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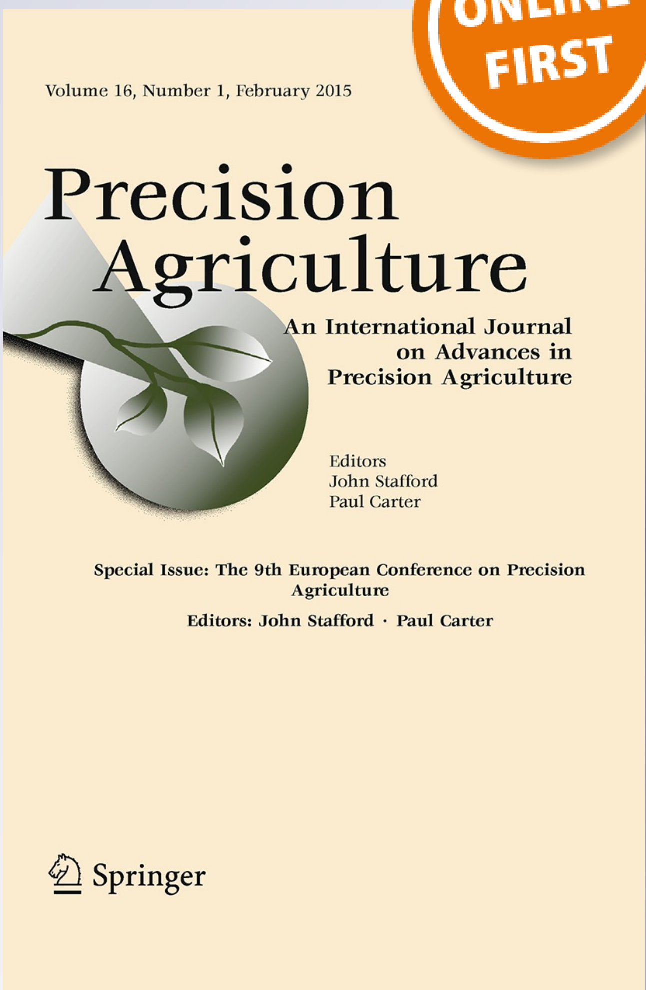

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# Site-specific fertilizer nitrogen management in irrigated transplanted rice (*Oryza sativa*) using an optical sensor

**Bijay-Singh · Varinderpal-Singh · Jaspreet Purba · R. K. Sharma · M. L. Jat · Yadvinder-Singh · H. S. Thind · R. K. Gupta · O. P. Chaudhary · P. Chandna · H. S. Khurana · Ajay Kumar · Jagmohan-Singh · H. S. Uppal · R. K. Uppal · Monika Vashistha · Raj Gupta**



**Abstract** Blanket fertilizer nitrogen (N) recommendations for large irrigated transplanted rice tracts lead to low N use-efficiency (NUE) due to field-to-field variability in soil N supply and seasonal variability in yield. To achieve high NUE, a fertilizer N management strategy based on visible and near-infrared spectral response from plant canopies using a GreenSeeker$^{TM}$ optical sensor was evaluated. Seven field experiments were conducted during 2005–2007 at two locations in the Indo-Gangetic plains of South Asia to define relationships between in-season sensor measurements at panicle initiation (PI) stage and up to 2 weeks later, and yield of rice. During 2006–2010, seven field experiments were conducted to assess the sensor-based N management strategy and to work out the prescriptive N management to be followed prior to applying sensor-guided fertilizer dose. During 2010 and 2011, the sensor-based N management strategy was evaluated versus farmers' fertilizer practice at 19 on-farm locations. Relationships with $R^2$ values 0.51 ($n = 131$), 0.45 ($n = 74$) and 0.49 ($n = 131$), respectively, were observed between in-season sensor-based estimates of yield at 42 (PI stage), 49 and 56 days after transplanting of rice and actual grain yield of rice. Applications of 30 kg N $ha^{-1}$ at transplanting and 45 kg N $ha^{-1}$ at active tillering stage were found to be the appropriate prescriptive strategy before applying the GreenSeeker-guided dose at PI stage. Sensor-guided N management resulted in similar grain yields as the blanket rate farmer practice, but with reduced N rates, i.e. greater recovery efficiency (by 5.5–21.7 %) and

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agronomic efficiency [by 4.7–11.7 kg grain (kg N applied)$^{-1}$]. This study revealed that high yields coupled with high NUE in transplanted rice can be achieved by replacing blanket fertilizer recommendation by an optical sensor-based N management strategy consisting of applying a moderate amount of fertilizer N at transplanting and enough fertilizer N to meet the high N demand during the period between active tillering and PI before applying a sensor-guided fertilizer N dose at PI stage of rice.

**Keywords** Fertilizer nitrogen management · Optical sensor · Irrigated rice · Site-specific nitrogen management

## Introduction

The majority of farmers in the Indo-Gangetic Plains and elsewhere in South Asia apply fertilize N to irrigated rice (*Oryza sativa* L.) following blanket recommendations for large regions having similar climate and landforms. The blanket recommendation consists of applying 120–150 kg N ha$^{-1}$ in three equal split doses at transplanting, active tillering and panicle initiation (PI) stages of rice crop. Many farmers often apply fertilizer N in doses even higher than the blanket recommendations to ensure that there is no yield loss due to N deficiency. Due to large temporal and field-to-field variability in soil N supply, broad-based blanket recommendations always lead to application of fertilizer N more than the need of the crop in many fields thereby restricting efficient use of fertilizer N (Adhikari et al. 1999; Dobermann et al. 2003). Not applying N when it is needed by the crop and using N more than the requirement of the crop are the main reasons for low N use-efficiency (NUE). Improving the match between crop N demand and the N supply from soil and/or the applied N fertilizer is likely to be the most promising strategy to increase NUE. As the size of more than 50 % of operational land holdings in South Asia is less than 2 ha, fertilizer NUE can be improved through field-specific fertilizer N management that takes care of both spatial and temporal variability in soil N supply.

Recent advances in N management for transplanted rice consist of reduced early N application to match the relatively low demand of young rice plants and varying rates and distribution of fertilizer N within the growing season as per crop demand. Both photosynthetic rate, which is closely related to leaf N status, and biomass production serve as sensitive indicators of the crop demand for N during the growing season. As rice leaf color is a good indicator of leaf N content, the Leaf Colour Chart (LCC) developed through collaboration of the International Rice Research Institute (IRRI) with agricultural research systems of several countries in Asia (IRRI 1996) and chlorophyll meter (SPAD meter) are increasingly being used as tools for evaluating color of the leaves. These gadgets are becoming popular, easy-to-use tools for managing fertilizer N in rice in Asia (Varinderpal-Singh et al. 2010). Both LCC and SPAD meter do not take into account the biomass production and expected yields for working out fertilizer N requirements. Also, threshold values for monitoring leaf N status using a chlorophyll meter or LCC need to be adjusted for varieties.

Use of optical sensors which measure visible and near-infrared (NIR) spectral response from plant canopies to detect N stress is rapidly increasing. The GreenSeeker™ canopy sensor (NTech Industries, Inc., Ukiah, California, USA) is a commercially available and widely used active optical sensor that employs red (650 ± 10 nm) and NIR (770 ± 15 nm) wavebands. While chlorophyll contained in the palisade layer of the leaf controls reflectance of the visible light, reflectance of the NIR electromagnetic spectrum depends upon the structure of mesophyll tissues, which reflect as much as 60 % of all incident NIR radiation (Campbell 2002). Measured spectral reflectance is expressed as spectral vegetation indices such as the normalized difference vegetation index (NDVI) calculated as:

$$\mathrm{NDVI} = \frac{F_{\mathrm{NIR}} - F_{\mathrm{Red}}}{F_{\mathrm{NIR}} + F_{\mathrm{Red}}} \quad (1)$$

where $F_{\mathrm{NIR}}$ and $F_{\mathrm{Red}}$ are respectively the fractions of emitted NIR and red radiation reflected back from the sensed area. The NDVI has been shown to provide an appraisal of photosynthetic efficiency, productivity potential and potential yield (Peñuelas et al. 1994; Ma et al. 2001; Raun et al. 2001) and have been found to be sensitive to leaf area index, green biomass (Peñuelas et al. 1994) and photosynthetic efficiency (Aparicio et al. 2002). Raun et al. (2001) showed that expected yield, as determined from NDVI obtained with the GreenSeeker optical sensor, was closely related to the actual grain yield of wheat. Using the expected yields and NDVI as measured by an optical sensor, Raun et al. (2001, 2002) developed concepts of a response index and a potential yield, and defined a fertilizer N optimization algorithm for estimating mid-season fertilizer N requirement of wheat based on N demand for the predicted yield while taking into account seasonally dependent crop responsiveness to applied N. Raun et al. (2002) and, recently, Li et al. (2009) and Bijay-Singh et al. (2011) showed that prediction of wheat response to N applications guided by an optical sensor was positively correlated to measured N response and resulted in increased NUE.

