Computers and Electronics in Agriculture 110 (2015) 114–120

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

A framework for refining nitrogen management in dry direct-seeded rice using GreenSeeker™ optical sensor

A.M. Ali [a,b,*], H.S. Thind [a], Varinderpal-Singh [a], Bijay-Singh [a]

[a] Department of Soil Science, Punjab Agricultural University, Ludhiana 141004, India
[b] Department of Soil Fertility and Microbiology, Desert Research Centre, El-Mataryia, Cairo 11753, Egypt

ARTICLE INFO

Article history:
Received 25 November 2013
Received in revised form 11 October 2014
Accepted 21 October 2014

Keywords:
Dry direct-seeded rice
Nitrogen management
GreenSeeker^{TM} optical sensor

ABSTRACT

To reduce the amount of wasted reactive nitrogen (N) reaching the environment and to achieve high N fertilizer use efficiency, a site-specific N management strategy using GreenSeeker™ optical sensor (GS) was evaluated in dry direct-seeded rice (DDSR) in the north-western India. Four field experiments were conducted during 2011–2013 to develop an optical sensor algorithm for fine tuning in-season N fertilizer applications. It was demonstrated that panicle initiation of rice is the appropriate stage for applying GS guided N fertilizer dose. Application of a prescriptive dose of 60 kg N ha^{-1} in two or 90 kg N ha^{-1} in two or three equal split doses, followed by a corrective N dose guided by GS at panicle initiation stage resulted in rice yield levels comparable to that obtained by following general recommendation, but with lower total N fertilizer application. On an average, N use efficiency was improved by more than 12% when N fertilizer management was guided by GS as compared to when general N fertilizer recommendation was followed. The results prove the inadequacy of general recommendations for N fertilizer management in DDSR and possibility of increasing N use efficiency along with high rice yield levels through site-specific N fertilizer management using GS.

1. Introduction

In the Indo-Gangetic plain of South Asia, nitrogen (N) fertilizer in rice is generally managed following a general recommendation over large areas. To ensure high crop yields, farmers often apply doses of N fertilizer higher than the general recommendation. As recovery efficiency of applied N fertilizer in rice at on-farm locations rarely exceeds 30% (Bijay-Singh et al., 2001; Ladha et al., 2005), a large amount of N is lost from the soil–plant system. One of the major factors contributing to low N use efficiency is the uniform application rates of N fertilizer to spatially variable landscapes. Uniform applications within fields discount the fact that N supplies from the soil, crop N uptake, and responses to N are different spatially (Inman et al., 2005). Efficient use of N fertilizer is restricted due to large temporal and field-to-field variability when broad-based general recommendations are used (Adhikari et al., 1999; Dobermann et al., 2003; Varinderpal-Singh et al., 2010).

In recent years, a shift from transplanted rice to direct-seeded rice (DSR) has initiated in several countries of South and Southeast Asia (Kumar and Ladha, 2011). Besides higher economic returns, DSR is easy to plant, less labour intensive, consumes less water (Bhushan et al., 2007), conducive to mechanization (Khade et al., 1993) and emits less methane (Ko and Kang, 2000; Bhatia et al., 2012). Dry seeding of rice and subsequent dry soil conditions avoid water application of water for puddling and maintenance of submerged soil conditions, and thus reduces the overall water demand (Sharma et al., 2002; Sudhir-Yadav et al., 2011). However, loss of N due to denitrification, volatilization and leaching is likely to be higher in dry DSR (DDSR) than in the transplanted rice (Singh and Singh, 1988; Davidson, 1991). Generally, low rice yields have been demonstrated to be mainly due to insufficient N uptake (Kropff et al., 1993).

GreenSeeker™ optical sensor (GS) is emerging as tool for site-specific need based N fertilizer management in cereals. It uses normalized difference vegetation index (NDVI) based on reflectance of radiation in the red and near infrared bands. Raun et al. (2001) found that the relationship between NDVI and grain yield of winter wheat was the highest between growth stages Feekes 4 and 6. Raun et al. (2002) developed an algorithm that can estimate midseason N requirement of winter wheat. Their work has shown that the N use efficiency of winter wheat was improved by more

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* Corresponding author at: Department of Soil Fertility and Microbiology, Desert Research Centre, El-Mataryia, Cairo 11753, Egypt.

E-mail addresses: alimohamed1982@yahoo.com, alimohamed1982@gmail.com (A.M. Ali).

http://dx.doi.org/10.1016/j.compag.2014.10.021
0168-1699/

than 15% when this approach was employed compared with conventional N rate recommendations. Raun et al. (2005) further refined the N application algorithm using the coefficient of variation from NDVI readings. Bijay-Singh et al. (2011) observed that high N use efficiency in irrigated wheat grown in Northwest India can be achieved by replacing general fertilizer recommendation by an optical sensor based N management strategy.

A considerable amount of research is required before producers in South Asia, and elsewhere, will be able to use optical sensors in different crops. Algorithms for applying N fertilizer to DDSR need to be developed under local environmental conditions. The objective of this study was to develop an optical sensor algorithm that can be used to translate GS optical sensor readings into appropriate in-season N applications to ensure high DDSR yields as well as N fertilizer use efficiency as compared to general recommendations.

