Improving Active Canopy Sensor-based In-season N Recommendation using Plant Height Information for Rain-fed Maize in Northeast China

Xinbing Wang[1], Yuxin Miao[1,2], Tingting Xia[1], Rui Dong[1], Guohua Mi[1], and David J. Mulla[2]

1. College of Resources and Environment Sciences, China Agricultural University, Beijing, 10093, China

2. Precision Agriculture Center, Department of Soil, Water and Climate, University of Minnesota, St. Paul., MN, 55108, USA

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Abstract. *The inefficient utilization of nitrogen (N) fertilizer due to leaching, volatilization and denitrification has resulted in environmental pollution in rain-fed maize production in Northeast China. Active canopy sensor-based in-season N application has been proven effective to meet maize N requirement in space and time. The objective of this research was to evaluate the feasibility of using active canopy sensor for guiding in in-season N fertilizer recommendation for rain-fed maize in Northeast China and determine if the plant height information could be used to further improve the accuracy of in-season N recommendation. Nitrogen response trials were conducted in four growing seasons with four planting densities. Split plot treatments included six N application rates (0, 60, 120, 180, 240, and 300 kg ha^{-1}) at each year-density with three replications. One third of the N was applied as basal fertilizer, and the rest as side-dressing at V8-V9 stage of spring maize. The GreenSeeker active canopy sensor was used at the 8-9 leaf growth stage (V8–V9) to collect the vegetation index (NDVI), which was used with the N fertilizer optimum algorithm (NFOA) to calculate in-season N fertilizer side-dressing rates. Plant height and yield were obtained at V8–V9 and harvest stage respectively. The results showed that both NDVI and NDVI*Height could predict the yield potential accurately. The NFOA recommended higher side-dressing N rates using NDVI*Height than NDVI. The average total N rate based on NDVI*Height-NFOA recommendation was closer to economically optimum N rate than based on NDVI-NFOA. It is concluded that using plant height information together with GreenSeeker NDVI can improve the accuracy in N recommendations for rain-fed maize in Northeast China than only using NDVI.*

Keywords. *Rain-fed maize, Economically optimum N rate, Active canopy sensor, plant height, Precision nitrogen management*

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Introduction

To achieve high grain yield, over or unbalanced use of nitrogen (N) fertilizer is common in maize production (Huang et al. 2007; Chen 2008; Chen et al. 2011). However, because of the temporal and spatial variability of soil properties, N supplying capacity could vary greatly across or within fields. Additionally, crop N need can vary temporal or spatially as well due to the variability in yield potential (Shanahan et al. 2008; Thompson et al. 2015). Consequently, the unreasonable N fertilization can result in low N use efficiency (NUE) and ecological environment pollution (Qiu et al. 2014; Guo et al. 2010; Miao et al. 2011). Precision N management through in-season variable rate N application has provided the capability to increase grain yield and N use efficiency and protect the environment (Vina et al. 2004; Gebbers 2010; Zhang et al. 2002). So far, the development of active canopy sensor-based precision N management is still very slow, especially in the rain-fed maize region of Northeast China, which is the most important and largest rain-fed maize production region, accounting for 35% of China's maize production (China's National Bureau of Statistics, 2015).

GreenSeeker (NTech Industries, Inc., Ukiah, CA) is an active canopy sensor that has been commonly used for monitoring crop growth status and adjusting N fertilizer rates according to the crop's requirements (Stanislawmarek 2009). Maize yield potential could be predicted in season using NDVI measured by GreenSeeker sensor (Teal 2006). The N fertilizer optimization algorithm (NFOA) developed by Raun et al. (2002 and 2005) has been widely used to make in-season N fertilizer recommendations. Crop plant height as a single factor could be used to estimate the vegetative growth and potential yield of maize (Sharma et al. 2016). It is a highly sensitive growth parameter and influenced by soil water content (Hussain et al. 1999), texture (Kladivko et al. 1986), fertilizer rate (Kapusta et al. 1996), and cultivation methods (Sharma and Franzen 2014). A study by Machado et al. (2002) revealed that by using plant height, 90% and 61% of the variation in total dry matter and grain yield, respectively, could be explained in a dry year.

The objectives of this study were to: (1) calibrate in-season N fertilizer recommendation algorithm (NFOA) with plant height based on GreenSeeker sensor; (2) validate the performance of the NFOA in rain-fed maize precision N management in Northeast China.