Unlike in wheat, one of the important technical problems in using optical sensors in transplanted rice is the interference of the exposed water background in reflectance measurements. Normally, water transmits most incident radiation in the visible spectrum, which results in small reflection of light. The interference due to water standing on the soil surface should be minimized if optical sensor measurements are made at an advanced stage of rice crop when crop canopy is fully developed. Extent of canopy development around the PI stage of a rice crop (about 6 weeks after transplanting) or later ensures minimal interference in the measurement of NDVI from the water on the soil surface. The work of Kanke (2013) revealed that the water background (turbid or clear) in rice fields did not significantly alter spectral reflectance at or beyond the PI stage of the crop. While a close relationship between biomass production and rice grain yield has been reported by Wells et al. (1989), several researchers estimated rice growth and N status using mid-season spectral reflectance measurements with crop canopy sensors (Sims and Gamon 2002; Xue et al. 2004; Zhang et al. 2006; Nguyen et al. 2006; Stroppiana et al. 2009; Bajwa et al. 2010; Ali et al. 2014). Xue et al. (2014) developed a sensor-determined topdressing N model for rice based on the target yield approach and the split fertilization approach but only for applying fertilizer at the PI stage of the rice crop. Similarly, Nguyen et al. (2008) and Tubaña et al. (2011) advocated use of the PI stage for topdressing fertilizer N in rice using canopy reflectance.

The first objective of the present investigation was to develop relationships between rice grain yield and NDVI measurements made by a GreenSeeker optical sensor so that fertilizer N doses could be calculated. The second and major objective was to evaluate optical sensor-based N management in irrigated rice versus the current prevalent blanket fertilizer N recommendations in the Indo-Gangetic Plains in South Asia. GreenSeeker-based N management scenarios were also evaluated versus farmers' fertilizer practices at on-farm locations. Since GreenSeeker-guided N application could be made only once at or after the PI stage, it was important to define the appropriate set of prescriptive N applications at transplanting and active tillering stages of rice which preceded it. Thus, another major objective of the study was to evaluate different combinations of fertilizer N applications at transplanting and active tillering stages of the crop in terms of improving overall fertilizer NUE when combined with optical sensor-guided fertilizer N application.

## Materials and methods

### Experimental sites

Field experiments were conducted during 2005–2011 rainy seasons at 12 on-experimental station sites on a Typic Ustipsamment (Fatehpur sandy loam) soil at Ludhiana (30.88° N, 75.85° E) and at two on-experimental station sites on a Typic Ustochrept soil at Karnal (29.69°N, 76.98°E) in northwestern India. Experiments were also carried out at 19 on-farm locations in the district of Ludhiana (between 30.57° to 31.02°N and 75.30° to 76.33°E) in the state of Punjab. All the sites are located in the Indo-Gangetic plains in northwestern India. The climate of Ludhiana and Karnal is sub-tropical, semi-arid with average annual rainfall of 733 and 696 mm, respectively. Both at Ludhiana and Karnal, 75–80 % of the annual rainfall is received during June–September when rice is grown. The mean monthly temperatures during the rice season varied from 29.3 to 33.8 °C at Ludhiana and from 28.6 to 33.2 °C at Karnal. Some characteristics of surface (0–150 mm) soil samples collected from the 14 on-station experimental sites are described in Table 1.

**Table 1** Some characteristics of the surface soil (0–150 mm) of the 14 on-station experimental sites

| Location and experiment | pH[a] | Electrical conductivity[a] (dS $m^{-1}$) | Organic C (g $kg^{-1}$)[b] | Sand (g $kg^{-1}$) | Clay (g $kg^{-1}$) | Mineral-N[c] (mg $kg^{-1}$) | Total N[d] (g $kg^{-1}$) |
|---|---|---|---|---|---|---|---|
| Ludhiana, Exp. 1 | 7.1 | 0.22 | 0.40 | 785 | 86 | 8.9 | 0.61 |
| Karnal, Exp.2 | 7.9 | 0.28 | 0.39 | 697 | 134 | 9.8 | 0.71 |
| Ludhiana, Exp. 3 | 7.1 | 0.18 | 0.37 | 794 | 91 | 7.5 | 0.52 |
| Karnal, Exp.4 | 8.1 | 0.26 | 0.38 | 666 | 143 | 10.2 | 0.73 |
| Ludhiana, Exp. 5 | 7.2 | 0.21 | 0.42 | 729 | 101 | 9.3 | 0.63 |
| Ludhiana, Exp. 6 | 6.9 | 0.17 | 0.36 | 810 | 86 | 7.2 | 0.53 |
| Ludhiana, Exp. 7 | 7.2 | 0.19 | 0.40 | 767 | 93 | 8.1 | 0.58 |
| Ludhiana, Exp. 8 | 7.1 | 0.18 | 0.37 | 799 | 85 | 5.7 | 0.53 |
| Ludhiana, Exp. 9 | 7.0 | 0.20 | 0.39 | 783 | 88 | 6.9 | 0.56 |
| Ludhiana, Exp. 10 | 7.0 | 0.21 | 0.43 | 824 | 99 | 8.1 | 0.62 |
| Ludhiana, Exp. 11 | 7.1 | 0.18 | 0.38 | 756 | 84 | 6.1 | 0.55 |
| Ludhiana, Exp. 12 | 7.2 | 0.17 | 0.36 | 726 | 82 | 5.3 | 0.53 |
| Ludhiana, Exp. 13 | 7.1 | 0.19 | 0.39 | 787 | 89 | 6.4 | 0.57 |
| Ludhiana, Exp. 14 | 7.1 | 0.21 | 0.41 | 810 | 98 | 7.8 | 0.63 |

[a] 1:2 soil/water

[b] Walkley (1947)

[c] Bremner (1965b)

[d] Bremner (1965a)

## Experimental design and treatments

### *Calibration experiments*

Seven field experiments (Experiment 1–7) were conducted in three rice seasons (2005–2007) at Ludhiana and Karnal to develop relationships for predicting yield of rice from in-season optical sensor measurements. Four fertilizer N levels (60, 120, 180 and 240 kg N ha$^{-1}$) were applied to rice either whole at transplanting or in two split doses—half at transplanting and remaining half at 21 days after transplanting (DAT). A no-N control plot was also maintained in each experiment. The highest N dose was twice the blanket recommendation for the region (120 kg N ha$^{-1}$) and it was assumed that at 240 kg N ha$^{-1}$, N would not be limiting throughout the rice growing season. In all the seven experiments, the nine treatment plots were laid out in randomized complete block design with three replications. In all the treatments of the seven experiments, measurements with a GreenSeeker optical sensor were made at 42 (PI stage), 49 and 56 DAT stages of rice. At maturity, grain yield data were recorded.

