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Active canopy sensor-based precision N management strategy for rice

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Abstract China consumes more than 1/3 of global N fertilizers for rice with less than 1/5 of the world rice planting area. As a consequence, N efficiency is low and nitrate pollution risk is high. Developing efficient N management strategies and technologies for rice are therefore needed. Here, we developed an active canopy sensor-based precision N management strategy for rice in Northeast China. Four site-years of field N rate experiments were conducted in 2008 and 2009 in Sanjiang Plain, Heilongjiang, China. The GreenSeeker active sensor was used to collect rice canopy reflectance data at different growth stages. Three on-farm experiments were conducted in 2011 to evaluate the performance of the developed strategy. The results show

that the crop sensor can be used to calculate rice yield potential without additional topdressing N application at stem elongation or booting stage. The GreenSeeker-based precision N management strategy has a regional optimum N rate of 90–110 kg N ha⁻¹ as initial total amount and 45 and 20 % as basal and tillering N application. It uses the crop sensor to estimate the topdressing N rate at stem elongation stage. GreenSeeker-based precision management and chlorophyll meter-based site-specific N management increased the partial factor productivity of farmers by 48 and 65 %, respectively, without significant change in grain yield. The crop sensor-based N management strategy can therefore improve N use efficiency of rice. It is more suitable for practical on-farm applications, and will contribute to the sustainable development of rice farming.

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1 Introduction

Rice (*Oryza sativa* L.) is the most important cereal crop for human consumption in the world, being the staple food for more than 3 billion people (Cantrell and Teeves 2002). Using 19 % of the world's rice planting area, China accounted for 29 % of the world's total annual rice production in 2006 (FAOSTAT 2008), but consumed 36 % of nitrogen (N) fertilizer used for rice production in the world (Peng et al. 2010). Over-application of N fertilizers as well as improper timing are among the major problems for rice management in China, and have resulted in very low N use

efficiencies (NUE) among major rice production countries (Peng et al. 2009). Therefore, developing efficient N management strategies and technologies for rice is crucially important for agricultural sustainability and food security.

Scientists at International Rice Research Institute have developed site-specific N management (SSNM) strategy to improve NUE of rice (Dobermann et al. 2002; Peng et al. 2010). The first step in this approach is to set an attainable yield target, and then estimate indigenous N supply, represented by yield without N fertilizer application. N response can then be estimated by calculating the yield difference between target yield and yield without receiving N application. With realistic agronomic NUE (agronomic N efficiency (AE_N)), the N application rate can be estimated. The total N rate is usually split into four doses, with 35, 20, 30, and 15 % being applied before transplanting, at mid-tillering, panicle initiation, and heading stages, respectively. In-season adjustments of $\pm 10 \text{ kg N ha}^{-1}$ will be made for the actual rates at mid-tillering and panicle initiation based on leaf N status estimated by chlorophyll meter or leaf color chart (Peng et al. 2010). This practice has been evaluated in different parts of China during the past decade, and reduced an average of 32 % of N fertilizer and increased yield by 5 % compared with farmer's practice (Peng et al. 2010). Given the success, its wider adoption is limited by several factors. The yield at N-omission plots, target yield, N response, and AE_N in a given year are influenced by many factors, and difficult to be estimated accurately, so the total N rate is only a rough estimate. The in-season adjustment of $\pm 10 \text{ kg N ha}^{-1}$ may not be adequate to really meet the crop N need. Monitoring leaf N status using chlorophyll meter or leaf color chart is still time-consuming for large fields, and their threshold values need to be adjusted frequently due to changes of varieties, making it difficult for most farmers to implement in their fields. After discussing these limitations, Peng et al. (2010) pointed out that remote sensing technologies may be able to overcome some of these problems.

Crop canopy sensors can be used to estimate crop growth in a population or community rather than individual plant or leaf, and are more efficient and suitable for large scale applications than leaf sensors (Xue and Yang 2008). Many studies have been conducted to estimate rice growth and N status using crop canopy sensors (Nguyen et al. 2006; Stroppiana et al. 2009; Bajwa et al. 2010). For practical in-season site-specific management applications, the crop sensor should be active, having its own light source to be weather independent. It should preferably be multispectral to reduce the cost compared with hyperspectral sensors. An algorithm should also be developed to relate sensor readings not only to rice N status, but to specific N recommendation rates as well.