Materials and methods

Study Site Description and Experimental Design

This study was conducted from 2014 to 2017 at Lishu Experiment Station of China Agricultural University (43.3°N, 124.1°E), located in Lishu County, Jilin Province, China. This area was a typical rain-fed spring maize region in Northeast China, where about 80% of the annual average precipitation occurred between May and September. From 2014 to 2017, the cumulative precipitation was 414.9, 347.3, 660.6 and 509.9 mm, and the growth degree days (GDD) was 1615.7, 1678.0, 1706.7, and 1691.2 °C during the growing season of spring maize, respectively. The soil type at this study location was classified as black soil, equivalent to typical Haploboroll in the USDA Soil Taxonomy (1998).

Each experiment had the same six N rate treatments (0, 60, 120, 180, 240, and 300 kg ha^{-1}) with three planting densities: 55,000, 70,000, 85,000 plant ha^{-1}, and had three replications with plot area being 108 m^2. For each plot, N fertilizer was applied in two split applications: 1/3 as basal application before planting, and the remaining 2/3 as side-dressing at the V8-V9 growth stage. In each plot 1/4 area did not receive the side-dressing N application as the split plot. Sufficient phosphate (90 kg P_2O_5 ha^{-1}) and potash (90 kg K_2O ha^{-1}) fertilizers were applied before planting to make sure phosphorus (P) and potassium (K) nutrients were not limiting. All plots were kept free of weeds, insects and diseases with chemicals based on standard practices. No irrigation was applied during the plant growth period.

Active Canopy Sensor Data Collection and Plant Sampling

The GreenSeeker ACS Model 505 was used in this research. This sensor detects crop canopy reflection in red (R: 650–670 nm) and near-infrared (NIR: 755–785 nm) spectral regions, allowing calculation of the Normalized Difference Vegetation Index (NDVI). It has a nadir viewing angle with a field of view of 0.0052–0.0145 m^2 and acquisition interval from 20 to 1500 ms. At V8-V9 stage of spring maize, the GreenSeeker sensor readings were collected by holding the sensor at approximately 0.7 m over canopy of the plants in each plot and walking at a constant speed. The NDVI was calculated directly by the in-built software of GreenSeeker sensor, and ten group VI readings were generated per second. Then the readings collected from one plot were averaged to represent that experimental plot.

The maize plant samples were acquired right after collecting sensor readings, and four plants were randomly selected from each plot. Plant height was measured from the stem bottom to the leaf top. At maturity stage, grain yield was determined by harvesting 20 m^2 area of each plot and standardized to 14% grain moisture content.

Sensor based N recommendation algorithm

For the NFOA, the yield potential with no side-dressing N (YP0) was estimated by the in-season estimate of yield (INSEY) based on NDVI (INSEY_NDVI) or both NDVI and plant height (INSEY_(NDVI*Height)), which was calculated as the NDVI (or NDVI*Height) divided by the number of growing degree days (GDD) between planting and sensing where GDD was greater than zero with a growth threshold value of 10 °C. The harvest response index (RI_Harvest) was calculated by dividing the average yield of plots receiving sufficient N application (Nrich) by the average yield of a check plot or plot without receiving the side-dressing N at V8-V9 stage. In the above analyses, the 300 kg N ha^{-1} treatment was used as N rich treatment plot. In-season RI_VIs (RI_NDVI and RI_(NDVI*Height) at V8-V9 stage) were calculated in the same way as RI_Harvest. The predicted RI_Harvest could be estimated from the in-season RI_VIs (RI_NDVI or RI_(NDVI*Height)) acquired from Greenseeker sensor. The yield potential with additional N (YPn) was calculated by multiplying YP0 and RI_harvest estimated by RI_NDVI (or RI_(NDVI*Height)). Therefore, the N fertilizer recommendation (Nrequirement) was calculated by dividing the difference between YPn with YP0 by the nitrogen fertilizer agronomy efficiency (AEn).

