QUANTIFYING SPATIAL VARIABILITY OF INDIGENOUS NITROGEN SUPPLY FOR PRECISION NITROGEN MANAGEMENT IN NORTH CHINA PLAIN

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ABSTRACT

Over- and mis-application of nitrogen (N) fertilizers have been commonly reported in North China Plain (NCP), resulting in low N use efficiency and high risk of environmental pollution. Precision N management is a promising approach to significantly improve N management by matching N supply with crop demand in rate, space and time. Several questions need to be answered before appropriate precision N management strategies can be successfully implemented in intensively managed agricultural fields of NCP: 1). How large is field-to-field and within-field variability in indigenous soil N supply? 2). Is the variability spatially structured within a field and/or across different fields? 3). Can chlorophyll meter and active canopy crop sensor like GreenSeeker be used to monitor winter wheat (*Triticum aestivum* L.) N status variability and make in-season N recommendations in NCP? This study was conducted to answer these questions. Winter wheat plant samples were collected on 25 x 25 m grids at jointing stage and harvesting stage from seven farmer's fields receiving no fertilizers in Quzhou County, Hebei Province in 2007 and analyzed for aboveground biomass, N concentration and uptake. At jointing stage, chlorophyll meter readings and canopy reflectance index NDVI were also collected using SPAD 502 chlorophyll meter and GreenSeeker canopy sensor, respectively. Preliminary analysis indicated that indigenous N supply varied significantly both from field to field and within field, ranging from 26 to 235 kg ha^{-1} at jointing stage, and from 33 to 320 kg ha^{-1} at harvest. The spatial variability had either weak or moderate spatial structure. Both chlorophyll meter and GreenSeeker sensor are very useful for in-season N management in winter wheat in North China Plain.

Keywords: Indigenous N Supply, Precision N management, Spatial Variability, In-season N Management, Chlorophyll Meter, Crop Canopy Sensor.

INTRODUCTION

Problems of nitrogen (N) fertilizers have been repeatedly reported in North China Plains (NCP), which resulted in low N use efficiency, and high risk of environmental pollution (Zhao et al., 2007; Cui et al., 2008ab; Ju et al., 2006, 2009). One important reason contributing to this problem is that current blanket N recommendations are made for a region (a county or a township) and do not take into account of the household-to-household or field-to-field variability in soil fertility and management. Precision agricultural technologies would have a good potential to improve N use efficiency, by taking both spatial and temporal variability in soil N supply and crop demand into consideration (Miao et al., 2009). A good understanding of spatial variability in indigenous soil N supply and crop N demand is required before appropriate precision N management (PNM) strategies can be successfully developed and implemented. However, studies on the field-to-field and within-field variability in these important parameters are very limited in small scale farming.

In NCP, some previous research has been conducted to estimate indigenous N supply (INS). Based on on-farm (in farmers' fields) experiments conducted at 229 sites across 2003-2005 in seven key winter wheat-summer maize production regions in NCP, Cui et al. (2008c) reported that winter wheat and summer maize yield in N omission plots ranged from 2.40 to 8.52 t ha^{-1} (average = 5.62 t ha^{-1}), and from 3.39 to 9.87 t ha^{-1} (average=7.32 t ha^{-1}), respectively. The INS ranged from 62 to 212 kg N ha^{-1}(average=127 kg N ha^{-1}) and from 69 to 202 kg N ha^{-1} (average = 142 kg N ha^{-1}) for winter wheat and summer maize, respectively. This large field to field variation in INS demonstrated the importance to develop SSNM strategies that will take INS into the consideration. This led to several related questions: How large is the variability in INS within farmers' fields as compared with field to field variability? Is the within-field variability in INS spatially structured? This information is important for deciding whether SSNM should be field-specific or within-field variability should be managed as well in NCP. So far, no studies have been conducted to answer these questions.

In addition to estimate optimum N rate, proper non-destructive diagnostic technologies are also needed to estimate crop N status and demand at important growth stages to allow in-season adjustments. Chlorophyll meter (CM) has been commonly used for such purposes (Shanahan et al., 2008; Samborski et al., 2009). In order to avoid the influence of factors other than N stress, like different varieties or genotypes, growth stages, water stresses, pests and diseases, etc., a well-fertilized reference strip or plot is usually used (Samborski et al., 2009). N sufficiency index (NSI) can be calculated by dividing CM readings of the field to be fertilized by CM readings of the reference strip or plot. If NSI is less than a threshold value (0.92 to 0.95), it indicates N deficiency and additional N needs to be applied. Otherwise, N side-dressing or topdressing may not be needed or should be reduced. This approach can be used for management zone (MZ)-specific N management in large fields, or field-specific N management if the fields are small and within-field variability can be ignored. However, it is still very time consuming to use this tool for diagnosing large crop fields or across many small fields (Miao et al., 2009).