GreenSeeker handheld sensor (Trimble Navigation Limited, Sunnyvale, CA, USA) is an active optical crop canopy sensor with a red ($650 \pm 10 \text{ nm}$) and a NIR ($770 \pm 15 \text{ nm}$)

waveband. A nitrogen fertilizer optimization algorithm (NFOA) has been developed to make in-season N recommendation for winter wheat (*Triticum aestivum* L.) by Ruan et al. (2002, 2005). In this approach, potential yield with no additional N (YP_0) can be estimated before N topdressing by in-season estimate of yield (INSEY), which is calculated by dividing normalized difference vegetation index (NDVI), collected by the GreenSeeker sensor, by the number of days from planting to the date of sensing with growing degree days greater than 0°C (Raun et al. 2002). Then an in-season response index (RI) is determined by dividing NDVI at plots or strips receiving nonlimiting N application by NDVI at fields to be fertilized or receiving no N application (RI_{NDVI}). The RI_{NDVI} determined in-season can be used to estimate the crop responsiveness to additional N application (Hodgen et al. 2005). The potential yield with added N fertilization (YP_N) can be estimated by multiplying YP_0 and RI. The N requirement is estimated by multiplying yield response (subtracting YP_0 from YP_N) by grain N concentration and average NUE. This in-season N management approach has been successfully evaluated for wheat in USA (Raun et al. 2002), Mexico (Ortiz-Monasterio and Raun 2007), China (Li et al. 2009a; Cao et al. 2012), and India (Bijay-Singh et al. 2011).

Will the GreenSeeker crop sensor-based precision N management (PNM) strategy work for rice? Can we use the sensor to predict rice yield potential and responses to additional N fertilizers before topdressing N application? Up to date, little research has been reported to answer these questions. Xue and Yang (2008) used a multispectral CropScan sensor to calculate NDVI and modified the NFOA algorithm for rice. They increased AE_N by 20 % compared with standard N management practice in Jiangsu Province of south China. One of the important technical problems in using optical sensors in transplanted rice is the interference of water standing on the soil surface in reflectance measurements. However, this interference should be minimized if optical sensor measurements are made at an advanced stage of rice crop when crop canopy is fully developed. The objective of this study is to evaluate the potential of developing GreenSeeker canopy sensor-based in-season site-specific N management strategy for rice in Northeast China, which is a fast-growing rice-farming region crucial for China's food security (Fig. 1).

2 Materials and methods

2.1 Study site

The study area is located in the Sanjiang Plain (47.2°N , 132.8°E), which is an alluvial plain of three rivers, Heilongjiang, Songhua, and Wusuli River and covers about $108,900 \text{ km}^2$ in Heilongjiang Province, Northeast China. It is bordered by Siberia in the north and east. The mean



Fig. 1 Large-scale rice farming in Jiansanjiang, Heilongjiang Province, Northeast China. Each farmer's household manages an average of about 25 ha land. Jiansanjiang has 740,000 ha arable land, and 86 % is rice. The commercial grain rate is about 95 %, making this region increasingly important for China's food security

annual air temperature is about 1–2 °C and the mean yearly precipitation ranges from 500 to 600 mm (Wang and Yang 2001). Average temperatures reach −18 °C in January and 21–22 °C in July. The frost-free period is only about 120–140 days long (Zhang et al. 2009). The maximum values of temperature and precipitation are both observed in July and August. The rainfall from June to September covers about 72 % of the annual amount, with 59 % of the yearly precipitation occurring from June to August (Yan et al. 2002).

Originally, the Sanjiang Plain was dominated by marshes but it was converted to agricultural production about 60 years ago, and during the past two decades, rice farming has become dominant in this region. The most abundant soils are wet black clays with a general thickness of more than 20 cm. The soils offer high concentrations of organic matter and nutrients, being very favorable for agricultural production (Zhou and Liu 2005).

Two sites were selected for this study, with the same soil type (Albic soil). Rice has been continuously planted since 1992 at site 1, while site 2 has a shorter rice planting history, starting from 2002. For site 1 in 2008, soil pH, organic matter, available N, Olsen phosphorous (P), and available potassium (K) were 5.9 g kg^{−1}, 35.1 g kg^{−1}, 157 mg kg^{−1}, and 30 mg kg^{−1}, respectively. For site 1 in 2009, the corresponding soil properties were 5.9 g kg^{−1}, 36 g kg^{−1}, 202 mg kg^{−1}, 10.8 mg kg^{−1}, and 141 mg kg^{−1}, respectively. Soil pH in site 2 was 6 for both years, while organic matter, available N, Olsen P and available K were 32.9 g kg^{−1}, 175 mg kg^{−1}, 37 mg kg^{−1}, and 121 mg kg^{−1}, respectively in 2008. They were 35.8 g kg^{−1}, 115 mg kg^{−1}, 29.9 mg kg^{−1}, and 201.6 mg kg^{−1}, respectively, in 2009.