2. Materials and methods

2.1. Experimental sites

Field experiments with DDSR were conducted during three consecutive years (2011, 2012 and 2013) on a Typic Ustipsamment (Fatehpur loamy sand) soil at the research farm of the Punjab Agricultural University, Ludhiana (30° 56′ N, 75° 52′ E), located in the northwestern India. The climate of Ludhiana is subtropical with annual rainfall of 730 mm year^{-1}, about 80% of which occurs from June to September. The mean monthly temperatures during the rice seasons range between 23.4 and 37.4 °C. Initial soil samples collected from each experiment were mixed, air dried, sieved, and analyzed for physical and chemical characteristics (Table 1).

2.2. Treatment details in different experiments

Two categories of experiments were established. The experiments in 2011 and 2012 were designed to understand the relation between N uptake, grain yield and NDVI in rice cultivar PR114. In the experiment conducted in 2011 season, along with a no-N control, urea N levels of 120, 150 and 180 kg N ha^{-1} were applied either at 0, 35 and 63 days after sowing (DAS) or 14, 35 and 63 DAS in three equal split doses and at 0, 28, 49 and 70 or 14, 28, 49 and 70 DAS in four equal split doses in PR114 cultivar. In the 2012 experiment, 0, 60, 90, 120, 150, 180, 210 and 240 kg N ha^{-1} were applied as urea in four (14, 28, 49, 70 DAS) equal split doses. The purpose of applying a range N fertilizer rate was to establish plots with different yield potentials. In the second category, the experiments were conducted in 2013 season with two rice cultivars PR114 and PR115. These experiments aimed at validating the established sensor algorithms. Sensor-based N management treatments were tested to determine N fertilizer application at 60 DAS for PR115 (shorter duration cultivar) and at 70 DAS for PR114 (medium duration cultivar) when different doses of N were applied as prescriptive N management (Tables 2 and 3). These timings coincided with panicle initiation growth stage, which was selected as the appropriate stage to apply N fertilizer doses guided by optical sensor. In all the four experiments, the treatment plots were arranged in a randomized complete block design with three replications. Also, in each experiment, an N-rich strip was established by applying 200 kg N ha^{-1} in split doses to ensure that N was not limiting.

2.3. Soil and crop management

Prior to sowing rice, the land was plowed twice to about 20 cm depth and leveled. A basal dose of 13 kg P ha^{-1} as single superphosphate and 25 kg K ha^{-1} as muriate of potash was applied at the time of sowing. Rice was sown in the first fortnight of June in all the experiments by drilling the seed (40 kg ha^{-1}) with a seed-cum-fertilizer drill at a row to row spacing of 20 cm (plot size 19.8 m^2). The field was surface-irrigated immediately after sowing. Weeds were controlled by applying a pre-emergence herbicide (pendimethalin) at 1 DAS, and a post-emergence herbicide (bispyribac) at 21 DAS. Weeds that escaped these treatments were removed manually at 45 DAS. The irrigation was applied at 3–4 day interval but it was stopped during rainfall events.

2.4. NDVI measurements

Spectral reflectance expressed as NDVI was measured using a handheld GreenSeeker™ optical sensor unit (NTech Industries Incorporation, Ukiah, CA, USA). The readings were collected by holding the unit at a height of about 1 m above the plant canopy. The sensor unit has self-contained illumination in both the red (656 nm with about 25 nm full width half magnitude (FWHM)) and near infrared (NIR) (774 with about 25 nm FWHM) bands. The GS calculates NDVI as:

$$\mathrm{NDVI} = (F_{\mathrm{NIR}} - F_{\mathrm{RED}})/(F_{\mathrm{NIR}} + F_{\mathrm{RED}})$$

where F_{NIR} and F_{RED} are, respectively, the fractions of NIR and red radiation reflected back from the sensed area. The sensor samples at a very high rate (approximately 1000 measurements per second) and averages measurements between outputs. The sensor outputs NDVI at a rate of 10 readings per second with travel velocities at a slow walking speed of about 0.5 m s^{-1}.

2.5. Plant sampling measurements and analysis

At maturity, rice crop was harvested manually. Grain and straw yields were recorded from a net area of 8 m^2 from the center of different treatment plots. Grains were separated from straw. Grain and straw samples of rice collected from each plot were air dried at 70 °C in a hot air oven. Grain yields were adjusted to 14% moisture content. Straw yields were expressed on an oven-dry basis. The dried samples were ground and N content in grain and straw

Table 1
Soil (0–15 cm) properties of experimental sites at Ludhiana, India.

Experiment	Sand (%)	Clay (%)	pH[a]	EC (dS m^{-1})[b]	Organic carbon (g kg^{-1})[c]	Available P (kg ha^{-1})[d]	Available K (kg ha^{-1})[e]
Experiment 1, 2011	67	13.7	7.2	0.16	3.3	11	108
Experiment 2, 2012	68	14.3	7.6	0.24	3.5	18	140
Experiment 3, 2013 (PR114 cultivar)	77	6.2	7.4	0.15	3.1	10	99
Experiment 4, 2013 (PR115 cultivar)	65	14.7	7.6	0.25	3.7	14	155

EC Electrical conductivity.
[a] 1:2 soil/water suspension.
[b] 1:2 soil/water supernatant.
[c] Walkley and Black (1934).
[d] Olsen et al. (1954).
[e] Pratt (1965).