Ground-based crop canopy sensor can avoid the limitations of CM and is a more promising approach for in-season diagnosis of crop N status and demand. GreenSeeker canopy sensor (NTech Industries, Inc., Ukiah, CA) is a popular active optical sensor using a red (650 ± 10 nm) and a NIR (770 ± 15 nm) waveband. Normalized difference vegetation index (NDVI) obtained from this sensor has been used to compute an in-season response index (RI), which is determined by dividing NDVI at plots or strips receiving non-limiting N application by NDVI at fields to be fertilized or receiving no N application. Mullen et al. (2003) found that RI_{NDVI} at Feeks stage 5, 9 and 10.5 (Large, 1954) could explain over 56% of the response index calculated at harvest ($RI_{HARVEST}$) by dividing crop yield receiving non-limiting N fertilizers by yield receiving no N fertilizers, as proposed by Johnson and Raun (2003). Hodgen et al. (2005) found that both RI_{NDVI} and RI calculated using plant height ($RI_{PLANTHEIGHT}$) at Feeks 4-6 could be used to predict $RI_{HARVEST}$, with R^2 being 0.75 and 0.74, respectively. The RI_{NDVI} determined in-season can be used to estimate the crop responsiveness to additional N application. According to Hodge et al. (2005), a site with RI_{NDVI} less than 1.10 was considered non-responsive to N fertilization, and RI_{NDVI} between 1.10 and 1.25 indicated marginally responsive. Potential yield with no additional N (YP_0) can be estimated by in-season estimate of yield (INSEY), which is calculated by dividing NDVI by the number of days from planting to the date of sensing with growing degree days greater than 0) (Raun et al., 2002). The potential yield with added N fertilization (YP_N) can then be estimated by multiplying YP_0 and RI. The N requirement can then be estimated by multiplying yield response (subtracting YP_0 from YP_N) by grain N concentration and average N use efficiency (NUE). Using this approach, Li et al. (2009) increased NUE of winter wheat from around 13% of the farmer's practice to 61%, based on experiments conducted on 30 farmer's fields in Shandong Province of NCP. However, no studies have evaluated either CM or GreenSeeker for estimating within-field variability in crop N demand and topdressing N rates in small scale farming of China.

The objectives of this study were to 1) determine magnitude of field-to-field and within-field variability in INS, winter wheat N status and demand; 2) characterize their spatial structures; and, 3) evaluate CM and GreenSeeker sensor for in-season estimation of field-to-field and within-field variability in winter wheat N status and demand in NCP.

MATERIAL AND METHODS

Study Site Description

Seven fields next to each other were selected for this study in Quzhou County, Hebei Province, located on the NCP. These seven fields belonged to a farm and were rented to seven farmers to manage. Winter wheat and summer maize were the main cropping system for many years. The area of each field varied from 1.52 to 7.35 ha (Table 1), and the total area is about 20 ha. In 2006, these seven fields were donated to China Agricultural University for research. To prepare for long-term field experiments, winter wheat was planted to all these seven fields early October, 2006, and no fertilizer was applied to remove residual nutrient effects on future field experiments. This provided a rare opportunity for us to study field-to-field and within-field variability in INS and crop N demand.

Spectral Reflectance Measurement

From April 13-15, 2007, when the crop was at Feeks growth stage 6, canopy spectral reflectance was measured using the GreenSeeker active canopy sensor on a 25 x 25 m grid across the seven fields (Figure 1). At each grid point, three 1 m^2 winter wheat were randomly selected and canopy reflectance data were collected using the active GreenSeeker Hand Held optical sensor. The sensor was held approximately 0.6 to 1.0 m above the canopy. Two vegetation indices, NDVI and ratio vegetation index (RVI, NIR/RED) were calculated using the sensor’s built-in software. Sensor readings were averaged to represent the vegetation indices at each grid point.

Plant Sampling and Analysis

Following GreenSeeker sensing, CM readings were taken at mid-length of the uppermost fully expanded leaf from 30 randomly selected wheat plants near each grid point using SPAD 502 (Minolta, Ramsey, NJ). The average SPAD meter readings were used for further analysis.

Aboveground biomass was destructively sampled by randomly cutting a 1 m2 vegetation from sensor scanned plants near each grid point. At harvest, a similar procedure was used to collect aboveground biomass at each grid point, with grain and straw being separated. All plant samples were later oven dried at 70 ^{o}C to constant weight and then weighed and ground. Plant and grain N concentration was determined using the Kjeldahl method. The plant N uptake was determined by multiplying whole-plant N concentration and dry biomass.