2.2 Nitrogen rate experiments

Field experiments were conducted from 2008 to 2009 at these two sites to develop relationships between INSEY

and YP₀, as well as RI calculated with GreenSeeker sensor data and harvested yield data (response index at harvest (RI_{HARVEST})). A randomized split plot design with four blocks was used, with the exception of three blocks at site 2 in 2009. The main plot consisted of five N rates: 0, 35, 70, 105, and 140 kg N ha^{−1}, which were applied as three splits: 45 % as basal N before transplanting, 20 % at tillering stage, and 35 % at stem elongation stage. In order to evaluate the potential of using GreenSeeker sensor to estimate rice yield potential without the third N application (YP₀) at stem elongation stage, each plot was divided into two parts: 10×10 m as the main plot and 5×10 m as the subplot without receiving the third N application. In 2009, three additional N treatments were included for evaluating different N management strategies, with the basal and tillering N application being the same as the treatment of 105 kg ha^{−1}, but the third N application was adjusted based on in-season N diagnosis. Since this is not the focus of this study, we would not discuss the results of these treatments, but only use data from the subplots not receiving the third N application to develop the N management strategy. For all treatments, 60 kg P₂O₅ and 75 kg K₂O ha^{−1} in the form of Ca (H₂PO₄)₂ and KCl were incorporated into the soil before transplanting. The N source for all experiments was urea. Rice seedlings were prepared in greenhouse and transplanted into the experimental fields on May 29 (site 1) and May 13 (site 2) in 2008 and May 24 (site 1) and May 20 (site 2) in 2009, respectively. A widely used rice variety in this region, Kongyu 131, was used for all the experiments.

2.3 On-farm evaluation experiments

Three on-farm experiments were conducted in cooperation with three farmers in 2011 to evaluate the GreenSeeker-based precision N management strategy (PNM-GS) vs. chlorophyll meter-based SSNM strategy (SSNM-CM) and farmer's practice (FP). For FP, all the three farmers applied a total of 150 kg N ha^{−1}, but the first two farmers applied 60 kg ha^{−1} as basal fertilizer, 30 kg ha^{−1} 5 days after transplanting (regreening), and 60 kg ha^{−1} at tillering stage, while the third farmer's field was newly converted from corn field to rice farming, and the farmer applied 27 kg ha^{−1} as basal fertilizer, 28 kg ha^{−1} 5 days after transplanting, 88 kg ha^{−1} at tillering, and 7 kg ha^{−1} at stem elongation. For the first two farmers, the SSNM-CM strategy applied 40 kg ha^{−1} as basal fertilizer, 20 kg ha^{−1} 5 days after transplanting, the topdressing N rates at panicle initiation and booting stages were adjusted based on chlorophyll meter values, and a fixed rate of 10 kg ha^{−1} was applied at heading stage. For the third farmer's field, 27 and 25 kg ha^{−1} were applied as basal and regreening fertilizer, respectively, 9.2 kg ha^{−1} at tillering and the topdressing N rate at stem elongation stage was adjusted

based on chlorophyll meter values. Different chlorophyll meter threshold values were used for different varieties (40–42 for Kenjiandao 6, 39–41 for Longjing 29, and 38–40 for Longjing 26 and Kongyu 131). When the chlorophyll meter readings were below the threshold values, topdressing N rate will be increased 10 kg ha⁻¹, if the readings were in the optimum range, then the topdressing rate will be applied as originally planned. If the chlorophyll meter readings are above the threshold values, then topdressing N rate will be reduced by 10 kg ha⁻¹. For the GreenSeeker-based PNM strategy, the basal N rate was the same as SSNM-CM, the first topdressing rate at regreening was 25 kg ha⁻¹, and the second topdressing at stem elongation was estimated based on the GreenSeeker sensor-based method as developed in this study. The details of N application for different N management strategies are given in Table 1. P and K fertilizer application and other management followed the regional recommendations.

2.4 GreenSeeker sensor data collection

The GreenSeeker hand-held optical reflectance sensor was used in this research. It uses active radiation from red and near-infrared band independent of solar conditions. The device uses the software to calculate NDVI and ratio vegetation index (RVI, NIR/Red) directly and generates sensor readings at a rate of 10 readings per second. Sensor readings (NDVI and RVI) were collected 0.5 m above the rice canopy across each plot, except plants near the plot borders, and the average values were used to represent each plot. Sensor readings were collected at five different stages in 2008 and 2009 (panicle initiation, stem elongation, booting, before heading, and heading stage). The third topdressing N is usually applied at stem elongation, and there is a possibility of delayed application to booting stage due to

weather, labor, or other practical limitations in production agriculture, so only data from these two stages were used for this study.