Statistical analysis

The data collected from the N rate experiments were pooled together to determine the variation of grain yield with N rates to decide the agronomic optimum N rate (AONR) and economically optimum N rate (EONR), and then randomly divided into two datasets: 75% of the observations were used for calibration of algorithms and 25% of the observations were used to validate the algorithms. The coefficients of determination (R^2) of the relationships between VIs and agronomic parameters were analyzed using Excel 2013, and the analysis of variation (ANOVA) of different N recommendation rates was performed using SPSS 19.0 (SPSS Inc., Chicago, Illinois, USA)

Results

The determination of optimum N rates

The maize grain yield response to N fertilizer application rates is shown in Fig. 1. The quadratic with plateau response curve was able to fit the relationship between grain yield with N application rate (R^2=0.61). The grain yield increased significantly with N fertilizer application rate and reached a plateau at a rate of 258 kg N ha^{-1}, which was defined as the AONR. When considering the price of maize grain (0.62 \$ grain kg^{-1}) and N fertilizer (0.29 \$ N kg^{-1}), the EONR was 248 kg ha^{-1} in Northeast China for black soil. Both the AONR and EONR were higher than the regional optimum N rate (RONR) at 180-200 kg ha^{-1} in Northeast China for maize (Cui et al. 2018).

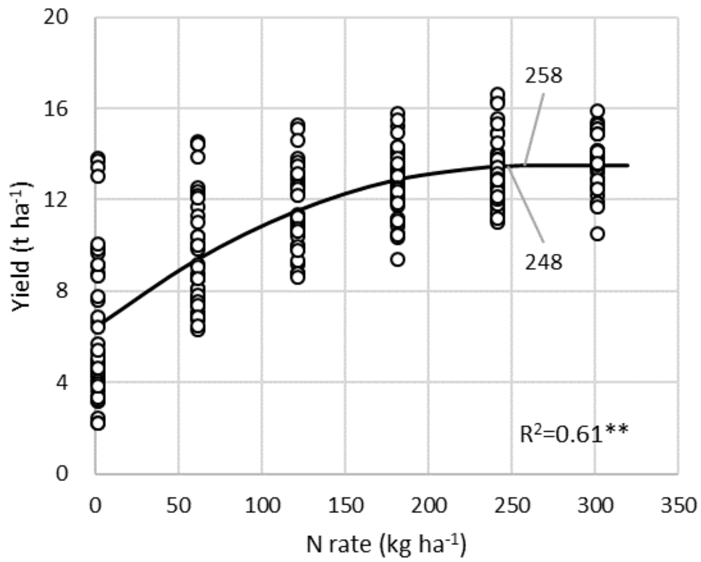

Fig. 1 Maize grain yield response to total N fertilizer rates across all year-densities (RONR: 180-200 kg ha^{-1}, AONR: 258 kg ha^{-1}, EONR: 248 kg ha^{-1})

Parameters determination of NFOA algorithms

The INSEY_NDVI and INSEY_(NDVI*Height) were used for YP0 across different years and densities. The YP0 was exponentially related with INSEY_NDVI ($YP0=0.46*e^{184.69*INSEY\_NDVI}$) (Fig. 2), and this relationship explained 69% of the variation in YP0 (Fig. 2a). Compared with INSEY_NDVI, the INSEY_(NDVI*Height) also had an exponential relation with YP0 ($YP0=2.18*e^{0.66*INSEY\_(NDVI*Height)}$), but it could explain slightly more (72%) of the variability in YP0 (Fig. 2b). When the YP0 was more than 12 t ha^{-1}, INSEY_(NDVI*Height) could overcome the saturation exhibited by INSEY_NDVI. Across all years and densities, the relationship between RI_NDVI (and RI_(NDVI*Height)), at V8-V9 growth stage, with RI_harvest at grain maturity stage was excellent (Fig. 3). The RI_harvest had a linear relationship with both RI_NDVI (R^2=0.70, RSS=24.34) (Fig. 3a) and RI_(NDVI*Height) (R^2=0.63, RSS=30.35) (Fig. 3b).

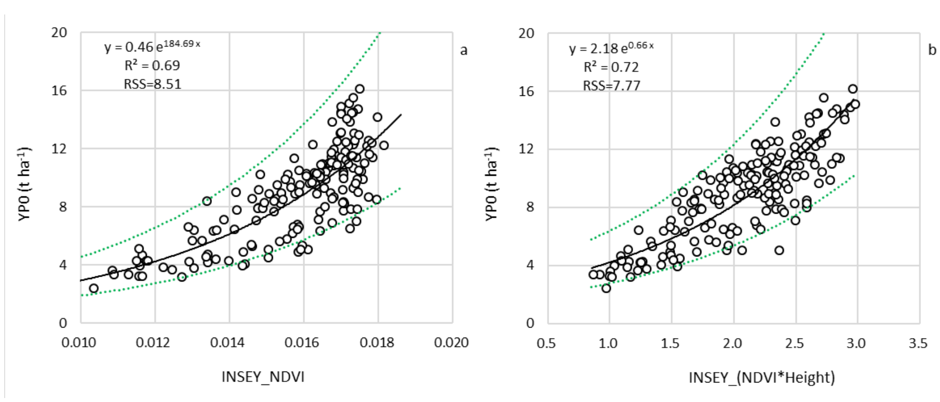

Fig. 2 The relationship between yield potential (YP0) and INSEY_NDVI (a) and INSEY_NDVI*Height (b) before the fertilizer side-dress of spring maize. The green dotted line is 95% prediction band

