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Evaluating a Crop Circle active sensor-based in-season nitrogen management algorithm in different winter wheat cropping systems

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The objective of this study was to evaluate the performance of a Crop Circle sensor-based precision nitrogen (N) management (PNM) strategy in different winter wheat cropping systems under on-farm conditions in North China Plain (NCP). Four farmer's fields were selected for on-farm experiments in Laoling County, Shandong Province of NCP in 2015-2016. In each field, the PNM strategy was evaluated in two winter wheat cropping systems: farmer's conventional management (FCM) and regional optimum crop management (ROCM). In each cropping system, there were two N management strategies: 1) FCM or ROCM; 2) PNM. The results indicated that the PNM strategy significantly increased partial factor productivity (PFP) by 29% in the FCM system, but did not have any significant improvement in the ROCM system. The ROCM system, using either regional optimum N management or PNM, significantly increased both grain yield and PFP than the FCM system.

Keywords: precision in-season nitrogen management, regional optimum nitrogen management, partial factor productivity

Introduction

The world's population is expected to reach 9 billion people by 2050. It is a great challenge to ensure both food security and sustainable development at the same time (Zhao *et al*., 2013; Chen *et al*., 2014). Wheat is an important food crop in China, and over-application of nitrogen (N) fertilizers is very common in North China Plain (NCP), resulting in serious environmental problems (Miao *et al*., 2011).

Precision N management (PNM) aims to optimize N fertilizer inputs by considering both spatial and temporal variability in crop N demand and N supply and has been regarded as a promising strategy to improve N use efficiency (NUE) and protect the environment (Miao *et al*., 2007; Cao *et al*., 2012; Diacono *et al*., 2013). The GreenSeeker active crop canopy sensor-based PNM strategy has been demonstrated to significantly increase NUE for winter wheat and rice as compared with farmer's practice in China, but did not increase crop yield (Li *et al*., 2009 and Yao *et al*., 2012). In recent years, scientists have developed regionally optimum crop management (ROCM) practices to increase crop yield, resource use efficiency and reduce environmental pollution at the same time. Such strategies don't consider field to field soil fertility and crop growth variability or year to year weather differences; therefore, there are still rooms for further improvements. It is a practical strategy to combine PNM and ROCM practices to increase both grain yield and NUE compared with farmer's practice and to further improve NUE compared with ROCM (Zhao *et al*., 2013).

The GreenSeeker sensor has two spectral bands (red and near-infrared) and vegetation indices, with the normalized difference vegetation index (NDVI) being commonly used in PNM. This index becomes saturated at medium and high biomass conditions (Yao *et al*., 2014; Cao *et al*., 2015). Crop Circle ACS 470 is a relatively new user-configurable active canopy sensor, with a choice of six different spectral bands covering blue, green, red, red edge and near-infrared regions. Some red edge-based vegetation indices derived from this sensor were found to be able to overcome the saturation problem of NDVI and were more suitable for high yield cropping systems (Cao *et al*., 2015; 2016). Cao *et al*. (2017) developed a new Crop Circle ACS 470 sensor-based PNM strategy for winter wheat, which needs further evaluation under on-farm conditions. The objective of this study was to evaluate the newly developed Crop Circle ACS 470 sensor-based PNM strategy in two different winter wheat cropping systems: farmer's conventional management (FCM) and ROCM under on-farm conditions in NCP.

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Material and Methods

Experimental site

The experiments were carried out in 2015–2016 in Laoling County, Shandong Province of NCP. The climate is warm-temperate semi-humid continental monsoon. It has annual sunshine hours of 2509.4 and the annual mean temperature is 12.4°C, with the maximum and minimum being 13.6°C and 11.2°C, respectively. The annual mean precipitation is 527.1 mm and the mean frost-free period is 198 days. Winter wheat is generally planted in early October and harvest in early June the following year.

Experimental design

Four famer's fields were selected for this study. In each field, there were four treatments: FCM, PNM in the FCM system (PNM&FCM), ROCM, PNM in the ROCM system (PNM&ROCM). The fertilizer application is shown in Table 1.