2.5 Plant sampling and measurements

Aboveground biomass was measured destructively by randomly clipping three to five hills of scanned rice plants with average tillers of each plot following each GreenSeeker sensor data collection in each plot. All plant samples were rinsed with water, and roots were removed, then the aboveground plant biomasses were put into oven at 105 °C for 30 min, and then dried at 70 °C to constant weight. The samples were later weighed, ground, and analyzed for N concentration using the Kjeldahl-N method. Rice was harvested in mid-September. Yield was determined by harvesting three 1 m² area of each plot and adjusted to a moisture content of 14 %.

2.6 Statistical analysis

The INSEY was calculated as NDVI (or RVI) divided by the number of growing degree days (GDD)>0 from transplanting to sensing. The GDD is calculated using the following equation:

$$\text{GDD} = \frac{(T_{\min} + T_{\max})}{2} - 12.5^{\circ}\text{C} \quad (1)$$

where $T_{\min}$ and $T_{\max}$ represent daily ambient low and high temperatures.

$\text{RI}_{\text{HARVEST}}$ indicates the actual crop response to applied N (Johnson and Raun 2003) and was calculated as follows:

$$\text{RI}_{\text{HARVEST}} = \frac{\text{Yield}_{\text{Nrich}}}{\text{Yield}_{\text{CK}}} \quad (2)$$

Table 1 Nitrogen application details for the on-farm experiments conducted to evaluate GreenSeeker sensor-based N management in 2011

Field	Treatment	Base N kg ha ⁻¹	Topdressing N_1st kg ha ⁻¹	Stage	Topdressing N_2nd kg ha ⁻¹	Stage	Topdressing N_3rd kg ha ⁻¹	Stage	Topdressing N_4th kg ha ⁻¹	Stage	Total N kg ha ⁻¹
1	FP	60	30	RG	60	Tillering	0				150
	SSNM	40	20	RG	15	PI	20	Booting	10	Heading	110
	PNM	40	25	RG	29.4	SE	0				94.4
2	FP	60	30	RG	60	Tillering	0				150
	SSNM	40	20	RG	15	PI	20	Booting	10	Heading	110
	PNM	40	25	RG	43.5	SE	0				108.5
3	FP	27	28	RG	88.4	Tillering	7	SE			150.4
	SSNM	27	25	RG	9.2	Tillering	30	SE			91.2
	PNM	27	25	RG	9.2	Tillering	39	SE			100.2

FP farmer's practice; SSNM site-specific N management guided by chlorophyll meter diagnosis; PNM precision N management guided by GreenSeeker sensor readings; RG regreening stage, 5 days after transplanting; PI Panicle initiation; SE stem elongation

where Yield_Nrich is the average yield of plots receiving sufficient N application, and Yield_CK is the average yield of a check plot or plot without receiving the third N application at stem elongation stage.

In-season RIs (RI_{NDVI} and RI_{RVI}) were calculated in the same way as $RI_{HARVEST}$, with the exception that NDVI or RVI was used instead of yield. The yield potential with additional N (YP_N) was calculated by multiplying YP_0 and $RI_{HARVEST}$ estimated by RI_{NDVI} (or RI_{RVI}). In the above analyses, the 140 kg N ha⁻¹ treatment was used as N rich treatment. Correlation, regression, and analysis of variance were conducted using STATISTICA 6.0 (StatSoft, Inc., Tulsa, OK, USA) and MicroSoft Excel (MicroSoft Cooperation, Redmond, WA, USA).

3 Results and discussion

3.1 Rice grain yield as affected by different nitrogen rates at different site-years

Rice grain yield was increased significantly by N fertilizer application, and generally reached a plateau at 105 kg ha⁻¹ (Fig. 2), even though results of analysis of variance indicated that yield at 105 kg ha⁻¹ were not significantly different from yield at 70 or 140 kg N ha⁻¹. Site 2 consistently had higher grain yield at any N rate or in any of the 2 years, indicating that site 2 had better soil fertility, with higher soil P content than site 1, even though they had similar soil pH and organic matter content. After over 20 years of continuous rice planting, site 1 may be deficient in certain micro-nutrients, because only N, P, and K fertilizers are generally applied. Compared with 2008, 2009 had a very cool, rainy, and cloudy growing season, especially in June and July, which significantly reduced grain yield as well as responses to N fertilizer application as compared with 2008. These results demonstrate the need for site-specific and in-season

N management, because yield potential is significantly influenced by soil properties, management history, and weather conditions.