Table 2
Evaluation of GreenSeeker™ optical sensor-based N management in dry direct-seeded rice cultivar PR115 at Ludhiana, India.

Treatment	N fertilizer application (kg N ha^{-1})						Grain yield (Mg ha^{-1})	Total N uptake (kg ha^{-1})	RE_N[c]	AE_N[c]	PFP_N[c]
	14 DAS[a]	28 DAS	42 DAS	49 DAS	60 DAS[b]	Total					
1	–	–	–	–	–	–	4.39c	58.7c	–	–	–
2	37.5	37.5	–	37.5	37.5	150	6.52ab	106.4a	31.8b	14.2bc	43.5de
3	–	60	–	–	91.3	151.3	5.83b	91.6b	21.8c	9.5d	38.5ef
4	–	60	–	–	89	149	6.20ab	101.7ab	28.9bc	12.1cd	41.6e
5	–	90	–	–	101.4	191.4	6.13ab	102.4ab	22.8bc	9.1d	32.0f
6	–	90	–	–	93	183	6.25ab	105.8a	25.8bc	10.2d	34.2f
7	20	20	–	20	66.3	126.3	6.20ab	110.7a	41.2a	14.3bc	49.1cd
8	20	20	–	20	46.5	106.5	6.48ab	104.4ab	42.9a	19.6ab	60.8ab
9	30	30	–	30	46	136	6.97a	114.7a	41.2a	19.0ab	51.3c
10	30	30	–	30	33.6	123.6	6.89ab	111.7a	42.9a	20.2ab	55.8bc
11	30	–	30	–	50.9	110.9	7.00a	110.9a	47.1a	23.5a	63.1a
12	30	–	30	–	50.8	110.8	6.76ab	108.2a	44.7a	21.4ab	61.0ab
13	45	–	45	–	6.2	96.2	6.52ab	102.5ab	45.6a	22.1ab	67.7a
14	45	–	45	–	8.6	98.6	6.74ab	103.9ab	45.9a	23.7a	68.2a

Means within a column followed by different letters differ at $P < 0.05$ by Duncan's Multiple Range Test (DMRT).

Treatment # 3, 5, 7, 9, 11 and 13 are based on the algorithm, N fertilizer (kg ha^{-1}) $= \frac{120-(236.53\times NDVI^{2.949})}{0.6}$, and Treatment # 4, 6, 8, 10, 12 and 14 are based on the algorithm, N fertilizer (kg ha^{-1}) $= \frac{120-(132.67\times SI^{-2.926})}{0.6}$.

[a] DAS, days after sowing.

[b] Sensor-based N application in Treatment # 3 to14.

[c] RE_N: recovery efficiency of applied N (%), AE_N: agronomic efficiency of N (kg grain kg^{-1} N), PFP_N: partial factor productivity of N (kg grain kg^{-1} N).

Table 3
Evaluation of GreenSeeker™ optical sensor-based N management in dry direct-seeded rice cultivar PR114 at Ludhiana, India.

Treatment	N Fertilizer application (kg N ha^{-1})						Grain yield (Mg ha^{-1})	Total N uptake (kg ha^{-1})	RE_N[c]	AE_N[c]	PFP_N[c]
	14 DAS[a]	28 DAS	42 DAS	49 DAS	70 DAS[b]	Total					
1	–	–	–	–	–	–	0.70b	23.6b	–	–	–
2	37.5	37.5	–	37.5	37.5	150	2.41a	56.3a	21.8b	11.4a	16.1a
3	–	60	–	–	75.8	135.8	2.35a	62.6a	28.7ab	12.2a	17.3a
4	–	60	–	–	82.4	142.4	2.30a	54.7a	21.9b	11.2a	16.2a
5	–	90	–	–	65.8	155.8	2.62a	65.9a	27.2ab	12.3a	16.8a
6	–	90	–	–	52.2	142.2	2.72a	67.8a	31.1ab	14.2a	19.1a
7	20	20	–	20	71.9	131.9	3.61a	74.0a	38.2a	22.1a	27.4a
8	20	20	–	20	55.8	115.8	2.79a	61.9a	33.1ab	18.1a	24.1a
9	30	30	–	30	46	136	3.01a	68.9a	33.3ab	17.0a	22.1a
10	30	30	–	30	38.9	128.9	2.64a	68.1a	34.5ab	15.1a	20.5a
11	30	–	30	–	55.8	115.8	2.91a	67.3a	37.8a	19.1a	25.2a
12	30	–	30	–	60.7	120.7	3.09a	69.7a	38.2a	19.8a	25.6a
13	45	–	45	–	52.2	142.2	3.33a	74.2a	35.6ab	18.5a	23.4a
14	45	–	45	–	45	135	2.74a	66.9a	32.1ab	15.1a	20.3a

Means within a column followed by different letters differ at $P < 0.05$ by Duncan's Multiple Range Test (DMRT).

Treatment # 3, 5, 7, 9, 11 and 13 are based on the algorithm, N fertilizer (kg ha^{-1}) $= \frac{120-(236.53\times NDVI^{2.949})}{0.6}$, and Treatment # 4, 6, 8, 10, 12 and 14 are based on the algorithm, N fertilizer (kg ha^{-1}) $= \frac{120-(132.67\times SI^{-2.926})}{0.6}$.