Total N uptake at harvest was the sum of grain and straw N uptake. Due to some construction projects, no samples were collected for the first column near the west boarder of Field 1. Six farmer's fields near the study site were selected, and GreenSeeker sensor data, SPAD meter readings and plant samples were collected from three representative 1 m^2 area in each farmer's field. Since most farmers apply more N fertilizers than necessary, these fields were used as N-rich reference plots.

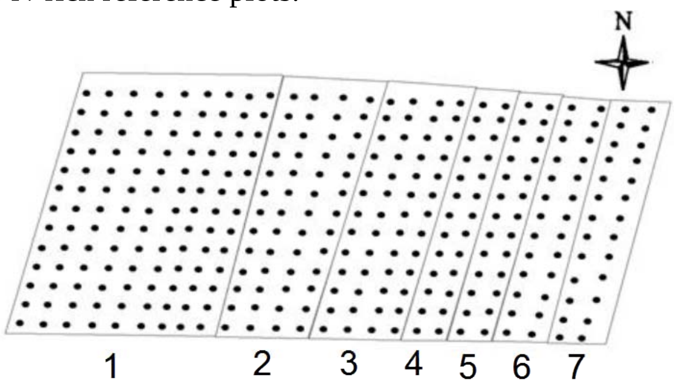

Fig. 1. Sampling locations in the seven research fields.

Statistical Analysis

Semi-variogram analyses were conducted using GS+ version 5.3a (Gamma Design Software, Plainwell, MI, USA). Isotropic models were fitted in all cases and selection of semi-variogram models was mainly based on Residual Sums of Squares (RSS) and coefficients of determination (R^2) (Robertson 2000). The ratio of structural variance C over the sill of the semivariograms was used to indicate the extent of spatial dependence (Robertson et al. 1997). Mean correlation distance (MCD) provides a practical way to estimate the distance at which soil or crop properties are highly related, especially when spatial dependence is not strong(Han et al., 1994; Solie et al. 1999):

$$MCD = \frac{3}{8} * \frac{C}{C_0 + C} * A$$

(1)

where C_0 is the nugget variance, C is the structural variance, and A is the effective range of spatial dependence.

To use CM and GreenSeeker readings to diagnose plant N status and estimate N demand, NSI and RI_{NDVI} were calculated. Since no N rich plots were established in this study, we selected data from five grids that had both high SPAD and NDVI values and averaged them for use as reference values in the calculation of NSI and RI_{NDVI}. This approach is similar to the virtual reference strip (VRS) concept proposed by Holand Scientific company (Samborski et al., 2009) and confirmed by comparing them with data collected from 6 surrounding farmer's fields receiving adequate preplant N application. The average values were very similar.

Descriptive statistics and correlation analysis were performed using STATISTICA 6.0 (StatSoft, Inc., Tulsa, OK,USA). Spatial distribution maps of selected parameters were generated using either kriging, inverse distance weighting (IDW) or radial basis functions available in the Geostatistical Analyst extension in ArcGIS (ESRI, Redlands, CA,USA), depending on which method gave the best cross-validation results.

RESULTS AND DISCUSSION

Variability of Indigenous Nitrogen Supply

Winter wheat yield without any fertilization varied significantly across the seven fields, ranging from as low as 845 to 7627 kg ha^{-1} (average =3779 kg ha^{-1}, and CV=29.72%). Aboveground N uptake (representing INS) had higher variability compared with the yield, ranging from 22.1 to 233.1 kg ha-1 (average=98 kg ha^{-1}, and CV=36.34%) (Table 1).

Field to field variability was quite obvious. Field 1 had the highest yield and plant N uptake, while Field 3 had the lowest, and the yield and N uptake difference between these two fields were 1715 and 61.5 kg ha^{-1}, respectively.

Within-field variability in some fields was as high as overall variability across the seven fields. Field 3 not only had the lowest yield and N uptake, but also the highest variability for these two parameters, with CVs being about 34 and 34%, respectively.

Field 5 had the lowest variability in yield and N uptake, with CVs being 18.76 and 17.49%, respectively.

Across all the seven fields, average above-ground plant N uptake varied from 25.96 to 164.36 kg ha^{-1} (mean=96.08 kg ha^{-1}; CV=41.52%) and from 33.38 to 319.54 kg ha^{-1} (mean =143.54 kg ha^{-1}; CV=34.79%) at jointing and harvest stages, respectively (Table 1). Field 1 and Field 4 had the highest (180.68 kg ha^{-1}) and lowest (96.45 kg ha^{-1}) average soil N supply, respectively. Within a field, the CV varied from 17.97 to 33.48% (Table 1).