3.2 In-season prediction of rice yield potential

Current N recommendation strategies are mainly “yield-based”, setting a yield goal at the beginning of the growing season to estimate N requirements adjusted for various N credits, using an average grain N concentration and NUE (Shanahan et al. 2008). A major challenge to this approach is the difficulty to accurately estimate the yield goal before the season, because yield potential is greatly influenced by year-to-year variation in weather conditions. Even with irrigated crops, yield potential can still vary significantly from year to year due to variation in solar radiation and temperature (Schlegel 2005; Shanahan et al. 2008). Over- or under-estimation of yield goal will result in over- or under-recommendation of N fertilizers, leading to decreased NUE and environmental risks or limitation of yield. This temporal variability is as important as, or even more important than, spatial variability in crop N requirements, and should be better managed (Miao et al. 2011).

A better strategy is to set a realistic initial yield goal at the beginning of the growing season, based on our best knowledge of past yield histories, soil fertility, and productivity and characteristics of varieties to be used as well as management practices under normal weather condition. Basal N rate can be determined based on this initial yield goal and the corresponding N requirements for the early growth period. Before topdressing, the initial yield goal can be adjusted based on the diagnosis of rice plant growth, and weather conditions from transplanting to the stage for topdressing, and this adjusted yield goal is used to estimate new N requirement and topdressing N rate.

Before N topdressing, it is important to know how much yield can be achieved without YP_0 . This information can be used to estimate the amount of N already accumulated by the plant before topdressing, plus the amount of N to be supplied by the soil during the later part of the growing season. The INSEY is an estimate of daily growth rate or biomass production before topdressing and can be used to estimate yield potential (Shanahan et al. 2008).

At site 1, INSEY calculated with NDVI (INSEY (NDVI)) was linearly related with YP_0 at stem elongation stage ($R^2=0.67$). At booting stage, the relationship was polynomial and stronger ($R^2=0.72$) as compared with that at stem elongation stage (Table 2). INSEY calculated with RVI (INSEY (RVI)) showed similar relationship as INSEY(NDVI) at site 1, with R^2 being 0.69 and 0.74 at stem elongation and booting stages, respectively (Table 2).

At site 2, the relationship between INSEY (NDVI) and YP_0 was polynomial for both of the two stages, with R^2

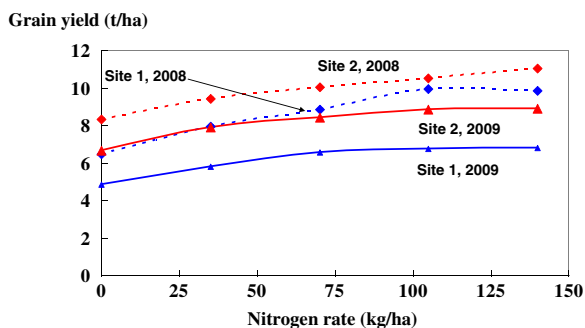


Fig. 2 Rice grain yield as affected by different N rates at different site-years. In general, rice yield reached a plateau at 105 kg N ha⁻¹. Note the higher rice yield at site 2 than site 1, and in 2008 than 2009. Rice yield was relatively more responsive to N application in 2008 than 2009

Table 2 Relationships between yield without additional topdressing N application (YP_0) and in-season estimate of yield estimated with GreenSeeker values ($INSEY_{NDVI}$ and $INSEY_{RVI}$) at different sites and growth stages across 2008 and 2009

Site	Stage	Index	Equation	R^2
1	SE	NDVI	$Y=427.56X+1.065$	0.67
1	SE	RVI	$Y=41.59X+2.93$	0.69
1	Booting	NDVI	$Y=349,260X^2-7416.22X+44.76$	0.72
1	Booting	RVI	$Y=841.29X^2-117.80X+9.66$	0.74
2	SE	NDVI	$Y=30,035X^2-355.28X+7.76$	0.50
2	SE	RVI	$Y=38.57X+4.80$	0.56
2	Booting	NDVI	$Y=268,839X^2-5214.01X+31.49$	0.76
2	Booting	RVI	$Y=508.36X^2-63.53X+8.64$	0.78
1 and 2	SE	NDVI	$Y=386.90X+2.39$	0.44
1 and 2	SE	RVI	$Y=39.92X+3.80$	0.52
1 and 2	Booting	NDVI	$Y=236,360X^2-4643.79X+28.66$	0.59
1 and 2	Booting	RVI	$Y=624.45X^2-77.79X+8.31$	0.73
1 and 2	SE and booting	NDVI	$Y=443.65X+1.86$	0.36
1 and 2	SE and booting	RVI	$Y=40.62X+3.48$	0.52

SE stem elongation stage

being 0.50 and 0.76, respectively. The relationship between $INSEY$ (RVI) and YP_0 was linear and polynomial at stem elongation ($R^2=0.56$) and booting stage ($R^2=0.78$), respectively (Table 2).