The above models describing relationships between VIs and YP0 were further evaluated with the validation dataset (Figs. 4 and 5). Across different years and densities, the NDVI and NDVI*Height models performed similarly for predicting YP0 (R^2 = 0.68 and 0.70, respectively), with similar RMSE (0.20 and 0.19 t ha^{-1}) (Figs. 4a and 4b). The NDVI*Height index performed better when the YP0 was more than 12 t ha^{-1}. The validation results also indicated that NDVI and NDVI*Height models could predict RI_harvest well across all years and densities, with R^2, and RMSE being 0.63 and 0.69, and 0.23 and 0.30, respectively (Fig. 5a and 5b).

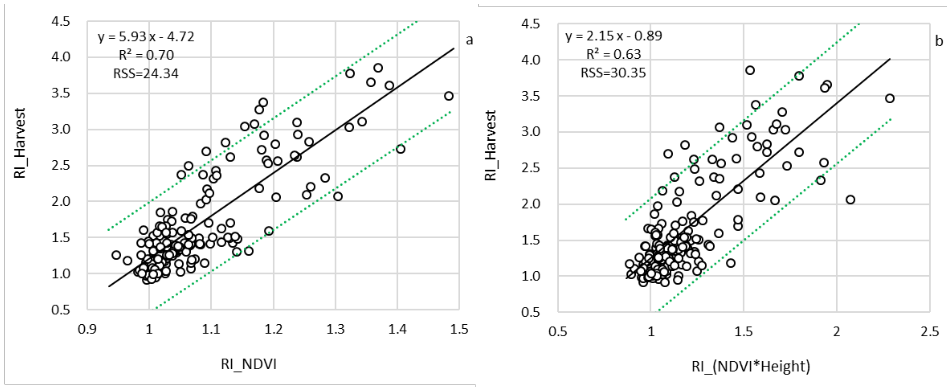

Fig. 3 The relationship between RI_Harvest and RI_NDVI (a) and RI_NDVI*Height (b) before the fertilizer side-dress of spring maize. The green dotted line is 95% prediction band

N fertilizer recommendation from NFOA algorithms

After the NFOA algorithms were calibrated and validated, the plots with side-dressing N fertilizer were used to evaluate the recommended N rates with the NFOA algorithms. The change of recommended side-dressing N fertilizer rates based on NFOA-NDVI and NFOA-(NDVI*Height) algorithms are shown in Table 1. For the NFOA algorithm based on NDVI, the recommended side-dressing N fertilizer rates significantly decreased from 294 kg ha^{-1} to 116 kg ha^{-1} as the basal N fertilizer rates increased from 0 kg ha^{-1} to 60 kg ha^{-1}. However, there was no significant difference in the recommended side-dressing N rates for the basal N rates from 60 to 100 kg ha^{-1}. Compared with the NFOA algorithm based on NDVI, NFOA algorithm based on NDVI*Height provided higher recommended side-dressing N rates (26, 15, 18, 23, 25, 22 kg ha^{-1}) at each basal N rate from 0 to 100 kg ha^{-1}. Similarly, the recommended side-dressing N rates were not significantly different for the basal N rates from 60 to 100 kg ha^{-1}. The recommended total N rates (basal N rate plus recommended side-dressing N rate) are shown in Table 2. These results indicate that the recommended total N rates were not significantly different for basal N rates from 40 to 100 kg ha^{-1}, either based on the NDVI or NDVI*height algorithm. Compared with the RONR (180-200 kg ha^{-1}), both algorithms recommended higher average total N rates (216 and 237 kg ha^{-1}), while they recommended lower average total N rates than AONR (258 kg ha^{-1}). The average total N rate recommended by the NDVI*height based NFOA algorithm was similar to the EONR (248 kg ha^{-1}).