[a] DAS, Days after sowing.

[b] Sensor-based N application in Treatment # 3 to14.

[c] RE_N: recovery efficiency of applied N (%), AE_N: agronomic efficiency of N (kg grain kg^{-1} N), PFP_N: partial factor productivity of N (kg grain kg^{-1} N).

was determined by digesting the samples in sulphuric acid (H_2SO_4), followed by analysis of total N by the Kjeldahl method (Yoshida et al., 1976).

2.6. Statistical analysis and calculations

Correlation and regression analysis were performed using Statistical Product and Service Solutions (SPSS 18.0). The analysis of variance for yield parameters was conducted to determine the effects of sensor based N management on DDSR performance. Duncan's multiple range test (DMRT) was used at the 0.05 probability level to test differences between treatment means.

The N use efficiency measures, recovery efficiency (RE), agronomic efficiency (AE) and partial factor productivity (PFP) as described by Cassman et al. (1998) were computed as:

$$\mathrm{RE}\ (\%) = \frac{\text{Total N uptake in N fertilized plot} - \text{Total N uptake in plots receiving no N fertilizer}}{\text{Quantity of N fertilizer applied in N fertilized plot}} \times 100$$

$$\mathrm{AE}\ (\text{kg grain kg}^{-1}\ \text{N applied}) = \frac{\text{Grain yield in N fertilized plot} - \text{Grain yield in plots receiving no N fertilizer}}{\text{Quantity of N fertilizer applied in N fertilized plot}}$$

$$\mathrm{PFP}\ (\text{kg grain kg}^{-1}\ \text{N applied}) = \frac{\text{grain yield in N fertilized plot}}{\text{Quantity of N fertilizer applied in N fertilized plot}}$$

3. Results and discussion

3.1. Response of grain yield to nitrogen uptake

The grain yield response to N uptake as observed from the multi-rate N fertilizer treatments generated a high degree of grain yield and N uptake variability from the pooled data of 2011 and 2012 seasons (Fig. 1). Grain yield of DDSR was found to be dependent on N uptake following a polynomial quadratic function (Fig. 1); maximum grain yield was achieved at 138 kg N uptake ha^{-1}. This relationship provides a measure of total N uptake by the crop for achieving a certain grain yield level and it can prove very useful in developing algorithms for improving N fertilizer management strategies. For example, a projected yield of 6.5 Mg ha^{-1} can be achieved at N uptake of 120 kg ha^{-1}; it can be considered as the target N uptake for which N fertilizer application level can be worked out using the algorithm being developed with GS measurements.

3.2. Relationship between NDVI and grain yield

Correlation coefficients of the relation between DDSR grain yield and NDVI measurements made with GS at different dates during crop growth are shown in Fig. 2. These reveal that NDVI measurements at 42 DAS exhibited very low r values with DDSR grain yield recorded at maturity. The relationship tended to improve at 56 DAS ($r = 0.511$). The highest r value (0.797) between NDVI and grain yield was obtained at 70 DAS; it declined to 0.754 and 0.674 at 84 and 98 DAS, respectively. The weak relationship observed at 42 and 56 DAS could be due to low N uptake at early growth stage. The crop growth stage at which the highest r value was recorded (at 70 DAS) coincided with panicle initiation. Low values of coefficients of correlation between grain yield and NDVI at later crop growth stages can be attributed to canopy closure influence on the sensor field of view, as noted by Teal et al. (2006) in maize and Ali et al. (2014) in DDSR. Based on the correlation analysis of the data obtained in the present study, it can be concluded that NDVI readings when recorded at panicle initiation growth stage explain to a large extent the variability in rice yields at maturity. This observation also suggests that panicle initiation growth stage of DDSR is the right growth stage to apply need based N fertilizer using NDVI measurements.

3.3. Development of sensor algorithms for in-season N fertilizer application

The GS estimates NDVI values from the reflectance of red and infrared bands, it is defined by leaf greenness as well as plant biomass. As N uptake by the crop is defined by the product of plant biomass and N content, it should be related to NDVI. Thus, we propose that N application should be based on relationship between sensor readings (NDVI) and N uptake by plant. When total N uptake was regressed against NDVI readings collected at panicle initiation stage of DDSR, a strong power function was observed (Fig. 3). The empirical model that can be used to estimate total N uptake was worked out as:

$$\text{N uptake } (\text{kg ha}^{-1}) = 236.53 \times \text{NDVI}^{2.949}$$

The estimated N uptake and the projected N uptake can provide an estimate of the required amount of N fertilizer to correct N uptake. The difference in N uptake must be divided by an efficiency factor to work out the actual amount of N fertilizer. Peng and Cassman (1998) found that recovery efficiency of N applied at panicle initiation growth stage of rice reaches 74–78%. The average recovery efficiency of N fertilizer at this growth stage in the study area is 60% (Ali, 2014). Therefore, 0.6 has been taken as an efficiency factor to be reasonably achievable under conditions in the north-western India. Hence, the functional algorithm that can be used to define optimum N fertilizer rate using NDVI measurements with GS can be written as:

$$\text{N fertilizer } (\text{kg ha}^{-1}) = \frac{120 - (236.53 \times \text{NDVI}^{2.949})}{0.6}$$