Combining all site-years, $INSEY$ (NDVI) was linearly related with YP_0 at stem elongation stage ($R^2=0.44$), while the relationship was polynomial at booting stage ($R^2=0.59$; Table 2). The relationship was significantly improved with $INSEY$ (RVI) with R^2 being 0.52 and 0.73 for stem elongation and booting stages, respectively (Table 2, Fig. 3).

Considering practical application of this technology, farmers may apply topdressing N during a window from stem elongation to booting stages, and it would be more convenient if a model could be used to predict YP_0 across this period. Using sensing data from stem elongation to booting stage across site-years, $INSEY$ (NDVI) and $INSEY$

(RVI) could explain 36 and 52 % of YP_0 variability (Table 2).

For sensor-based N management strategies, NDVI has always been used to calculate $INSEY$ to predict grain yield of wheat (Raun et al. 2002, 2005; Li et al. 2009a; Bijay-Singh et al. 2011; Thomason et al. 2011), corn (Teal et al. 2006), and rice (Xue and Yang 2008). However, our results indicated that RVI may be a better index for calculating $INSEY$ and estimating rice grain yield in Northeast China, especially when data from higher-yielding site (site 2) were included. It has been reported that RVI was more sensitive to high crop biomass than NDVI, while NDVI performed better during early vegetative growth stage (Wanjura and Hatfield 1987; Raun et al. 2001). Li et al. (2010) also found that NDVI became saturated at winter wheat biomass of 3.7 t ha^{-1} , while RVI was linearly related to biomass.

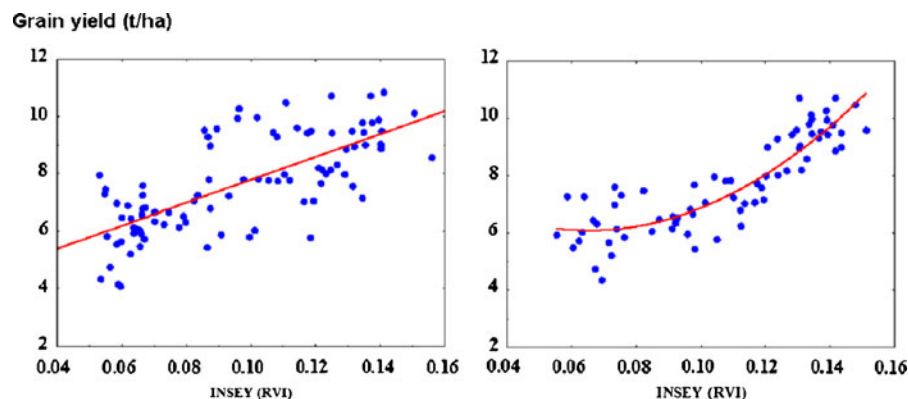


Fig. 3 Relationship between in-season estimate of yield calculated using ratio vegetation index ($INSEY$ (RVI)) with rice grain yield without topdressing nitrogen application (YP_0) at stem elongation (left) and booting (right, $Y=624.45X^2-77.79X+8.31$, $R^2=0.73$, $P<0.001$) stages across site-years. Note the better relationship at later growth

stage (booting) than at stem elongation stage and the difference of the relationship: linear at stem elongation and polynomial at booting stage ($Y=39.92X+3.80$, $R^2=0.52$, $P<0.001$ for stem elongation, and $Y=624.45X^2-77.79X+8.31$, $R^2=0.73$, $P<0.001$ for booting stage)

3.3 In-season prediction of rice responsiveness to topdressing nitrogen application

After estimating YP_0 , the next important question is how rice yield will respond to additional topdressing N fertilizer application. N topdressing rate will be positively related to this responsiveness.