A handheld GreenSeeker optical sensor unit was used to measure spectral reflectance expressed as NDVI. The optical sensor measures from a 0.6 × 0.01 m area when held at a distance of approximately 0.6–1.0 m from the illuminated surface. The sensor unit has self-contained illumination in both the red [656 nm with ~25 nm full width half magnitude (FWHM)] and NIR (774 with ~25 nm FWHM) bands. The device measured the fraction of emitted light reflected from the crop to calculate NDVI as described in Eq. 1. The GreenSeeker measures NDVI at a rate of 10 readings per s. The crop was sensed at a height of approximately 0.9 m above the crop canopy with the sensor kept perpendicular to the row and centered over the row. Travel velocities were at a slow walking speed of approximately 0.5 m s$^{-1}$ resulting in NDVI readings averaged over distances of <0.05 m. In-season estimated yield, proposed by Raun et al. (2002) as the measure of the daily accumulated biomass from the time of transplanting to the day of sensing, was calculated by dividing the NDVI data by the number of days from transplanting to sensing having growing degree-days (GDD) >0. Growing degree-days were computed on a daily basis as:

$$\mathrm{GDD} = (\mathrm{Tmin} + \mathrm{Tmax})/2 - \mathrm{Tbase} \quad (2)$$

where Tmin and Tmax represent daily ambient low and high temperatures and Tbase, the base temperature was taken as 12.5 °C. The yield potential with no additional fertilization ($YP_0$) was calculated using an empirically-derived function relating in-season estimated yield to yield potential as:

$$YP_0 = a \times (\text{estimated yield})^b \quad (3)$$

where a, b are constants.

### *Evaluation experiments*

*On-station experiments* Four field experiments (Experiment 8–11) were conducted at Ludhiana during 2006–2009 to evaluate optical sensor-based site-specific N management versus blanket recommendation. In Experiments 8 and 9, conducted in 2006 and 2007, respectively, treatment plots were laid out in randomized complete block design with three replications. In Experiments 10 and 11, treatments were laid out in a split plot design with three replications. Rice cultivars constituted the main plots and fertilizer treatments were laid out in sub-plots. Urea was the source of N fertilizer in all the studies. In all the experiments, a no-N control and the blanket recommendation of applying 120 kg N $ha^{-1}$ in three equal split doses at 0, 21 and 42 DAT constituted the two fertilizer treatments.

In Experiments 8 and 9, two sets of five treatments each constituted the ten treatments besides a no-N control and blanket recommendation treatment. In the first set, GreenSeeker-guided fertilizer N dose was applied at 42 DAT. Fertilizer N doses applied at transplanting and at 21 DAT were:

1. 20 kg N $ha^{-1}$ at transplanting + 40 kg N $ha^{-1}$ at 21 DAT.
2. 20 kg N $ha^{-1}$ at transplanting + 60 kg N $ha^{-1}$ at 21 DAT.
3. 30 kg N $ha^{-1}$ at transplanting + 30 kg N $ha^{-1}$ at 21 DAT.
4. 30 kg N $ha^{-1}$ at transplanting + 50 kg N $ha^{-1}$ at 21 DAT.
5. 40 kg N $ha^{-1}$ at transplanting + 40 kg N $ha^{-1}$ at 21 DAT.

In the second set of five treatments, fertilizer N doses as described above were applied at 7 and 28 days before applying a GreenSeeker optical sensor-guided dose at 49 DAT.

In Experiment 10, treatments were laid out in a split plot design with two rice cultivars (PAU201 and PHB71) in the main plots. In the sub-plots, there were seven treatments consisting of a no-N control, blanket recommendation and the five treatments in the first set described above. GreenSeeker-guided fertilizer N dose was applied at 42 DAT.

In Experiment 11 conducted in 2009, besides a no-N control, two treatments were tested on three rice cultivars—PAU 201, PUSA 44 and HKR 127. While one treatment consisted of the blanket recommendation of applying 120 kg N $ha^{-1}$ in three equal split doses, in the other, 30 kg N $ha^{-1}$ was applied at transplanting and 45 kg N $ha^{-1}$ at 21 DAT before applying a GreenSeeker-guided N dose at PI stage around 42 DAT.

During 2009 and 2010 rice seasons, Experiments 12, 13 and 14 were conducted to evaluate the GreenSeeker-based site-specific N management strategy versus blanket recommendation for five different rice cultivars. The blanket recommendation consisted of applying 120 kg N $ha^{-1}$ in three equal split doses at 0, 21 and 42 DAT. The GreenSeeker treatment consisted of applying 30 kg N $ha^{-1}$ at transplanting and 45 kg N $ha^{-1}$ at 21 DAT before applying a sensor-guided dose at 42 DAT.

*On-farm experiments* During 2010 and 2011 rice seasons, experiments were carried out at 19 on-farm locations (9 in 2010 and 10 in 2011) in the district of Ludhiana to evaluate GreenSeeker-based N management strategy versus farmers' fertilizer practice (FFP) and LCC-based real time fertilizer N management. In the optical sensor treatment, before applying a GreenSeeker-guided dose of fertilizer N at 42 DAT, 30 and 45 kg N $ha^{-1}$ were applied at transplanting and 21 DAT of rice. The real time N management using LCC consisted of application of a dose of 30 kg N $ha^{-1}$ at transplanting of rice and doses of 30 kg N $ha^{-1}$ whenever colour of the first fully opened leaf from the top was less shade four of the LCC; starting 15 days after transplanting up to initiation of flowering.

In all of the on-station and on-farm experiments, an N-rich strip was established by applying 240 kg N $ha^{-1}$ in split doses to ensure that N was not limiting. The N-rich strips exhibited the highest NDVI values as measured by GreenSeeker optical sensor. The NDVI measurement from the N-rich strip was divided by NDVI of the test plot to calculate the response index ($RI_{NDVI}$) to fertilizer N (Johnson and Raun 2003). The yield of the test plot achievable by applying additional fertilizer N (YPn) was estimated as the product of $YP_0$ and $RI_{NDVI}$ (Raun et al. 2002). To use the algorithm to compute fertilizer N to be applied, the difference in estimated N uptake between YPn and $YP_0$ was determined by multiplying the difference between YPn and $YP_0$ by 1.20—the average N content in grain at harvest expressed as a percentage for rice grown in the Indo-Gangetic plains of South Asia. The difference in N uptake between $YP_0$ and YPn was then divided by an efficiency factor (taken as 0.5 to be reasonably achievable under South Asian conditions; Yadvinder-Singh et al. 2007) to work out the fertilizer N dose as:

$$\text{Fertilizer N dose} = \frac{1.20 \times (YP_n - YP_0)}{100 \times 0.5} \quad (4)$$

In this equation, YPn and $YP_0$ are expressed in kg $ha^{-1}$ so as to calculate fertilizer dose in kg N $ha^{-1}$. The values of $YP_0$ used in the fertilizer algorithm for computing fertilizer N doses to be applied in evaluation experiments conducted in 2006 and 2007 (Experiments 8 and 9) were based on in-season estimated yield—$YP_0$ relationships developed from data collected from experiments conducted up to 2005 and 2006, respectively.

## Crop management

After removing crop residues, the land was ploughed, puddled and leveled for transplanting 4- to 5-week-old rice seedlings at 200- by 150-mm spacing during 15 June–06 July in 20–28 $m^2$ treatment plots in different experiments and years. A dose of 26 kg P $ha^{-1}$ [as $Ca(H_2PO_4)_2$], 25 kg K $ha^{-1}$ (as KCl) and 10 kg Zn $ha^{-1}$ (as $ZnSO_4 \cdot 7H_2O$) was incorporated into the soil before the last puddling. During the rice season, the plots were irrigated with well and canal water (1 100–1 400 mm) to supplement rainfall. Plots were kept flooded for 3 weeks after transplanting; thereafter, the crop was irrigated at 2-days intervals. Although the soil did not remain flooded for more than 8–10 h after irrigation, anaerobic conditions prevailed for more than 75 % of the rice growth period. Hand weeding was done, and pest control followed standard practices. Different rice varieties grown (PR 114—duration 145 days, PR 115—duration 125 days, PR 116—duration 144 days, PR 118–duration 150 days, PR120—duration 132 days, PAU 201—duration 144 days, PUSA 44—duration 152 days, HKR 127—duration 140 days, HKR 47—duration 135 days, PBH71—duration 132 days) were modern semi-dwarf types with small variation in yield potential and harvest index. Table 2 lists age of nursery, date of transplanting and date of maturity of different rice cultivars in the calibration and evaluation experiments.