Farmers cannot produce the same yield in the same field every year even if same cultivar is planted at the same date. This is because temporal variability in crop growth has a large impact on yield levels through variable responsiveness of crop to applied N fertilizer. Unfortunately, temporal variability cannot be predicted from one year to the next in advance. However, the concept of sufficiency index (SI) can take care of not only the field to field variability, but also the temporal variability. Mullen et al. (2003) reported that the in-season response index based on NDVI sensor readings from a non-N limiting reference area presented a viable method for identifying environments where the potential to respond to N fertilizer exist. To determine SI in the present study, N fertilizer was applied to a strip at a rate sufficient to ensure that N was not limited (200 kg N ha^{-1}). The sufficiency index was calculated as:

$$\text{SI} = \frac{\text{NDVI of the reference treatment}}{\text{NDVI of the measured treatment}}$$

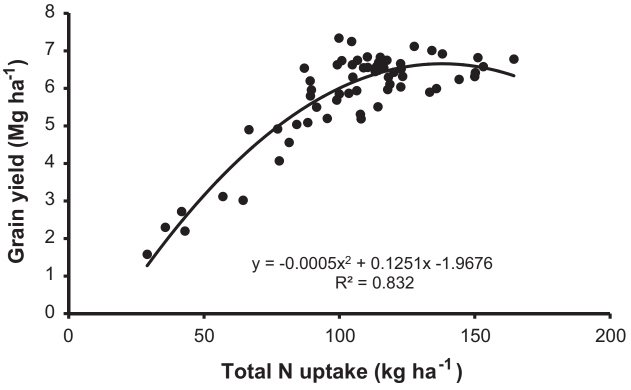

Fig. 1. Relationship between total N uptake and direct-seeded rice grain yields.

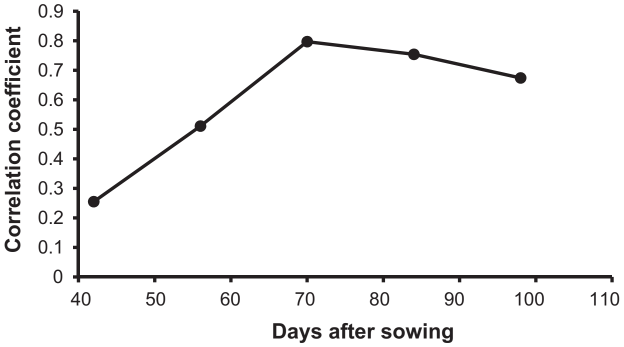

Fig. 2. Evolution of correlation coefficient for NDVI and rice grain yields at different days after sowing.

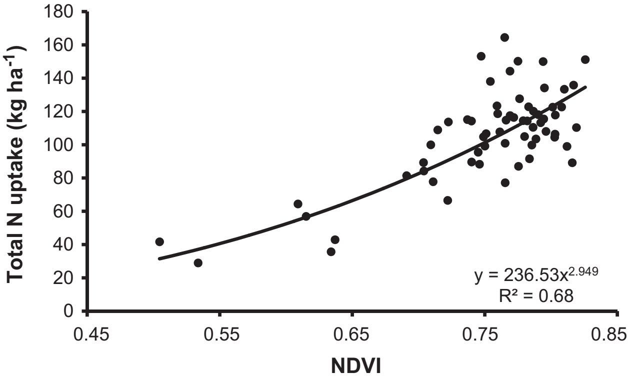

Fig. 3. Relationship between total N uptake and NDVI at panicle initiation growth stage of rice fitted to power function.

Total N uptake was regressed against SI at panicle initiation growth stage and a strong power function was observed (Fig. 4). The empirical model used to estimate total N uptake was found to be:

$$\text{N uptake }(\text{kg ha}^{-1}) = 132.67 \times \text{SI}^{-2.926}$$

With a projected N uptake 120 kg N ha^{-1} and recovery efficiency 60%, the functional algorithm that can be used to define N fertilizer rate based on SI can thus be written as:

$$\text{N fertilizer }(\text{kg ha}^{-1}) = \frac{120 - (132.67 \times \text{SI}^{-2.926})}{0.6}$$

Using this algorithm, response of DDSR to applied N can be worked out in different seasons which in turn can help define in-season complimentary N supply. Fig. 5 depicts the framework used in this study to develop sensor-based N fertilization. This approach can be employed for developing algorithms that can be used in managing N fertilizer for different crops and in diverse environmental conditions.

3.4. Validation of the optical sensor algorithms

Application of 150 kg N ha^{-1} in four equal split doses constitutes the general recommendation of DDSR in Punjab in northwestern India where field experiments reported in the present investigation were conducted. Ali et al. (2014) demonstrated that applying N fertilizer for DDSR as per general recommendation at Ludhiana is higher than the economic N fertilizer application level. Different GS optical sensor-based N fertilizer management scenarios were evaluated for two cultivars PR115 and PR114. In Tables 2 and 3 are shown the prescriptive N management in the form of applying different doses of N fertilizer at different times. Optical sensor-based N management was practiced at panicle initiation growth stage (60 DAS for PR115 and 70 DAS for PR114 cultivars) using the two algorithms as developed in this study. The prescriptive N management scenarios consisting of applying 60 or 90 kg N ha^{-1} at different times were combined with corrective N management as guided by optical sensor (Tables 2 and 3).