At site 1, both RI_{NDVI} and RI_{RVI} were significantly correlated with $RI_{HARVEST}$ at stem elongation stage, with R^2 being 0.43 and 0.59, respectively (Table 3). However, the correlation was not significant at site 2. Across site-years at stem elongation stage, R^2 was 0.22 and 0.29 for RI_{NDVI} and RI_{RVI} , respectively (Table 3). At booting stage, however, the relationships between $RI_{HARVEST}$ and RI_{NDVI} or RI_{RVI} at both sites or across site-years were weaker than at stem elongation stage, with R^2 s being less than 0.3 (Table 3). Across site-years and growth stages (from stem elongation to booting stage), the R^2 was 0.24. These results are different from those achieved with winter wheat in Oklahoma (Mullen et al. 2003) or India (Bijay-Singh et al. 2011). Mullen et al. (2003) got R^2 of 0.56, 0.77, and 0.70 at Feekes stage 5, 9, and 10.5, respectively, for $RI_{HARVEST}$ and RI_{NDVI} , while Bijay-Singh et al. (2011) achieved R^2 of 0.90 at Feekes stage 5–6 or 7–8. Mullen et al. (2003), however, only used data from check plots (0 kg N ha⁻¹) and N rich plots, while we used data from all the different N rate treatments without receiving the third topdressing N application. Another significant difference is that their yield was not more than 4.5 t ha⁻¹, while in our study, the check plots could produce grain yield over 4.5 t ha⁻¹, and could even reach over 8 t ha⁻¹, and the

plots receiving sufficient N applications could produce over 10 t ha⁻¹ grain yield (Fig. 2). At these high yield levels, the NDVI values would become saturated at booting stage, when the average plant biomass of each treatment varied from 2,030 to 8,280 kg ha⁻¹ across site-years and N rates (data not shown). Li et al. (2010) found that GreenSeeker NDVI became saturated when winter wheat biomass reached 3736 kg ha⁻¹. This result indicates the limitation of GreenSeeker sensor for plant N status diagnosis and N management at later growth stages under high-yielding conditions.

3.4 Strategy for in-season site-specific nitrogen management of rice

For rice production in China, N application rates by farmers varied greatly across the country. Based on a national survey conducted in 2000 and 2002, the average N application rate for rice was 215 kg ha⁻¹, but the provincial or regional average N rates ranged from 153 to 341 kg ha⁻¹ (Zhang et al. 2007). The average N application rate is around 150 kg ha⁻¹ in Heilongjiang Province, the lowest in China, but farmer application rates varied from 34.5 to 353.6 kg ha⁻¹, based on a survey conducted in 2004 (Peng et al. 2007). In a recent survey conducted in Qixing Farm of Heilongjiang Province in 2009 and 2010, farmer N application rates for rice varied from 48 to 209 kg ha⁻¹. Considering the real situation of China with great number of small rice plots, and the general lacking in soil and plant testing services in the countryside, Zhu (2006) proposed a practical regional optimum N rate (RONR) strategy for rice N management. In this strategy, a regional optimum N rate is recommended for the whole region to avoid significant over- or under-application problems, and then adjust the rate based on soil fertility, variety, management history, and planting dates, etc. for a specific field. Their results indicated that in Changshu, Jiangsu Province, the site-specific optimum N rates ranged from 182 to 273 kg ha⁻¹ and RONR was 218 kg ha⁻¹. Using the RONR, rice yield was only reduced by 0.3 % compared with site-specific optimum N rates.

After knowing the RONR, there is a need to split the N into three or four doses. Currently, most farmers apply the N in two or three split doses at early growing season (basal, regreening, and tillering applications) without considering crop N needs at later growth stages. Based on previous research and the results of this study, the RONR for Sanjiang Plain can be set to 100–105 kg ha⁻¹ and split into four doses: 45, 20, 15, and 20 % for basal, early tillering, panicle initiation, and meiotic stages, respectively, to optimize grain yield and quality (Zhao 2008; Li et al. 2009b).

Based on the above discussions, a practical precision N management strategy in Sanjiang Plain of Northeast China can use 90–110 kg N ha⁻¹ as RONR, and apply 45 and 20 % as basal and tillering fertilizers, respectively. At stem

Table 3 Relationships between response index calculated with yield ($RI_{HARVEST}$) and response index calculated with GreenSeeker values (RI_{NDVI} and RI_{RVI}) at different sites and growth stages across 2008 and 2009

Site	Stage	Index	Equation	R^2
1	SE	NDVI	$Y=1.18X-0.02$	0.43
1	SE	RVI	$Y=0.89X+0.24$	0.59
1	Booting	NDVI	$Y=0.97X+0.16$	0.17
1	Booting	RVI	$Y=0.39X+0.73$	0.22
2	SE	NDVI	NS	NS
2	SE	RVI	NS	NS
2	Booting	NDVI	NS	NS
2	Booting	RVI	NS	NS
1 and 2	SE	NDVI	$Y=0.75X+0.43$	0.22
1 and 2	SE	RVI	$Y=0.57X+0.59$	0.29
1 and 2	Booting	NDVI	$Y=0.93X+0.22$	0.12
1 and 2	Booting	RVI	$Y=0.56X^2-0.88X+1.46$	0.28
1 and 2	SE and booting	NDVI	$Y=0.84X+0.32$	0.20
1 and 2	SE and Booting	RVI	$Y=0.30X^2-0.23X+1.10$	0.24