At maturity, crops were harvested by hand at ground level. Grain and straw yields of rice were determined from an area of 12.6–15.4 $m^2$ located at the center of each plot. Grains were separated from straw using a plot thresher, dried in a batch grain dryer and weighed. Grain moisture was determined immediately after weighing. Grain weight for rice was expressed at 140 g $kg^{-1}$ water content. Straw weights were expressed on oven-dry basis.

## Plant sampling and analysis

Grain and straw sub-samples were dried at 70 °C and finely ground to pass through a 0.5-mm sieve. Nitrogen content in grain and straw was determined by digesting the samples in sulphuric acid ($H_2SO_4$), followed by analysis for total N by a micro-Kjeldahl method (Yoshida et al. 1976). The N content in grain multiplied by grain yield (oven-dry basis) plus N content in straw multiplied by straw yield (oven-dry basis) provided an estimate of total N uptake.

**Table 2** Age of nursery, date of transplanting, and date of maturity of different rice cultivars in calibration and evaluation experiments conducted during 2005 to 2010 at Ludhiana and Karnal in northwestern India

| Experiment | Year | Location | Cultivar | Age of nursery (days) | Date of transplanting | Date of maturity |
|---|---|---|---|---|---|---|
| 1 | 2005 | Ludhiana | PR115 | 29 | 15 June 2005 | 28 September 2005 |
| | | | PR118 | 40 | | 08 October 2005 |
| 2 | 2005 | Karnal | HKR47 | 31 | 22 June 2005 | 06 October 2005 |
| 3 | 2006 | Ludhiana | PR115 | 31 | 23 June 2006 | 25 September 2006 |
| | | | PR118 | 38 | 06 July 2006 | 2 November 2006 |
| 4 | 2006 | Karnal | HKR47 | 32 | 18 June 2006 | 2 October 2006 |
| 5 | 2006 | Ludhiana | PHB71 | 30 | 02 July 2006 | 11 October 2006 |
| 6 | 2007 | Ludhiana | PHB71 | 33 | 18 June 2007 | 01 October 2007 |
| 7 | 2007 | Ludhiana | PAU201 | 33 | 20 June 2007 | 13 October 2007 |
| 8 | 2006 | Ludhiana | PR118 | 39 | 18 June 2006 | 09 October 2006 |
| 9 | 2007 | Ludhiana | PR118 | 40 | 19 June 2007 | 12 October 2007 |
| 10 | 2008 | Ludhiana | PAU201 | 34 | 05 July 2008 | 22 October 2008 |
| | | | PHB71 | 32 | | 14 October 2008 |
| 11 | 2009 | Ludhiana | PAU201 | 33 | 20 June 2009 | 09 October 2009 |
| | | | PUSA44 | 38 | | 15 October 2009 |
| | | | HKR127 | 34 | | 07 October 2009 |
| 12 | 2009 | Ludhiana | PR120 | 34 | 18 June 2009 | 30 September 2009 |
| | | | HKR127 | 35 | | 05 October 2009 |
| 13 | 2010 | Ludhiana | PR118 | 39 | 01 July 2010 | 21 October 2010 |
| | | | PR120 | 36 | | 09 October 2010 |
| 14 | 2010 | Ludhiana | PR114 | 38 | 25 June 2010 | 10 October 2010 |
| | | | PR116 | 36 | | 14 October 2010 |

## Data analysis

Data generated from the four experiments conducted for evaluating the optical sensor-based N management were analyzed following analysis of variance (ANOVA) using IRRISTAT version 5.0 (International Rice Research Institute, Philippines) and mean comparisons were performed based on least significant difference (LSD) test at 0.05 probability level. The data generated from the calibration experiments were used to fit relationships between in-season estimated yield and $YP_0$. Power functions of the type $YP_0 = a \times (\text{estimated yield})^b$ where a, b are constants, coefficients of determination ($R^2$) and 95 % prediction and confidence bands were determined using MS EXCEL (Microsoft Corporation, Redland, CA, USA).

The NUE measures—recovery efficiency (RE) and agronomic efficiency (AE) as described by Baligar et al. (2001) were computed as follows:

$$\text{RE}\ (\%) = \frac{(\text{total N uptake in N fertilized plot} - \text{total N in no N plot})\ \times\ 100}{(\text{quantity of N fertilizer applied in N fertilized plot})} \quad (5)$$

where, N uptake is the total N uptake in grain and straw.

$$\text{AE (kg grain/kg N applied)} = \frac{\text{(grain yield in N fertilized plot} - \text{grain yield in no N plot)}}{\text{(quantity of N fertilizer applied in N fertilized plot)}} \quad (6)$$

## Results and discussion

### Prediction of potential yield of rice with in-season optical sensor measurements

The rate of increase of NDVI expressed as NDVI divided by the age of the crop in days provides an index of the achievable yield. This index, called in-season estimate of yield or INSEY determined at different stages of the crop should relate to the actual grain yield (GY) obtained at maturity of the crop. The stage at which a strong INSEY-GY relationship is obtained can be used for getting an estimate of achievable yield potential of the crop in subsequent years. Thus development of INSEY-GY relationships based on data from

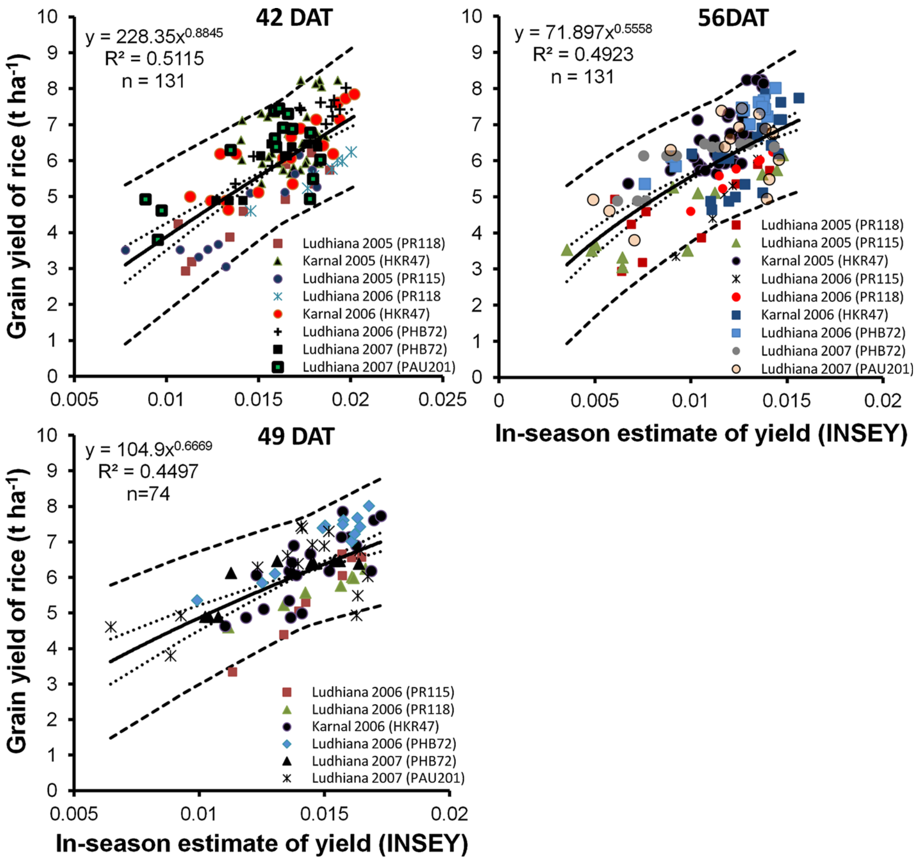


**Fig. 1** Relationships between in-season estimate of yield (INSEY) and grain yield of rice at 42, 49 and 56 days after transplanting stages. The *dotted lines* near and far from the regression line show 95 % confidence and prediction bands, respectively