The FCM system was managed by the farmers according to his conventional practices using narrow-row seeding (17 cm row spacing) with 300 kg seeds ha^{-1}. The ROCM system applied 219 kg N ha^{-1} in total, with 81 and 138 kg N ha^{-1} being applied as basal fertilizer before planting and as topdressing at Feekes 6 stage (BBCH 31, stem elongation stage), respectively. The ROCM integrated a series of high-yielding and high efficiency technologies, using wide-row planting (27 cm row spacing and 165 kg seeds ha^{-1}) methods. In the PNM&FCM treatments, the same amount of basal N fertilizers as the farmers was generally applied, with the exception where one farmer applied 150 kg N ha^{-1} as basal fertilizer and the PNM&FCM treatment reduced the basal fertilizer rate. For PNM&ROCM, the basal N rate was the same as ROCM. For both PNM&FCM and PNM&ROCM, the topdressing N was applied at Feekes 6 stage based on the Crop Circle ACS470 sensor-based algorithm developed by Cao *et al.* (2017). Other managements of PNM&FCM and PNM&ROCM were the same as FCM and ROCM, respectively. The N source for topdressing was urea. No obvious water, weed, pest or disease stress was observed during the growing seasons.

Table 1 *Fertilizer application rates for different treatments in four famers' fields.*

Field		N Rate(kg ha^{-1})			P Rate (kg ha^{-1})	K Rate (kg ha^{-1})
		Basal	Topdressing	Total		
F1	FCM	150	206	356	180	26
	PNM&FCM	108	139*	247	180	26
	ROCM	81	138	219	132	42
	PNM&ROCM	81	142*	223	132	42
F2	FCM	134	192	326	180	26
	PNM&FCM	134	141*	275	180	26
	ROCM	81	138	219	132	42
	PNM&ROCM	81	144*	225	132	42
F3	FCM	63	150	227	180	26
	PNM&FCM	64	140*	204	180	26
	ROCM	81	138	219	132	42
	PNM&ROCM	81	146*	227	132	42
F4	FCM	108	206	314	180	26
	PNM&FCM	108	156*	264	180	26
	ROCM	81	138	219	132	42
	PNM&ROCM	81	146*	227	132	42

*The topdressing rate was determined according to the Crop Circle ACS 470 sensor-based N recommendation algorithm (Cao *et al.*, 2017).

Sensor data collection

The Crop Circle ACS-470 sensor was used to collect canopy reflectance across each plot at approximately 0.7–0.9 m above wheat canopy at 10 Hz (10 readings per second) in each plot at Feekes 6 stage, and the average values were used to represent each plot. The sensor path was parallel to the seed rows or the beam of light was perpendicular to the seed row.

Plant sampling and measurements

Plant samples were taken from scanned plants following sensing data collection in each plot at Feekes 6 stage. They were dried in the ovens at 105°C for 30 minutes and then at 75°C until constant weight for determination of dry weight biomass. The sub-samples ground to pass a 1 mm screen in a sample mill were mineralized using sulfuric acid—hydrogen peroxide (H_2SO_4–H_2O_2), and plant N concentration (PNC) was determined using the Kjeldahl method. The early season plant N uptake (PNU) was determined by multiplying PNC by dry aboveground biomass. At maturity stage, three 1 m^2 areas were selected randomly in each plot for grain yield determination. Grain yield was adjusted to 14.5% moisture content.

Data analysis

The statistical analysis was performed using Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and SPSS18.0 (SPSS Inc., Chicago, Illinois, USA).

Results

Predicting early season plant nitrogen uptake

The early season PNU estimation model developed by Cao *et al.* (2017) was used to predict the early season PNU in the farmer's fields for estimating topdressing N application rate. The results indicated that the performance of this model was acceptable, with R2 being 0.71 (Figure 1).

Nitrogen application rate

On average, the FCM system applied 303 kg ha^{-1} N fertilizers, which is typical in NCP. The PNM&FCM reduced N application by an average of 18% than FCM. The ROCM system applied 219 kg N ha^{-1}, which was a reduction of 28% compared with FCM. The PNM&ROCM system applied similar amount of N fertilizers as ROCM (Table 2).

Field-specific analysis indicated that all the improved management systems saved more N fertilizers in Field 1 than

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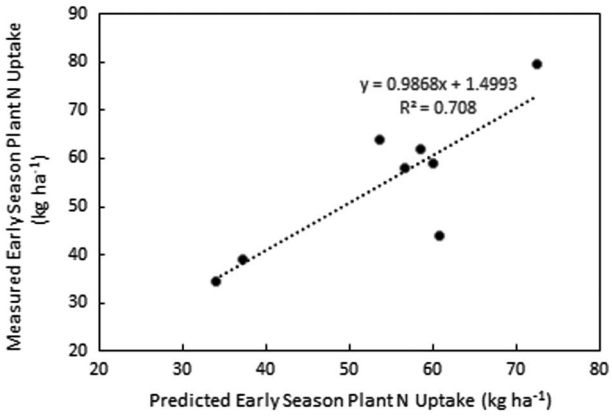


Figure 1 The relationship between predicted early season plant N uptake (PNU) using the model developed by Cao *et al.* (2016b) and the measured PNU in the farmer's fields.