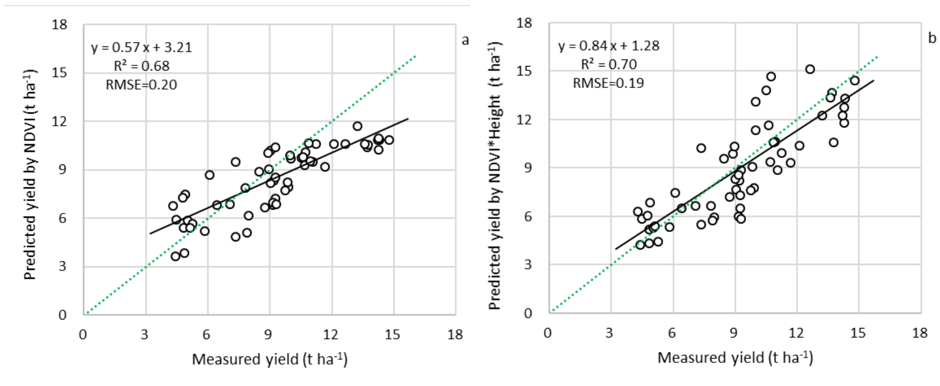

Fig. 4 The relationship between measured yield and predicted yield by INSEY_NDVI (a) and INSEY_NDVI*Height (b) before the fertilizer side-dress of spring maize. The green dotted line is the 1:1 line

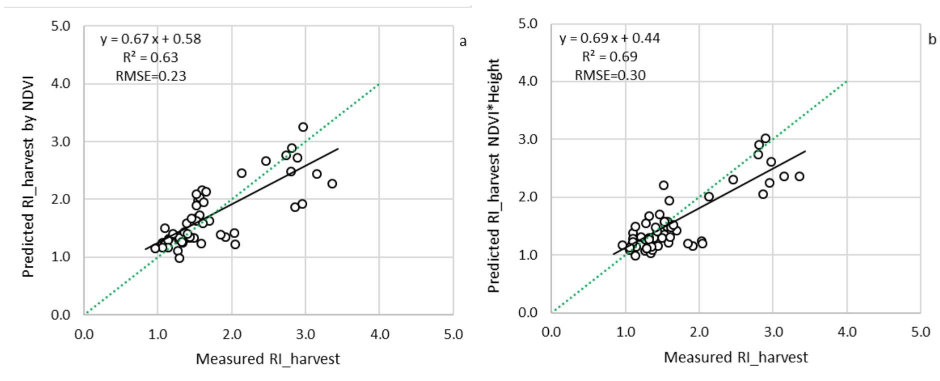

Fig. 5 The relationship between measured RI_harvest and predicted RI_harvest by INSEY_NDVI (a) and INSEY_NDVI*Height (b) before the fertilizer side-dress of spring maize. The green dotted line is the 1:1 line

Table 1 Recommend side-dress N rate (kg ha^{-1}) based on GS-NFOA

Index	Base N rate (kg ha^{-1})						
	0	20	40	60	80	100	Ave
NDVI	294±17 a	231±16 b	135±13 c	116±9 d	102±6 d	96±3 d	166
NDVI*Height	320±17 a	246±15 b	173±10 c	139±8 d	128±8 d	118±7 d	187

Note: Lower case letters indicate significant differences between treatments at the P< 0.05 level.

Table 2 Recommend total N rate (kg ha^{-1}) based on GS-NFOA

Index	Base N rate (kg ha^{-1})						
	0	20	40	60	80	100	Average
NDVI	294±17 a	251±16 b	195±13 c	176±9 c	182±6 c	196±3 c	216
NDVI*Height	320±17 a	266±15 b	213±10 c	199±8 c	208±8 c	218±7 c	237

Note: Lower case letters indicate significant differences between treatments at the P< 0.05 level.

Conclusions

The results indicated that the AONR and EONR were higher than the RONR. The NDVI*Height based NFOA could overcome the saturation effect of NDVI and could improve the prediction of in-season maize yield potential compared with the NDVI based NFOA. Both NDVI and NDVI*Height based NFOAs could be used to recommend side-dressing N rates at the V8-V9 stages. The average recommended total N rate based on the NDVI*Height NFOA was closer to the EONR than the average N rate recommended by the NDVI based NFOA. It is concluded that the GreenSeeker active canopy sensor-based NFOA algorithm with plant height information could provide more accurate N recommendations for rain-fed maize in Northeast China than the algorithm with only NDVI information.

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