different cultivars, times of transplanting, fields and seasons constitutes an important step in the development of N management strategies using an optical sensor. In Fig. 1 are shown x–y graphs between INSEY at 42, 49 and 56 DAT from Experiments 1 to 7 conducted with different rice cultivars at Ludhiana and Karnal, and the grain yield of rice at maturity. With rice transplanting dates ranging from 15 June to 06 July, the values of $R^2$ for the relationship between INSEY and GY were observed to be 0.51 (n = 131) at 42 DAT when panicle differentiation starts in rice, 0.45 (n = 74) 1 week after the PI stage and 0.49 (n = 131) 2 weeks after the PI stage. The INSEY-GY relations shown in Fig. 1 support the argument that potential yield can indeed be predicted but it may not be realized because post-sensing condition could adversely impact the final grain yield. It may be mentioned here that for calculating GreenSeeker-guided fertilizer N doses in 2006 (Experiment 8) and 2007 (Experiment 9), INSEY-GY relations based on data from 1 year (2005) to 2 years (2005 and 2006) were used. These relations were very close to the relationships developed using all the data from 3 years. From data collected from multi-rate experiments conducted during 2008–2010, Tubaña et al. (2012) found that rice yield can be satisfactorily predicted using INSEY-GY relations within a 3-week period starting at PI. They observed the highest $R^2$ for this relationship at 1 week after PI stage of rice. Yao et al. (2012) used a crop sensor to calculate rice yield potential without additional topdressing N application at stem elongation stage. Xue et al. (2014) and Harrell et al. (2011) found that rice grain yield was positively correlated with NDVI measurements at PI stage. Shibayama and Akiyama (1991) showed a high potential for predicting rice grain yield from NDVI calculated from second derivative analysis.

The concept of INSEY as developed by Raun et al. (2002) is unique as it provides an estimate of the yield potential ($YP_0$) of a given region without additional N fertilizer (i.e., what the field would yield, all factors being equal, without any additional fertilizer applied). An adequately strong relationship between INSEY as computed from NDVI measurements made by the GreenSeeker optical sensor and yield potential constitutes the first step in determining fertilizer doses to be applied for correcting in-season N deficiencies in rice. The INSEY-GY functions ought to be unique for different geographic regions and irrigation practices. The relationships shown in Fig. 1 clearly suggest that for transplanted rice as grown in the western Indo-Gangetic Plains in South Asia, biomass produced per day was a reliable predictor of grain yield.

## Optical sensor-guided fertilizer N doses for correcting in-season N deficiency

GreenSeeker optical sensor-guided fertilizer N dose is first defined by the yield potential with no additional fertilization ($YP_0$) and the yield achievable by applying additional fertilizer N (YPn) (Raun et al. 2002). As YPn is obtained by multiplying $YP_0$ with $RI_{NDVI}$, the fertilizer N dose determined by the optical sensor is essentially defined by the $YP_0$ estimated from INSEY-GY functions (Fig. 1) and $RI_{NDVI}$ obtained by dividing NDVI of the N-rich strip with that of the field where fertilizer is to be applied. The $R_{INDVI}$ allowed estimation of the yield level that can be expected by applying additional N because it was positively and strongly correlated ($R^2 = 0.93$) with ratio of the highest yield obtained at any N level or in the N rich strip and that in the test plot ($RI_{Harvest}$) in the calibration experiments.

As both $YP_0$ and $RI_{NDVI}$ are not only defined by the supply of N mineralized from soil organic matter or deposited through rainfall or irrigation but also by the supply of fertilizer N to the crop before the sensing date, the amount of fertilizer N applied at transplanting and at active tillering (21 DAT) strongly influences the amount of GreenSeeker-guided fertilizer N to be applied 42 or 49 DAT of rice. As shown in Tables 3, 4 and 5, the prescriptive N management in the form of applying different doses of fertilizer N at transplanting of rice and at 21 DAT greatly influenced the dose of fertilizer N as guided by GreenSeeker.

Before applying a GreenSeeker-guided dose of fertilizer at 42 or 49 DAT, total N applied at transplanting and at 21 DAT was either 60 or 80 kg N $ha^{-1}$. In all the 3 years of experimentation (Tables 3, 4 and 5), fertilizer N dose to be applied at 42 or 49 DAT as calculated from the optical sensor was higher when total fertilizer N applied before the sensing date was 60 rather than 80 kg N $ha^{-1}$. Among the three treatments to which 80 kg N $ha^{-1}$ was applied, the sensor-guided fertilizer N dose was the lowest in the treatment to which 30 and 50 kg N $ha^{-1}$ were applied at transplanting and at 21 DAT, respectively. As NDVI depends upon both biomass and greenness of canopy, relatively less biomass production in the treatment in which only 20 kg N $ha^{-1}$ was applied at transplanting of rice and relatively less greenness in the treatment receiving only 40 kg N $ha^{-1}$ at 21 DAT resulted in low optical sensor-guided fertilizer N doses.

Fertilizer N doses as computed from optical sensor measurements made at 42 or 49 DAT are also defined by the NUE factor used in the fertilizer N optimization algorithm given by Raun et al. (2002). In the present study, this factor has been arbitrarily fixed at 0.5 keeping in view that NUE for transplanted rice at on-farm locations in the Indo-Gangetic Plain is generally less than 50 % (Yadvinder-Singh et al. 2007). It may be fine-tuned as more data are generated in the years to come. Since efficiency factor as used in the fertilizer N optimization algorithm pertains only to the N dose guided by the GreenSeeker optical sensor, one should be able to set its value as high as 0.7, but its validity needs to be checked by further experimentation.

**Table 3** Evaluation of GreenSeeker optical sensor based fertilizer N management in rice (cultivar PR 118) at Ludhiana during 2006 (Experiment 8)

| Treatment | Fertilizer N applied (kg N $ha^{-1}$) at days after transplanting | | | | | | Total N applied (kg $ha^{-1}$) | Rice grain yield (t $ha^{-1}$) | Total N uptake (kg $ha^{-1}$) | $AE_N^a$ | $RE_N^b$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 7 | 21 | 28 | 42 | 49 | | | | | |
| 1 | 0 | | 0 | | 0 | | 0 | 3.85 | 68.1 | – | – |
| 2 | 40 | | 40 | | 40 | | 120 | 6.19 | 132.3 | 19.1 | 53.0 |
| 3 | 20 | | 40 | | 28* | | 88 | 5.73 | 112.8 | 22.2 | 51.1 |
| 4 | 20 | | 60 | | 12* | | 92 | 6.06 | 118.7 | 23.9 | 54.6 |
| 5 | 30 | | 30 | | 32* | | 92 | 5.63 | 119.2 | 19.7 | 55.1 |
| 6 | 30 | | 50 | | 14* | | 94 | 6.48 | 125.7 | 28.1 | 61.5 |
| 7 | 40 | | 40 | | 17* | | 97 | 6.14 | 126.8 | 23.4 | 60.0 |
| 8 | | 20 | | 40 | | 29* | 89 | 5.79 | 113.9 | 21.6 | 51.2 |
| 9 | | 20 | | 60 | | 19* | 99 | 6.00 | 120.5 | 21.8 | 53.6 |
| 10 | | 30 | | 30 | | 32* | 92 | 5.66 | 115.8 | 19.8 | 51.5 |
| 11 | | 30 | | 50 | | 17* | 97 | 6.35 | 124.7 | 25.9 | 58.3 |
| 12 | | 40 | | 40 | | 20* | 100 | 6.01 | 124.0 | 21.4 | 55.4 |
| LSD ($p = 0.05$) | | | | | | | | 0.334 | 7.35 | 4.06 | 5.03 |

[a] Agronomic efficiency of applied N [kg grain (kgN applied)$^{-1}$]

[b] Recovery efficiency of applied N (%)

* GreenSeeker guided N application

Evaluation of optical sensor-based N management versus blanket recommendation

Application of fertilizer N at the rate of 120 kg N ha$^{-1}$ in three equal split equal doses at transplanting, active tillering and PI has been found beneficial in increasing grain yield and N uptake of transplanted rice, and it is a general blanket recommendation over a vast area in the Indo-Gangetic Plain (Meelu et al. 1987). As rice seedlings need about 7 days to recover from transplanting shock (Meelu and Gupta 1980), N uptake within 3 weeks of transplanting should be small. Since there is high N demand by rice during the period between 21 and 42 DAT (De Datta 1981), the GreenSeeker-guided fertilizer N application at 42 or 49 DAT was combined with five different scenarios of prescriptive N management consisting of application of 20, 30 or 40 kg N ha$^{-1}$ at transplanting and 40, 50 or 60 kg N ha$^{-1}$ at 21 DAT as listed in Tables 3, 4 and 5. In the Experiments 8, 9 and 10, the five scenarios have been evaluated four and two times with GreenSeeker-guided dose applied at 42 and 49 DAT, respectively.