Table 2 *The average total N application rate, yield and N partial factor productivity (PFP) for different crop management systems*

Treatment	Total N Rate (kg ha^{-1})	Yield (kg ha^{-1})	PFP (kg kg^{-1})
FCM	303 ± 61a*	9.01 ± 0.5b	31 ± 7.8c
PNM-FCM	247 ± 31b	9.80 ± 0.4b	40 ± 7.1b
ROCM	219 ± 0b	10.12 ± 0.6a	47 ± 4.1a
PNM-ROCM	226 ± 1b	10.62 ± 0.1a	47 ± 1.9a

*Values followed by different letters within a column are significantly different ($P < 0.05$)

other fields, due to the high N application rate by the farmer in Field 1. In Field 2 and 4, the three systems saved 50–100 kg N ha^{-1} than the FCM system. In Field 3, the three systems applied similar amount as the FCM system (Figure 2).

Grain yield and yield components

Compared with FCM, the PNM&FCM, ROCM and PNM&ROCM systems increased yield by an average of 9%, 12% and 18% over FCM, respectively. The PNM-ROCM system produced the highest yield, which was 5% higher than ROCM (Table 2). The PNM&FCM system increased about 1.4 t ha^{-1} yield than FCM in both Field 1 and Field 3, but did not increase yield in either Field 2 or Field 4. The PNM&ROCM system had the highest yield in Field 1, which was 13% higher than ROCM. In Field 2, the corresponding increase was 6%. In Field 3 and Field 4, these two systems produced similar yield (Figure 3).

The yield component data indicated that the number of spikes was similar among different crop management systems, while the ROCM and PNM&ROCM systems had higher number of grains per spike and thousand-grain weight (Table 3). In the same crop management system, these yield components were not significantly affected by PNM.

Partial Factor Productivity

The PNM&FCM systems increased PFP by an average of 29% over FCM (Table 2). The ROCM and PNM&ROCM systems

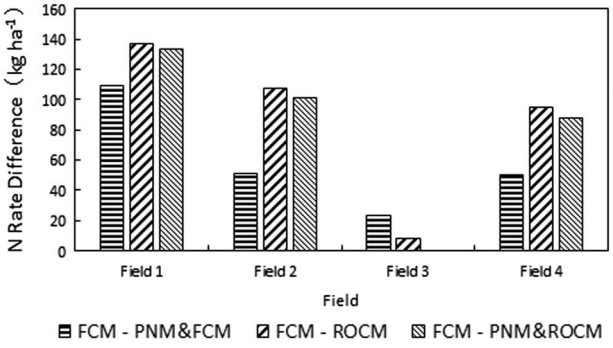


Figure 2 The total N rate differences between farmer's conventional management (FCM) and precision N management (PNM) in FCM (PNM&FCM), regional optimum crop management (ROCM) and PNM in ROCM (PNM&ROCM) systems in different fields.

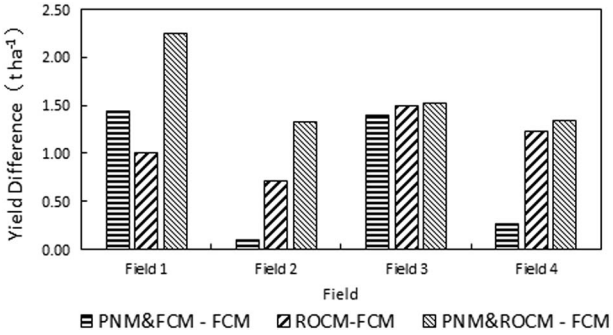


Figure 3 The yield difference between precision N management (PNM) in farmer's conventional management (FCM) (PNM&FCM), regional optimum crop management (ROCM) and PNM in ROCM (PNM&ROCM) systems and FCM (PNM&FCM minus FCM, ROCM minus FCM, and PNM&ROCM minus FCM) in different fields.

had the same PFP, which was 52% higher than the FCM system. The PNM&FCM improved PFP the most in Field 1 over FCM, which was an increase of 70%. In other three fields, the increase was all about 20%. In Fields 1, 2 and 4, the ROCM and PNM&ROCM all further increased PFP over PNM&FCM, while the PNM&ROCM only further increased PFP by 10% over ROCM in Field 1 (Figure 4).