The data listed in Tables 2 and 3 show that a statistically similar grain yield was obtained in different N treatments. The mean grain yield ranged between 4.39 and 7.00 Mg ha^{-1} for PR115 cultivar, and 2.30 and 3.61 Mg ha^{-1} for PR114 cultivar. The yields of cultivar PR114 were conspicuously low, possibly because the experiment was established in a loamy sand soil which dries out quickly so that low soil moisture storage becomes a yield limiting factor. At about 85 DAS, the experiment was infected by a fungus disease (brown spots). The disease could not be controlled effectively by the applied fungicide. Consequently, as shown in Table 3, grain yields were lower than the projected. The disease severity was in gradient with replications. We excluded the most infected replication, and the reported data is the average of the two replications.

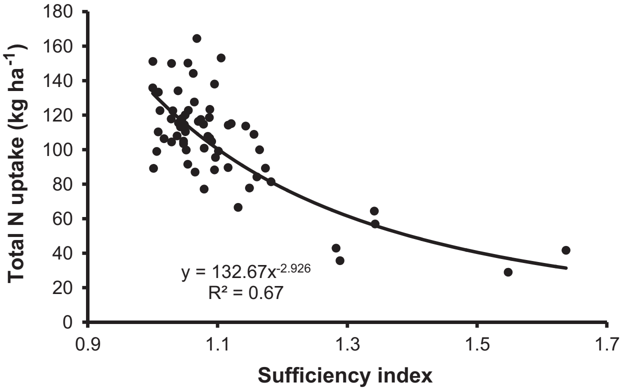

Fig. 4. Relationship between total N uptake and sufficiency index of NDVI at panicle initiation growth stage of rice fitted to power function.

As can be seen from data in Tables 2 and 3, the highest yield was obtained by applying prescriptive dose of 90 kg N ha^{-1} in two or three split doses, or 60 kg N ha^{-1} in two equal split doses along with application of a corrective N fertilizer dose as panicle initiation stage as guided by GS. The GS guided N management overcame the heterogeneity in rice growth caused by different prescriptive N management scenarios. Applying the corrective N management at panicle initiation stage resulted in statistically similar yield in all treatments. The data suggest that rice has a remarkable ability to response to N fertilizer at panicle initiation growth stage, seemingly because of high N demand.

As expected, GS underestimated the N fertilizer needs of DDSR when used close to a N fertilizer application event. For example, when total prescriptive dose of N was applied at 28 DAS, the amount of N fertilizer guided by GS at panicle initiation growth stage turned out to be higher than when similar amount of N was applied in two equal split doses (14 and 42 DAS) or at three equal split doses (14, 28 and 49 DAS). Possibly, it is because N is subjected to losses with passage of time after application of the prescriptive doses of N. Application of large N fertilizer doses at this growth stage (28 DAS) should be susceptible to losses via leaching, volatilization and denitrification. Application of 60 or 90 kg N ha^{-1} in one dose at 28 DAS did not work well due to overestimation of the corrective N fertilizer dose at panicle initiation growth stage. In rice cultivar PR115, application of a prescriptive N dose of 90 kg N ha^{-1} as compared to 60 kg N ha^{-1} at 28 DAS possibly adversely affected growth of DDSR seedlings. The toxicity induced by urea application at early growth has been identified as the main cause responsible for reduced early seedling growth in dry land crops (Bremner, 1995; Qi et al., 2012). This was not encountered in PR114 cultivar because of susceptibility of N to leaching due to lighter texture of the soil as compared to in the field where PR 115 cultivar was grown.

Data pertaining to N use efficiency parameters as listed in Tables 2 and 3 show that the GS guided N treatments resulted in higher use efficiencies as compared to when fertilizer was managed following general recommendation. When appropriate prescriptive N fertilizer applications are followed (60 or 90 kg N ha^{-1} in two or three equal splits) before using a GS sensor-guided N fertilizer application, an average increase (average of Trt7 to Trt14 vs. Trt2) of 12.1% and 13.6% recovery efficiency, 6.3 and 6.7 kg grain kg^{-1} N agronomic efficiency and 16.1 and 7.6 kg grain kg^{-1} N partial factor productivity vis-à-vis general recommendation were observed in PR115 cultivar and PR114 cultivar, respectively. This increase in N-use efficiency parameters was due to production of similar yield, while using less N fertilizer as compared with general recommendation. Therefore, using GS to manage N fertilizer could effectively avoid yield losses with lower rates of N fertilizer and, subsequently, the environment would be less at risk than when N fertilizer is applied following general recommendation for the region. An exception for the high N use efficiency is when prescriptive doses of 60 or 90 kg N ha^{-1} were applied as a single dose at 28 DAS. While producing statistically similar yield, it resulted in lower N use efficiencies as compared to those observed by following general recommendation. Obviously, applied N was not retained in the soil for extended periods and was readily lost from the soil–plant system. The performance of the two algorithms developed in this study is very similar. A possible explanation for this might be that DDSR responsiveness to N fertilizer in the validation year was similar to that in the years when algorithms were established. Keeping in view the findings of this study, further research will be needed to explore