In two of the five treatments, 60 kg N ha$^{-1}$ was applied before applying the optical sensor-guided dose of N at 42 or 49 DAT (Tables 3, 4, 5). In both these treatments, sensor-guided dose was greater than in the three treatments receiving total 80 kg N ha$^{-1}$ at transplanting and at active tillering stages. But the grain yield of rice was the lowest in the two treatments receiving 20 kg N ha$^{-1}$ at transplanting and 40 kg N ha$^{-1}$ at 21 DAT, and 30 kg N ha$^{-1}$ both at transplanting and at 21 DAT before applying the GreenSeeker-guided fertilizer N dose. In five out of six comparisons in Experiments 8, 9 and 10, the two treatments receiving 60 kg N ha$^{-1}$ before the sensor-guided dose performed significantly inferior to the blanket recommendation of applying 120 kg N ha$^{-1}$ in three equal split

**Table 4** Evaluation of GreenSeeker optical sensor based fertilizer N management in rice (cultivar PR 118) at Ludhiana during 2007 (Experiment 9)

| Treatment | Fertilizer N applied (kg N ha$^{-1}$) at days after transplanting | | | | | | Total N applied (kg ha$^{-1}$) | Rice grain yield (t ha$^{-1}$) | Total N uptake (kg ha$^{-1}$) | AE$_N^a$ | RE$_N^b$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 7 | 21 | 28 | 42 | 49 | | | | | |
| 1 | 0 | | 0 | | 0 | | 0 | 3.05 | 62.2 | – | – |
| 2 | 40 | | 40 | | 40 | | 120 | 5.01 | 101.3 | 16.7 | 32.9 |
| 3 | 20 | | 40 | | 21* | | 81 | 4.72 | 88.7 | 20.4 | 32.3 |
| 4 | 20 | | 60 | | 10* | | 90 | 4.98 | 100.0 | 21.7 | 41.5 |
| 5 | 30 | | 30 | | 23* | | 83 | 4.71 | 92.6 | 20.6 | 36.3 |
| 6 | 30 | | 50 | | 12* | | 92 | 5.27 | 102.3 | 24.9 | 43.8 |
| 7 | 40 | | 40 | | 8* | | 88 | 4.94 | 100.4 | 21.3 | 43.7 |
| 8 | | 20 | | 40 | | 38* | 98 | 4.73 | 96.2 | 17.2 | 34.4 |
| 9 | | 20 | | 60 | | 31* | 111 | 4.93 | 104.4 | 16.7 | 38.0 |
| 10 | | 30 | | 30 | | 35* | 95 | 4.61 | 99 | 15.9 | 38.3 |
| 11 | | 30 | | 50 | | 23* | 103 | 5.24 | 105.4 | 21.9 | 41.8 |
| 12 | | 40 | | 40 | | 20* | 100 | 4.95 | 100.9 | 19.3 | 38.3 |
| LSD (p = 0.05) | | | | | | | | 0.277 | 6.10 | 3.14 | 5.71 |

[a] Agronomic efficiency of applied N [kg grain (kgN applied)$^{-1}$]

[b] Recovery efficiency of applied N (%)

* GreenSeeker guided N application

**Table 5** Evaluation of GreenSeeker optical sensor based N management in rice cultivars PAU201 and PHB71 at Ludhiana, 2008 (Experiment 10)

| Cultivar | Fertilizer N applied (kg N ha$^{-1}$) days after transplanting | | | Total N applied (kg ha$^{-1}$) | Rice grain yield (t ha$^{-1}$) | Total N uptake (kg ha$^{-1}$) | $AE_N^a$ | $RE_N^b$ |
|---|---|---|---|---|---|---|---|---|
| | 0 | 21 | 46 | | | | | |
| PAU201 | 0 | 0 | 0 | 0 | 4.16 | 64.2 | – | – |
| | 40 | 40 | 40 | 120 | 6.46 | 113.7 | 19.1 | 41.0 |
| | 20 | 40 | 46* | 106 | 6.02 | 107.0 | 17.3 | 40.5 |
| | 20 | 60 | 37* | 117 | 6.13 | 115.6 | 17.0 | 43.5 |
| | 30 | 30 | 48* | 108 | 6.11 | 113.0 | 18.6 | 44.8 |
| | 30 | 50 | 29* | 109 | 6.62 | 117.1 | 22.8 | 48.6 |
| | 40 | 40 | 37* | 117 | 6.28 | 113.5 | 18.1 | 42.4 |
| PHB71 | 0 | 0 | 0 | 0 | 3.42 | 52.1 | – | – |
| | 40 | 40 | 40 | 120 | 6.02 | 109.5 | 21.6 | 47.3 |
| | 20 | 40 | 46* | 106 | 5.69 | 101.1 | 21.2 | 46 |
| | 20 | 60 | 41* | 121 | 5.99 | 112.9 | 21.3 | 49.9 |
| | 30 | 30 | 49* | 109 | 5.79 | 104.1 | 21.6 | 47.3 |
| | 30 | 50 | 31* | 111 | 6.34 | 113.0 | 26.5 | 54.9 |
| | 40 | 40 | 39* | 119 | 6.00 | 110.9 | 21.8 | 49.0 |
| LSD ($p = 0.05$): cultivar | | | | | 0.136 | 3.20 | 2.54 | 3.76 |
| Fertilizer | | | | | 0.245 | 4.11 | 3.08 | 5.23 |
| Cultivar × fertilizer | | | | | 0.318 | 5.66 | 3.41 | 7.04 |

[a] Agronomic efficiency of applied N [kg grain (kgN applied)$^{-1}$]

[b] Recovery efficiency of applied N (%)

* GreenSeeker guided N application

doses (Tables 3, 4, 5). Application of 20 kg N ha$^{-1}$ at transplanting or 30 kg N ha$^{-1}$ at the active tillering stage was inadequate and resulted in low yield levels. In experiments carried out by Bijay Singh et al. (2012) too, a dose of 20 kg N ha$^{-1}$ at transplanting proved to be inadequate for achieving high yields of rice. Also, application of 40 or 45 kg N ha$^{-1}$ at 21 DAT along with 30 kg N ha$^{-1}$ both at transplanting and 42 DAT stages resulted in high rice yields. Thus, GreenSeeker-based N management in rice cannot lead to high rice yields and NUE unless adequate N supply is ensured both at transplanting and active tillering stages of the crop.

Among the three prescriptive N management scenarios in which a total of 80 kg N ha$^{-1}$ was applied before applying a sensor-guided dose of fertilizer N, the highest yield of rice grain was observed when 30 kg N ha$^{-1}$ was applied at transplanting and 50 kg N ha$^{-1}$ was applied at 21 DAT. This treatment significantly out-yielded the other two treatments in which total N applied before applying the GreenSeeker-guided dose was 80 kg N ha ha$^{-1}$, but was similar to the blanket recommendation treatment in which 120 kg N ha$^{-1}$ was applied in three equal split doses (Tables 3, 4 and 5). However, due to the fact that total fertilizer N application in this treatment was substantially less than 120 kg N ha$^{-1}$, agronomic and recovery efficiencies recorded for this treatment turned out to be significantly higher than that for blanket recommendation treatment as well as most other treatments. Total N uptake and recovery efficiency were influenced by total amount of N applied. Thus, for some treatments, these were statistically similar to the highest values recorded for the treatment in which 30 kg N $ha^{-1}$ was applied at transplanting and 50 kg N $ha^{-1}$ was applied at 21 DAT before applying the sensor-based dose at 42 or 49 DAT. The trends in grain yield and NUE as observed in Experiments 8, 9 and 10 suggest that to achieve high NUE in GreenSeeker-based N management, it is essential to apply at least 30 kg N $ha^{-1}$ at transplanting and more than 40 kg N $ha^{-1}$ at the active tillering stage at 21 DAT.