SE stem elongation stage

elongation stage, the GreenSeeker sensor can be used to estimate YP_0 , and $RI_{HARVEST}$, and indirectly YP_N ($YP_0 \times RI_{HARVEST}$). The yield gap ($YP_N - YP_0$) can then be determined, and a practical AE_N can be used to estimate the topdressing N rate. This AE_N should not be AE_N for the whole growing season, but for the topdressing N, which should be higher than the whole season. Using the main and subplot data of the 105 kg ha⁻¹ treatment in our study, we determined the average yield difference due to the topdressing N application at stem elongation stage was 0.86, 0.49, 1.24, and 1.35 t ha⁻¹ for site 1 (2008), site 2 (2008), site 1 (2009), and site 2 (2009), respectively. The corresponding AE_N for the third topdressing N application was 23.44, 13.22, 33.7, 1 and 36.80 kg kg⁻¹, respectively. The average value of 26.79 kg kg⁻¹ can be used for practical application of this strategy in this region.

The results from the on-farm evaluation experiments indicated that the GreenSeeker-based precision N management strategy applied an average of 103 kg N ha⁻¹, similar to the SSNM strategy based on chlorophyll meter (98.3 kg N ha⁻¹). Grain yield was not significantly different among different N management strategies, even though the SSNM-CM (9,548 kg ha⁻¹) approach increased yield by 6.9 % over FP (8,930 kg ha⁻¹). Both SSNM-CM (98.2 kg kg⁻¹) and PNM-GS (88.2 kg kg⁻¹) strategies significantly increased partial factor productivity (PFP, kilogram grain produced by 1 kg applied N) by 65 and 48 %, respectively, as compared with FP (59.5 kg ha⁻¹), with the SSNM-CM strategy having the highest PFP, even though the two optimized strategies were not significantly different.

This GreenSeeker-based precision N management strategy has several advantages compared with the SSNM-CM strategy. It adjusts the topdressing N application rate at stem elongation stage based on potential yield response to additional N application rather than a fixed rate of adjustment based on chlorophyll meter values. It uses canopy sensor rather than leaf sensor, and thus is faster under field conditions. It is less influenced by environmental light conditions, because the GreenSeeker sensor is an active sensor with its own light source. This strategy adopts N-rich plots as reference plots to minimize the influence of different varieties and other environmental factors. The GreenSeeker-based strategy also reduced N topdressing times as compared with the SSNM strategy used in this study, and thus can save labor costs.

Future studies are needed to improve in-season prediction of rice responsiveness to additional N application ($RI_{HARVEST}$) under high-yielding conditions, further improve the strategy with more site-years of data and different varieties, evaluate this strategy against RONR and SSNM strategies with different varieties and under more diverse on-farm conditions. It is also important to integrate this sensor-based N management strategy into high yield crop management systems to achieve both high yield and high N use efficiency simultaneously for food security and sustainable development.

4 Conclusions

Our study indicated that the GreenSeeker active crop canopy sensor could be used to estimate yield potential and responsiveness to additional topdressing N application at stem elongation or booting stage, but the performance was less satisfactory at the higher yielding site. The RVI index worked better than NDVI for estimating these parameters, especially across site-years. A practical precision N management strategy for rice can be developed for the Jiansanjiang region, using the regional optimum N rate of 90–110 kg ha as the initial total amount and 45 and 20 % as basal and tillering N application, and then using GreenSeeker sensor to estimate the topdressing N rate at stem elongation (or booting) stage. Three on-farm evaluation experiments indicated that this GreenSeeker-based strategy achieved similar grain yield as farmer's practice, but significantly increased PFP. Compared with chlorophyll meter-based site-specific N management, this GreenSeeker-based strategy achieved slightly lower yield and PFP, but the difference was not significant. This approach is faster for data collection and less influenced by environmental light conditions due to the use of active canopy sensor and saves labor costs due to reduced topdressing application times. This strategy can improve nitrogen use efficiency of rice, is more suitable for practical on-farm applications, and has the potential to contribute to the sustainable development of rice farming. Future studies are needed to improve in-season prediction of yield potential and responsiveness to topdressing N application under high yielding conditions, further improve the strategy with more site-years of data and different varieties, conduct more on-farm experiments to evaluate this strategy against the regional optimum N rate and the chlorophyll meter-based SSNM strategies under different on-farm conditions and integrate this strategy into high yield crop management systems to achieve both high yield and N use efficiency simultaneously for food security and sustainable development.

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