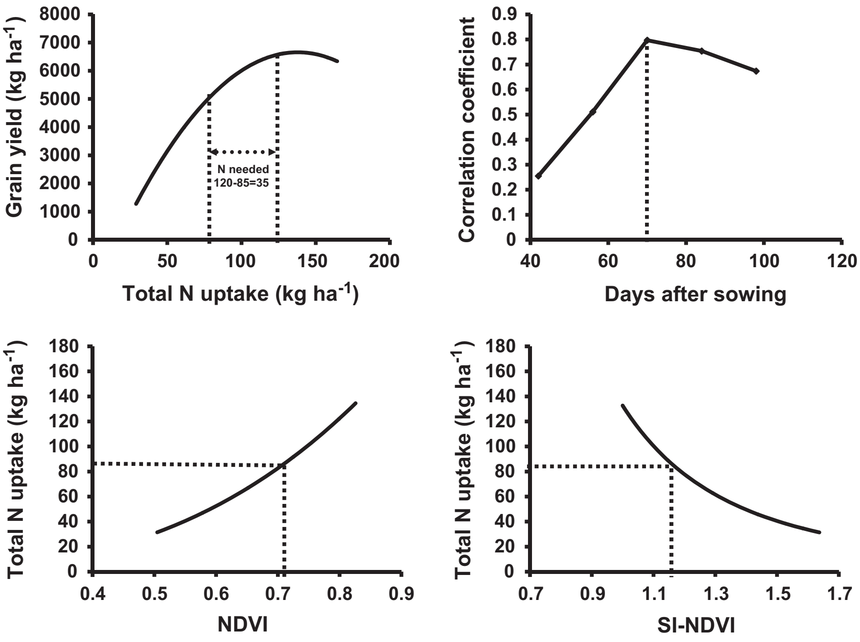

Fig. 5. Depiction of the developed concept for sensor-based recommendation for N fertilization. (a) Response of grain yield to N uptake. (b) Evolution of the correlation coefficients between NDVI readings recorded at different days after sowing and grain yield at maturity. (c) Prediction of N uptake in-season using NDVI explained by power function. (d) Prediction of the in-season N uptake using SI-NDVI based power function.

the differences between the two algorithms when tested under diverse environmental conditions.

4. Conclusions

To improve N fertilizer use efficiency in DDSR, GreenSeeker™ optical sensor can prove to be an effective tool. Measurements made with optical sensor at panicle initiation stage of DDSR could satisfactorily predict the grain yield at maturity. Thus, panicle initiation was found to be the appropriate stage of the crop to apply corrective N fertilizer doses as guided by the optical sensor. Two algorithms for in-season N management based on optical sensor measurements proposed in this study helped maintain high grain yield and high N use efficiency. Prescriptive N fertilizer management consisting of applying 60 in two or 90 kg N ha^{-1} in two or three equal split doses followed by a corrective GS guided N fertilizer application at panicle initiation stage can lead to improved N fertilizer use efficiency without any penalty in yield along with savings in total N fertilizer application as compared with general recommendation. Further testing of the performance of the algorithms based on the SI and NDVI measurements in managing N fertilizer in diverse environmental conditions is needed.

References

Adhikari, C., Bronson, K.F., Panaullah, G.M., Regmi, A.P., Saha, P.K., Dobermann, A., Olk, D.C., Hobbs, P.R., Pasuquin, E., 1999. On-farm N supply and N nutrition in the rice-wheat system of Nepal and Bangladesh. Field Crops Res. 64, 273–286.

Ali, A.M., 2014. Site-specific Nitrogen Management for Dry Direct-Seeded Rice. Ph.D. Dissertation, Punjab Agricultural University, Ludhiana, India.

Ali, A.M., Thind, H.S., Sharma, S., Varinderpal-Singh, 2014. Prediction of dry direct-seeded rice yields using chlorophyll meter, leaf color chart and GreenSeeker optical sensor in northwestern India. Field Crops Res. 161, 11–15.

Bhatia, A., Pathak, H., Jain, N., Singh, P.K., Tomer, R., 2012. Greenhouse gas mitigation in rice–wheat system with leaf color chart-based urea application. Environ. Monit. Assess. 184, 3095–3107.

Bhushan, L., Ladha, J.K., Gupta, R.K., Singh, S., Tirol-Padre, A., Saharwat, Y.S., Gathala, M., Pathak, H., 2007. Saving of water and labor in a rice–wheat system with no-tillage and direct seeding technologies. Agron. J. 99, 1288–1296.

Bijay-Singh, Bronson, K.F., Yadvinder-Singh, Khera, T.S., Pasuquin, E., 2001. Nitrogen-15 balance as affected by rice straw management in a rice-wheat rotation in northwest India. Nutr. Cycl. Agroecosys. 59, 227–237.

Bijay-Singh, Sharma, R.K., Jaspreet-Kaur, Jat, M.L., Martin, K.L., Varinderpal-Singh, Yadvinder-Singh, Chandna, P., Choudhary, O.P., Gupta, R.K., Thind, H.S., Uppal, H.S, Jagmohan-Singh, Khurana, H.S., Ajay-Kumar, Uppal, R.K., Vashistha, M., Raun, W.R., Gupta, R.K., 2011. Assessment of the nitrogen management strategy using an optical sensor for irrigated wheat. Agron. Sust. Dev. 31, 589–603.

