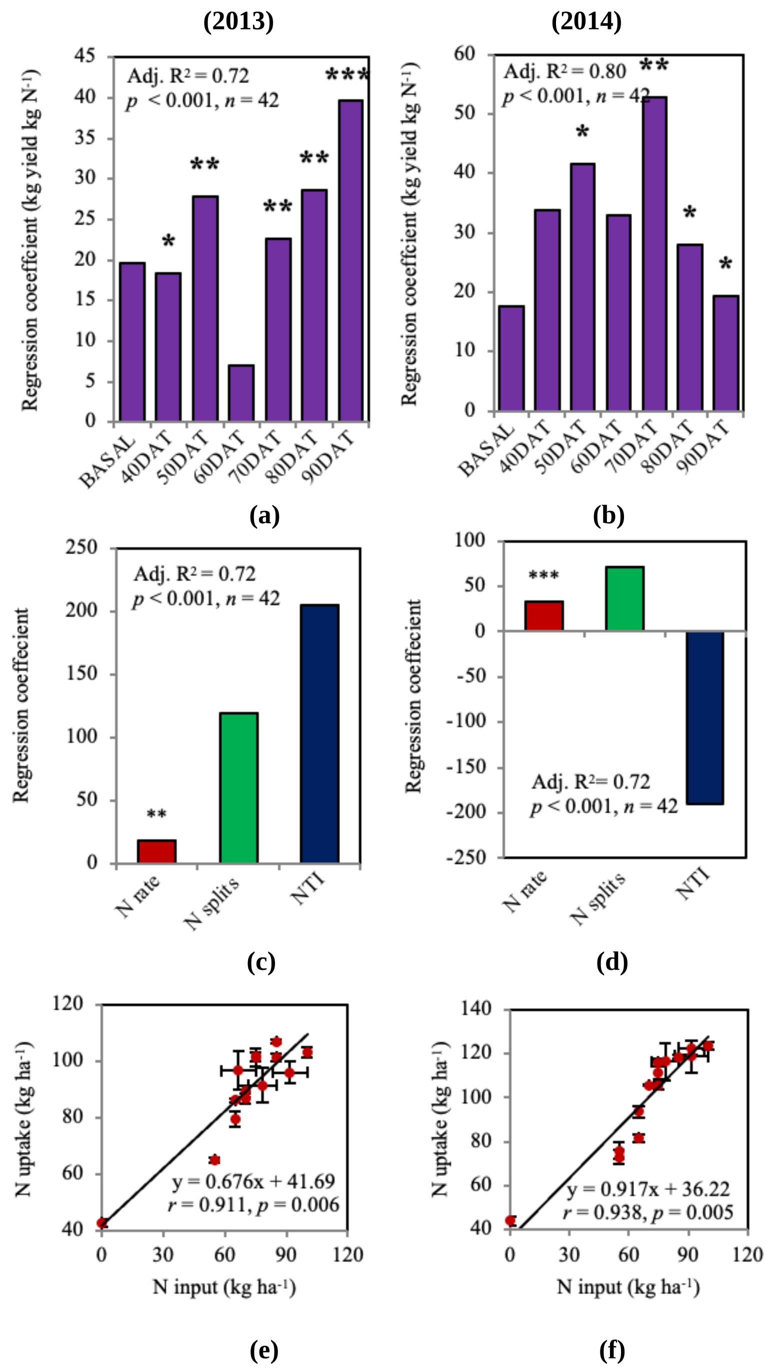

Figure 1. Weightage of regression coefficient of N scheduling at different growth stages (independent varaibales) to explein their relative influence on rice grain yield (dependent variable) based on linear mixed regression model (**a, b**). Weightage of regression coeefcient of N rate, N splits and NTI variables (independent varaibales) to explain their relative influence on rice yield (**c, d**). Linear relationship between fertlizer-N input and N uptake in rice in the year 2013 and 2014 (Experiment 1, Optimization trial) (**e, f**). NTI, N timing index defines the earliness or delay in the application of fertilizer-N. DAT, days after transplanting. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

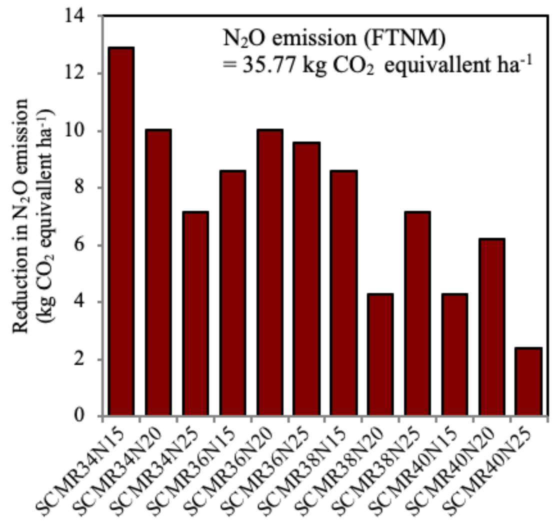

Figure 2. Simulated estimates of the reduction in N_2O emission (projected) in different RTNM treatments compared to the FTNM treatment (Experiment 1).