The schedule of applying fertilizer N at 7 and 28 DAT and GreenSeeker-guided dose at 49 DAT was tested to know whether the performance of GreenSeeker at 42 DAT was sufficient. In view of the results obtained in Experiments 8, 9 and 10, it became evident that rather than applying fertilizer at 7, 28 and 49 DAT, the schedule based on critical growth stages of rice should be followed. Before applying a GreenSeeker optical sensor-guided dose of fertilizer N at 42 DAT, 30 kg N $ha^{-1}$ and 45 kg N $ha^{-1}$ should be applied at transplanting and at 21 DAT stages of rice. The decision to apply 45 kg N $ha^{-1}$ at 21 DAT was also supported by the experiments reported by Bijay Singh et al. (2012). Therefore, in Experiments 11, 12, 13 and 14, GreenSeeker optical sensor-based N management strategy finalized as application of 30 kg N $ha^{-1}$ at transplanting, 45 kg N $ha^{-1}$ at 21 DAT and sensor-guided dose of N at 42 DAT, was tested versus the blanket recommendation for different rice cultivars.

Tables 6 and 7 show comparison of GreenSeeker-based N management versus blanket fertilizer N recommendation for transplanted rice in terms of grain yield and NUE for seven cultivars (PR114, PR116, PR118, PR120, HKR127, PAU201, PUSA44). In the nine comparisons made in Experiments 11 to 14, GreenSeeker-guided N dose applied at 42 DAT varied from as low as 6 kg N $ha^{-1}$ to as high as 33 kg N $ha^{-1}$ but grain yield of rice produced by applying total amount of fertilizer N varying from 81 to 108 kg N $ha^{-1}$ was similar to that obtained in the blanket recommendation treatment receiving 120 kg N $ha^{-1}$. As time of application of the three split doses in both the treatments was the same, it seems that in the blanket recommendation, fertilizer dose applied at transplanting and/or PI stages was more than the need of the crop. Agronomic efficiency of the treatments with GreenSeeker-based N management was higher than that of the blanket recommendation treatments in 8 out of 9 comparisons (Tables 6, 7). Except for rice cultivars PR114 and PR116 in Experiment 14, N uptake by rice in the GreenSeeker treatment was similar to that observed in the blanket recommendation treatment. It suggests that gains in rice yields by following the sensor-based N management strategy were actually due to more efficient utilization of applied N than when blanket recommendation was followed. It is also evident from the significantly higher recovery efficiency observed in the GreenSeeker-based N management than in the blanket recommendation treatment in 8 out of 9 comparisons in Experiments 11–14 (Tables 6, 7).

Evaluation of optical sensor-based N management strategy versus farmers' practice and LCC-based real time N management strategy at 19 on-farm locations revealed that farmers are applying too much fertilizer N to rice and when it is not needed by the crop. Farmers applied from 92 to 180 kg N $ha^{-1}$ but produced significantly less rice yield than in LCC- or GreenSeeker-based N management strategies in 6 out of 19 sites (Table 8). In contrast, range of total fertilizer N application was 60–90 kg N $ha^{-1}$ in LCC- based N management and 75–97 kg N $ha^{-1}$ in the GreenSeeker-based N management. There was no significant difference in rice yield obtained by applying fertilizer N as per the two strategies (Table 8). Similar performance of LCC and GreenSeeker-based N management in well managed experiments was expected. As GreenSeeker takes into account both leaf greenness as well

**Table 6** Evaluation of GreenSeeker optical sensor based N management in three rice cultivars at Ludhiana, 2009 (Experiment 11)

| Cultivar | Treatment | Total N applied (kg ha$^{-1}$) | Rice grain yield (t ha$^{-1}$) | Total N uptake (kg ha$^{-1}$) | $AE_N^a$ | $RE_N^b$ |
|---|---|---|---|---|---|---|
| PAU 201 | No–N control | 0 | 3.99 | 57.8 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 6.96 | 131.7 | 24.7 | 61.6 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + Sensor guided N dose at 42 DAT | 102 | 7.16 | 130.8 | 31.0 | 71.5 |
| PUSA 44 | No–N control | 0 | 3.94 | 63.1 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 6.38 | 121.6 | 20.3 | 48.7 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + Sensor guided N dose at 42 DAT | 97 | 6.37 | 117.0 | 25.1 | 55.6 |
| HKR 127 | No–N control | 0 | 3.75 | 57.9 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 6.04 | 120.4 | 19.1 | 52.1 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + Sensor guided N dose at 42 DAT | 102 | 6.16 | 117.7 | 23.8 | 58.6 |
| LSD ($p = 0.05$): cultivar | | | 0.160 | 3.69 | 1.43 | 4.39 |
| Fertilizer treatment | | | 0.253 | 4.09 | 2.53 | 3.36 |
| Cultivar × fertilizer treatment | | | 0.439 | 7.09 | 4.37 | 5.82 |

[a] Agronomic efficiency of applied N [kg grain (kgN applied)$^{-1}$]

[b] Recovery efficiency of applied N (%)

as plant biomass in contrast to LCC which decides fertilizer N management only based on leaf colour, the former should prove a better tool even in not very well managed rice fields. In on-farm experiments in China, Yao et al. (2012) observed that GreenSeeker-based N management increased the partial factor productivity of farmers by 48 % without significant change in grain yield. The data from on-farm sites suggest that farmers are using N fertilizers in rice very inefficiently and there is a huge scope to improve fertilizer NUE by following optical sensor-based strategies.

Dobermann et al. (2002) advocated a site-specific N management to increase fertilizer NUE of irrigated rice that involved N application based on the crop N demand determined by climatic factors (solar radiation and temperature) and indigenous N (Cassman et al. 1996) at critical growth stages with upward or downward adjustments of N topdressings based on leaf N status measured with SPAD meter. In 179 fields, Dobermann et al. (2002) observed an increase in NUE by 30–40 % by following this strategy. Although the approach followed in the present study is not exactly similar, the element of adjusting the actual rates at PI as per leaf N status and biomass has been extended in a way that total N to be applied in the season is also defined. The data generated from the seven evaluation experiments convincingly proves that prescriptive N management at transplanting and

**Table 7** Evaluation of GreenSeeker optical sensor based site-specific N management vis-à-vis blanket recommendation for fertilizer N in rice during 2009 and 2010 at Ludhiana, India

| Cultivar (year) | Treatment | Total N applied (kg ha$^{-1}$) | Rice grain yield (t ha$^{-1}$) | Total N uptake (kg ha$^{-1}$) | $AE_N^a$ | $RE_N^b$ |
|---|---|---|---|---|---|---|
| *Experiment 12* | | | | | | |
| PR120 (2009) | No–N control | 0 | 3.37 | 52.5 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 8.23 | 150.2 | 40.6 | 81.4 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + sensor guided N dose at 42 DAT | 103 | 8.33 | 144.6 | 48.2 | 89.4 |
| HKR 127 (2009) | No–N control | 0 | 5.01 | 71.2 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 7.26 | 125.4 | 18.7 | 45.1 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + sensor guided N dose at 42 DAT | 101 | 7.38 | 123.8 | 23.5 | 52.1 |
| LSD ($p = 0.05$): cultivar | | | 0.194 | 7.11 | 6.76 | 4.20 |
| Fertilizer treatment | | | 0.320 | 6.20 | 4.62 | 5.46 |
| Cultivar × fertilizer treatment | | | 0.453 | 8.77 | 6.53 | 6.53 |
| *Experiment 13* | | | | | | |
| PR118 (2010) | No–N control | 0 | 3.15 | 54.6 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 6.06 | 119.4 | 24.3 | 54.0 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + Sensor guided N dose at 42 DAT | 108 | 6.36 | 118.9 | 30.2 | 59.5 |
| PR120 (2010) | No–N control | 0 | 3.35 | 57.3 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 6.34 | 120.2 | 24.9 | 52.4 |