Discussion

In the FCM system, using similar amount of basal N rate (except in Field 1) and only adjusting topdressing N application based on Crop Circle ACS 470 sensor-based N recommendation as developed by Cao *et al.* (2017), PNM increased 9% yield using 18% less N fertilizers, resulting in an increase of 29% PFP. The basal N application rate was quite high except in Field 3, and should be further reduced to about 80 kg ha^{-1} as adopted in the ROCM system. This way, the PFP could be further improved. In Field 1, the PNM strategy reduced the basal N rate from 150 kg ha^{-1} to 108 kg ha^{-1}, which resulted in an increase of 70% for PFP in this field.

The ROCM system reduced seeding rate by 45%, decreased N rate by 28%, but increased yield by 12% and improved PFP by 52% as compared with FCM. In FCM, the

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Table 3 *The average number of panicles, grains per spike and thousand-grain weight for different crop management systems*

Treatment	Number of Spikes (million ha^{-1})	Grains Per Spike	Thousand-Grain Weight (g)
FCM	6.06 ± 0.4a*	33.6 ± 0.8b	38.8 ± 1.2b
PNM&FCM	6.09 ± 0.4a	35.3 ± 1.7b	39.9 ± 1.2b
ROCM	6.32 ± 0.5a	37.6 ± 0.8ab	42.5 ± 1.0a
PNM&ROCM	6.18 ± 0.4a	37.8 ± 1.9a	42.8 ± 0.8a

*Values followed by different letters within a column are significantly different ($P < 0.05$)

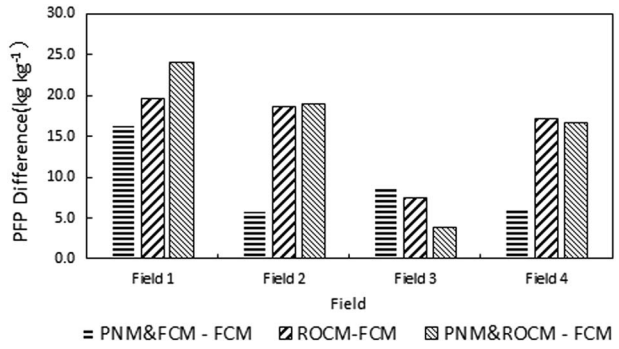


Figure 4 The PFP difference between precision N management (PNM) in farmer's conventional management (FCM) (PNM&FCM), regional optimum crop management (ROCM) and PNM in ROCM (PNM&ROCM) systems and FCM (PNM&FCM minus FCM, ROCM minus FCM, and PNM&ROCM minus FCM) in different fields.

high planting density and N application rates resulted in more unproductive tillers. The ROCM system reduced planting density and N rate, which resulted in more productive tillers. Over-application of N fertilizers can also negatively affect the grain filling process and result in delayed maturity. As a result, the number of spikes was similar between ROCM and FCM, but ROCM and PNM&ROCM systems had higher grains per spike and thousand grain weight, and higher crop yields. This should result in significant increase in economic returns, which will be determined in further analysis.

An objective of this study was to determine if the PNM strategy can further improve NUE in the ROCM system. The result of this study indicated that the PNM strategy did not significantly increase yield or PFP as compared with ROCM. This was only based on results from 1 year and four fields, and more studies are needed to further test these systems. In addition, the sensor-based PNM was developed using data collected in Quzhou, Hebei Province, while the study was conducted in Laoling, Shandong Province. Although they are all located in NCP, they were about 300 km apart and farmers used quite different varieties. The sensor-based algorithm should probably be further updated using local data.

Conclusions

This study evaluated the Crop Circle ACS 470 sensor-based PNM strategy as developed previously for winter wheat in both FCM and ROCM systems. The results indicated that the PNM strategy significantly increased PFP by 29% in the FCM system, but did not have any significant improvement in the ROCM system, as compared with the farmer's N management practice or the regional optimum N management. This result was based on only one year's results obtained from four farmer's fields. More studies are needed to further evaluate this PNM strategy in different crop management systems under more diverse on-farm conditions.

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