Bremner, J.M., 1995. Recent research on problems in the use of urea as a nitrogen fertilizer. Fert. Res. 42, 321–329.

Cassman, K.G.S., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Doberman, A., Singh, U., 1998. Opportunities for increased nitrogen use efficiency from improved resource management in irrigated rice systems. Field Crops Res. 56, 7–38.

Davidson, E.A., 1991. Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers, J.E., Whitman, W.B. (Eds.), Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes. The American Society of Microbiology, Washington, DC, pp. 219–235.

Dobermann, A., Witt, C., Abdulrachman, S., Gines, H.C., Nagarajan, R., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Simbahan, G.C., Adviento, M.A.A., 2003. Soil fertility and indigenous nutrient supply in irrigated rice domains of Asia. Agron. J. 95, 913–923.

Inman, D., Khosla, R., Westfall, D.G., Reich, R., 2005. Nitrogen uptake across site specific management zones in irrigated corn production systems. Agron. J. 97, 169–176.

Khade, V.N., Patil, B.D., Khanvilkar, S.A., Chavan, L.S., 1993. Effect of seeding rates and level of N on yield of direct-seeded (Rahu) summer rice in Konkan. J. Maharashtra Agric. Univ. 18, 32–35.

Ko, J.Y., Kang, H.W., 2000. The effects of cultural practices on methane emission from rice fields. Nutr. Cycl. Agroecosys. 58, 311–314.

Kropff, M.J., Cassman, K.G., Van Larr, H.H., Peng, S., 1993. Nitrogen and yield potential of irrigated rice. Plant Soil 155 (156), 391–394.

Kumar, V., Ladha, J.K., 2011. Direct seeding of rice: recent developments and future research needs. Adv. Agron. 111, 297–413.

Ladha, J.K., Pathak, H., Krupnik, T.J., Six, J., Van-Kessel, C., 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv. Agron. 87, 85–156.

Mullen, R.W., Freeman, K.W., Raun, W.R., Johnson, G.V., Stone, M.L., Solie, J.B., 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95, 347–351.

Olsen, S., Cole, C., Watanabe, F., Dean, L., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular Nr 939, US Gov. Print. Office, Washington, D.C.

Peng, S., Cassman, K.G., 1998. Upper threshold of nitrogen uptake rates and associated nitrogen fertilizer efficiencies in irrigating rice. Agron. J. 90 (2), 178–185.

Pratt, P.F., 1965. Potassium. In: Black et al., C.A. (Ed). Methods of Soil Analysis, Part 2. Agronomy, vol. 9, Amer. Soc. Agron., Meddison, Wis., pp. 1023–1031.

Qi, X., Wu, W., Peng, S., Shah, F., Huang, J., Cui, K., Liu, H., Nie, L., 2012. Ammonia volatilization from urea application influenced germination and early seedling growth of dry direct-seeded rice. Sci. World J. (Article ID 857472).

Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Lukina, E.V., Thomason, W.E., Schepers, J.S., 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93, 131–138.

Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Mullen, R.W., Freeman, K.W., Thomason, W.E., Lukina, E.V., 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94, 815–820.

Raun, W.R., Solie, J.B., Stone, M.L., Martin, K.L., Freeman, K.W., Mullen, R.W., Zhang, H., Schepers, J.S., Johnson, G.V., 2005. Optical sensor-based algorithm for crop nitrogen fertilization. Commu. Soil Sci. Plant Anal. 36, 2759–2781.

Sharma, P.K., Bhushan, L., Ladha, J.K., Naresh, R.K., Gupta, R.K., Balasubramanian, V., Bouman, B.A.M., 2002. Crop–water relations in rice–wheat cropping systems and water management practices in a marginally sodic, medium-textured soil. In: Bouman, B.A.M. et al. (Eds.), Water-Wise Rice Production. IRRI, Los Baños, Philippines, pp. 223–235.

Singh, G.R., Singh, T.A., 1988. Leaching losses and use efficiency of nitrogen in rice fertilized with urea supergranules. J. Ind. Soc. Soil. Sci. 36, 274–279.

Sudhir-Yadav, Humphreys, E., Kukal, S.S., Gill, Gurjeet, Rangarajan, R., 2011. Effect of water management on dry seeded and puddled transplanted rice. Part 2. Water balance and water productivity. Field Crops Res. 120, 123–132.

Teal, R.K., Tubana, B.S., Girma, K., Freeman, K.W., Arnall, D.B., Walsh, O., Raun, W.R., 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98, 1488–1494.

Varinderpal-Singh, Bijay-Singh, Yadvinder-Singh, Thind, H.S., Gupta, R.K., 2010. Need based nitrogen management using the chlorophyll meter and leaf colour chart in rice and wheat in South Asia: a review. Nutr. Cycl. Agroecosys. 88, 361–380.

Walkley, A., Black, I.A., 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–37.

Yoshida, S., Forno, D.A., Cock, D.H., Gomez, K.A., 1976. Laboratory Manual for Physiological Studies of Rice, third ed. International Rice Research Institute, Los Baños.