**Table 7** continued

| Cultivar (year) | Treatment | Total N applied (kg ha$^{-1}$) | Rice grain yield (t ha$^{-1}$) | Total N uptake (kg ha$^{-1}$) | $AE_N^a$ | $RE_N^b$ |
|---|---|---|---|---|---|---|
| 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + sensor guided N dose at 42 DAT | 81 | 6.31 | 117.3 | 36.6 | 74.1 | |
| LSD (p = 0.05): cultivar | | | 0.147 | 1.96 | 2.39 | 5.50 |
| Fertilizer treatment | | | 0.293 | 5.45 | 3.94 | 5.45 |
| Cultivar × fertilizer treatment | | | 0.414 | 7.71 | 5.57 | 7.71 |
| *Experiment 14* | | | | | | |
| PR114 (2010) | No–N control | 0 | 3.21 | 49.7 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 6.39 | 124.9 | 26.5 | 62.1 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + Sensor guided N dose at 42 DAT | 93 | 6.45 | 113.9 | 34.8 | 69.1 |
| PR116 (2010) | No–N control | 0 | 3.23 | 51.5 | – | – |
| | 120 kg N ha$^{-1}$ applied in 3 equal split doses at 0, 21and 42 DAT of rice | 120 | 6.49 | 121.1 | 27.2 | 58.1 |
| | 30 kg N ha$^{-1}$ at transplanting + 45 kg N ha$^{-1}$ at 21 DAT + sensor guided N dose at 42 DAT | 90 | 6.42 | 111.0 | 35.5 | 66.2 |
| LSD (p = 0.05): cultivar | | | 0.285 | 2.49 | 3.42 | 0.70 |
| Fertilizer treatment | | | 0.195 | 3.97 | 2.62 | 4.77 |
| Cultivar × fertilizer treatment | | | 0.276 | 5.62 | 3.70 | 6.76 |

[a] Agronomic efficiency of applied N [kg grain (kgN applied)$^{-1}$]

[b] Recovery efficiency of applied N (%)

**Table 8** Evaluation of GreenSeeker based site-specific N management strategy in rice vis-à-vis leaf colour chart based real time N management and farmer's fertilizer practice at 19 on-farm locations in Ludhiana district during 2010 and 2011

| Site number, surface soil texture, soil organic C (%), rice cultivar, date of rice transplanting | Farmers' fertilizer practice | | Leaf colour chart based real time N management[a] | | Optical sensor based N management[b] | | LSD (p = 0.05) for comparing means of grain yield |
|---|---|---|---|---|---|---|---|
| | Total N applied (kg $ha^{-1}$) | Grain yield (t $ha^{-1}$) | Total N applied (kg $ha^{-1}$) | Grain yield (t $ha^{-1}$) | Total N applied (kg $ha^{-1}$) | Grain yield (t $ha^{-1}$) | |
| 1. Sandy loam, 0.41, Pusa 44, 18 June 2010 | 115 | 5.61 | 60 | 5.32 | 75 | 5.53 | ns |
| 2. Sandy loam, 0.50, Pusa 44, 22 June 2010 | 115 | 7.55 | 60 | 7.46 | 84 | 7.70 | ns |
| 3. Sandy loam, 0.49, Pusa 44, 23 June 2010 | 115 | 9.45 | 60 | 9.37 | 94 | 9.23 | ns |
| 4. Loamy sand, 0.21, Pusa 44, 15 June 2010 | 115 | 8.67 | 60 | 8.80 | 94 | 8.53 | ns |
| 5. Loamy sand, 0.25, Pusa 44, 26 June 2010 | 115 | 8.54 | 60 | 8.24 | 85 | 8.58 | ns |
| 6. Sandy loam, 0.66, Pusa 44, 26 June 2010 | 115 | 8.63 | 60 | 8.68 | 86 | 8.64 | ns |
| 7. Sandy loam, 0.49, HKR 127, 26 June 2010 | 114 | 7.69 | 60 | 8.18 | 97 | 8.02 | 0.30 |
| 8. Sandy loam, 0.55, Pusa 44, 01 July 2010 | 104 | 8.00 | 60 | 7.70 | 90 | 7.80 | ns |
| 9. Loam, 0.59, Pusa 44, 14 July 2010 | 92 | 8.43 | 60 | 8.36 | 86 | 8.04 | ns |
| 10. Loamy sand, 0.34, Pusa 44, 23 June 2011 | 180 | 4.58 | 90 | 5.37 | 80 | 4.99 | 0.39 |
| 11. Sandy loam, 0.44, HKR 127, 23 June 2011 | 180 | 4.27 | 90 | 5.31 | 80 | 4.92 | 0.46 |
| 12. Sandy loam, 0.48, Pusa 44, 18 June 2011 | 180 | 4.09 | 90 | 4.47 | 80 | 4.24 | 0.32 |
| 13. Sandy loam, 0.42, HKR 127, 19 June 2011 | 140 | 6.43 | 60 | 6.12 | 83 | 6.13 | ns |
| 14. Loamy sand, 0.33, PR 120, 25 June 2011 | 120 | 6.07 | 90 | 6.23 | 85 | 5.90 | ns |
| 15. Sandy loam, 0.55, PR 116, 25 June 2011 | 150 | 6.21 | 90 | 6.10 | 93 | 6.22 | ns |
| 16. Sandy loam, 0.49, Pusa 44, 21 June 2011 | 120 | 6.44 | 60 | 6.38 | 87 | 6.21 | ns |
| 17. Sandy loam, 0.40, HKR 127, 21 June 2011 | 180 | 5.58 | 90 | 5.73 | 95 | 5.48 | ns |
| 18. Loam, 0.56, Pusa 44, 27 June 2011 | 180 | 3.93 | 90 | 4.56 | 93 | 4.51 | 0.45 |
| 19. Sandy loam, 0.48, PR 120, 28 June 2011 | 170 | 3.90 | 90 | 4.58 | 82 | 4.75 | 0.51 |

[a] 30 kg N $ha^{-1}$ at transplanting + 30 kg N $ha^{-1}$ whenever colour of the first fully opened leaf from the top was less shade 4 of the leaf colour chart; starting 15 days after transplanting up to initiation of flowering

[b] 30 kg N $ha^{-1}$ at transplanting + 45 kg N $ha^{-1}$ at 21 DAT + GreenSeeker optical sensor guided dose at 42 DAT

active tillering stage influences not only grain yield and N uptake by rice but also the total N applied when an adjustable dose option based on the biomass and canopy colour is applied at PI growth stage of the crop.

Recently, N rate recommendations derived from spectral indices have been tested by a few workers and these have shown promise to increase NUE. Xue and Yang (2008) used a multi-spectral CropScan sensor to calculate NDVI and modified the N fertilizer optimization algorithm for rice. They increased agronomic efficiency by 20 % compared to standard N management practice in Jiangsu Province of South China. Xue and Yang (2008) also tested a similar approach based on an index using NDVI readings from a non-limited N fertilizer field and NDVI reading from farmers practice and found that determining optimum mid-season N rates using remote sensing technology is feasible. Xue et al. (2014) developed a sensor-determined topdressing N model for rice based on the target yield and split fertilization approach, and observed a significant increase in rice yield and profit as compared to farmers' practice of managing fertilizer N.

## Conclusions

For irrigated transplanted rice grown in the Indo-Gangetic Plain of South Asia, the GreenSeeker optical sensor can reliably predict the yield potential of the crop through in-season measurement of NDVI at the PI stage. Using yield potential and response index calculated from NDVI measurements of the test field and an N-rich strip, fertilizer N dose to be applied at the PI stage of rice can be computed as per need of the crop in a given field and season. However, due to the fact that GreenSeeker-guided fertilizer N dose can be applied only once at the PI stage of transplanted rice, it must be integrated with application of adequate amounts of fertilizer N both at transplanting and at active tillering stages of the crop. A combination of a moderate prescriptive dose of 30 kg N $ha^{-1}$ at transplanting and a dose of 45 kg N $ha^{-1}$ at the active tillering stage is sufficient to meet the high N demand by rice during the period between active tillering and PI. A corrective GreenSeeker-guided fertilizer N application at PI stage can lead to improved fertilizer NUE. Greater NUE with GreenSeeker-guided N management resulted from using lower N fertilizer rates than with blanket N applications, but with no grain yield reductions.

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