Table 1. Descriptive statistics of winter wheat yield and above ground N uptake in the seven farmer's fields in Quzhou, Hebei Province, China.

Field	N	Grain Yield				Total N Uptake			
		Mean	Min.	Max	CV%	Mean	Min	Max	CV%
		--------- kg ha^{-1}------				--------- kg ha^{-1}----------			
1	101	4411	2282	7267	19.82	126.5	63.0	233.1	24.88
2	52	3634	1352	5746	27.23	93.7	31.0	167.0	28.49
3	52	2696	1014	4817	33.17	65.0	22.1	121.6	34.25
4	26	2837	845	4394	27.12	65.5	29.4	103.7	27.05
5	26	3998	2958	5577	18.76	93.2	60.2	129.4	17.49
6	26	3894	1944	6084	25.22	88.9	37.8	138.8	29.27
7	26	4358	2366	6253	26.15	107.9	68.5	165.8	30.03
All	309	3779	845	7267	29.72	98.0	22.1	233.1	36.34

Spatial Structures of Indigenous Nitrogen Supply

Wheat N uptake showed either weak or moderate spatial structure either across the several different fields or within individual field (Table 2), and the range of spatial dependence within a field varied from 48 – 112 m, but the mean correlation distance was all less than 21 m. Across different fields, however, the spatial dependence was stronger than within a field.

Table 2. Geostatistical parameters of above-ground winter wheat nitrogen uptake at harvest stage.

Field	N	Ratio†	A‡	MCD§	Model¶
		--%--	------m------		
1	101	20.90	49.3	3.86	G
2	52	63.65	85	20.29	S
3	52	47.17	90	15.92	S
All	309	66.93	368	92.36	S

† Ratio: The ratio of structural variance C over sill (C0+C), where C0 is nugget

‡ A: effective range of spatial dependence

§ MCD: mean correlation distance;

¶Semi-variogram model: S=Spherical; G=Gaussian.

Evaluating Chlorophyll Meter and GreenSeeker Sensor for Estimating N Responsiveness

The N Sufficiency Index (NSI) (Peterson, 1993) based on SPAD meter readings (Fig. 2, left) and N Response Index (Mullen et al., 2003) based on GreenSeeker NDVI (Fig. 2, right) at jointing stage all indicated that Field 3 and 4 would be most responsive to N application, and the winter wheat yield and N uptake at harvest indicated these two fields had the lowest yield and N uptake, indicating that these two methods are effective in estimating winter wheat responsiveness to additional N application.

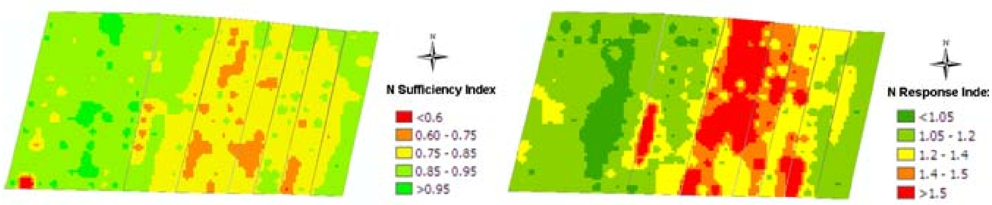

Fig. 2. N sufficiency index (NSI) based on SPAD meter readings (left) and N response index (RI) based on GreenSeeker NDVI (right) at jointing stage.

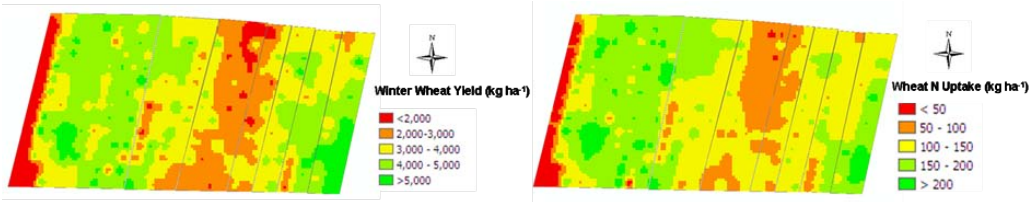

Fig. 3. Winter wheat yield (left) and wheat N uptake at harvest time (right).

CONCLUSION

Indigenous N supply varied significantly both within individual field and across different fields, the spatial dependence, however, was not strong. Both chlorophyll meter (SPAD meter) and crop canopy sensor (GreenSeeker) showed good potential for detecting winter wheat N deficiency and response to additional N application at jointing stage, which is the critical stage for topdressing N application in North China Plain. and application in precision crop N management.

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